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Synopsis of Some Preliminary Computational
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Area G

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Synopsis of Some Preliminary Computational Studies Related to Unsaturated Zone Transport at Area G

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Abstract

Computational transport models are described with applications in three problem areas related to unsaturated zone moisture movement beneath Area G. These studies may be used to support the ongoing maintenance of the site Performance Assessment. The three areas include; one, a 1-D transient analysis with average tuff hydraulic properties in the near surface region (in the top ~ 10') with computed results compared to field data, two, the influence on near surface transient moisture percolation due to realistic distributions in hydraulic properties derived statistically from the observed variance in the field data, and three, the west to east moisture flow in a 2-D steady geometry approximation of the Pajarito Plateau.

Results indicate that a simple transient model for transport of moisture volume fraction fits field data well compared to a moisture pulse observed in the active disposal unit, pit 37. Using realistic infiltration boundary conditions for summer showers and for spring snow melt conditions, the computed moisture pulses show significant propagation to less than 10' depth, in agreement with observations at several boreholes at Area G. Next, the hydraulic properties were varied on a 2-D grid using statistical distributions based on the field data means and variances for the hydraulic parameters. Near surface transient percolation in these conditions shows a 'qualitatively realistic' percolation with a spatially variable wave front moving into the tuff, however, the flow does not channel into preferred paths and suggests there is no formation of 'fast paths' which could enhance transportation of contaminants. Finally, moisture transport is modeled through an unsaturated 2-D slice representing the upper stratigraphic layers beneath Area G and a west-to-east cut of several miles to examine possible lateral movement from the west where percolation is assumed to be greater than at Area G. Results show some west-to-east moisture flux consistent with the assumed west-to-east profile for the percolation boundary conditions. The addition of evaporation boundary conditions at mesa edges leads to quantitatively good agreement with field observations of moisture except in the lower stratigraphic layers within the mesa. Here the computed moisture exceeds the field observations and suggests that the vapor flux and evaporative moisture loss are significant factors to the observed moisture profiles in this region. The simulations which include evaporation at mesa edges suggest that the mesa top hydrology is uncoupled with the deeper stratigraphies beneath the mesa and the canyon bottoms, at least in locations where the hydrology is undisturbed by site operations.

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Summary

Computational transport models are described with applications in three problem areas related to unsaturated zone moisture movement beneath Area G. These studies may be used to support the ongoing maintenance of the site Performance Assessment. The three areas include a 1-D transient analysis with average tuff hydraulic properties in the near surface region (in the top 10') with computed results compared to field data, the influence on near surface transient moisture percolation due to realistic distributions in hydraulic properties derived statistically from the observed variance in the field data, and west to east moisture flow in a 2-D steady geometry approximation for the Pajarito plateau.

A 1-D (vertical) transient analysis uses the transport equation for moisture volume fraction, θ , where the near surface hydraulic properties are assumed constant. Using average tuff properties (unit 2b), code results are compared to a transient moisture pulse observed in pit 37 during the mid-'96-'97 annual period. The large moisture pulse observed in the field is attributed to a local 'bath-tubbing' in a low area near the moisture monitor ports, however, the magnitude does not greatly exceed the percolation predicted in a wet year from the skewed distribution expected for long term percolation [Springer, 96]. Computed results are in good agreement with the field data for this event, and the code is used to predict transients resulting from more typical summer shower conditions and from realistic spring snow melt conditions. These code results agree with field observations that under most conditions the seasonal moisture transients decay within 10' from the surface.

Study of near surface transient percolation was extended in a 2-D model to explore the role of the variability of hydraulic properties within a single stratigraphic unit. Transients were modeled as a moisture pulse through a zone where each grid cell had hydraulic properties determined by statistical generation based on the observed variability of the actual parameters in field samples from Unit 2b (the upper tuff layer at Area G). It was observed that under the model conditions there was no evidence for 'fast-path' formation or flow which develops in strongly preferential channels from the statistically variable properties. The computed results are qualitatively realistic in appearance.

Moisture flow through the unsaturated zone of the upper layers in the Pajarito plateau is modeled using the transport of matric potential. A 2-D steady geometry is approximated which includes the upper most several stratigraphic layers from Area G, a west to east distance of the order, 10-20 km, and internal boundary conditions to simulate the edges of local mesas in the terrain. Moisture results show a west to east trend dependent upon assumed net infiltration boundary condition profiles, with distinct moisture

differences at the stratigraphic unit interfaces as expected in the matric potential model formulation. The lateral flow is small in most layers and consistent with the assumed infiltration boundary conditions. The computations agree with field data in most stratigraphic units with a significant exception in the lower interior layers of the mesa, where the computed moisture exceeds the field data even with evaporating mesa edges included in the simulation.

This supports the extensive field data evidence that vapor phase flux has been a significant contributor to drying these regions at depth and therefore the moisture profiles are dependent upon the vapor phase contribution to moisture flux. Future work in the 2-D west-to-east modeling which couples the liquid and vapor phase contributions to moisture flux would be expected to match field data throughout the profiles. The vapor flux can be modeled as a diffusive term which enhances the flux proportional to the gradient of the matric potential (head). This term is based on an empirical evaluation of the in-situ vapor diffusivity [Vold and Eklund, 96A] which will drive a significant fraction of the moisture flux at low moisture content for the hydraulic flow parameters in tuff [Vold, 96B].

Introduction

Transport in the unsaturated zone is important to the Performance Assessment of the Los Alamos low level waste disposal facilities at Area G [Hollis, et.al.'97]. Previous computational studies have analyzed a base case for the 'long-term site performance' based on expected parameters and taken into consideration some of the major factors contributing to variations and uncertainties in the hydraulic data inputs [Birdsell, et.al., '95, Birdsell, et.al., '97]. It is only possible to cover a finite set of parameters in examining model variability, and so there is an ongoing effort to refine the modeling and to reduce the uncertainties inherent in these long term predictions. This report summarizes computational studies in three select areas which may be used to support the ongoing maintenance of the site Performance Assessment, and may serve as preliminary assessments and guidance to more detailed computational analyses in the future.

The three areas examined here include 1-D transient analysis in the near surface region (in the top 10'), the influence on 2-D transient near surface moisture percolation due to realistic distributions in hydraulic properties derived statistically from the observed variance in the field data, and the west to east moisture flow in a 2-D steady geometry approximation for the Pajarito plateau. This report first summarizes the basic equations and computational methods used in the moisture transport models and then describes the results from the three computational study areas. The discussion and conclusions sections integrate the results from the three study areas.

