LA-UR-97-**- 5 2 0 2**

Title:

Synopsis of Recent Moisture Flux Analyses
Relevant to the Unsaturated Zone at Area G

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Abstract

Previous analyses are summarized and new results are presented concerning the unsaturated zone transport of moisture in liquid and vapor phases and the surface water balance at the Los Alamos disposal facility, Area G, and in surrounding canyon and mesa locations. A Darcy flux analysis is described which estimates the local liquid phase recharge rate from borehole moisture data combined with the hydrogeologic properties of the subsurface media. Vapor flux driven by moisture gradients is estimated from an empirical diffusion coefficient determined by comparison of computational models and field measurements of tritium efflux from disposal shafts. The anomalously large in-situ diffusion coefficient has been related to barometric pumping acting on the large effective permeability due to a fracture network in the mesa subsurface and this coefficient is rederived here.

Surface water balance studies provide estimates of the recharge at the ground surface which provides the input boundary condition to the computational modeling of contaminant transport in the unsaturated zone. In this report, data for surface water run-off, and evapotranspiration measurements from different sources are reviewed briefly. Evapotranspiration data from LANL ESH Division is plotted to examine trends and uncertainties. The data show several cm/yr difference between precipitation and evapotranspiration which are assumed approximately equal to the percolation averaged across the Pajarito Plateau. The Darcy flux analyses indicate this almost entirely percolates down through the canyon bottoms and not the mesa tops.

Darcy flux results show three vertical zones in the mesa (at Area G), a near surface region with significant downward liquid movement ($\sim$ cm/yr), a dry lower zone where vapor phase is a significant contribution to moisture flux and imposed on this dry zone is a moisture spike near the vapor phase notch (VPN). The moisture movement in the dry zone is small ($\sim$ mm/yr) and is directed upward at many locations. The moisture flux direction at the VPN is ambiguous with indications the layer has unique hydrologic properties and may also act a source to the local vertical recharge rate by diverting lateral moisture movement or by interaction with the fracture network. Mesa drying appears to be related to mesa width with Area L and the edge of Area G showing the driest profiles and least moisture flux relative to central Area G and TA46. In the undisturbed state, the mesa has a negligible recharge which is continuous throughout its volume and most percolation into the mesa top is apparently lost in the lower portion of the mesa through evaporation to the fracture network and to the mesa sides. Additionally, the mesa appears to wick moisture up from deeper layers to be lost as evaporation from the 'vapor phase dominated' region in the lower half of the mesa. Disposal operations have a significant impact on this picture of the natural hydrology and the recharge beneath disposal units is probably best inferred from moisture profiles and hydraulic properties measured directly in the disposal units.

Synopsis of Recent Moisture Flux Analyses Relevant to the Unsaturated Zone at Area G

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Synopsis of Recent Moisture Flux Analyses Relevant to the Unsaturated Zone at Area G

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Introduction

This report summarizes selected recent analyses relevant to the assessment of the site performance for disposal facilities at Los Alamos (Area G) regarding unsaturated zone transport of moisture in liquid and vapor phases and the surface water balance. Much of the analyses methods have been reported previously but in several separate and detailed reports. These do not always reflect the overview possible with hindsight. The present report is an attempt to integrate the author's previous results into a cohesive whole. Due to project time constraints, this report is incomplete in some areas.

The focus is on analyses by the present author to try to unify this work. Previous reports which reviewed and integrated a broader set of hydrology data and analyses for Area G include [IT, 87], [Turin, 95], [Rogers, et.al., 97], [Vold, et.al., 96A], [Vold, et.al., 96B], and the Area G Performance Assessment [Hollis,et.al.,97].

This report first reviews the basis for the Darcy flux analyses and its inherent uncertainties, as detailed in previous reports. Results from the previous works are then reviewed and discussed and in some cases, elaborated in an attempt for clarification. New results of the Darcy Flux Analyses are presented and discussed for Area G mesa top locations, nearby canyon locations and a second mesa top location (TA46 west of Area G). Select evapotranspiration and precipitation data from TA6 are presented and discussed. The conclusions section draws a picture of the hydrology which unifies the study results reported here and in previous reports for the undisturbed and disturbed site locations.

Summary of Previous Work: Methods and Previous Results

Darcy Flux Analyses: Unsaturated Zone Liquid Phase Transport

Darcy Flux Analyses as presented here refers to a variety of methods for estimating the local moisture flux (typically the vertical component or

recharge rate) from in-field data including moisture content profiles and subsurface hydrogeologic transport properties of the unsaturated media. It applies to liquid phase flux as described in this section and is also extended to estimate vapor phase flux under conditions where a vapor phase diffusion coefficient is empirically determined from in-situ data. This empirical derivation of the vapor phase diffusion coefficient is summarized in a following section. The basis for these estimates of local recharge rate are described here, summarizing previous reports [Vold,96A,Vold,96B].

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 or multispecies flow there can be source terms and diffusive flux with respect to the bulk flow. In this multiphase context, and assuming negligible variation in water density, the liquid water density is replaced by its volume fraction. Then, a continuity equation for the liquid phase volume fraction, θ , can be written

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

where q is the volume fraction flux (Darcy flow) and S_θ is a source or sink term for the liquid phase in the porous media. In the unsaturated zone, considering liquid phase transport only, the flux can be written

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

where $[\theta]$ denotes a functional dependence upon the moisture content, and h_m is the matric head, assumed here to equal the capillary tension or the negative of the suction head. The unit vector in the vertical axis, z , is directed upward, so the vertical component of flux can be written

$$\Gamma_z = -K[\theta] \{ (\partial h_m[\theta] / \partial z) + 1. \}, \quad (4)$$

Under conditions where the variability in porous media properties can be neglected (i.e., within a single relatively uniform stratigraphic unit), then $\partial h_m[\theta]/\partial\theta$ is approximately constant, and this expression can be simplified in terms of the gradient in moisture content alone, as

$$\Gamma_z \sim -K[\theta] \{ (\partial h_m[\theta]/\partial\theta)(\partial\theta/\partial z) + 1. \}, \quad (5)$$

This is useful in some simple estimates of recharge but is not generally accurate, and Eqn.4 is preferred for the flux estimate when it can be evaluated.

Returning to the more general flux expression, Eqn.4, the discretized vertical flux evaluated at node, $i+1/2$, where i is an index of vertical position, is

$$\Gamma_{z(i+1/2)} = -K[\theta]_{i+1/2} \left(\frac{(h_m[\theta]_{i+1} - h_m[\theta]_i)}{(z(i+1) - z(i))} + 1. \right) \quad (6)$$

This is a fairly general expression for the local vertical Darcy flux or recharge rate. There are several alternatives for the evaluation of this expression from field data. Key issues in the practical evaluation are the data availability, cost, and the data uncertainty.

A reasonably direct evaluation of Eqn.6 at a point in the unsaturated zone could be written

$$\Gamma_{z(i+1/2)} = -K[\theta]_{i+1/2}, dK/d\theta[UFA]_{i+1/2} \left(\frac{(h_m[WAM,TCP]_{i+1} - h_m[WAM,TCP]_i)}{(z(i+1) - z(i))} + 1. \right) \quad (7)$$

where the brackets, $[]$, include a specific experimental evaluation method, so that, $h_m[WAM,TCP]$ is a water activity meter or thermocouple psychrometer determination of the matric potential from a small sample at the location of interest, and $K[\theta, dK/d\theta[UFA]]$ implies an unsaturated conductivity estimate from a derivative curve, $dK/d\theta$, (determined by UFA data on a locally recovered sample), evaluated at a locally measured moisture content, θ . Problems with this direct method include uncertainties in each measurement type, especially in the WAM measurement [Vold,96B], large costs associated

with in-situ TCP, and UFA data, and practical difficulties with making several different measurements on the same 'sample' location.

