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VERIFICATION OF A 1-DIMENSIONAL MODEL FOR PREDICTING SHALLOW INFILTRATION AT YUCCA MOUNTAIN

Joseph A. Hevesi
U.S. Geological Survey
Box 327, MS 721
Mercury, Nevada 89023
(702) 295-5998

Alan L. Flint
U.S. Geological Survey
Box 327, MS 721
Mercury, Nevada 89023
(702) 295-5805

Lorraine E. Flint
Foothill Eng. Consultants
Box 327, MS 721
Mercury, Nevada 89023
(702) 295-6002

ABSTRACT

A characterization of net infiltration rates is needed for site-scale evaluation of groundwater flow at Yucca Mountain, Nevada. Shallow infiltration caused by precipitation may be a potential source of net infiltration. A 1-dimensional finite difference model of shallow infiltration with a moisture-dependant evapotranspiration function and a hypothetical root-zone was calibrated and verified using measured water content profiles, measured precipitation, and estimated potential evapotranspiration. Monthly water content profiles obtained from January 1990 through October 1993 were measured by geophysical logging of 3 boreholes located in the alluvium channel of Pagany Wash on Yucca Mountain. The profiles indicated seasonal wetting and drying of the alluvium in response to winter season precipitation and summer season evapotranspiration above a depth of 2.5 meters. A gradual drying trend below a depth of 2.5 meters was interpreted as long-term redistribution and/or evapotranspiration following a deep infiltration event caused by runoff in Pagany Wash during 1984. An initial model, calibrated using the 1990 to 1992 record, did not provide a satisfactory prediction of water content profiles measured in 1993 following a relatively wet winter season. A re-calibrated model using a modified, seasonally-dependent evapotranspiration function provided an improved fit to the total record. The new model provided a satisfactory verification using water content changes measured at a distance of 6 meters from the calibration site, but was less satisfactory in predicting changes at a distance of 18 meters.

INTRODUCTION

Yucca Mountain is located approximately 160 km northwest of Las Vegas, Nevada, and is being studied as a potential site for a high level nuclear waste repository[1]. The location is within the northern Mojave Desert region of the southern Basin and Range physiographic province, and average annual precipitation for the site is estimated to be 170 mm[2]. Most of this precipitation occurs during the winter to early spring season, from November to April, and is caused by regional frontal systems carrying moisture eastward from the Pacific Ocean, causing low intensity storms lasting 1 to 2 days with precipitation often occurring as snow at higher elevations[3,4]. A more variable, yet potentially wet season also occurs during the summer monsoon period from July through August[3,4]. This season is typified by localized, convective-type storms producing short duration yet high intensity precipitation events.

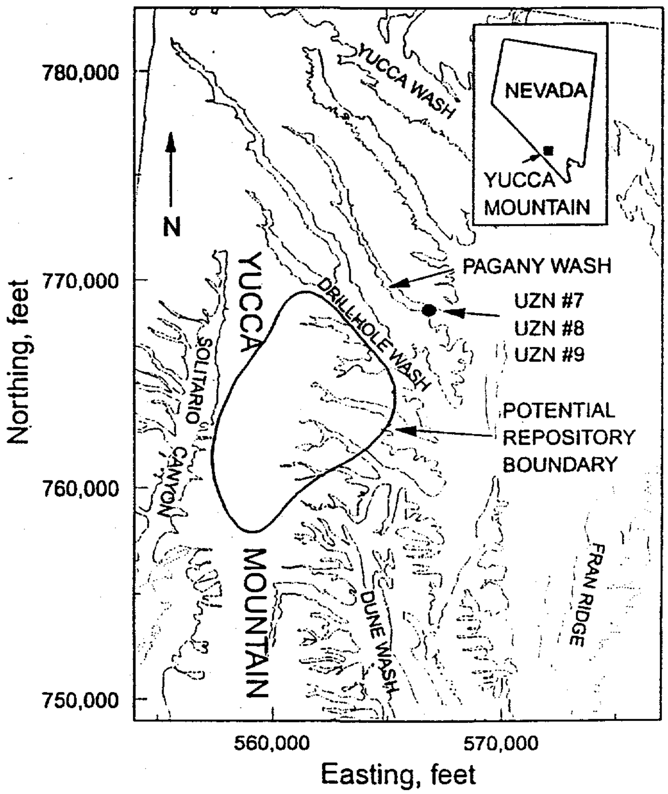

Figure 1. Location of potential repository boundary on Yucca Mountain and study site in Pagany Wash.

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DISCLAIMER

A quantitative determination of net infiltration at Yucca Mountain is needed to help define upper boundary conditions for site-scale flow models of the relatively thick unsaturated zone which includes the potential repository horizon[5,6,7]. Shallow infiltration and percolation resulting from precipitation (*P*) is a potential source of net infiltration[8]. Numerical models of shallow infiltration can be used to estimate net infiltration under both present and potential future climatic conditions. Hevesi and Flint[9] developed and calibrated a 1-dimensional model of shallow infiltration in an alluvial wash on Yucca Mountain using measured volumetric water content (θ) profiles, measured *P*, and estimated evapotranspiration (*ET*). This study presents a verification of a model similar to their initial model using records obtained in 1993 and also using θ profiles measured at boreholes located 6 and 18 meters from the calibration site. The objective was to improve model calibration and to provide a qualitative measure of model accuracy for predicting shallow infiltration and percolation through alluvial deposits in response to *P* during periods when runoff does not occur.

METHODOLOGY

Study Site Description

Pagany Wash is a northwest to southeast trending fault-controlled drainage on the eastern slope of Yucca Mountain (Figure 1). The alluvium consists of poorly sorted silt to pebble sized gravel with intermittent cobbles and boulders, and with layers of calcium carbonate in varying stages of consolidation[10]. The underlying bedrock is the Tiva Canyon member of the Paintbrush Tuff formation, which is a moderately welded ash-flow tuff. Measured θ profiles from borehole UZN #7, located in the center of the active channel of Pagany Wash, were used for model development and calibration. The depth of the alluvium bedrock contact at UZN #7 is 12.3 meters, and the borehole has a total depth of 13.5 meters. The profiles were measured by logging the borehole at monthly intervals using a neutron moisture meter. Profiles obtained from two additional boreholes, UZN #8 and UZN #9, were used for model verification. UZN #8 is located on the north side of the active channel at a distance of 6 meters from UZN #7. The depth of the alluvium at UZN #8 is 12.2 meters and the total depth of the borehole is 13.2 meters. UZN #9, located 18 meters north of UZN #7, is on the alluvial terrace adjacent to the active channel, with the alluvium bedrock contact at a depth of 10.7 meters and a total depth of 11.9 meters.