Unsaturated Zone Moisture Flux Equations

The continuity equation for mass, ρ , in a single species flow is written

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \Gamma = 0. \quad (1)$$

where Γ is the mass flux. In multiphase and or multispecies flow there can be source terms and diffusive flux with respect to the bulk flow.

In the context of a multiphase flow and in cases where the density within the liquid phase, ρ_l , is approximately constant, a continuity equation for the liquid phase moisture content expressed as a volume fraction, θ , can be written as

$$\frac{\partial \theta}{\partial t} + \nabla \cdot q = S_\theta \quad (2)$$

where q is the volume flux and S_θ is a source or sink term to the liquid phase. In the unsaturated zone, considering liquid phase transport only, the flux can be written

$$q = -K[\theta] \{ \nabla h_m[\theta] + z \} \quad (3)$$

where $[\theta]$ denotes a functional dependence upon the moisture content, and h_m is the matric head. Inserting Eqn.3 into Eqn.2 gives the standard 'mixed form' of Richards equation, where θ is the conserved quantity but the flux is in terms of the gradient in matric head, h_m . These can be solved directly using non-linear equation solvers.

Traditional methods of computational solution for transport equations rely on the same conserved quantity in the time derivative and in the flux terms. The form in Eqns.2-3 can be converted to an equation for h_m using

$$\frac{\partial \theta}{\partial t} = \frac{d\theta}{dh} \frac{\partial h_m}{\partial t} \quad (4)$$

which then gives the transport equation for h_m as

$$\frac{d\theta}{dh} \frac{\partial h_m}{\partial t} + \nabla \cdot (-K[\theta] \{ \nabla h_m[\theta] + z \}) = S_\theta. \quad (5)$$

An alternative form, useful in some situations, can be written for θ , by noting

$$\nabla h_m[\theta] = \frac{\partial h_m}{\partial \theta} \nabla \theta + \frac{\partial h_m}{\partial f_m} \nabla f_m \quad (6)$$

where f_m is an empirical function describing the matric potential as a function of moisture content, and f_m may itself vary as a function of position. In regions where the matric properties are approximated to be uniform in space, this simplifies as

$$\nabla h_m[\theta] \sim \frac{dh}{d\theta} \nabla \theta \quad (7)$$

which gives an evolution equation for θ in the form

$$\frac{\partial \theta}{\partial t} + \nabla \cdot \left(-K[\theta] \left\{ \frac{dh}{d\theta} \nabla \theta + z \right\} \right) = S_\theta. \quad (8)$$

This form has computational advantages as it is similar to a diffusion-convection problem with the inhomogeneous diffusion coefficient equal to the soil diffusivity, D_s , given as

$$D_s[\theta] = K[\theta] \left| \frac{dh}{d\theta}[\theta] \right|. \quad (9)$$

As noted, Eqn.8 is limited in application to regions where the matric properties can be represented with a single function of moisture content. This form is not accurate when the hydraulic properties vary significantly in space. In that case, accuracy requires using Eqn.5, or using Eqn.2-3 together which requires a more sophisticated non-linear solver technique.

Computational Models Implementation

1-D Near Surface Transient Model

The 1-D near surface transient model assumes uniform hydrologic properties, and therefore solves for θ , using a 1-D version of Equation 8. The unit vector in the vertical axis, z , is directed upward, so the vertical component of volume flux can be written

$$q_z = -K[\theta] \{ (\partial h_m[\theta]/\partial \theta)(\partial \theta/\partial z) + 1 \}. \quad (10)$$

Hydrologic properties are taken from the mean stratigraphic properties for (Unit 2b) Bandelier Tuff as recently revised [Vold,97B]. Differences between crushed and intact tuff are neglected as previous comparisons suggest the hydraulic property differences are small.

The computational model uses standard central differencing for the diffusive term (first term on RHS of Eqn.10), and 'upwind' differencing for the conductive term, $-K[\theta]$, using the value from the neighbor cell at the next higher vertical location ($iz+1$). In both terms, the unsaturated conductivity at the previous time step is used to simplify the integration method, which is implicit for the diffusion term and explicit for the conduction term. The time

step is controlled so that the convection velocity times the time step remains less than the vertical grid size. This simple procedure is seen in the Results section to work well for the near surface transients.

2-D Percolation with Statistical Variability of the Hydraulic Parameters

The 2-D model solves for the matric potential, Eqn.5, so that variable stratigraphic properties can be accurately included. The vertical component of volume flux can be written

$$q_z = -K[\theta] \{ (\partial h_m[\theta]/\partial z) + 1. \}, \quad (11)$$

The discretization model uses similar basic techniques as described above for the vertical component of the moisture volume fraction. A horizontal component of moisture flux, q_x , contains only the diffusivity term, or

$$q_x = -K[\theta] (\partial h_m[\theta]/\partial x). \quad (12)$$

This horizontal component of the diffusive contributions to transport of the matric potential are coupled to the vertical diffusivity terms in a fully 2-D implicit scheme based on a standard Linear Biconjugate Gradient method [Press, et.al.,92]. The vertical advection term is lagged in an explicit treatment, and limits the time step required for numerical stability.

Hydraulic properties were input to the model considering the arithmetic and the geometric mean and standard deviations for the upper tuff layer at Area G, unit 2b as summarized in [Vold, 97B], based on 8 core samples. Properties include the measured saturated conductivity, K_{sat} , and saturated moisture, θ_{sat} , and the van Genuchten parameters fit to the moisture characteristic curves, α and N , and residual moisture. Parameters with large variability were assumed to be log-normal (α , K_{sat} , θ_{res}) and parameters with smaller deviations were assumed to be normally distributed (N , θ_{sat}). No correlation between parameters was assumed, so each was varied independently.

A 2-D square computational grid with zones on the order of 10 cm was setup with random properties in each grid cell based on the field data statistics. This statistical procedure involves equating a random number, R_n , to the cumulative probability density function, $cpdf$, which is of the form

$$cpdf = 0.5 + 0.5 \operatorname{erf}[z]. \quad (13)$$

For a normal distribution in the variable, u , then

$$z = (u - u_{av})/(\sqrt{2} \sigma) \quad (14)$$

and for a log-normal distribution, then all the parameters, u , u_{av} , and σ , are calculated after a log transform, taking the natural log of the data. A non-

linear equation solver (bisection algorithm) is used to back calculate z implied in equating (13) to a random number. The actual hydraulic property for a grid zone is then computed from the randomly determined value for z using the actual property statistics in Eqn. 14 for normally distributed parameters and using the log transformed data in Eqn.14 for log-normally distributed parameters. A new random number is generated at each grid point and for each of the five hydraulic properties, consistent with the assumption that the properties are independent.