Reduction in costs and uncertainties can be achieved by focusing on the relatively precise determinations of moisture content from neutron probes [e.g., Vold, 1997] and using the van Genuchten-Mualem functions to represent the hydraulic properties. Using in-situ determinations of θ , and van Genuchten-Mualem functions, both evaluated at each point in the vertical profile would be expressed

$$\Gamma_z(i+1/2) = -K[\theta_{i+1/2}, dK/d\theta[\theta_{i+1/2}, vG-M_{i+1/2}]] \left(\frac{(h_m[\theta_{i+1}, vG-M_{i+1}] - h_m[\theta_i, vG-M_i])}{(z(i+1) - z(i))} + 1. \right) \quad (8)$$

This expression has been evaluated in limited situations where data is available such as the profile in borehole G-5 [Rogers,et.al.,95], [Rogers,et.al.,96] and in profiles traversing the Vapor Phase Notch. These latter results have not been published in detail, but will be summarized in this report.

Using local in-situ profiles of θ , and van Genuchten-Mualem functions which have been evaluated as average quantities over a region (specific stratigraphic unit) in the vertical profile would give:

$$\Gamma_z(i+1/2) = -K[\theta_{i+1/2}, dK/d\theta[\theta_{i+1/2}, vG-M_{ave}]] \left(\frac{(h_m[\theta_{i+1}, vG-M_{ave}] - h_m[\theta_i, vG-M_{ave}])}{(z(i+1) - z(i))} + 1. \right) \quad (9)$$

This estimate of the flux has been used in most of the results presented in this report, though we have explored the use of the flux estimate in Eqn.7 and 8.

The advantage of this flux estimate, Eqn.9, is that only a relatively small library of stratigraphic property means (and their variances to evaluate uncertainties) is required, and can be based on a limited set of samples in each stratigraphic unit rather than obtaining detailed hydrologic properties at every field point of interest. Only the moisture content itself (and its gradient) is required at each location of interest and this is measured cheaply, easily and relatively precisely with a neutron probe.

A disadvantage in going to stratigraphic unit averaged properties is the uncertainty introduced in the averaging. This uncertainty was analysed extensively in two reports [Vold96A,Vold,96B] based on measured variance in the field data. Uncertainty results were found to be tolerable but the property averaging introduces considerable 'noise' into the flux estimates. The 'noise' is driven by the uncertainty in N , the van Genuchten exponential parameter, which unavoidably has a large impact on the moisture flux estimate uncertainty. Even by refining estimates of its variance based on the smaller variation along a profile measured in G-5 [DBSA, 95], this term dominates the sensitivity of the moisture flux estimate at a single point location. Thus, some averaging (in space or time or both) over the flux results is required to obtain reliable 'trends' in the data that represent actual field conditions. This is discussed in a following section, Uncertainties, and will be more clear in the examples discussed in the Results sections.

Darcy Flux Analyses: Moisture Flux Source Terms

For a given evaluation of the profile of flux using one the above approximations to Eqn.4, one can also evaluate a 'source term' to the vertical flux or recharge rate. The simplest 'source term' expression is just the difference in vertical flux at two adjacent points in the vertical profile, or

$$S_i [cm/yr] = \Gamma_z(i+1/2) - \Gamma_z(i-1/2) \quad (10)$$

This source is non-zero, when the sum of three terms is nonzero; the phase source term, S_θ in Eqn.2, the time variation in moisture content, $\partial\theta/\partial t$, and the lateral flux. Some combination of these effects are implied for a non-zero source term in Eqn.10.

The moisture flux source term may also be expressed as a characteristic time scale over which the moisture content is changing, S_{ti} , at vertical location, i . This source term is equivalent to the time over which the local moisture content would be removed by the flux rate of the local source term, i.e., the time scale for moisture change if the entire source term were attributed to a moisture change in time. This source is normalized per depth interval and as described previously [vold] can be written

$$S_{ti} [yr] = \theta_i \Delta z_i / (\Gamma_z(i+1/2) - \Gamma_z(i-1/2)). \quad (11)$$

The moisture source terms in Eqn.10 or 11 can be applied to the vapor phase flux as well, using the following equations for vapor flux.

Darcy Flux Analyses: Unsaturated Zone Vapor Phase Transport

The vapor flux through the pore space of the unsaturated zone can be driven by gradients in pressure, temperature or moisture content. As detailed previously [Vold], this flux can be written as a combination of the convective air flow and diffusive flow generated by fluctuations in temperature and pressure. An expression for the total vapor phase moisture flux in terms of gradients in three state variables for the vapor: pressure, temperature and moisture content is then based on the general vapor flux expression,

$$\Gamma_v = \theta_a \rho_v u_a - D_v \nabla \rho_v . \quad (12)$$

This can be expanded under assumptions which are realistic under most environmental conditions [Vold,96B, Vold,96C] as

$$\Gamma_v = - \theta_a \rho_v \frac{K_p}{\mu \varepsilon} \nabla p - D_{v(T)} \frac{M_v}{RT} \frac{dp_s}{dT} \nabla T - D_{v(\theta)} \frac{M_v p_s}{RT h_c} \frac{dh_m}{d\theta} \nabla \theta \quad (13)$$

where the air convective flow, u_a from Eqn.12, is driven by the pressure gradient term and the diffusive flux in Eq.12 has a ∇T and a $\nabla \theta$ component. The $\nabla \theta$ component, $\frac{dh_m}{d\theta} \nabla \theta$, can also be evaluated in a more general way in terms of the matric potential gradient, considering $\frac{dh_m}{d\theta} \nabla \theta = \nabla h_m$. (this more general form is used in the vapor flux analyses described later. The vapor phase diffusion coefficient, D_v , has been written as two different factors to account for the possibility of different values driving the temperature and moisture gradient terms. The entire set of coefficients in the last term comprise an 'effective diffusion coefficient', D_{eff} , for vapor flux driven by gradients in the liquid phase moisture content, $\nabla \theta$. This flux is driven by the very small change in vapor pressure over regions of varying liquid moisture content. It is negligible in many circumstances for 'classical values of the diffusion coefficient' (binary diffusion or water vapor into air). The convective flux in this case is driven only by the pressure gradient assuming

constant density air, and ignores a possible flux from air density variations due to moisture variations between the subsurface pore spaces and the open atmosphere. This is assumed to be a small flux contribution.

Tritium efflux calibration study

It is this effective vapor diffusion coefficient in Eqn.13 which was evaluated by in-field observations of the characteristic scale lengths for tritium migrating from the tritium disposal shafts at Area G [Vold and Eklund, 96A]. It was found to be 60 times greater than the 'classical diffusion' [note that the original report, [Vold and Eklund, 96A] stated 40 times greater, which was in error]. This anomalously large diffusion is great enough to drive a small but significant vapor flux at moisture contents less than about 4% (volumetric) in most of the tuff materials in the subsurface at Area G.

