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SHALLOW INFILTRATION PROCESSES IN ARID WATERSHEDS
AT YUCCA MOUNTAIN, NEVADA

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ABSTRACT

A conceptual model of shallow infiltration processes at Yucca Mountain, Nevada, was developed for use in hydrologic flow models to characterize net infiltration (the penetration of the wetting front below the zone influenced by evapotranspiration). The model categorizes the surface of the site into four infiltration zones. These zones were identified as ridgetops, sideslopes, terraces, and active channels on the basis of water-content changes with depth and time. The maximum depth of measured water-content change at a specific site is a function of surface storage capacity, the timing and magnitude of precipitation, evapotranspiration, and the degree of saturation of surficial materials overlying fractured bedrock. Measured water-content profiles for the four zones indicated that the potential for net infiltration is higher when evapotranspiration is low (i.e winter, cloudy periods), where surface concentration of water is likely to occur (i.e. depressions, channels), where surface storage capacity is low, and where fractured bedrock is close to the surface.

INTRODUCTION

Net infiltration, the quantity of water moving downward from the surface below the depth influenced by evapotranspiration,[1] is an important input for hydrologic flow models designed to calculate flux through the thick unsaturated zone at Yucca Mountain.[2] Characterizing infiltration in arid lands often is a qualitative endeavor, as there are many errors associated with measuring or estimating upward and downward surface flux at an arid site.[3,4] Low rainfall leads to large measurement and mass-balance calculation errors. Heterogeneous, rocky and shallow surficial material (soils) also make it difficult to characterize infiltration in arid lands. An objective conceptualization of the processes affecting shallow infiltration is required to define the physical system by a reasonable number of representative surface units. This study develops a conceptual model of infiltration processes by using a field method that averages and smoothes many of the short-term fluctuations in surface-water content yet allows for the estimation of long-term downward flow.

The depth of infiltration of water into the soil/rock profile fluctuates on a seasonal basis, but estimates can be made of long-term trends and an average depth of penetration can be established. Examination of borehole core samples and surface excavations has indicated that most of the fractures in the shallow soil or bedrock are filled with calcium carbonate materials from repeated wetting and drying. This fracture filling is found to varying depths in different locations, ranging from 3 to 15 m. The depth of seasonal water pulses, observed by geophysical logging of a network of boreholes, roughly corresponds to the depth of the calcium carbonate materials, which identifies a conceptual zone of evapotranspiration and a depth at which net infiltration is likely to occur.

The presence of fractures affects can increases the penetration of water into the profile. The fracture fill causes an increase in storage capacity at the surface but allows for deeper penetration of water due to the general lack of plant roots. Fracture flow will not be initiated if the surrounding matrix has smaller pores than the aperture of unfilled fractures under unsaturated condition but can more readily occur in filled fractures depending on the moisture characteristic curve of the fill material. If pulses of water do flow into fractures, the generally higher conductivity of the fractures, along with the smaller volume, will conduct the water to greater depths.

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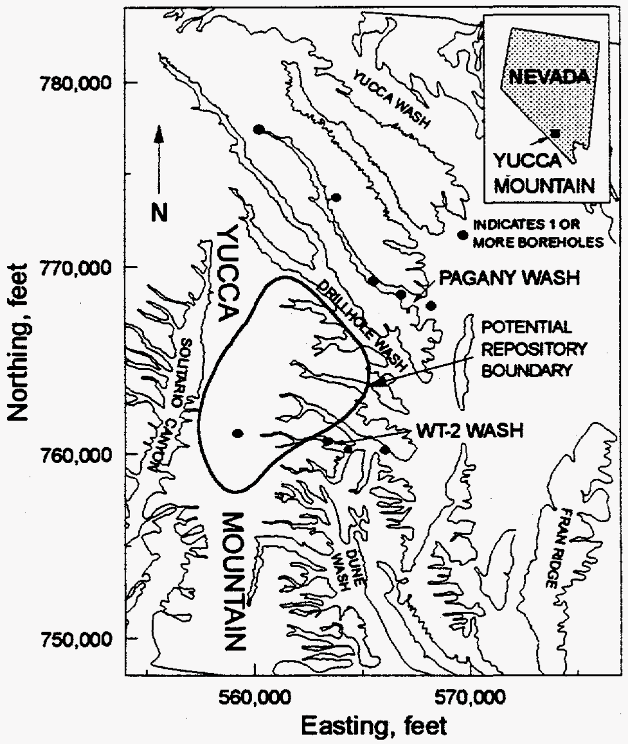

Figure 1. Map of Yucca Mountain area with 2 study areas and boreholes indicated.