2-D Lateral Flux Model

This model is similar to the previous case, solving Eqn.5 for the transport of matric potential. In order to examine the flow along interfaces which are sloped and not horizontal, the moisture flux was separated into a vertical component and a lateral component along the angle assumed for the stratigraphic slope, rather than exactly horizontal. This implies that the coordinates are not exactly orthogonal but a reasonable orthogonal approximation can be made using a control volume differencing along the lateral axis. This lateral axis is oriented to represent a 'gentle slope' (from the west to east on the Pajarito Plateau), making a dip of angle ϕ from the horizontal (where $\phi \sim 3$ degrees for the Pajarito plateau). The lateral moisture flux, q_s along this axis is then just,

$$q_s = -K[\theta] \{ (\partial h_m[\theta]/\partial s) + \sin \phi \}, \quad (15)$$

where ds is along the lateral flux axis. This length, ds is related to the horizontal distance, dx , as $dx/ds = \cos \phi$. The area through which the lateral flux moves, A_s , is used in the computational finite difference scheme, and is proportional to a length, dl , related to the regular vertical grid distance, dz , as $dl/dz = \sin \phi$. The code is written so that the angle, ϕ , can be varied arbitrarily as a function of horizontal distance, x . Somewhat further generalization would be required to allow the formulation to apply to the case where the slope angle also varies with depth as needed to represent stratigraphic layers which are not parallel.

2-D Lateral Flux Solution Methods

Equation 5 is integrated over a control volume and discretized using standard techniques to obtain an algebraic equation at each grid cell. For example, the discretized vertical flux from Eqn.10 evaluated at node, $i+1/2$, is

$$q_z(i+1/2) = -K[\theta]_{i+1/2} \left(\frac{(h_m[\theta]_{i+1} - h_m[\theta]_i)}{(z(i+1) - z(i))} + 1. \right) \quad (16)$$

Using the relations described with Eqn.15, the lateral moisture flux is discretized using standard control volume differencing methods. The coupled equations on the 2-D spatial grid are solved as a single linear system using a linear biconjugate gradient subroutine [Press, et.al., 92]. The 2-D diffusivity terms are implicit but the advection is explicit and the coefficients are lagged. Thus, the transient solution is not accurate and is used only as a relaxation means to obtain the steady state converged solution. While the transients are not accurate, the pseudo-time needed to converge to a steady state probably reflects a realistic characteristic time scale for the system to evolve. This value is discussed later.

The boundary conditions used in the 2-D lateral flux simulations are described in the Results section, where the detailed geometry of the problem under consideration is presented.

2-D Lateral Flux Initial Conditions

Initial conditions can be specified as a constant moisture or matric potential throughout the region or as profiles which are self-consistent along each vertical column of grid cells and consistent with the local surface flux boundary condition specified. This vertically self-consistent profile is found by considering the steady state source free moisture flux along each 1-D vertical axis. Simplifying Eqn.5 for these assumptions, this case is governed by

$$\frac{\partial}{\partial z} \left(-K[\theta] \left\{ (\partial h_m[\theta]/\partial z) + 1. \right\} \right) = 0. \quad (17)$$

Integrating once gives the vertical flux, Γ_z , which must be constant in this case and is specified as the surface flux boundary condition, Γ_{bc} , or

$$-K[\theta] \left\{ (\partial h_m[\theta]/\partial z) + 1. \right\} = \Gamma_z = \Gamma_{bc}. \quad (18)$$

Rearranging

$$\partial h_m[\theta]/\partial z = -1. - \Gamma_{bc} / K[\theta] \quad (19)$$

and integrating again, the result can be written as a finite difference expression

$$\Delta h_m[\theta] = h_m[\theta]_1 - h_m[\theta]_0 = \Delta z (-1. - \Gamma_{bc} / K[\theta]), \quad (20)$$

which can be integrated vertically upward along z , from a known value, the boundary condition at the bottom of the region.

This provides the solution to the source free 1-D case along each vertical column in the 2-D problem, and is a good first guess to the actual 2-D problem. The 2-D problem is then already consistent along each vertical

column of cells with the ground surface percolation boundary condition prescribed at that location and then evolves as a 'relaxation' due to lateral flux balancing the moisture flow between adjacent vertical columns. We have found in many simple cases (e.g., horizontal box geometry with realistic gradients in the surface percolation boundary condition) that the final relaxed solution is very close to the initial guess provided by solving Eqn.20 along each vertical column of grid cells.

Several discretizations were compared in solving Eqn. 20, integrating it upward from the lower boundary condition. The moisture flux is downward and may be dominated by the hydraulic conductivity in the upper layers, so that an implicit formulation in the integration from lower elevations may be appropriate. Eqn. 20 was discretized using 'upwinding' (fully implicit integration evaluating K at the next higher elevation during each integration step), using an explicit method evaluating K at the current elevation, akin to a 'downwinding' integration, using a mean K from the current and the next elevation (akin to Crank Nicolson integration) and also a geometric average value of K between the current and next elevation. Each method produced nearly identical results except the geometric averaged values which differed by ~10-20%. The explicit integration was then used in the code to set the initial conditions when a 'self-consistent vertical profile option was selected for the initial condition.

Results and Discussion

Moisture Pulse Transients

Pit 37(w) Field Data for a Moisture Pulse (9/96-5/97)

The first study involves comparison of the 1-D transient model results to an observed moisture pulse seen in neutron probe data collected in the borehole at the west end of in pit 37, denoted (37(w)). This data and profiles in several boreholes at Area G were summarized recently in [Vold,97A]. The pulse was observed during the fall '96 to summer '97 time frame and has been attributed to a redistribution of the active disposal pit topography, which led to 'bath-tubbing' near the moisture monitoring boreholes during that time. First, some field data from pit 37 is examined.

Figure 1 presents moisture profiles (volumetric percent by neutron probe) vertically through the upper 35' of disposal unit 37 (west end), showing 1994 data (top left), mid-1996 data (top right), and comparisons of 1994 and 1996 profiles without a depth correction (bottom left) and with a 2' depth shift to the '94 data (bottom right). This shows that by shifting the data to account for differences between the years in defining the elevation where $z = 0$, and that prior to the surface grading in the fall of '96, there was a negligible change in moisture profile over the two year period from '94 to '96.

Figure 2 shows moisture profiles (volumetric percent by neutron probe) vertically through the upper 35' of disposal unit 37 (west end), data from August, 1996 to May, 1997, showing increased moisture content migrating downward throughout the year. The same data is displayed so that the moisture pulses are better resolved in Fig. 3 showing moisture content verses depth and time over approximately one year (8/95 to 6/96). The left figure shows the actual resolution of the neutron moisture probe and the right figure shows a smooth interpolation of the data. Two moisture pulses are resolved near the surface occurring in the fall (following summer rains) and in the spring (following snow melt), with the snow melt moisture pulse being more significant in this case.