Development of a numerical model

The continuity equation provided the framework for a 1-dimensional vertical infiltration model:

$$\Delta S_z = P - ET - R_{off} + R_{on} \pm I_z \quad (1)$$

where ΔS_z = the change in water storage between the reference depth *z* and the ground surface, *P* = precipitation, *ET* = evapotranspiration, *R* = surface flow, and I_z = net infiltration/exfiltration at the reference depth. For this study, *P* was measured, *ET* was estimated, *R* was assumed to be insignificant during the study period, and I_z at the bottom of the borehole was assumed to be negligible relative to *P* and *ET*. To simulate ΔS as a function of transient unsaturated flow through the vertical profile, a 1-dimensional finite difference approximation of Richards equation was used[11]:

$$\Delta S_z = \frac{\delta(\theta)}{\delta t} = \frac{\delta}{\delta z}\left[K(\theta)\left(\frac{\delta\psi}{\delta z} - 1\right)\right] + U(\theta,z,t) \quad (2)$$

where *K* = conductivity, ψ = matric water potential, *t* = time, *z* = depth below ground surface, and $U(\theta,z,t)$ = a specified flux term for including *P* and *ET* in the model. Vapor flow was omitted from the flow model, and isothermal conditions were assumed. *P* was treated as rain (snow cover was neglected) and was modeled as a specified positive flux for the top element, conditioned to the available storage capacity. *ET* was modeled as a negative flux for all elements within an estimated root zone. Both *P* and *ET* fluxes were assumed constant over time increments of 2-hours. Initial conditions were defined using measured water content profiles. Boundary conditions were specified using a no-flow (impermeable) upper boundary and a constant-head lower boundary, as determined by the initial conditions. Discretization of the study site was defined using a constant vertical spacing of 0.1 meters from ground surface to the depth of each borehole.

The Brooks and Corey functions were used to define *K* and ψ in terms of θ:

$$K = K_S\left(\frac{\theta}{\phi}\right)^{\left(\frac{2}{L}+3\right)} \qquad \psi = \psi_E\left(\frac{\theta}{\phi}\right)^{-L} \quad (3)$$

where K_S = saturated hydraulic conductivity, ψ_E = air-entry potential, ϕ = porosity, and *L* = an empirical coefficient. Values for ϕ, K_S, ψ_E, and *L* were specified for each element, allowing for variable material properties throughout the profile. Measurements of ϕ, K_S, ψ_E, and *L* for the bedrock underlying the alluvium were obtained from core samples[12]. K_S at the top of the profile was estimated based on field measurements using a double-ring infiltrometer at a site 0.5 km from UZN #7[13]. Values of ϕ for the alluvium profile were estimated using the θ profiles and also measurements of ϕ obtained for a profile at a site 6 km southeast of Pagany Wash[14]. The remaining parameters needed to define the model for the alluvium profile were estimated using measurements presented by Fischer for the Beatty low-level waste site approximately 50 km west of UZN-7[15]. The postion of contacts for modeled layers within the alluvium were estimated by visual inspection of the measured θ profiles.

Determination of Specified Flux Terms

Precipitation was measured using a heated, tipping bucket gage located at the study site and also using collection-type gages located at each borehole in the transect. Potential evapotranspiration (*PET*) was estimated using the Priestley-Taylor equation:

$$PET = \frac{\alpha}{Lh}\left[\frac{S}{(S+\gamma)}\,(R_n - G)\right] \tag{4}$$

where Lh = the latent heat of vaporization, α = an empirically determined coefficient which indirectly relates to the advection term in the energy balance, S = the slope of the saturation-vapor-density curve, γ = the psychrometric constant, R_n = net radiation, and G = ground heat flux. Estimates of R_n and G were obtained for 2-hour periods using measured incoming solar radiation and air temperature[10,16]. Estimates of Lh and $S/(S+\gamma)$ were calculated using the measured averaged air temperature for each 2-hour period[10].

To model *ET*, the α coefficient in the Priestley-Taylor equation was defined as an empirical function of simulated θ for each element within the estimated root-zone[17]:

$$\begin{aligned} \alpha_i &= W_i A & \theta_i &\ge C+\theta_i^R \\ \alpha_i &= W_i B\left[\frac{\theta_i-\theta_i^R}{\phi_i-\theta_i^R}\right] & \theta_i^R &< \theta_i < C+\theta_i^R \\ \alpha_i &= 0 & \theta_i &\le \theta_i^R \end{aligned} \tag{5}$$

where θ^R_i = a specified residual water content, W_i = a weighting factor, A, B, and C are empirical model coefficients, and i = the element index for all elements within a hypothetical root-zone extending from the surface to an estimated root-zone depth. Values for W_i were assumed to decrease with depth, and were conditioned by setting the sum of the W_i profile equal to unity so as not to exceed *PET*.

Model Calibration and Verification

The three model coefficients, *A*, *B*, and *C*, along with the root-zone depth and the W_i profile, were calibrated by trial and error fitting of simulated θ profiles with measured θ profiles obtained at UZN #7. Simulated θ profiles were obtained using the measured January 11, 1990 θ profile as initial conditions, and estimating the θ^R_i profile for the root zone to be 85% of the initial θ profile. Model performance was based on a visual comparison of the simulated relative water content change (*RWCC*) for selected depth intervals with the measured *RWCC*, and also a comparison of simulated θ profiles with measured profiles. A model similar to the model defined by Hevesi and Flint[9], calibrated using records obtained for the period of January 11, 1990 to October 25, 1992, was verified using records obtained from October 25, 1992 to October 13, 1993. A final calibration at UZN #7 was performed using the total 3.8 year record from January 11, 1990 to October 13, 1993. The re-calibrated model was verified using the estimated material properties and measured January 11, 1990 initial conditions for the UZN #8 and UZN #9 sites. Estimated θ^R_i values were again assumed to be approximately 85% of the initial conditions at both sites. The depth of the root-zone was also adjusted at each site so as not to extend below the alluvium-bedrock contact. The remaining parameters defining the *ET*-function and the root-zone were unchanged.