SITE DESCRIPTION

Yucca Mountain is located in the northern Mojave Desert in southern Nevada (Fig. 1). It is an uplifted, faulted ridge consisting of a series of layered, nonwelded and welded, variably fractured and saturated volcanic tuffs. The topography of the mountain has been defined by erosional processes on the sloping ridge and along faults and fault scarps that have created a series of washes that are downcut to varying degrees into different bedrock layers. The washes are primarily east-west and northwest trending, have gentle to steep slopes, and have available energy loads that vary greatly for much of the year. The bedrock exposed at the surface or directly underlying alluvial cover ranges from nonwelded, unfractured rock that has 40 percent porosity, to densely welded, highly fractured rock that has less than 10 percent porosity. The alluvial/colluvial surficial deposits have varying degrees of soil development and thickness and have a gravelly texture, with rock fragments (>2 mm) constituting between 20 and 90 percent of the total volume. Deeper soils in the center of washes have developed cemented calcium carbonate layers. In this paper, all unconsolidated surficial materials will be referred to as soil. Because of the high variability and range of properties and surface features, descriptions are qualitative in terms of slope, aspect and depth. General descriptions are for the purpose of identifying processes and mechanisms of surface and subsurface flow in relatively distinctive topographic positions, but they necessarily overlap in areas. Work is ongoing to distinguish between surface infiltration zones on the basis of slope, aspect, depth of soil, and elevation for the purpose of large-scale models, and to incorporate all of the surface-water content measurements from 1986 to the present.

Average annual precipitation at the site has been estimated to be 170 mm.[5] Precipitation occurs as localized storm cells in the summer when the evapotranspiration (ET) demand is very high. Most of the water will be lost to evapotranspiration processes within several days unless there is enough rainfall to produce runoff or subsequent storms providing water for deeper penetration. These storms can create runoff in one wash while an adjacent wash receives no rain at all. Precipitation in the winter occurs as snow or rain and in large stratiform storm patterns. ET is low at this time of year, and lower precipitation rates or slowly melting snow may penetrate.

Topographic Positions

In this study, infiltration processes and mechanisms are defined on the basis of four topographic positions--ridgetop, sideslope, terrace and channel (Fig. 2). Over an area within the boundaries of the site-scale model,[2] the ridgetop locations encompass about 14 percent of the total area, the sideslopes 62 percent, the terraces 22 percent and the active channels 2 percent. The ridgetop locations are generally flat to gently sloping and are higher in elevation than the other areas. They have relatively shallow to no surficial deposits but are relatively stable morphologically. Existing soils are fairly well developed, and thin calcium carbonate layers occasionally are present. Some perennial channels have somewhat deeper soils, and some concentrated surface runoff occurs. Bedrock at ridgetop locations is moderately to densely welded (5 to 25 percent porosity) and moderately to highly fractured. Vegetation consists of well-established, relatively shallow-rooted, blackbrush/desert thorn associations[6]. The slope and elevation in this position tend to retain snowfall in the winter for several weeks at a time.