Figure 4 shows the moisture pulse integral (in cm of water) for the two pulses in pit 37 as a function of time. The pulse integral is simply the net moisture integrated over the depth profile at each time after subtracting out the 'background moisture', equal to the average of the profiles in Fig. 1. Each pulse shows a steep rise as more moisture inflows, and then a gradual decrease from the pulse maximum as the moisture source has apparently been removed, and the moisture decreases by evaporation losses at the ground surface and by lateral dissipation, thus, relaxing the moisture profile at depth at this location. The peak influx of moisture for the two pulses is about 12 cm and 14.5 cm, which far exceeds the normal percolation, estimated to be about 0.5 cm/yr on the average based on several estimation methods [Hollis, et.al., 97], [Vold, et.al 96]

Figure 5 compares the moisture pulse magnitude verses time by two estimates (pulse max height or pulse integral moisture) for the first pulse (Moisture pulse 1 - autumn, 1996) seen in pit 37w. Either method shows a similar profile in time with a peak near 50-60 days after the latest background profile (09/18/97), and a gradual decrease after that due to evaporative losses and lateral dissipation. Figure 6 shows an extrapolated estimate of pulse start date by the two methods (shown in Fig. 5) for moisture pulse 1. This was helpful in determining an 'initial time' for the computational model, and also for comparing to annual precipitation data as discussed later in Figs. 11-13.

Figure 7 shows the moisture pulse 1 (fall '96) verses depth for selected times as measured by neutron probe. This first pulse was compared to computational model results as discussed in the following section.

Pit 37(w) Moisture Pulse - Field Data Compared to Calculation

Calculational results from the model of moisture volume fraction transport in a homogenous matrix (Eqn. 8) are shown in Fig. 8 for the above moisture pulse #1, assuming a constant background of 8% volumetric moisture content, and assuming tuff, unit 2b hydraulic properties [Vold, 97B]. The calculations use the moisture integral observed in the field, ~12cm, and input this to the ground surface over a short pulse (a few hours) which defines the initial time in the simulation.

The calculation can be compared to the field data in Fig.7. The field data pulse is assumed to have started at ~ 9/20/96, so that the 12/24/96 profile is at time ~ 95 days, when the maximum volume content is ~ 12% and the pulse front (vol%=10%) is at 13' depth. In the calculation at this time, (midway between the 74 and 130 day output) the maximum volume content is ~12% and the moisture pulse front (vol%=10%) is at about 12' depth. At the earlier date, 11/07/96, time since pulse initiation is ~ 50d, where the field data shows maximum vol%~14% and the moisture front (vol%=10%) is at 10' depth. In the calculation at 51 days, the maximum vol%~13% and the moisture front (vol%=10%) is at 10' depth.

Agreement is quantitatively good to better than 10% at later dates, which can also be seen in comparing Figs.9 and 10, which show the apparent Darcy flux over time, expressed as an average annual flux (cm/yr). Figure 9 shows Darcy flux estimated from the change in position of the moisture front with depth as measured in the field data. Figure 10 shows Darcy flux estimated from the change in position of the moisture front with depth as determined in the computed moisture front. The apparent flux per year is large initially and decays rapidly in time as the pulse duration is much shorter than the full year. The initial conditions are somewhat unknown for the field data (sometime after 09/20/96), and assumed to be a large slug in the calculations which leads to larger differences in the earlier times, and better agreement at later times when the results become less sensitive to the actual shape of the moisture pulse at early times.

Computed Results for Expected Seasonal Transients

Before applying the computational model to seasonal transients it is worth estimating the infiltration boundary conditions expected under 'normal conditions', i.e., without the 'bath-tubbing effect' which has apparently led to the unusually large slug of moisture percolating into pit 37 in the '96-'97 period.

Figure 11 shows precipitation data (24hr totals) at WR/TA54 verses Julian day for 1996 [data from LANL, ESH-17, website]. Fig.12 shows the same data as a cumulative precipitation at WR/TA54 (24hr total) verses Julian day for 1996. This shows that at the time of the pit 37 moisture pulse (at ~ 200-250 Julian days) the integral precipitation for the year was 8-10 in, or about 23 cm. Comparing to the moisture pulse magnitude estimates above, almost half of that precipitation percolated into pit 37 during this time. This can be compared to 0.5 cm/yr expected under 'mean conditions' [Hollis, et.al., 97], [Vold, et.al.,96], and compared to the maximum expected values for annual percolation, of a few cm/yr, derived from differences in precipitation and evapotranspiration data taken at the west end of the Los Alamos site [Vold, 97C].

These considerations suggest that the pit 37 moisture pulse seen in 96-97 did not occur under normal percolation conditions. A bathtubbing effect

due to disposal operations and surface grading is implied as a likely explanation for the magnitude of the moisture pulse.

On the other hand, the annual percolation into a disposal unit (cm/yr) verses year is calculated from precipitation data series synthesized from local meteorologic data (provided by E. Springer [1996] as shown in Fig.13. This indicates that the expected annual percolation is highly skewed, as percolation occurs significantly only once every 5-10 years, with zero percolation in the intervening years, in ~80% of the years. The transient pulse observed in pit37 is not that far out of line with the expectations for a "high percolation year" for the undisturbed case.

Next, we turn to transients for expected infiltration conditions. A summer shower case is simulated by specifying a precipitation event of 1" in one hour, which represents a 'typical maximum' summer storm event (observed once or twice every year or two). This is input to a uniform background of 8% moisture volume content, which is typical for Area G near surface conditions during the 'rainy season'. After the rain, evaporation at the surface and percolation to deeper elevations occurs. Figure 14 shows the calculated results for this moisture transient (~1" precipitation over a one hour duration) at several times. Top and bottom figures show the same data on different scales, which allows one to consider the early time moisture spike in the top figure and the slower decrease in moisture by surface evaporation and deep percolation at later times out to 32 days.

A snow melt condition is simulated by assuming the average March precipitation total (~1") occurs continuously over the duration of the month, with no net evaporation occurring. Recent examination of local evapotranspiration data at TA-6 [Vold, 97C] shows that evapotranspiration is very small at this time of the year and so these simulation conditions are fairly close to a 'typical worst case' for snow melt. Figure 15 shows the moisture transient calculated for this maximum spring snow melt case (average March total precipitation of ~1" is input continuously over the month). This lower percolation rate produces a moisture pulse of smaller magnitude compared to the summer shower case.