RESULTS

Measured Water Content Profiles and Climatic Record

Figure 2 indicates the maximum and minimum measured θ at UZN #7 for the 3.8 year study period and measured θ profiles for selected months in 1992 and 1993. Runoff was not recorded during the study period. The expected seasonal wetting and drying of the upper profile was most pronounced during 1992 and 1993 due to relatively wet winters for both years. Maximum changes in θ above a depth of 3 meters were measured during 1993. Profile changes below a depth of 3 meters were less distinct, although a comparison of the maximum and minimum profiles indicated changes in water content throughout the profile. The general shape of the profile was interpreted as indicating heterogeneity of the alluvium, as opposed to transient conditions.

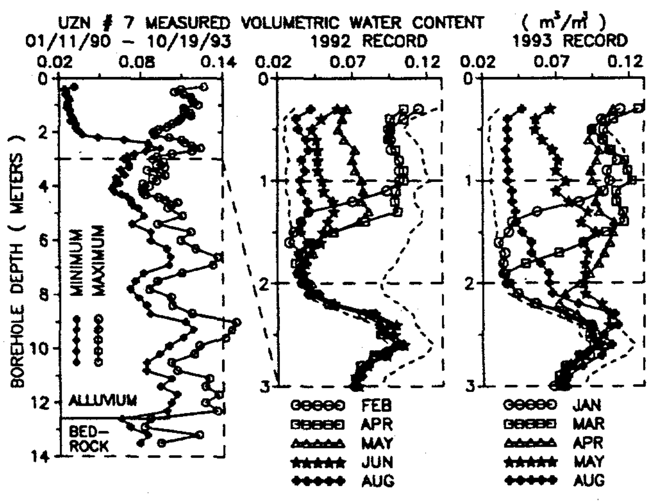

Figure 2. Maximum and minimum measured θ at UZN #7, and selected θ profiles for 1992 and 1993.

Measured *P* and estimated Priestley-Taylor *PET* (using an α coefficient of 1.26) indicated a relatively dry year for 1990 and relatively wet winter seasons of 1992 and 1993, with a maximum daily *P* of 45 mm measured during December of 1992 (Figure 3). Most *P* in 1992 and 1993 occurred during the winter when *PET* was at a minimum. Total *PET* exceeded total *P* for the study period by a factor of approximately 6. The actual record used in the model consisted of average 2-hour rates for *P* and *PET*, thus diurnal effects on *PET* were accounted for. The record for *P* is not identical to the initial record used by Hevesi and Flint[9] for the period of 1990 through 1992 because of revisions made in storm timing and duration[18].

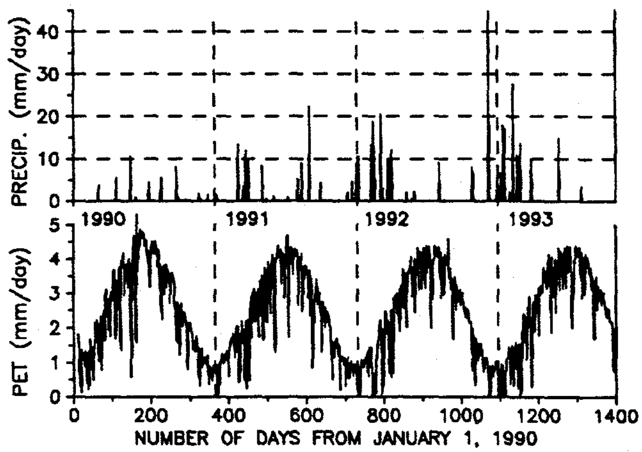

Figure 3. Measured daily climatic record at UZN #7 from January 1990 through October 1993.

A comparison of total monthly *P* and *PET* with *RWCC* for 4 depth intervals indicated an increase in *RWCC* above a depth of 2 meters during months when *P* exceeded *PET* (Figure 4). A trend of decreasing *RWCC* below 2 meters seemed independent of monthly *P* and *PET*, with the exception of an increase for the 2 to 5 meter depth interval following the 1993 winter season. The drying trend was interpreted as a combination of *ET*, lateral losses, and possibly gravity drainage from the profile following deep infiltration caused by a runoff event in 1984[10].

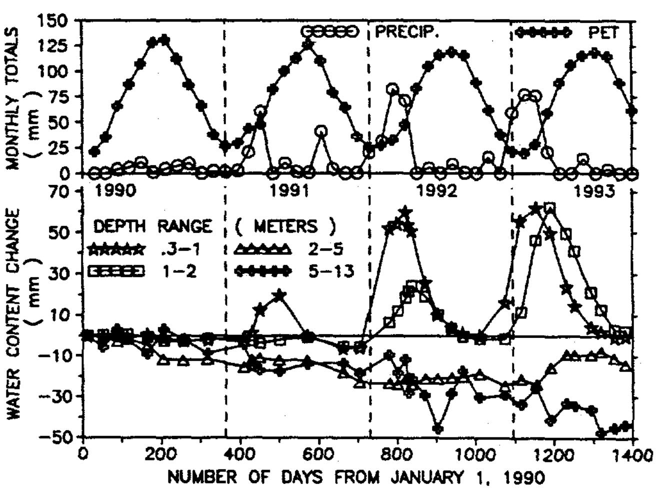

Figure 4. Comparison of total monthly *P* and *PET* with measured *RWCC* at UZN #7 from January 11, 1990 for 4 selected depth ranges.