It is this vapor flux, the third term in Eqn.13 driven by the empirically determined effective vapor diffusion coefficient which is analyzed and reported here in the results section. The equation is discretized similarly to that in Eqn.6 to estimate the local flux from the field quantities.

abstract

There is field data of tritium efflux from the ground surface and tritium concentrations in boreholes which indicate migration of tritiated water vapor through the tuff in the unsaturated zone from the buried disposal shafts located on a narrow mesa top at Area G, Los Alamos, NM. Comparisons of field data to computational modeling results are consistent with an effective in-situ vapor phase diffusion coefficient of $1.5 \times 10^{-3} \text{ m}^2/\text{s}$, or a factor of 60 greater than the binary diffusion coefficient for water vapor in air [Vold and Eklund, 96A].

A model is derived to explain this observation of anomalously large diffusion, which relates an effective vapor or gas phase diffusion coefficient in the fractured porous media to the subsurface propagation of atmospheric pressure fluctuations (barometric pumping). The near surface (unattenuated) diffusion coefficient is independent of mode period under the simplified assumptions of a complete 'mixing mechanism' for the effective diffusion process. The unattenuated effective diffusion driven by this barometric pumping is proportional to an average media permeability times the sum of the square of pressure mode amplitudes, while the attenuation length is proportional to the square root of the product of permeability times mode

period. There is evidence that the permeability needed to evaluate the pressure attenuation length is the in-situ value, approximately that of the matrix. The diffusion which results using Area G parameter values is negligible in the matrix but becomes large at the effective permeability of the fractured tuff matrix. The effective diffusion coefficient predicted by this model, due to pressure fluctuations and the observed fracture characteristics, is in good agreement with the observed in-situ diffusion coefficient for tritium field measurements. It is concluded that barometric pumping in combination with the enhanced permeability of the fractured media is a likely candidate to account for the observed in-field migration of vapor in the near surface unsaturated zone at Area G. The model results imply that vapor flux through fracture apertures is potentially an order of magnitude larger than the vapor flux through the matrix.

Vapor diffusion model for fractured porous media

The mechanism which enhances the effective diffusion of vapor within the mesa subsurface at Area G is still uncertain. One model to explain it assumes barometric pumping due to atmospheric pressure fluctuations [Vold, 96C]. The pressure fluctuation spectrum was analysed and quantified for input into this model in a separate report [Vold, 96D]. The pressure fluctuation model for enhanced subsurface transport in its original form predicts a diffusion coefficient which is in good agreement in magnitude with the empirical diffusion coefficient [vold and Eklund, 96]. There is still some concern [Neeper, personal communication, 96] that the model is incomplete and therefore may erroneously obtain the 'correct' answer. This is discussed in more detail in the following section on Model Derivation.

In [Vold, 96C], a model is proposed for in-situ vapor phase diffusion driven by barometric pumping which acts on the effective in-situ permeability of the subsurface. Diffusion is evaluated for the field conditions observed at the Los Alamos mesa top low level radioactive waste disposal facility. The effective permeability is controlled by the fracture network characteristics, and this is shown in the model to lead to a large effective diffusion coefficient. The value for the diffusion coefficient from the model is in agreement with the value derived from field observations of the diffusion of tritium vapor from the disposal shafts at the facility. A practical

consequence of the model derives from the mechanism for the enhanced in-situ diffusion which suggests that all gas or vapor phase species in the disposal shafts are expected to diffuse through the fractured tuff with the same diffusion coefficient. This model study provides a technical basis for this assumption made in the Area G Performance Assessment [Vold, 97A]

The agreement in the diffusion coefficient value from the model with the value derived from field observations may be a fortuitous combination of simplifications made in the model [Neeper, 96, personal communication]. Even so, the model may correctly relate the critical mechanisms to the resulting effective diffusion. These points are best illustrated by a brief review of the analysis from that study.

Model Derivation

This model is reviewed here in some detail because of minor errors which appeared in the original derivation describing this model [Vold,96C] and in the derivation of the empirical vapor diffusion coefficient from in-situ tritium migration data [Vold and Eklund, 96A]. (The errors did not change the final vapor flux estimates in [Vold,96B])

An effective diffusion coefficient for a species within the pore gas air is proposed to result from the periodic advective movement of subsurface pore gas (or gas within fractures or other macropore spaces), driven by atmospheric pressure fluctuations, in combination with a gradient in the 'diffusive' species within the pore gas air. For this process, a general diffusion coefficient, D , is proposed as a characteristic step size, d , times an advective speed, u . These are related to time and space dependent quantities, $d(z,t)$ and $u(z,t)$, so the product must be evaluated as an appropriate integral of a general form,

$$D = c \int \int d(z,t) u(z,t) dz dt \quad (14)$$

where c is a normalization constant, related to one over $\int \int dz dt$.

The integral depends on the detailed mechanisms for mixing of the vapor or contaminant gas within the air in the pore gas spaces, which leads to some phase shift between the displacement, d , and the speed, u . This could be accounted for generally as a 'phase shift fraction', f_{ps} , allowing one to write the general diffusion coefficient as

$$D \sim f_{ps} du, \quad (15)$$

where the value for f_{ps} derives from the details of the integration. This phase shift was not accounted for explicitly in [Vold], but was assumed implicitly to be unity, indicating a simplified assumption of 'complete mixing', or a negligible phase shift between the displacement and the speed. This would give a maximum estimate for the diffusion coefficient from this process.

As detailed in [Vold], the pore gas speed, u , (component of velocity normal to the ground surface) at depth, z , is a sum over modes identified by period length, τ_m , with pressure attenuation scale length, L_m , and driven by atmospheric pressure fluctuations of mode amplitude, Δp_m . The pressure fluctuations attenuate with depth, z , into the subsurface media with average characteristic permeability, K_p , giving a pore gas speed driven by atmospheric pressure fluctuations of the form,

$$\begin{aligned} u(z,t) &= - \frac{K_p}{\mu \epsilon} \nabla p [z,t] \\ &= \sqrt{2} \frac{K_p}{\mu \epsilon} \sum_{m=1}^{\infty} \left((\Delta p_m / L_m) e^{-z/L_m} \sin(2\pi t / \tau_m - x/L_m + \pi/4) \right), \end{aligned} \quad (16)$$

where μ is the air viscosity, ϵ is the media porosity, and the pressure mode attenuation length, L_m , is given by

$$L_m = \sqrt{\frac{k_p p_0 \tau_m}{\mu \epsilon \pi}} \quad (17)$$

where k_p is an effective permeability appropriate to the attenuation of pressure perturbations with increasing depth. An approximate displacement distance for the pore gas per cycle of the periodic convective flux is, $d \sim u(z,t)\tau_m$, which gives an expression for the effective diffusion coefficient, D_{pm} , due to the periodic convective motion of a single mode, and in the presence of a gradient of the 'diffusive species', to be

$$D_{pm} \sim f_{ps} du \sim f_{ps} u^2(z,t) \tau_m \quad (18)$$

It is assumed that the time dependent oscillations and phase terms over all modes are appropriately averaged into the phase shift factor, f_{ps} (the details are omitted because they are complex not because they are trivial!). Substituting from Eqns#, the effective diffusion coefficient in porous media due to atmospheric pressure fluctuations summed over all modes is then written in the general form,

$$D_{pm} \sim f_{ps} u^2(z,t) \tau_m$$

$$= f_{ps} \left(2 \left(\frac{K_p}{\mu \epsilon} \right)^2 \sum_{m=1}^{\infty} \left((\Delta p_m / L_m) e^{-z/L_m} \right)^2 \right) \tau_m \quad (19)$$

and then using Eqn. #+1, for L_m in the denominator,

$$D_{pm} \sim f_{ps} \left(2 \left(\frac{K_p}{\mu \epsilon} \right)^2 \sum_{m=1}^{\infty} \left((\Delta p_m \left(\frac{\mu \epsilon \pi}{k_p p_o \tau_m} \right)^{1/2}) e^{-z/L_m} \right)^2 \right) \tau_m. \quad (20)$$