In both simulated events it is seen that the moisture pulse is significantly greater than the background initial conditions down to a depth of about 6'. This is in good agreement with the seasonal variations in the upper 10' observed at several boreholes at Area G [Vold,97A]. One example of the field data is reproduced in Fig. 16, showing moisture profile data from neutron probe measurements [Vold, 97A] in borehole 1121 at Area G. This shows the variation in time from 8/96 to 5/97, with the fall and spring moisture pulses evident in red near the top. Note that a depth index of zero in the figure corresponds to a depth of 1', so that the temporal variations in the field data are evident in green down to ~6' (depth index of 5 at late times for the spring pulse). This is in good agreement with the simulations seen in the previous figures and indicates a simple transient model with Tuff, unit 2b, properties gives reasonably accurate results for transient near surface percolation.

An important followup to this study might examine the transition to steady state from transients by modeling the transients in detail as in this study. Previous transient studies for the Area G PA [Birdsell, et.al., 97] examined transients only resolved to a annual average percolation rate. By following the transients in detail as in this study, it should be possible to more fully bridge our understanding from the transient moisture movement to the steady state movement for a typical year. This could possibly overcome a limitation in the previous uses of the FEHM code in Area G PA modeling that the surface boundary condition must be specified as a net infiltration rate. Unfortunately, this boundary condition is not easily determined from field data which is itself complicated and not always completely self-consistent [Vold, et.al.96].

By following realistic precipitation data on approximately an hourly time step for example, the actual percolation resulting from the precipitation and intermitant evaporation between percolation events would evolve self-consistently, at least for the late evaporation regime which is limited by the soil matrix loss and not the evaporation potential. To the extent the evaporation is controlled by the soil loss and thus the soil matrix properties, the transient solution will resolve the net percolation in a self consistent manner for a minimally vegetated surface area (probably a reasonable assumption for much of Area G). It might then be possible to adjust parameters or the code to more self-consistently include the effects of evaporation driven by the evaporation potential and effects of transpiration.

2-D Transients with Statistically Variable Hydrologic Properties

The methods were described above for the study of the statistical variations in hydraulic properties on the near surface percolation. The original goal was to determine if a simulated variability could lead to percolation channeling itself into preferred flow paths, along the path of least hydraulic resistance. In these simulations some initial runs were done as test cases for the transport of moisture volume fraction, θ , solving Eqn.8. This is not accurate for the variable property case, and so the final runs were done for transport of matric potential, Eqn.5. Each of these cases are difficult to run because the variable property conditions tend to restrict the time step in proportion to the pore water velocity at the grid point where it is maximum. Since the hydraulic properties are highly skewed, the combined unsaturated hydraulic conductivity is highly skewed, and so the maximum grid velocity tends to be orders of magnitude greater than the grid mean value and thus the time step is forced to an extremely small value. This problem is more pronounced for the transport of matric potential by Eqn.8, due to the nature of the transport coefficients derived from the statistical distributions.

The moisture volume fraction transport case is considered first. Figure 17 shows the initial condition moisture content corresponding to the statistically generated hydraulic parameters (unit 2b). Moisture content at 1 hr (at the end of the precipitation input) is seen in Fig. 18 for this case. Moisture

content at 2 hr (1 hr after the end of the precipitation input) is shown in Fig. 19 and at 7 hr (6 hr after the end of the precipitation input) in Fig. 20. The moisture front has a qualitatively realistic appearance as it propagates downward into the matrix. At each time, one grid point near the lower left appears to have a high moisture content (~25%), where apparently the random variability of the properties has assigned this point a more clay-like characteristic than would normally be expected in the tuff. The nature of the volume fraction transport equation (Eqn.8) is that it will be more diffusive and less accurate than it should be and so the formation of a fast-path to moisture flow is unlikely to be realized with this governing equation.

Calculations of the matric potential by Eqn.5 should be more accurate. Figure 21 shows moisture content after 5000 iterations (~20min during the precipitation input) for the statistically generated hydraulic parameters and the matric potential based calculation of moisture transport. There is only slight evidence of a moisture front propagation near the very top of the figure, due to the extremely small time steps required for numerical stability in the present scheme.

Figs.22-25 shows variations of this situation. Figure 22 shows matric or capillary potential -cm- after 5000 iterations (~20min during the precipitation input) for the statistically generated hydraulic parameters and a matric potential or h_m -based calculation of moisture transport. The initial condition in these calculations is a variable matric potential related to the grid statistical properties and assuming a uniform initial moisture volume content of 8% .

Figs.23-25 are for the case where the initial matric potential is constant, corresponding to the average moisture content value of 8%, while the actual initial distribution of moisture is calculated from the constant matric potential and the statistical parameters for each grid cell. This potential equilibrium 'initial condition' seems a better representation theoretically, but leads to huge variability in the moisture throughout the zones, probably greater than observed in the field [Vold and Eklund,96B].

Figure 23 shows matric or capillary potential -cm- (~20 min during the precipitation input) for the statistically generated hydraulic parameters and a matric potential (h_m) based calculation of moisture transport. Constant matric potential initial conditions were assumed, $h_m = -955$ cm (corresponding to $\theta \sim 8\%$ for these hydraulic properties (unit 2b). Figure 24 shows moisture content initial conditions for this case. Figure 25 shows the moisture content at 'late times' (5000 time steps or iterations, ~20 min during the precipitation input) for the same case. Although slight evidence of a moisture front is apparent in the matric potential after 5000 time steps (~20 minutes of precipitation (Fig.23) it is clear between Fig.24 and Fig.25 that the moisture content is still dominated by the variability in the initial conditions.

These simulations suggest there is no development of preferred paths for moisture movement due to the hydraulic property variability. The variability in the simulations probably overestimates the actual variability since the parameter variabilities are assumed independent and the field

variability represents variability across an entire stratigraphic unit and not within a small region represented by the computational simulations. The simulations are extremely difficult to follow for long times due to the time step restrictions inherent in the random variability of the hydraulic parameters, so the results here are far from conclusive. In future study, running these simulations out to a few hours after a major precipitation event would be more conclusive. Detailed comparisons against field data could be useful for calibrations.

2-D Hydrology Across Pajarito Plateau: W-E Stratigraphic Approximation (Otowi and above)

Geometry

The geometry is illustrated in Fig.26, showing cross-sections for the Pajarito Plateau West-to-East hydrology modeling study. The top figure shows a simplified N-S cross section of the mesa and lower units at Area G [from Vold, et.al., 96]. Bottom figure shows the W-E cross section of Pajarito Plateau [from LANL ESH18, original from W.Purtymun]. The model is a simple 'slanted box model' approximation to represent the upper stratigraphic layers in this W-E slice. Properties vary with depth according to the stratigraphic layers beneath Area G (as in Fig.26-top). These property and layer depth variations are extended through the west-to-east plane, and then a slope is added to the west-to-east axis using the lateral flux model described earlier. Initial simulations considered constant slopes of zero to five degrees along the west-to-east transect, and the final model geometry approximates the actual case in Fig.26-(bottom), with a slope of 3% across most of the region, steepening exponentially near the mountains (west boundary) to a maximum of about 10%. The actual stratigraphy west of Area G includes cooling units not present at Area G, which were represented in this simple approximation by the Area G stratigraphy. In all the simulation results, Area G conditions are located at about 80-90% of the W-E distance across the simulation (consistent with Fig.27(bottom)).