Measured and Estimated Material Properties

The general shape of the θ profiles were used to help define 3 separate layers for the alluvium at each borehole site (Figure 5). The January 1990 profiles defined the initial conditions and lower boundary conditions used for model calibration and verification. The saturation profiles for alluvium were assumed to increase with depth, with relatively dry conditions near the surface due to a period of drought preceding the study period. Average saturations for the alluvium below a depth of 2 to 3 meters were assumed to be approximately 30% for UZN #7 and UZN #8 located within the active channel, and 24% for UZN #9 located on the adjacent terrace. Values for ϕ derived from measured water content profiles and assumed saturation profiles ranged from 0.18 to 0.58. Average values of ϕ for model layers ranged from 0.25 to 0.37, which was also considered representative of average values measured at nearby field sites[10,14]. Values for the parameters K_S, ψ_E, and L for the 3 alluvium layers and lower bedrock layer, and also average values for θ, θ^R, ϕ, and θ/ϕ are listed in Table 1. To represent the heterogeneity of the alluvium, the ϕ_i values assigned to elements in the model were defined by the profiles in Figure 5. This is an important difference from the original model presented by Hevesi and Flint, which assumed a constant porosity throughout the alluvium[9].

Material	Model Layer	K_S (cm/sec)	ψ_E (J/Kg)	Brooks & Corey L Coeff.
Alluvium	1	4.9 x 10E-3	-1.4	5.5
Alluvium	2	1.0 x 10E-3	-10.0	6.5
Alluvium	3	2.3 x 10E-4	-1.4	5.5
Bedrock	4	4.4 x 10E-8	-50.0	3.1

Hole #	Depth Range (meters)	Model Layer	Average Values for Layer θ	θ^R	ϕ	θ/ϕ
UZN 7	0.1 - 1.5	1	.037	.031	.27	.14
	1.6 - 2.3	2	.049	.039	.25	.19
	2.4 - 12.3	3	.097	.082	.32	.30
	12.4 - 13.5	4	.086	.086	.14	.60
UZN 8	0.1 - 0.9	1	.049	.041	.30	.16
	1.0 - 2.0	2	.070	.058	.31	.22
	2.1 - 12.1	3	.098	.083	.30	.32
	12.2 - 13.2	4	.079	.079	.13	.60
UZN 9	0.1 - 1.5	1	.019	.016	.25	.07
	1.6 - 3.2	2	.057	.049	.37	.15
	3.3 - 10.6	3	.066	.056	.28	.24
	10.7 - 11.9	4	.057	.057	.09	.60

Table 1. Model layers, material properties, and initial conditions at UZN #7, #8, #9.

A 3.8 year (1,400 day) simulation was performed using no climatic input to analyze the predicted redistribution of the January 11, 1990 profile used as initial conditions. Simulated *RWCC* for 4 selected depth intervals indicated only minimal redistribution, with a maximum increase of 0.54 mm predicted for the 1 to 2 meter depth interval and a maximum decrease of -0.44 mm predicted for the 2 to 5 meter depth interval (Table 2). The total *RWCC* for the profile was -0.18 mm, indicating a net infiltration rate of approximately 0.05 mm/year at a depth of 13.5 meters. The result supports the assumption of net infiltration through the profile being insignificant relative to *P* and *ET* for the study period, and also supports the hypothesis that the measured drying trend at UZN #7 is due mostly to *ET* and lateral losses. The simulated infiltration rate is similar to an estimate of 0.04 mm/year obtained by Nichols for alluvium at the Beatty low-level radioactive waste site[19], and also to an estimated average rate of 0.02 mm/year for the Tiva Canyon bedrock[20].

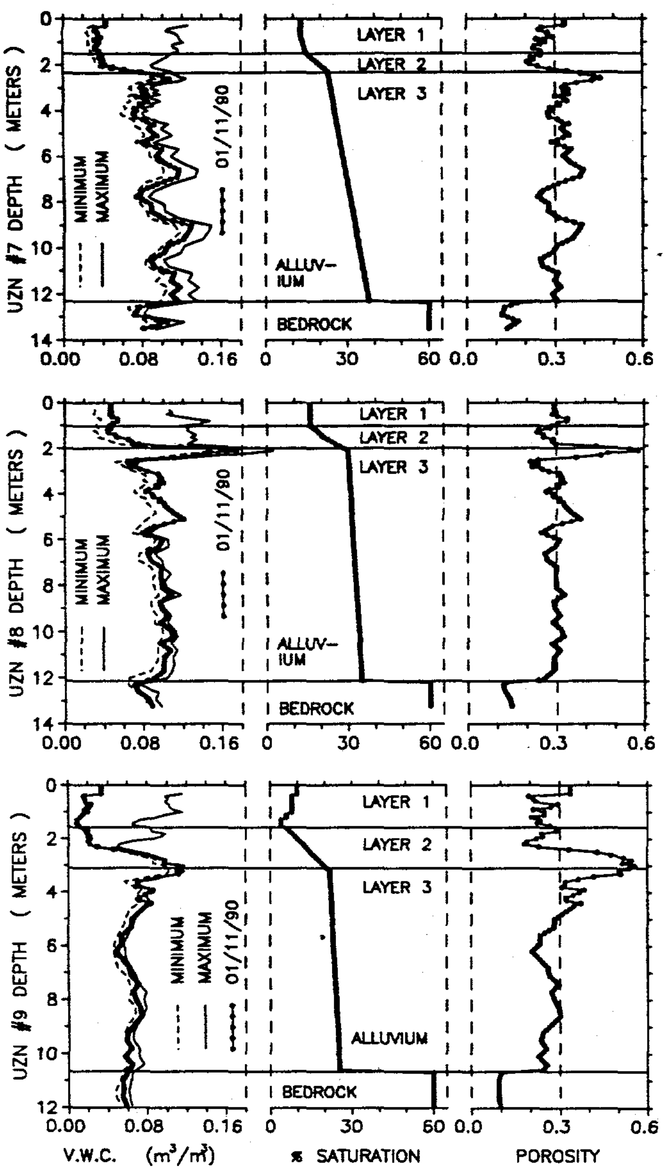

Figure 5. Estimated model layers, measured initial conditions (θ), estimated saturation (θ/ϕ), and estimated porosity at UZN #7, UZN #8, and UZN #9.

Simulation Time (days)	Depth Intervals (meters) 0 - 1	1 - 2	2 - 5	5 - 13.5	0 - 13.5
200	.001	.13	-.15	-.02	-.02
400	.003	.25	-.26	-.06	-.04
600	.005	.35	-.33	-.11	-.07
800	.01	.40	-.37	-.16	-.10
1000	.02	.45	-.40	-.22	-.12
1200	.03	.50	-.42	-.27	-.15
1400	.045	.54	-.44	-.32	-.18

Table 2. Model simulation results using no climatic input indicating total relative water content change (*RWCC*), in mm, for 5 depth intervals.