The period, τ_m , cancels and the expression simplifies as

$$D_{pm} \sim f_{ps} \left(2 \left(\frac{K_p}{\mu \epsilon} \right)^2 \left(\frac{\mu \epsilon \pi}{k_p p_o} \right) \sum_{m=1}^{\infty} \left(\Delta p_m e^{-z/L_m} \right)^2 \right). \quad (21)$$

In the near surface region, $z \ll L_m$, then $e^{-z/L_m} \sim 1$, and the near surface diffusion coefficient is approximately,

$$D_{pm}(z \sim 0) \sim f_{ps} \left(2 \left(\frac{K_p}{\mu \epsilon} \right)^2 \left(\frac{\mu \epsilon \pi}{k_p p_o} \right) \sum_{m=1}^{\infty} (\Delta p_m)^2 \right). \quad (22)$$

In the original derivation [Vold96C], it was assumed $K_p = k_p$, however, this led to discrepancies with the field data as discussed previously, so that the possibility K_p not equal to k_p was introduced.

The value of permeability that the air flow 'sees' corresponds to k_p in Eqn.16, while the permeability that effectively attenuates the pressure perturbations with increasing depth is k_p in Eqn.17. Ideally, these values are the same but in a complex heterogenous system, the appropriate averaging over large subsurface volumes might be different in each case, and so these permeabilities can be different.

Implied Liquid Flux -Summary of Previous Analyses

Liquid flux results were previously reported in [Vold,96A], based on the evaluation of Eqn.6, using stratigraphic unit averaged hydraulic properties and in-situ moisture profile data (mostly from neutron probe measurements, and some from core sample moisture analyses. A near surface region which is highly variable in depth (averages ~10m) and in moisture content shows significant downward flux (average of about 1cm/yr). Below this a dry region suggests a negligible liquid phase flow. Near the base of the mesa a moisture spike is coincident with the vapor phase notch (VPN). The implied flux near this spike suggests a local moisture source and dissipation from this horizon based on the analyses with assumed average hydraulic properties.

It has since been demonstrated [Vold,97B] that hydraulic properties do vary consistently through a vertical profile traversing this VPN. The implied flux from core samples throughout this region has been analysed and discussed in a later Results section of this report. Although the properties do vary in the VPN horizon from the adjacent horizons, the detailed analyses suggests there is still a moisture source at this horizon, perhaps a redirection of lateral moisture movement due to the unique properties in the horizon.

Implied Vapor Flux -Summary of Previous Analyses

Vapor flux results were previously reported in [Vold,96B], based on the gradient in matric potential, which is related to the moisture gradient term in Eqn.13. The flux expression is evaluated as

$$\Gamma_v = -D_v(\theta) \frac{M_v p_s}{RT h_c} \nabla h_m = -D_{eff} \nabla h_m[\theta] \quad (23)$$

where the gradient is evaluated as

$$\nabla h_m[\theta] = (h_m[\theta]_{i+1/2} - h_m[\theta]_{i-1/2}) / (z_{i+1/2} - z_{i-1/2}), \quad (24)$$

and $h_m[\theta]$ is evaluated from in-situ moisture profiles (neutron probe data) and using stratigraphic unit averaged matric properties to convert the moisture profile to a matric potential profile.

Results showed that vapor phase is a significant contribution to moisture flux when the moisture content is below about 4% in the tuff, where the liquid phase flux becomes negligible and the vapor flux is on the order of 1-2 mm/yr. This typically occurs in the lower portion of the mesa interior in a region denoted the 'vapor phase dominated flow regime'. This region is nearly coincident with the region identified in the liquid flux study where the liquid phase flux is negligibly small, and so this region is identified as a 'vapor phase barrier' to liquid phase moisture and contaminant movement.

Surface Water Balance

The unsaturated zone recharge rate depends upon the surface recharge, as studied for Area G in detail [Springer, 96]. The surface recharge or percolation depends upon the surface water balance between the sources of precipitation and manmade discharges and the losses due to runoff, evapotranspiration and percolation. Reliable estimates of each of the former terms could lead to an accurate estimate of the percolation. Precipitation data is relatively complete at several Los Alamos stations over long durations (see the LANL Weather machine on the internet from www.lanl.gov).

Laboratory Operations

Los Alamos county uses about 1.5 billion gallons of water per year (bgpy). The county uses 1 billion, and the Los Alamos lab uses about 0.5 bgpy. There are about 100 effluent discharge points from the lab facilities spread over about 50 square km, and much of the water usage is evaporated prior to discharge. Most of the discharge volume occurs at a few locations, primarily the power plant at TA3, and to a lesser extent from the treatment plant at TA50.

A simple estimate of the discharge quantity indicates that the discharge per area exceeds the natural precipitation rate in a local region near the discharge points. The area where the discharge rate exceeds the precipitation

can be estimated if one assumes the effluent discharge dissipates in an area which is ten times longer than its width. This corresponds to a simple estimate of hydraulic dispersion which is laterally one tenth of that along a flow axis, and the axis is determined here by the down stream channeling in the bottom of the discharge canyon. Under these conditions, the discharge from the steam power plant into Sandia canyon is expected to equal the background precipitation rate for a down canyon distance of about 4km. This is a reasonable approximation to the distance where Sandia canyon has a continuously observable surface water component.

This suggests that the laboratory discharges do have a significant impact on the hydrology but it is only on a fairly local scale. Thus, the lab discharges probably do not have a significant impact on the hydrology beneath Area G, but they probably do have a significant impact on the moisture profiles measured in Mortendad Canyon where an effluent discharge is located. The impact in Mortendad Canyon may influence the moisture flux results reported in this present study.

Surface Run-off

Run-off is calculated to be relatively small, on the order of 1mm/yr for the conditions of a disposal unit (3% slope) at Area G [Springer,96]. Run-off data has been collected only in recent years by LANL, ESH-18 [contact: Mike Alexander], in several gaging station around the Area G mesa. An informal report [Rogers and Associates for EM-SWO, LANL, 1996] estimated the annual run-off from Area G based on the detailed run-off data from Area G for the summer of 1995, and with a range of assumptions regarding run-off during the remainder of the year. The best estimate was that 5-6 % of the precipitation ran-off the mesa. This is high in comparison to the calculated run-off from the disposal units, however, the field data is an average over the drainage basins at Area G which includes the mesa edge and has an average run-off slope which is much greater than the 3% assumed in the calculated run-off from the disposal units. Although additional quantitative comparisons have not been completed, the larger run-off fraction seen in the field appears to be consistent with the smaller run-off calculated for the 3% disposal unit covers. Thus, it is expected that run-off is a negligible factor in the water balance on the disposal unit covers, and probably a small contribution in the mesa top hydrologic water balance.