Boundary Conditions

The left and right sides of the problem domain are taken to be symmetry axes so the lateral flux is zero along these boundaries. The bottom of the computational domain is in the Otowi (corresponding to elevation 6500' at the location of Area G). Moisture content, or the corresponding matric potential, known from field data is specified along the domain bottom. This occurs in the Otowi region, where the potential corresponds to an average moisture content of 11.5% based on the core samples considered to date. This value has also been scaled along the W-E axis to allow wetter

conditions toward the West based on the vertical profile initial conditions consistent with the local percolation.

The top of the computational domain is the ground surface boundary. A net time averaged percolation rate is specified at the surface boundary, which is expected to vary strongly as a function of precipitation and thus of west-to-east position. Fig. 27 (Top) shows the percolation rate boundary conditions used in the Pajarito Plateau W-E computational study. (Area G is at about 11.5 km.) These are scaled from data based on analyses [Springer, 96], as shown in Fig.27 (Bottom). This shows percolation versus precipitation rates calculated for a disposal unit with vegetative cover characterized by a 48 cm rooting depth with an exponential fit to the data points from the individual calculated cases. The gradient in average annual precipitation from east (near Area G) to west along Pajarito Plateau is about 14 to 19 inches, corresponding to net percolation under fixed soil conditions which can vary from about 4mm to 4 cm with a nominal rooting depth specified in the percolation model [Springer, 96].

Hydraulic Properties and Initial Conditions

Unsaturated hydraulic conductivity versus moisture content for the upper stratigraphic layers at Area G are seen in Fig. 28 (Top). These data are used in the computational model and will be useful for reference in the later discussions. Figure 28 (Bottom) shows the implied moisture content in each stratigraphic unit for fixed values of the recharge rate (assumed equal to the unsaturated hydraulic conductivity) and in comparison to field data (θ -vol%) mean and standard deviations in each unit. This is based on a unit gradient assumption, or simply assuming that the local recharge rate is the unsaturated hydraulic conductivity evaluated at the stratigraphic unit's mean moisture content.

Fig. 29 takes this one step further by integrating the vertical profiles up from the Otowi boundary condition, according to the self-consistent vertical profiles developed in Eqns.17-20. This shows implied moisture profiles for fixed values of the recharge rate and in comparison to field data means and standard deviations in each stratigraphic unit (labeled θ (in-situ) - vol.frac-). By integrating the moisture content vertically from assumed moisture content in the Otowi (depth = 6500'), the simplifying assumption is eliminated that recharge rate is equal to the unsaturated hydraulic conductivity. These curves in Fig.29 then represent a range in moisture content expected for the variation in percolation input across the West-to-east 2-D Pajarito Plateau model.

The initial conditions for moisture across the Plateau model are seen in Fig.30, when the self-consistent vertical profile initial condition option is specified (Eqn.20). The obvious feature is the horizontal layer at elevation equal to 30 in units of the grid index, where a high moisture content is

associated with the Vapor Phase Notch. In this case, the initial conditions for the 2-D Pajarito Plateau W-E simulations are essentially the 2-D representation of all moisture curves in Fig.29, for the full range of recharge rates corresponding to the ground surface boundary conditions given in Fig.27(top). As expected when lateral flow is small, this initial condition is found to be quite close to the converged steady solution in some cases, e.g., when the lateral slope is zero everywhere. Fig. 31 shows lateral moisture flux (cm/yr) implied by the initial conditions in the Pajarito Plateau W-E simulations, in the previous figure. This flux is small everywhere, with a maximum of about 1.5mm/yr near the vapor phase notch at the west end of the simulation, and values less about 0.5 mm/yr at the Area G conditions.

Computational Solutions

Figure 32 shows converged solutions (moisture content and vertical flux) for the slanted box-model approximation to the Pajarito Plateau W-E problem. These solutions converge after the 'psuedo-time' stepping or relaxation which corresponds to a period of about 800 years in most cases. This is assumed to represent a realistic characteristic time response for the hydrology of the plateau upper stratigraphic layers. The moisture content has changed only slightly from the initial conditions in Fig.30, based on the locally self-consistent vertical profiles. The change is largest in unit 2a (elevation index 40-48 in the Figs). The slight change leads to a more significant evolution of the vertical and lateral moisture flux components in this region.

The converged vertical flux in Fig.32 (bottom) shows values consistent with the percolation rates throughout most of the region, however, where unit 2a showed slight increases in moisture, it shows large increases in vertical and in lateral flux. Figure 33 shows converged solutions (lateral flux) for the box-model approximation to the Pajarito Plateau W-E problem for two slightly different sets of assumptions (geometry scale and grid size of the plateau). These variations give lateral flux in this unit 2a region in the range of 0.6 to 2 cm/yr at the west end of the simulation and closer to a few mm/yr near the Area G conditions (distance W to E ~ 7.5 (top fig.) or 50 (bottom fig.)). The flux magnitudes are consistent with Darcy flux analyses results reported elsewhere [Vold,96A, and Vold 97C].

The increased moisture and flux in unit 2a is opposite of the observations from the field which show this horizon to be very dry at all boreholes at Area G, and typically drier than one can expect from liquid flux alone. This implies vapor phase movement is significant in the real case, while it is not included in the present moisture flux model. The large flux computed in this horizon is consistent with the calculated moisture. Referring back to the hydraulic properties in Fig. 28(top), it is clear that the largest decrease in hydraulic conductivity between adjacent stratigraphic units occurs in going from unit 2a down to the next layer, unit 1b. This restricts recharge downward from unit 2a to 1b, the moisture builds up and then the

hydraulic conductivity increases, leading to a larger vertical and lateral flux within the unit 2a.

The results are consistent with the model input, but not consistent with field data in this region. Mesa edges could contribute to drying this region, where the increased lateral flux would then act to dry the region out faster as the moisture moves down slope and eventually out the edge of a mesa. This possibility was explored by adding interior boundary conditions in the model to represent drying at a mesa edge.