Calibration and Verification of Initial Model

Values for the parameters defining the initial root-zone and *ET*-function (Table 3), calibrated using the measured profiles for the period of January 11, 1990 to October 25, 1992, were similar but not identical to a previous calibration performed by Hevesi and Flint[9]. The use of a relatively deep root zone of 11.9 meters, with the W_i profile accounting for 12.5 percent of total *PET* below a depth of 2.1 meters, was necessary for providing a fit to the measured trend of decreasing water content in the lower portion of the profile. The use of a root zone to a depth of 2 to 3 meters was considered reasonable for vegetation at the study site[21]. Extension of a root zone below 3 meters was considered an empirical representation of moisture losses due to vapor flow and/or lateral flow.

The initial model was verified using records obtained from October 25, 1992 through October 13, 1993, with the October 25, 1992 profile as initial conditions. The verification was based on a qualitative comparison of predicted *RWCC* for 4 depth intervals with measured *RWCC* (Figure 6). Model performance was considered satisfactory in predicting the downward movement of a wetting front following winter season *P* in 1993, and also drying of the profile due to *ET* for the 0.3 to 1.0 meter depth interval. Model performance was considered unsatisfactory in terms of over-predicting moisture loss for the 1.0 to 2.0 meter depth interval relative to the measured decrease, and also in terms of under-predicting the increase in *RWCC* measured for the 2.0 to 5.0 meter depth interval.

ET-function parameters	Depth range (meters)	Element weight (W_i)	Total weight (%)
A = 1.26	0.1 - 0.1	0.2	20
B = 3.0	0.2 - 0.2	0.1	10
C = 0.08	0.3 - 0.6	0.05	20
	0.7 - 2.1	0.025	37.5
	2.2 - 3.9	0.0025	4.5
	4.0 - 11.9	0.001	8.0

Table 3. Calibrated parameters for intial ET-function and root-zone parameters.

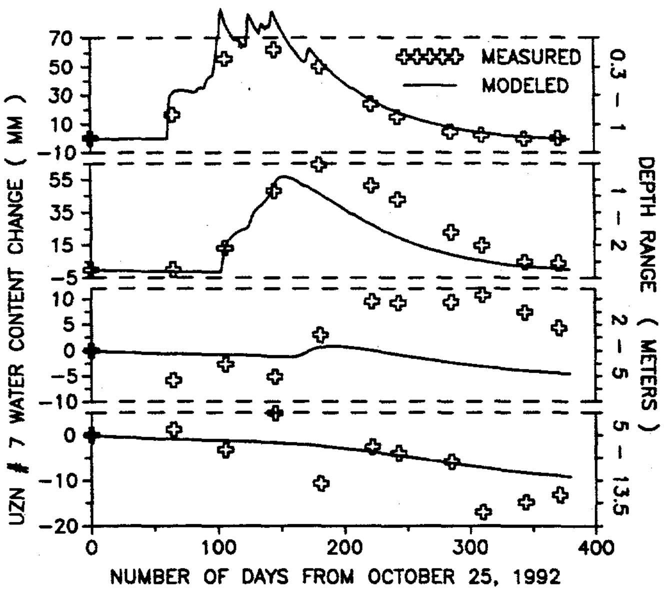

Figure 6. Comparison of simulated and measured water content changes (*RWCC*) at UZN #7 for 1993.

Calibration of a Modified Model

To improve model performance, the *ET*-function was modified to allow for variability in the *A*, *B*, *C*, and W_i parameters as a function of both depth and time:

$$\alpha_i = W_{i,t} \cdot A_{i,t} \qquad \theta_i \geq C_{i,t} + \theta_i^R$$

$$\alpha_i = W_{i,t} \cdot B_{i,t} \left[\frac{\theta_i - \theta_i^R}{\phi_i - \theta_i^R} \right] \qquad \theta_i^R < \theta_i < C_{i,t} + \theta_i^R \qquad (6)$$

$$\alpha_i = 0 \qquad \theta_i \leq \theta_i^R$$

where *t* refers to a time index corresponding to either a winter season or a summer season model. This modification allowed for the modeling of an "active" summer season and an "inactive" winter season root-zone. Calibrated parameters for the modified *ET*-function were defined for 6 depth ranges to a total depth of 12.2 meters (Table 4). The summer season parameters defined an increase in *ET* for a given *PET* relative to the winter season parameters above a depth of 2.5 meters. A seasonal effect was not modeled below 2.5 meters. A seasonal change in W_i was also defined above a depth of 2.1 meters (Table 5).

A comparison of calibration results between the initial model (model 1) and the modified model (model 2) with measured *RWCC* indicated an improved calibration using model 2 following the winter season of 1993 for the 1 to 2 and the 2 to 5 meter depth intervals (Figure 7). The models provided similar results for simulating the trend of decreasing water content in the lower portion of the

UZN #	Depth Range (meters)	Season Begin Date	End Date	ET-function Parameters A	B	C
7,8,9	0.1 1.4	11/01 05/01	04/30 10/31	1.26 1.50	2.0 3.5	0.10 0.05
7,8,9	1.5 1.7	11/01 06/01	05/31 10/31	1.26 1.26	0.5 2.5	0.12 0.10
7,8,9	1.8 2.5	11/01 06/01	05/31 10/31	1.26 1.26	0.1 0.5	0.20 0.20
7,8,9	2.6 3.0	01/01	12/31	1.26	2.5	0.20
7,8,9	3.1 5.1	01/01	12/31	1.26	3.5	0.20
7	5.2 12.2	01/01	12/31	1.26	4.0	0.20
8	5.2 12.1	01/01	12/31	1.26	4.0	0.20
9	5.2 10.6	01/01	12/31	1.26	4.0	0.20

Table 4. Calibrated parameters for modified ET-function.