Evapotranspiration

Evapotranspiration in the local area has been estimated from eddy correlation measurement data at TA-6 [data maintained by ESH-17, LANL] in informal analyses reports by Greg Stone, John Gray and others at LANL. Evapotranspiration data has been summarized [Vold and Eklund, 96B] from ground surface efflux measurements at Area G used in the assessment of tritium flux [Eklund and Vold, 95] from the disposal site.

The flux chamber measurements integrate evapotranspiration over a small area (0.13m^2) of the ground surface including the local vegetation to capture the transpiration component over an interval of about 4 hrs. Over 240 samples were taken, typically during the summer months and during the day. There are difficulties in trying to estimate an annual average evapotranspiration rate from this sample set, however the best estimate from the data was that only 70-75% of the precipitation is lost to evaporation or evapotranspiration.

Eddy correlation measures the latent heat which can be used to infer the evapotranspiration rate in a fairly straightforward manner, provided the evaporative flux is in fluctuations and not in a 'DC', or standing wave mode. This is mentioned because the unique topography of complex mesa tops and canyons could possibly generate a significant 'standing wave' component to the evaporation which would limit the accuracy of these results. Data of this type has been collected at TA6 by ESH-17 since 1992. This data is presented in the Results section, because it has not previously been analysed or reported to this author's knowledge, although several informal reports have discussed aspects of the data. It was reported [Greg Stone, ESH-17, personal communication, 1996] that eddy correlation measurements would be taken at the White Rock/TA54 meteorologic site (east boundary of Los Alamos labs) beginning in autumn, 1996. If this has occurred, that data would be of considerable interest in evaluating evaporation at Area G, and for comparison to the data presented in this report from the west end of the Los Alamos site (TA6).

Uncertainty

The uncertainties associated with the Darcy flux analyses described here were derived and quantified in detail in two previous reports [Vold,96A, Vold 96B] for the van Genuchten based parameter estimate and also for the water activity meter estimate of the matric potential. In the preferred analyses method presented here, using stratigraphic-unit averaged properties to back calculate moisture flux from in-situ moisture data, then the error in the liquid phase flux estimate is dominated by the error in the unsaturated hydraulic conductivity, where the uncertainty in the unsaturated conductivity is in turn dominated by the uncertainty in the van Genuchten exponent, N . This is somewhat obvious in hindsight because of the sensitivity to the exponential dependence.

To reduce the overall flux uncertainty, an attempt was made to refine our estimate of N . This was based on vertical profiles of N plotted from analyses on core samples every 10' throughout the borehole G-5 at Area G. It is seen from these profiles that the local variation in N is significantly smaller than the overall standard deviation across the stratigraphic unit, and thus the profile data can be used to reduce the local uncertainty in N and thus in the Darcy flux estimate. Even so, the exponent N dominates the error and the nature of propagation of errors from an exponential term is that the final uncertainty must be a significant fraction of the estimate itself. Thus the flux analysis at best has an error which is of the same order of magnitude as the result. This limits the uncertainty of any single flux estimate to be plus or minus $\sim 100\%$, however, when trends in regions of the vertical profile are apparent then 'average' flux estimates over these selected regions will have their uncertainties reduced by the square root of the number of points averaged together in the region averaged flux estimate. Roughly speaking, a 100% error on each point can be reduced to a 10% error on the region averaged flux determined by averaging 100 data points together ($\sqrt{100}/100 = 10\%$).

Analyses Results

Area G boreholes

An Area G facilities map showing the locations of boreholes discussed in this report is shown in Fig.1. Figure 2 shows moisture profiles measured by neutron probe in Area G vertical boreholes: 1117 (top-left), 1121 (top-rt), 1107 (bottom-left), and G5 (bottom-rt) for reference. Darcy flux results from these borehole profiles are discussed in this section. Unsaturated hydraulic conductivity verses moisture content for the upper stratigraphic layers at Area G (Fig.3 (Top)) shows the stratigraphic unit averaged properties used in the Darcy flux analyses. Figure 3 (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 mean and standard deviations of the field data (*theta-vol%*) in each unit. A comparison of this figure to the specific profiles in Fig.2 gives an indication of the magnitude of flux expected throughout these boreholes.

Figure 4 shows the magnitude of liquid phase vertical flux inferred from Darcy flux analysis in borehole 1117, where (*neg.of liq.flux*) implies downward flux and (*pos.liq.flux*) implies upward flux. There is no clear trend in the profile except near the moisture spike at the vapor phase notch (VPN at ~82') where the flux is consistently upward above the spike and downward below the spike. Figure 5 shows the magnitude of liquid phase vertical flux and the moisture source term (Eqn.10) inferred from Darcy flux analysis in borehole 1117, focusing on this region near the VPN. A local source and vertical flux away from the VPN horizon is evident in this case where constant hydraulic properties through the VPN are assumed.

The magnitude of liquid phase vertical flux compared to vapor phase contributions to flux inferred from Darcy flux analysis of borehole 1117 is seen in Fig. 6. The vapor flux magnitude is at least comparable to the liquid flux throughout the profile (except near the VPN) and dominates from about 40' to 76'. In Fig. 7, the magnitude of the moisture source term expressed as a characteristic time scale for the moisture content to evolve (Eqn.11) for the liquid phase vertical flux only is compared to that for the total flux including the vapor phase contributions, as inferred from Darcy flux analysis of borehole 1117.

Although the time scale for liquid moisture source becomes extremely long in the vapor dominated region (40-76') the total flux source term time scale remains smaller, in the 100-1000 year time frame, due to contribution to flux from the vapor phase. This 100-1000 year time frame may be a characteristic drying time for the mesa at this location. Fig. 8 shows moisture profiles and Cl concentrations [Cl data from Newman, 1996] in borehole 1117 for comparison to flux from Darcy analyses. The time scales inferred from the Cl data are much longer, in the range 1000- 10,000 or more years [Newman, 1996], and may be related to the assumptions in that analysis that the moisture flux is all liquid phase.

In Fig. 9 one sees the magnitude of liquid phase vertical flux inferred from Darcy flux analysis in borehole 1107, where (*neg.of liq.flux*) implies downward flux and (*pos.liq.flux*) implies upward flux. Trends clearly indicate upward movement decreasing in magnitude away from the VPN horizon (100' at this location), and probably a downward movement decreasing in magnitude below the VPN. (There is one point exception to this at 90' attributed possibly to bad data). The upper layers (to 60') seem to show distinct layers where the moisture flux is alternatively upward or downward. These may be directly correlated with the regions where statistically significant changes in moisture were measured over the year from '96 to '97, in the horizons: 1-10', 10-20', 30-40' and 50-60' [Vold,97B?]. A more detailed comparison of these Darcy flux results to those measured changes in moisture content may prove the best validation of the Darcy flux analysis method.

Figure 10 shows the magnitude of liquid phase vertical flux and the moisture source term inferred from Darcy flux analysis in borehole 1107. The moisture flux and source term vary near the VPN as seen in the previous borehole, and a similar local recharge source appears at the 50-60' horizon, coincident with the most significant change in moisture content measured in the hole [Vold, 97B?].