The results for moisture in several cases where mesa edges are represented by these internal evaporative drying boundary conditions are seen in Fig.34. Three mesa edges have been simulated in each figure by fixing the matric potential to a value corresponding to a slight increment above the residual moisture content at the vertical cells in three columns which arbitrarily define the west-east location of the mesa edges. The three columns extend down to about the vapor phase notch which is seen to be coincident with the canyon floors at many locations throughout the plateau, including at Area G.

The 3 cases in Fig.34 represent a range in moisture results for differing grid assumptions, and problem dimensions. The first figure shows results on a 60 x 60 cell grid with 20m grid size, the second and third on a 20 x 60 (x,y) grid with 20 m grid size and different convergence criteria. The results are sensitive to the grid size with moisture content increasing for larger grid spacing or grid numbers (along x), because the 'larger problem domain' introduces more total precipitation into the problem. The exact solution for the mesa edge cases is sensitive to the exact convergence criteria and initial conditions, where the middle and bottom case in Fig.34 represent a typical range.

The sensitivity to initial conditions and to convergence criteria for the mesa edge case is opposed to the box model results in the previous figures. Previously in the box model the converged solution was insensitive to the initial conditions or convergence criteria and the problem was well behaved. It appears that in the mesa edge drying cases, a converged solution can be obtained by balancing the near surface moisture flux, that is the precipitation at the mesa surface and the drying at the mesa edge come into a local balance, independent of what occurs at the deeper horizons. Thus, a converged solution looks very different for the different initial condition cases: constant moisture or self-consistent vertical profiles, because the solution doesn't depend strongly on what's going on at the deeper layers. Similar sensitivity to the choice of convergence criteria is seen in the results.

This apparently poor numerical behavior may be related to a real physical effect. The results imply that the moisture flux at the mesa top is completely uncoupled from the moisture flux through the deeper stratigraphies beneath the mesa. This is consistent with Darcy flux analyses in several boreholes [Vold,96A, Vold96B, Vold97C] which show moisture predominantly moving upward from beneath the mesa and downward only to the 'drying layer' or vapor phase dominated region near the lower portion

of the mesa interior. This is one more piece of evidence contributing to the idea that the mesa near surface hydrology is not coupled to the canyon bottom and deeper stratigraphy hydrology, at least in the undisturbed mesa locations. There is considerable evidence that at some locations where disposal operations have disturbed the natural hydrology [Vold97A], then the surface percolation may 'pass down' through the vapor phase dominated region and allow a continuous liquid phase transport downward from the disposal units and other surface disturbances.

In the cases in Fig.34, the grid dimensions represents a smaller cross-section than the entire Pajarito Plateau. On a scale representing the full Pajarito Plateau, the computed profile results tend to be much more moist than observed in the field. The 'mesa edge' model then suggests that realistic moisture profiles are obtained only for smaller scale mesas, i.e., the mesa edge to edge distance in the model results is more typical of a north to south cut than the longer west to east cuts.

Figure 35 shows moisture profiles vertically through three horizontal locations (ix = 18, 17, and 9) from the second case shown in Fig.34. Area G is located near conditions expected at ix = 18 or 17, while ix = 9 represents conditions expected at a point several km to the west of Area G. The profiles seen in Fig.35 top and middle panels are in good agreement over much of the profiles with borehole data from Area G, and represent respectively, the range of what one typically would see at a mesa edge or a mesa interior borehole location. The exception where the computed profiles and the field data disagree is in Units 2a and 1b (at elevation index 47 to 35, above the vapor phase notch moisture spike). In this range, the field data is much drier, and again the difference hints that vapor phase transport is significant through this region.

Conclusions

Transient modeling of a pulse of moisture through a disposal unit at pit 37 is in good agreement with field data. The same model was used to examine moisture pulses expected in realistic extreme conditions representing seasonal percolations, and found to be in agreement with borehole moisture data.

Transient modeling should be explored as a simple (but computationally intensive) way to implement more self consistent surface boundary conditions for the net flux or infiltration at the ground surface boundary. By following transients in time using small time steps as needed to preserve the accuracy of the calculations (less than one hour per time step), then net percolation will evolve self-consistently with input specified as precipitation. During periods following the precipitation transient, then evaporation (open flux boundary condition) at the surface will evolve self-consistently with evaporation limited by the soil properties. In this way a more self consistent percolation will be calculated, at least in the limits of

negligible vegetation and negligible 'potential evaporation' effects. This would estimate a minimum evaporation rate and thus a maximum percolation.

The 2-D transients showed no preferred paths for moisture percolation forming due to the inhomogeneities introduced by statistical variations in hydraulic properties on the computational grid. The correct transport equation for this case is the matric potential based transport equation, and this is difficult to solve under the severe time step restrictions imposed by the maximum hydraulic conductivity on the grid with randomly generated hydraulic properties. Simulations to later times might be of value in future studies to explore the issues introduced in this paper.

Moisture flux in a 2-D lateral flow model was examined to determine the possible significance beneath Area G of lateral moisture movement from the west to the east. There is some lateral flux coincident with each of the stratigraphic unit interfaces, however, the largest lateral flux in the computed solutions does not occur in the layers beneath the mesa but in the layers within the mesa. This leads to a moisture increase in the computed solutions where the field data shows the driest regimes. The discrepancy is likely related to the vapor phase flux in the lower stratigraphic layers within the mesa interior.

Converged solutions without mesa edges show large (with respect to field data) moisture content and correspondingly large lateral and vertical moisture flux components in the unit 2A. This is consistent with the basic hydraulic properties shown in Fig.28, where the largest decrease in hydraulic conductivity between two adjacent stratigraphic units occurs in going from 2a to 1b. This would tend to minimize the vertical flux from 2a down to 1b and thus would build up the moisture content in the overlying layer (2a) leading to the profiles seen in the computed solutions. Adding mesa edges to the simulations improves the agreement between the computed profiles and the field data, suggesting liquid phase has an important role when the mesas are small (considered in the north-south axis). The differences which remain between the computed solutions with or without mesas and the field data support the hypothesis that vapor phase transport is significant within the lower stratigraphic layers of the mesa interior. This could be tested in future work relatively easily by adding a vapor diffusive flux component to the moisture flux in the matric potential transport, Eqn.5. This vapor diffusion is driven by an empirically determined vapor diffusivity determined under in-situ conditions specific to the Area G disposal facility site [Vold and Eklund, 96A].

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Fig. 1 Moisture profiles (volumetric percent by neutron probe) vertically through the upper 35' of disposal unit 37 (west end), showing 1994 data (top left), mid-1996 data (top right), and comparisons of 1994 and 1996 profiles without a depth correction (bottom left) and with a 2' depth shift to the '94 data (bottom right).