UZN #	Winter Season Root-Zone Depth Range (meters)	Element Weight (W_i)	Total Weight (%)	Summer Season Root-Zon Depth Range (meters)	Element Weight (W_i)	Total Weigh (%)
7,8,9	0.1 0.1	0.4	40	0.1 0.1	0.2	20
7,8,9	0.2 0.2	0.2	20	0.2 0.2	0.1	10
7,8,9	0.3 0.4	0.1	20	0.3 0.6	0.05	20
7,8,9	0.5 0.5	0.035	3.5	--- ---	-----	-----
7,8,9	0.6 2.1	0.0025	4.5	0.7 2.1	0.025	37.5
7,8,9	2.2 5.1	0.0025	7.5	2.2 5.1	0.0025	7.5
7	5.2 12.2	0.0007	5	5.2 12.2	0.0007	5
8	5.2 12.1	0.0007	5	5.2 12.1	0.0007	5
9	5.2 10.6	0.0009	5	5.2 10.6	0.0009	5

Table 5. Calibrated parameters for modified root-zone.

profile. A comparison of simulated θ profiles with mea sured profiles indicated satisfactory performance for bot models in terms of predicting the downward movement (the wetting front during March 1, 1993, but model provided a better fit to the measured profiles from Ap through July of 1993 (Figure 8). Both models provided good fit to the measured decrease in θ below 3 meter Comparison of the simulated profile using model 2 with tl measured profile for October 13, 1993 indicated satisfa tory model performance in providing a fit to the measure decrease in θ throughout the 13.5 meter deep profi (Figure 9). It is important to note that the simulated dryir for the 3.8 year period was a result of the empirical E function and a 12.2 meter deep root-zone, and not drai age of the profile due to 1-dimensional unsaturated flo\

Verification of the New Model

A comparison of the predicted versus measur change in *RWCC* for the 4 selected depth intervals usi the total record at UZN #8 is indicated reasonable mo(

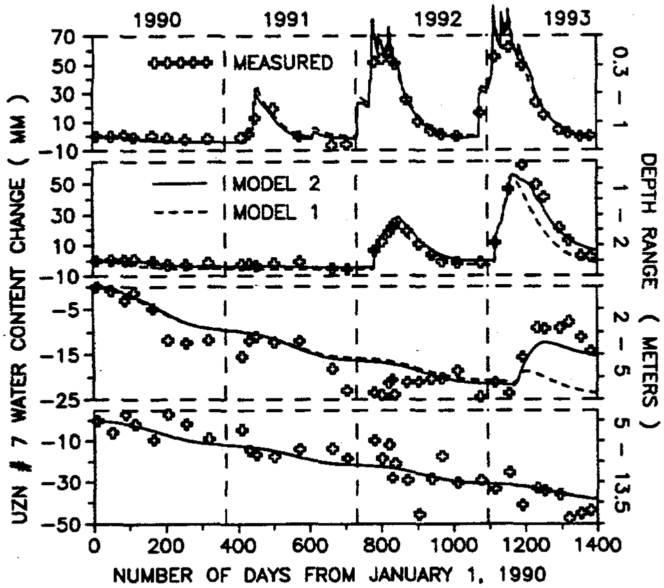

Figure 7. Calibration results: simulated and measured water content change (*RWCC*) for 4 depth intervalsat UZN #7

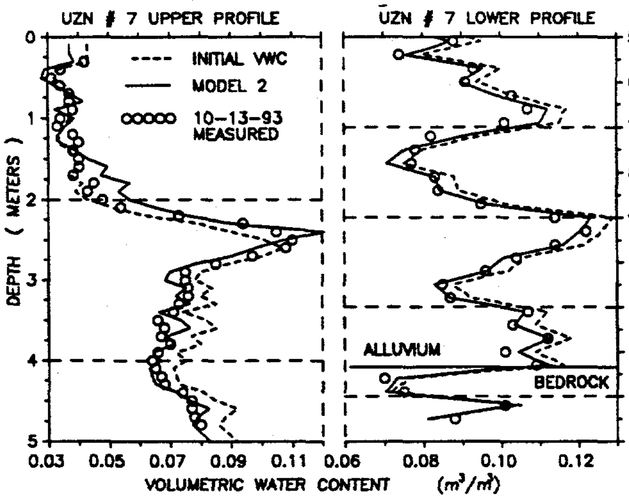

Figure 9. Comparison of simulated and measured θ profile for October 13, 1993 at UZN #7.