Figure 11 plots the magnitude of liquid phase vertical flux compared to vapor phase contributions to flux inferred from Darcy flux analysis of borehole 1107. Vapor phase dominates only in the region 60-80' in this borehole. Figure 12 compares the magnitude of the moisture source term expressed as a characteristic time scale to change the local moisture content (Eqn.11) for the liquid phase vertical flux (*liq.only*) compared to that for the

total flux (*tot*) with combined liquid and vapor phase contributions to flux, as inferred from Darcy flux analysis of borehole 1107. The vapor flux only reduces the effective time scale in the region, 60-80', where the vapor phase dominates the magnitude of the moisture flux. Figure 13 shows the magnitude of the moisture source term (see text) for the liquid phase vertical flux (*liq.only*) compared to that for the total flux (*tot*) with combined liquid and vapor phase contributions to flux, as inferred from Darcy flux analysis of borehole 1107. Except for the point previously noted at 90', there is a clear trend for upward vapor flux from the VPN at 100' up to 60'.

Figure 14 shows the magnitude of liquid phase vertical flux inferred from Darcy flux analysis in borehole G5, where (*neg.of liq.flux*) implies downward flux and (*pos.liq.flux*) implies upward flux. The results are similar to that for 1107 (note their close proximity as seen in Fig.1) with an upward flux decreasing in magnitude above the VPN (at 92' at this location). Above 60' trends are less obvious, but a downward flux of several cm/yr dominates especially in the 40-60' depth interval. Figure 15 shows magnitude of vapor phase vertical flux inferred from Darcy flux analysis in borehole G5, where (*neg.of vapor flux*) implies downward flux and (*pos. vapor flux*) implies upward flux. From 90' up to 60' there is a fairly clear trend for upward flux and a distinct downward trend from 45' down to 60', with the vapor flux thus converging to the 60' horizon. This is consistent with the location of the profile maximum in matric potential magnitude, as first noted by Gallaher and reported in Rogers, et.al.95].

The magnitude of liquid phase vertical flux is compared to vapor phase contributions to flux inferred from Darcy flux analysis of borehole G5 in Fig. 16. The vapor phase does not strongly dominate in any region but is comparable to the magnitude of the liquid flux throughout the depths, 60' to 80'. In Fig. 17 the magnitude of the moisture source term expressed as a characteristic time scale to change the local moisture content (Eqn.11) for the liquid phase vertical flux (*liq.only*) is compared to that for the total flux (*tot*) with combined liquid and vapor phase contributions to flux, as inferred from Darcy flux analysis of borehole G5. This agrees with the previous figure, that from 60-80' the vapor flux is comparable to the liquid flux, and significantly contributes to reducing the characteristic time scale for moisture change to be about 100 years in that region.

Figure 18 shows the magnitude of liquid phase vertical flux inferred from Darcy flux analysis in borehole 1121, where (*neg.of liq.flux*) implies downward flux and (*pos.liq.flux*) implies upward flux. This shows downward flux to about 70'. Below that, the liquid flux is small in magnitude but upward flux seems to dominate most of the depths from 80' to 120'. Figure 19 compares magnitudes of liquid phase vertical flux with vapor phase contributions to flux inferred from Darcy flux analysis of borehole 1121. This shows that down to about 70', the vapor flux is negligible, from 80' to 100' the vapor flux exceeds the liquid flux, and contributes significantly at most of the depths below 75'.

Figure 20 shows the magnitude of the moisture source term expressed as a characteristic time scale needed to change the local moisture content (see text) for the liquid phase vertical flux (*liq.only*) compared to that for the total flux (*tot*) with combined liquid and vapor phase contributions to flux, as inferred from Darcy flux analysis of borehole 1121. Again, the vapor flux contributes to this effective source term at most points below 60', and dominates in the range 80-110', so that the time scale never exceeds about 100-200 years. The liquid phase source term alone would be 500-1000 years in this region, 80-110'. Figure 21 shows the moisture profiles and Cl concentrations [Cl data from Newman, 1996] in borehole 1121 for comparison to flux from Darcy analyses. The Cl tends to peak in the depths just above the region of vapor flux.

Canyon locations

Moisture profiles (Fig. 22 top) and inferred vertical Darcy flux (Fig. 22 bottom) are seen from a borehole in Canada del Buey, adjacent to and north of Area G. Moisture data is from core samples taken from borehole CdBM1 [Rogers and Gallaher, 1995]. Unit interface locations distinguish alluvium, unit 1a, and the Otowi unit (from left to right). The inferred liquid flux settles down to a steady level in the Otowi (below 130') of about 1cm/yr, using the arithmetic mean saturated hydraulic conductivity for the Otowi unit (compared to a flux of about 0.4 cm/yr using the geometric mean saturated conductivity [Rogers, et.al.95], [Rogers, et.al.96]). The vapor flux is insignificant at all canyon locations and is not shown.

Figure 23 shows the moisture profiles (top) and inferred vertical Darcy flux (bottom) in two boreholes in Mortendad Canyon, a wet canyon to the

north and west of Area G. Moisture data is from core samples taken from boreholes MDM5.1 and MDM5.9 [Rogers and Gallaher,1995]). Unit interface locations distinguish alluvium, unit 1a, and the Otowi unit (from left to right). The two boreholes are near each other and cover different depths, so the data is combined in a single plot, noting that the 1a-Otowi interface is at 92' in one hole and 100' in the other so the overlap between the holes is not exact. Large moisture flux is seen in the upper layers and a clear downward trend is evident in the flux direction. The flux magnitude levels out as seen in the previous canyon profiles, in the Otowi layer, at this location to a downward flux of about 30-50 cm/yr.

This location is probably influenced by the effluent discharge from TA50, and is considered wetter than a representative 'wet canyon' which is more likely to exhibit a flux of 5-10 cm/yr [Rogers,et.al.,97], [Vold,et.al.,96B]. The largest values at this location, ~50cm/yr at 20% volumetric content corresponds to a pore water velocity of 2.5m/yr or about 8ft/yr. This seems to be consistent with some tracer studies [Stoker,et.al.] that indicate relatively rapid movement beneath some canyons.

Mesa top location: TA-46

Figure 24 shows the moisture profiles (top) and unsaturated conductivity in a borehole at TA-46 at a mesa-top location ~1km to the west of Area G. Moisture data by weight percent was provided by D. Broxton [personal communication, 96] from core samples. Unit interfaces distinguish the stratigraphic units: 3, 2, 1b, 1a, Tsankawi-Cerro Toledo, and the Otowi, from left to right. The unsaturated conductivity provides a first estimate of the local recharge rate. It was estimated here from the moisture data converted to volumetric fractions and then to unsaturated conductivity using stratigraphic averaged hydraulic properties for each unit.

Figure 25 compares the magnitude of liquid phase vertical flux inferred from Darcy flux analysis in this borehole at TA46, where (*neg.of liq.flux*) implies downward flux and (*pos.liq.flux*) implies upward flux. There is no clear trend until below the adjacent canyon floors (~400') where the flux is downward, ~ 0.5cm/yr until the Otowi (~600') where the downward flux increases in magnitude to about 2-3 cm/yr. This value agrees with the unsaturated hydraulic conductivity in the previous figure and confirms the validity of a unit gradient assumption at these depths.