Fig. 2 Moisture profiles (volumetric percent by neutron probe) vertically through the upper 35' of disposal unit 37 (west end), data from August, 1996 to May, 1997, showing increased moisture content migrating downward throughout the year.

Fig. 3 Moisture content verses depth and time over approximately one year (8/95 to 6/96 showing the same data as in the previous figure). The left figure shows the actual resolution of the neutron moisture probe and the right figure shows a smooth interpolation of the data. Two moisture pulses are resolved near the surface occurring in the fall (following summer rains) and in the spring (following snow melt), with the snow melt moisture pulse being more significant in this case.

Fig. 4 Moisture pulse integral for the two pulses in pit 37.

Fig.5 Moisture pulse magnitude verses time by two estimates (pulse max height or pulse integral moisture) for the first pulse (Moisture pulse 1 - autumn, 1996) seen in pit 37w.

Fig.6 Extrapolated estimate of pulse start date by the two methods (shown in Fig.5) for moisture pulse 1.

Fig. 7 Moisture pulse 1 (fall '96) verses depth for selected times as measured by neutron probe.

Fig.8 Calculation of moisture pulse 1 in approximation with a constant background of 8% volumetric moisture content

Fig. 9 Darcy flux estimated from the change in position of the moisture front with depth as measured in the field data.

Fig. 10 Darcy flux estimated from the change in position of the moisture front with depth as determined in the computed moisture front.

Fig.11
Precipitation at
WR/TA54
(24hr total)
verses Julian
day for 1996.

Fig.12
Cumulative
precipitation at
WR/TA54
(24hr total)
verses Julian
day for 1996.

Fig.13
Percolation into
disposal unit
(cm/yr) verses
years,
calculated from
precipitation
series
synthesized
from local
meteorologic
data (provided
by E. Springer
[1996].)

Fig.14 Moisture transient calculated for a maximum summer shower case (~1" precipitation over a one hour duration). Top and bottom figures show the same data on different scales.

Fig.15 Moisture transient calculated for a maximum spring snow melt case (average March total precipitation of ~1" is input continuously over the month).

Fig.16 Moisture profile data from neutron probe measurements [Vold, 1997] in borehole 1121 at Area G showing the distinct seasonal variation down to the depth index of about 5 (or at depth ~ 6' (depth index = depth(ft) -1). Time is from 8/96 to 5/97.

a

Fig. 17 Initial condition moisture content for the statistically generated hydraulic parameters.

Fig. 18 Moisture content at 1 hr (at the end of the precipitation input) for the statistically generated hydraulic parameters and a theta-based calculation of moisture transport.

Fig. 19 Moisture content at 2 hr (1 hr after the end of the precipitation input) for the statistically generated hydraulic parameters and a theta-based calculation of moisture transport.

Fig. 20 Moisture content at 7 hr (6 hr after the end of the precipitation input) for the statistically generated hydraulic parameters and a theta-based calculation of moisture transport.

Fig. 22 Matic or capillary potential -cm- after 5000 iterations (~20 min during the precipitation input) for the statistically generated hydraulic parameters and a matic potential or hm-based calculation of moisture transport (with constant moisture content initial conditions).

Fig. 21 Moisture content after 5000 iterations (~20 min during the precipitation input) for the statistically generated hydraulic parameters and a matic potential or hm-based calculation of moisture transport (with constant moisture content initial conditions).

Fig. 23 Matric or capillary potential -cm- (~20 min during the precipitation input) for the statistically generated hydraulic parameters and a matric potential (h_m) based calculation of moisture transport. Constant matric potential initial conditions were assumed, $h_m = -955$ cm (corresponding to $\theta \sim 8\%$ for these hydraulic properties (unit 2b).

Fig. 24 Moisture content initial conditions for the statistically generated hydraulic parameters and a matric potential (h_m) based calculation of moisture transport. Constant matric potential initial conditions were assumed, $h_m = -955$ cm (corresponding to $\theta \sim 8\%$ for these hydraulic properties (unit 2b).

Fig. 25 Moisture content (volume fraction) after ~20 min during the precipitation input for the statistically generated hydraulic parameters and a matric potential (h_m) based calculation of moisture transport. Constant matric potential initial conditions were assumed , $h_m = -955$ cm (corresponding to $\theta \sim 8\%$ for these hydraulic properties (unit 2b).

Fig. 26 Cross-sections for the Pajarito Plateau West-to-East hydrology modeling study. Top figure shows simplified N-S cross section of mesa at Area G [from Vold, et.al., 1996]. Bottom figure shows the W-E cross section of Pajarito Plateau [from Purtymun].

Fig. 27 (Top) Percolation rate boundary conditions used in the Pajarito Plateau W-E computational study. These are scaled from the data in the bottom figure as described in the text.

(Bottom) Percolation verses precipitation rates calculated for a disposal unit with vegetative cover characterized by a 48 cm rooting depth [data from E.Springer, 1996] with an exponential fit to the data points from the individual calculated cases.

Fig. 28 (Top) Unsaturated hydraulic conductivity verses moisture content for the upper stratigraphic layers at Area G. (Bottom) Implied moisture content in each stratigraphic unit for fixed values of the recharge rate (assumed equal to the unsaturated hydraulic conductivity) and in comparison to field data (theta-vol%) mean and standard deviations in each unit.

Fig. 29 Implied moisture profiles for fixed values of the recharge rate and in comparison to field data means and standard deviations in each stratigraphic unit (labeled *theta (in-situ) - vol.frac-*). Moisture profiles are obtained by integrating the moisture content vertically from assumed moisture content in the Otowi (depth = 6500'), thus eliminating the assumption that recharge rate is equal to the unsaturated hydraulic conductivity.

Fig. 30 Initial conditions (moisture content -vol%) in the Pajarito Plateau W-E simulations, derived from the combination of data in Figs.29 and 27(top) as described in the text.

Fig. 31 Lateral moisture flux (cm/yr) implied by the initial conditions (moisture content -vol%) in the Pajarito Plateau W-E simulation shown in the previous Fig.30.

Fig.32 Converged solutions (moisture content and vertical flux) for the box-model approximation to the Pajarito Plateau W-E problem.

C

Fig.33 Converged solutions (lateral flux) for the box-model approximation to the Pajarito Plateau W-E problem for two different sets of assumptions (see text).

Fig.34 Converged solutions (moisture content vol%) for the mesa edge model approximation (3 cases) to the Pajarito Plateau W-E problem for three different sets of assumptions (see text).

Fig. 35 Moisture profiles vertically through three horizontal locations (ix = 18, 17, and 9) from the second case shown in Fig.34. Area G is located near conditions expected at ix = 18 or 17, while ix = 9 represents conditions expected at a point several km to the west of Area G.

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