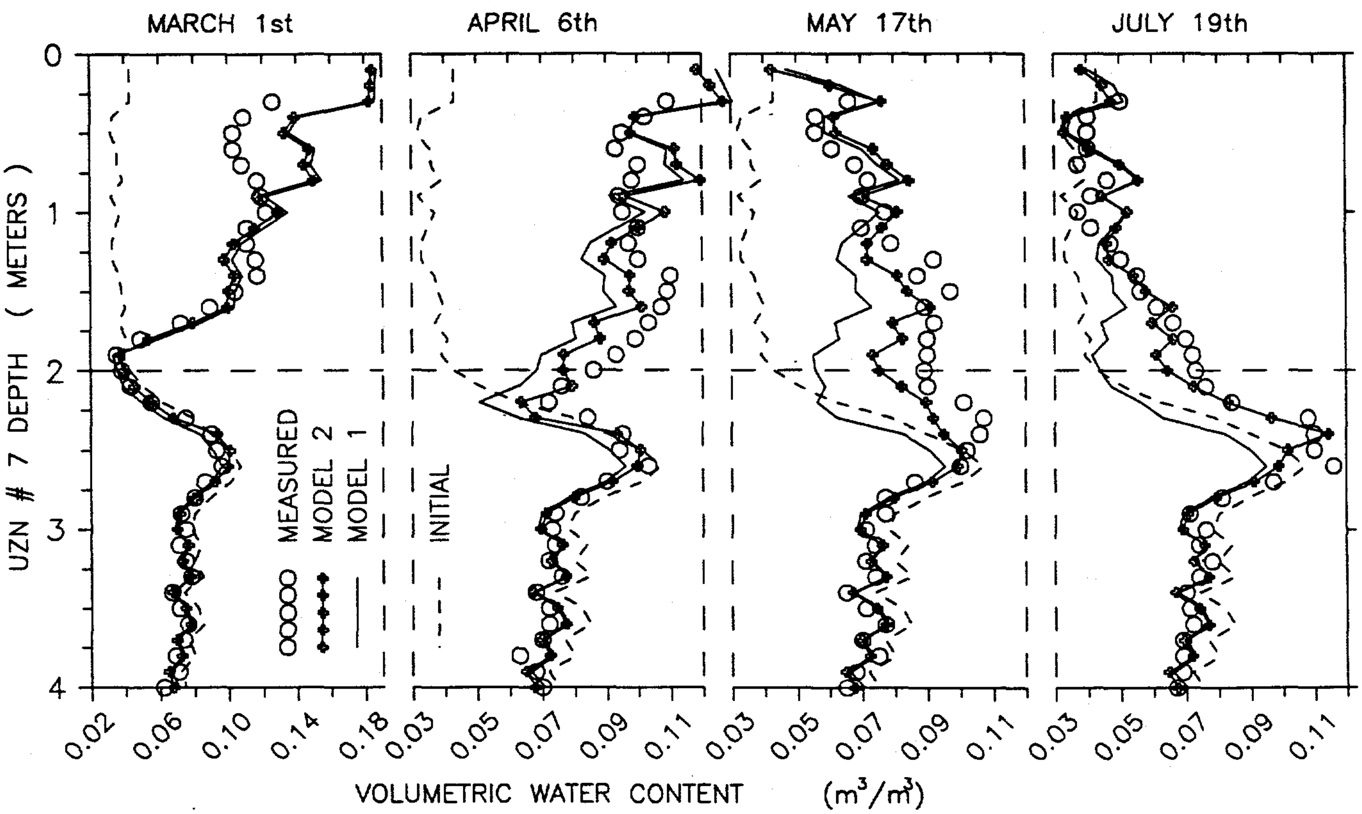

Figure 8. Calibration results: simulated and measured θ profiles for 4 selected months in 1993 at UZN #7, using models 1 and 2.

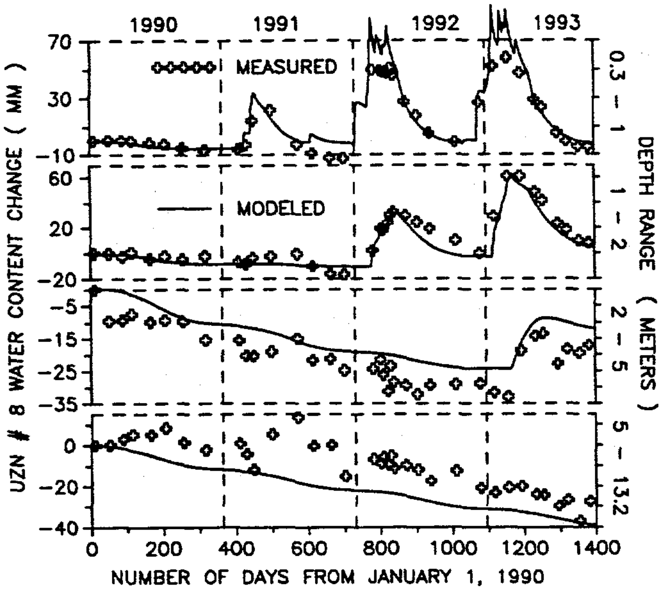

Figure 10. Verification results: model 2 predicted and measured *RWCC* beginning from 01/11/90 for 4 depth intervals at UZN #8.

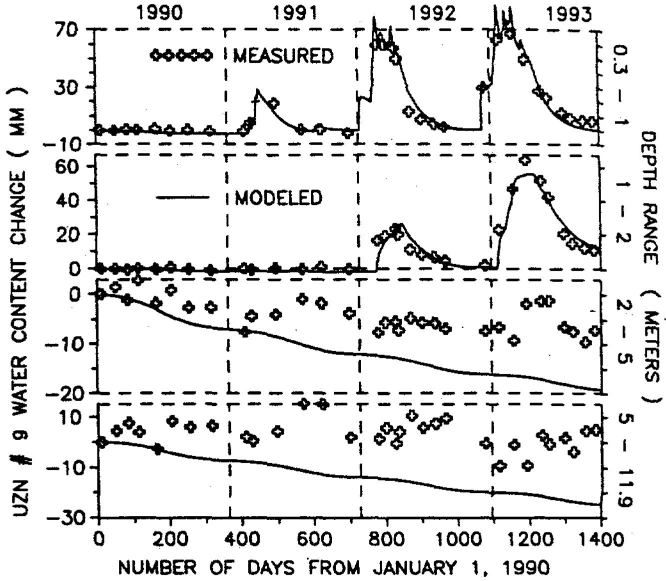

Figure 12. Verification results: model 2 predicted and measured *RWCC* beginninng from 01/11/90 for 4 depth intervals at UZN #9.

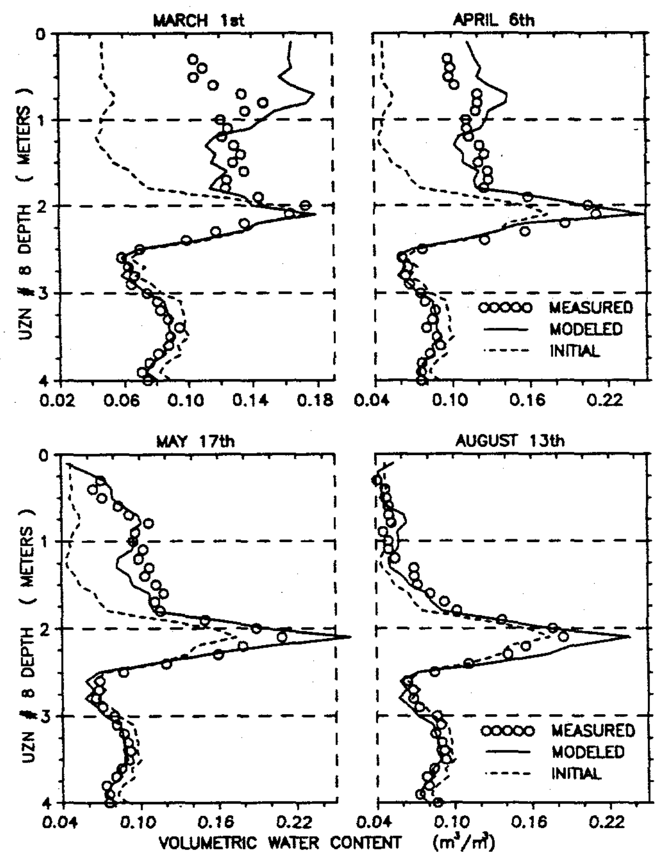

Figure 11. Verification results: model 2 predicted and measured θ profiles for 4 months in 1993 at UZN #8.