The magnitude of liquid phase vertical flux is compared to vapor phase contributions to flux inferred from Darcy flux analysis at TA46 in Fig. 26. The vapor flux is comparable to the liquid flux at most points down to 200', and then drops to an insignificant contribution below about 350' (near the adjacent canyon floor). Figure 27 shows the magnitude of the moisture source term expressed as a characteristic time scale to change the local moisture content (see text) for the total flux (*tot*) with combined liquid and vapor phase contributions, as inferred from Darcy flux analysis at TA46. This function is very 'noisy'. There may be a slight trend towards decreasing time scale with depth, implying increased moisture flux with depth (i.e., possibly lateral flux moisture sources). The depth independent average time scale is in the range of 100-1000 years with a very broad (geometric) distribution.

Evapotranspiration

We shift from Darcy flux analyses to a recent review of evapotranspiration (ET) and precipitation (Precip) data from TA6 (west end of the Los Alamos site). The evapotranspiration data presented here covers 1992 to 1996 and is from eddy correlation measurements by ESH-17, LANL. There is some concern that the eddy correlation instrumentation underestimates some of the fluctuation spectra and so the net ET data should be increased by 7% to account for this [G. Stone, personal communication, 96]. This will be considered in the following discussion, while the figures plot uncorrected data.

Figure 28 shows precipitation (top) and Evapotranspiration (bottom) monthly averaged values (mm/day) verses calender month for each year separately in the available four year record from '92 - '96. The precipitation is extremely variable. The ET is fairly consistent between years, but shows a low trend between March and June of '95-'96. This time period was the end of a record draught period locally, and there was much less moisture in the soil to evaporate than under normal conditions.

The year '95-'96 represents a 'rare' dry year, and probably acts to significantly reduce the ET averaged over a short interval (a few years) which includes this period. Figure 29 shows precipitation (top) and evapotranspiration (bottom) monthly averaged values (mm/day) verses calender month for three different record intervals in the available four year record. This confirms that a 3-4 year average appears to be significantly

reduced from a long term average when the '95-'96 record is included. In consideration of this, we have chosen to use the most complete record, all four years, but then to consider the possible error in the long term average value introduced by the draught year as a error to the final ET estimates. It is estimated that the long term ET average may be as much as 10% greater than that reflected in the short record including '95-'96, but the likely error in using this record is probably smaller (~5% based on examination of the curves in Fig.29(bottom)).

The ratio of ET to precipitation, ET/Precip, (top) and the net precipitation minus ET, Precip - ET, -mm/day- (bottom) is shown as monthly averaged values as a function of time (calender month) in Fig. 30 for the 4 year record. It is seen in Fig.30 (top) that ET exceeds precipitation on a monthly average only in April and June in the original data base, but during much of the summer, ET/Precip, is close to one. If ET is increased by 7-17%, to compensate for instrumental errors and a low ET biased year in 1996, then ET/precip ratio would exceed one for more than half of the year from March through September, excluding only August when the summer shower input exceeds the ET losses.

The annual averages of the data in Fig.30 are summarized in Table I.

Table I.

ET data consideration	ET fraction of precip. (ET/Precipitation) -annual average-	net precip. minus ET (Precipitation - ET)an.av - mm/day (cm/yr)-
with ET data in figs.	0.715	0.349 (12.7)
with 7% ET increase	0.765	0.283 (10.3)
with 17% (7+10%) ET	0.835	0.190 (6.92)

The first row shows the ET/Precip ratio and net (Precip-ET) from the four year data record. The second row corrects the values for an increase of 7% in the ET data, assuming this as the instrument correction [G.Stone, personal communication,96]. The third row adds another 10% to the ET amount which is considered to be a maximum correction for the bias in the record due

to the inclusion of the drought year. The last two rows are considered to bracket the expected values of interest.

It is assumed that the TA6 data (west end of Los Alamos) applies to Area G (east end of Los Alamos) by two assumptions to further bracket a range. One assumption is that the evapotranspiration at each location is the same, so that the lower precipitation rate at Area G implies a much smaller percolation rate. An alternate assumption is that the (ET/Precip) ratio is similar between TA6 and Area G and so the percolation at Area G is a fraction of the Area G precipitation, with the fraction taken from TA6. Both assumptions are considered to bracket the likely field condition.

Following the assumption that the evapotranspiration at each location is the same, we use the last column in the table and subtract the difference in precipitation between TA6 and TA54 (Area G). The precipitation difference is about 4-5" or 10 -12 cm/yr, which suggests (in comparison to the last column, lower two row numbers) there may be no net percolation at Area G under these assumptions. If one assumes the (ET/Precip) ratio is similar between TA6 and Area G, then the ~36cm of precipitation at Area G corresponds to $0.765 \times 36 = 27\text{cm}$ to $0.835 \times 36 = 30\text{ cm}$. This leaves 6-9 cm/yr for run-off or percolation. The maximum run-off from the mesa was estimated to be ~6cm, but the actual run-off from the disposal unit covers (sloped at only 3% inclination) was determined to be negligibly small. Thus, this estimate probably leaves 6-9 cm/yr of water going into percolation.

The two estimates bracket a range of percolation from 0 to 9 cm/yr at Area G. This ranges from less than expected to significantly more and could have significant impact on the performance assessment of the site for environmental transport. This underscores the need to obtain evapotranspiration data from TA54. If this available at the LANL TA54/WR meteorological station, the data should be examined on a priority basis.

Conclusions

An interesting outcome is that the flux inferred from the Darcy flux analyses appears too be in very good agreement with moisture changes actually measured in at least one borehole (1107) using neutron probes

[Vold,97C]. Additional comparison should be undertaken to further 'validate' the Darcy flux analyses methods.

The Darcy flux analyses reported here and related hydrologic studies reported previously lead to the following possible interpretation of the Pajarito Plateau hydrology. Figure 31 illustrates this 'quantified conceptual model' with a cross-section of Mesita del Buey (mesa site of Area G) showing the net moisture flux movement implied by the analyses. The arrows indicate dominant moisture flux paths and are approximately proportional in size to the amount of flux. The horizontal arrows indicate lateral flow, which is predominantly towards the viewer (east). The horizontal arrows at the edge of mesas indicates an evaporative loss which may actually be to the mesa sides or may be to the surface connected fracture network. The paths and estimated flow quantities are discussed as follows.

Evapotranspiration and precipitation data suggest that several cm/yr percolates into the plateau on the average. The Darcy flux analyses suggest that the percolation is very variable with location, with values above the average at most canyon locations and values much smaller on the mesas. Below the canyons the infiltration spreads laterally especially at stratigraphic contacts so that the vertical flux is fairly uniform near Area G by the depth of the Otowi layer and of the order of 1 cm/yr. Presumably this flux remains relatively uniform at greater depths, however, pressure-fluctuations seen by the ER Project in the basalt layers [Neeper, personal communication,96], suggest there may be a significant vapor flux there which could act to dry that region and reduce the liquid flux.

The Darcy flux analyses show trends at mesa locations, that moisture movement is significant (~cm/yr) and downward near the surface and small (~mm/yr) and upward in liquid and vapor phases through much of the lower portion of the Area G mesa. This suggests that the mesa acts something like a wick, pulling moisture from beneath the mesa, driven presumably by evaporation at the mesa sides and top through the surface-connected fracture network permeating the stratigraphic layers within the mesa. The 'vapor dominated region' in the lower portion of the mesa interior acts as a barrier to significant downward liquid phase flux in the undisturbed state, and allows the downward moisture movement to evaporate through the fracture network or the mesa sides. The downward movement of liquid flux is also

inhibited by the significant decrease in hydraulic conductivity in the lower portions of the mesa interior.