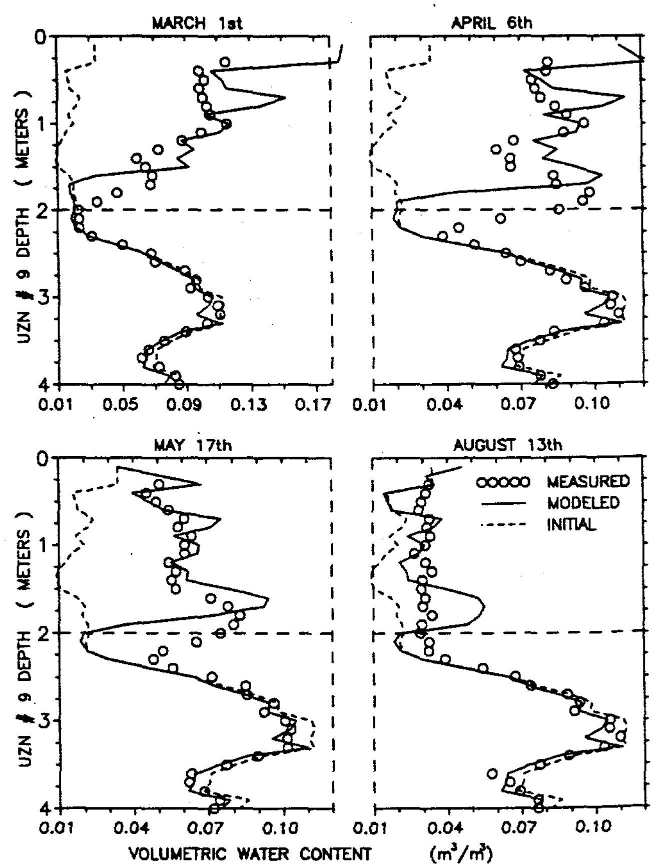

Figure 13. Verification results: model 2 predicted and measured θ profiles for 4 months in 1993 at UZN #9.

performance in predicting the seasonal trends and also the long-term trend of decreasing *RWCC* measured in the lower profile (Figure 10). The model over-predicts the increase in *RWCC* during the 1992 and 1993 winter seasons for the 0.3 to 1.0 meter depth interval, and also over-predicts the decrease in *RWCC* measured during the 1992 summer season. A comparison of the predicted and measured θ profiles at UZN #8 indicated favorable results in predicting the movement and shape of the wetting front and also the drying of the profile (Figure 11).

A comparison of predicted versus measured *RWCC* using the total record at UZN #9 also indicated satisfactory results for predicting the seasonal changes above 2 meters, but model predictions were unsatisfactory for the lower portion of the profile because a significant drying trend was not measured at UZN #9 (Figure 12). The lower profile of UZN #9 was not influenced by the 1984 runoff event which is hypothesized to be the cause of the long-term drying trend measured at the two boreholes located in the channel. Thus, the deep root-zone needed for models at UZN #7 and UZN #8 is inappropriate at UZN #9. Comparison of the simulated and measured θ profiles indicates a less satisfactory prediction of the downward movement of the wetting front, although predicted profile drying was satisfactory (Figure 13).

SUMMARY AND CONCLUSIONS

Measured volumetric water content (θ) profiles obtained from geophysical logging of 3 boreholes located in the alluvial channel of Pagany Wash on Yucca Mountain were used for developing, calibrating, and verifying a 1-dimensional finite difference model of shallow infiltration and percolation. Monthly profiles were obtained for a 3.8 year period during which runoff in the wash was not observed. The measured profiles were used to help estimate material properties for the alluvium, and for determining both the initial conditions and the lower boundary condition of the model. Precipitation and evapotranspiration (*ET*) were modeled using a specified flux term in the Richards equation for unsaturated flow. Potential evapotranspiration (*PET*) was estimated using the Priestley-Taylor equation. Actual *ET* was included in the model as a function of both *PET* and simulated θ within a hypothetical root-zone. Model calibration was performed by adjusting the parameters defining the *ET*-function for a trial and error fitting of simulated θ profiles with measured profiles.

Verification results using θ profiles measured in 1993 were not satisfactory for an initial model that was calibrated using the record from January 11, 1990 to October 25, 1992 for borehole UZN #7 located in the center of the active channel. A new model including a modified *ET*-function with a 12.2 meter deep root-zone was calibrated using the record from January 11, 1990 to October 13, 1993. The root-zone was necessary for modeling the seasonal changes in θ measured above 2.5 meters and the trend of gradually decreasing θ measured below 2.5 meters at sites located in the active channel. The trend was interpreted as long-term redistribution of moisture from deep infiltration following a runoff event in 1984, and could not be modeled as gravity drainage using the 1-dimensional model.

Above a depth of 2.5 meters, the time dependency of the *ET*-function was used to represent an active root-zone during the summer season and an inactive root-zone during the winter season. The depth dependency of the function was used to help differentiate between near-surface drying due to seasonal *ET* and deeper, long-term drying which may be due to lateral flow. Verification results for the new model were satisfactory using the record obtained from borehole UZN #8 located in the active channel at a distance of 6 meters from UZN #7. Results were less satisfactory using the record obtained from borehole UZN #9 located on the terrace adjacent to the active channel, at a distance of 18 meters from UZN #7. Although the seasonal θ change above 2 meters could be predicted, the measured profiles were harder to predict, and the predicted drying trend was not measured at UZN #9 because this location was not influenced by the 1984 runoff event. Failure of the model was considered to be the result of heterogeneous alluvium and non-equilibrium conditions caused by deep infiltration beneath the active channel following episodic runoff events.

Model verification provided a qualitative indication of the accuracy that can be expected from a 1-dimensional model of shallow infiltration for alluvium, but is not conclusive because the model parameters, as defined in this study, are conditioned to the measured initial θ profile. The accuracy of predictions made at un-monitored locations will be dependent on the accuracy of both the estimated material properties and initial conditions, which were observed to be variable throughout the alluvium.

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