There are indications that disposal operations have altered the natural hydrology to the extent the 'vapor phase barrier' may be non-existent beneath the disposal units. Therefore, it is a conservative but realistic assumption that moisture movement is downward from beneath the disposal units as characterized by the moisture profiles and hydraulic properties observed in the active disposal units. The present best estimate of this recharge is 0.5-1 cm/yr. The uncertainty in the surface recharge estimate is dominated by the uncertainty in the evapotranspiration. Future studies should focus on reducing this uncertainty.

Acknowledgements

This work was supported in part by the U.S. Department of Energy, Waste Management Offices. The author is indebted to the many individuals at LANL, who are real hydrologists and earth scientists and have contributed to the analyses discussed here and in previous reports upon which this analysis is built.

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Fig.1 Area G facilities map showing locations of boreholes discussed in this report.

Fig. 2 Moisture profiles measured by neutron probe in Area G vertical boreholes: 1117 (top-left), 1121 (top-right), 1107 (bottom-left), and G5 (bottom-right).

Fig.3 (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 mean and standard deviations of the field data (θ -vol%) in each unit.

Fig. 4 Magnitude of liquid phase vertical flux inferred from Darcy flux analysis in borehole 1117, where (*neg. of liq. flux*) implies downward flux and (*pos. liq. flux*) implies upward flux.

Fig. 5 Magnitude of liquid phase vertical flux and the moisture source term inferred from Darcy flux analysis in borehole 1117, focusing on the region near the vapor phase notch.

Fig. 6 Magnitude of liquid phase vertical flux compared to vapor phase contributions to flux inferred from Darcy flux analysis of borehole 1117.

Fig. 7 Magnitude of the moisture source term (see text) for the liquid phase vertical flux compared to that for the vapor phase contributions to flux, as inferred from Darcy flux analysis of borehole 1117.

Fig. 8 Moisture profiles and Cl concentrations [Cl data from Newman, 1997] in borehole 1117 for comparison to flux from Darcy analyses.

Fig. 9 Magnitude of liquid phase vertical flux inferred from Darcy flux analysis in borehole 1107, where (*neg.of liq.flux*) implies downward flux and (*pos.liq.flux*) implies upward flux.

Fig. 10 Magnitude of liquid phase vertical flux and the moisture source term inferred from Darcy flux analysis in borehole 1107.

Fig. 11 Magnitude of liquid phase vertical flux compared to vapor phase contributions to flux inferred from Darcy flux analysis of borehole 1107.

Fig. 12 Magnitude of the moisture source term expressed as a characteristic time scale to change the local moisture content (see text) for the liquid phase vertical flux (*liq.only*) compared to that for the total flux (*tot*) with combined liquid and vapor phase contributions to flux, as inferred from Darcy flux analysis of borehole 1107.

Fig. 13 Magnitude of the moisture source term (see text) for the liquid phase vertical flux (*liq.only*) compared to that for the total flux (*tot*) with combined liquid and vapor phase contributions to flux, as inferred from Darcy flux analysis of borehole 1107.

Fig. 14 Magnitude of liquid phase vertical flux inferred from Darcy flux analysis in borehole G5, where (*neg.of liq.flux*) implies downward flux and (*pos.liq.flux*) implies upward flux.

Fig. 15 Magnitude of vapor phase vertical flux inferred from Darcy flux analysis in borehole G5, where (*neg.of vapor flux*) implies downward flux and (*pos. vapor flux*) implies upward flux.

Fig. 16 Magnitude of liquid phase vertical flux compared to vapor phase contributions to flux inferred from Darcy flux analysis of borehole G5.

Fig. 17 Magnitude of the moisture source term expressed as a characteristic time scale to change the local moisture content (see text) for the liquid phase vertical flux (*liq.only*) compared to that for the total flux (*tot*) with combined liquid and vapor phase contributions to flux, as inferred from Darcy flux analysis of borehole G5.

Fig. 18 Magnitude of liquid phase vertical flux inferred from Darcy flux analysis in borehole 1121, where (*neg.of liq.flux*) implies downward flux and (*pos.liq.flux*) implies upward flux.

Fig. 19 Magnitude of liquid phase vertical flux compared to vapor phase contributions to flux inferred from Darcy flux analysis of borehole 1121.

Fig. 20 Magnitude of the moisture source term expressed as a characteristic time scale to change the local moisture content (see text) for the liquid phase vertical flux (*liq.only*) compared to that for the total flux (*tot*) with combined liquid and vapor phase contributions to flux, as inferred from Darcy flux analysis of borehole 1121.

Fig. 21 Moisture profiles and Cl concentrations [Cl data from Newman, 1997] in borehole 1121 for comparison to flux from Darcy analyses.

Fig. 22 Moisture profiles (top) and inferred vertical Darcy flux (bottom) in a borehole in Canada del Buey, adjacent to and north of Area G. Moisture data is from core samples taken from borehole CdBM1 [Rogers and Gallaher, 1995?]. Unit interface locations distinguish alluvium, unit 1a, and the Otowi unit (from left to right).

Fig. 23 Moisture profiles (top) and inferred vertical Darcy flux (bottom) in two boreholes in Mortendad Canyon, a wet canyon to the north of Area G. Moisture data is from core samples taken from boreholes MDM5.1 and MDM5.9 [Rogers and Gallaher,1995?]. Unit interface locations distinguish alluvium, unit 1a, and the Otowi unit (from left to right).

Fig. 24 Moisture profiles (top) and unsaturated conductivity in a borehole at TA46 at a mesa-top location ~1km to the west of Area G. Moisture data is from D. Broxton [personal communication, 96].

Fig. 25 Magnitude of liquid phase vertical flux inferred from Darcy flux analysis at TA46, where (*neg.of liq.flux*) implies downward flux and (*pos.liq.flux*) implies upward flux.

Fig. 26 Magnitude of liquid phase vertical flux compared to vapor phase contributions to flux inferred from Darcy flux analysis of borehole ??(TA46).

Fig. 27 Magnitude of the moisture source term expressed as a characteristic time scale to change the local moisture content (see text) for the total flux (*tot*) with combined liquid and vapor phase contributions, as inferred from Darcy flux analysis of borehole ??(TA46).

Fig. 28 Precipitation (top) and Evapotranspiration (bottom) monthly averaged values (mm/day) verses calender month for each year separately in the available four year record.

Fig. 30 Ratio of ET to precipitation (top) and the net precipitation minus ET -mm/day- (bottom) shown as monthly averaged values as a function of time (calendar month).

Fig. 31 Cross-section of Mesita del Buey (mesa site of Area G) showing the net moisture flux movement implied by the analyses reported here and in previous studies. The arrows indicate dominant moisture flux paths and are approximately proportional in size to the amount of flux. Some horizontal arrows indicate lateral flow (predominantly to the east, towards the viewer). The paths and estimated flow quantities are discussed in the text.

M98004332

Report Number (14) LA-UR -- 77 - 5202

Publ. Date (11) 1978 03

Sponsor Code (18) DOE/EM , XF

UC Category (19) UC - 2000 , DOE/ER

DOE