Because of the difficulty of drilling boreholes at very steep sideslope locations, field data in this position is limited to the lower sideslope of the washes. This location is distinguished from the terrace and channel locations by

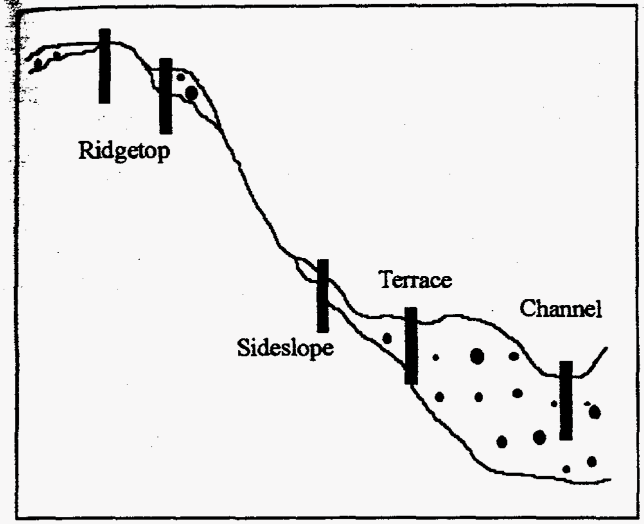

Figure 2. Idealized representation of topographic positions; ridgetop, sideslope, terrace and channel.

slope and depth of soils. It has very shallow to no soil cover, and in most locations, bedrock is densely welded and highly fractured. The slopes are approximately north or south facing and, therefore, have very different seasonal solar radiation loads. There are some locations where side channels concentrate runoff water. In general, the sideslopes tend to be more sparsely vegetated.

Terraces and channels are located at lower elevations in the main washes and have shallow cover in the upper washes and very deep soils further down the washes. A very small percentage of exposed bedrock exists in the washes, and almost all of that is nonwelded, highly porous tuff. The soil has varying degrees of calcium carbonate cementation, which often is quite extensive. The porosity of the soil ranges from 15 percent to 40 percent. The surface is relatively flat and dissected by old alluvial channels, and active channels. Channels are distinguished from the terraces by periodic runoff in the channels occurring under extreme precipitation conditions. The terraces generally are well vegetated having deeply rooted creosote and other smaller plants. The channels occupy a very small surface area of the wash and are more sparsely vegetated than the terraces.

DATASET AND METHODOLOGY

Volumetric water content profiles were measured using a neutron moisture probe (Model 503, Campbell Pacific Nuclear, Pacheco, CA)[a]. The tool is field calibrated in 18.0-cm diameter steel casing in boreholes that were dry-drilled. In this study water-content profiles were examined from 34 boreholes (drilled between 1986 and 1992), ranging from 6 to 19 m deep. The data were collected on a monthly basis at 0.1-m-depth intervals. Boreholes are located in various topographic positions having varying thicknesses of soil or volcanic tuffs in two small watersheds (Fig. 1). WT-2 wash is erosionally controlled, trending east to west, and is dissected into the eastern slope of Yucca Mountain. Pagany wash is fault-controlled, trending northwest, and is approximately 4 km north of WT-2 wash. Pagany wash receives slightly more rainfall because of higher elevation,[5] has thicker and more developed soils on the ridgetops, and steeper, shallower slopes in the wash.

The period for this study was January 1990 through April 1993. Drought conditions prevailed during the previous 4 years, which averaged about 60 to 75 percent of normal rainfall at 100 to 130 mm/yr. The volumetric water content in the boreholes had reached a steady level between 2 and 5 percent, which were the lowest measured water contents recorded since they were drilled in 1986. There was some relief from the drought in 1990 and the winters of 1991/92 and 1992/93 were wet (total rainfall of 280 and 370 mm respectively), and several storms produced runoff each year.

To evaluate the changes in water content in the various boreholes and to identify ongoing processes contributing to net infiltration relative to the four conceptual topographic locations, moisture profiles at 34 sites were analyzed in several ways. Profiles of volumetric water content were compared to assess the change in the volume of water content and depth of penetration (maximum depth of water-content change) over a winter season. The average change in water content was compared for depth intervals of 0.3 to 1 m, 1 to 2 m, 2 to 5 m and 5 to 10 m during a 3-year period. The variation in water content through the borehole profile was assessed by comparing the standard deviation of readings for each depth interval over a 10-month period. Finally, the apparent depth of fluctuation was compared to depth of overlying soil, as well as to the four topographic locations.

RESULTS

Moisture Profiles

Water contents prior to 1991 were very low throughout the borehole profiles, as shown in boreholes N7, N14, and N71 (Fig. 3). By October 1992, an increase in soil or bedrock water content was apparent.

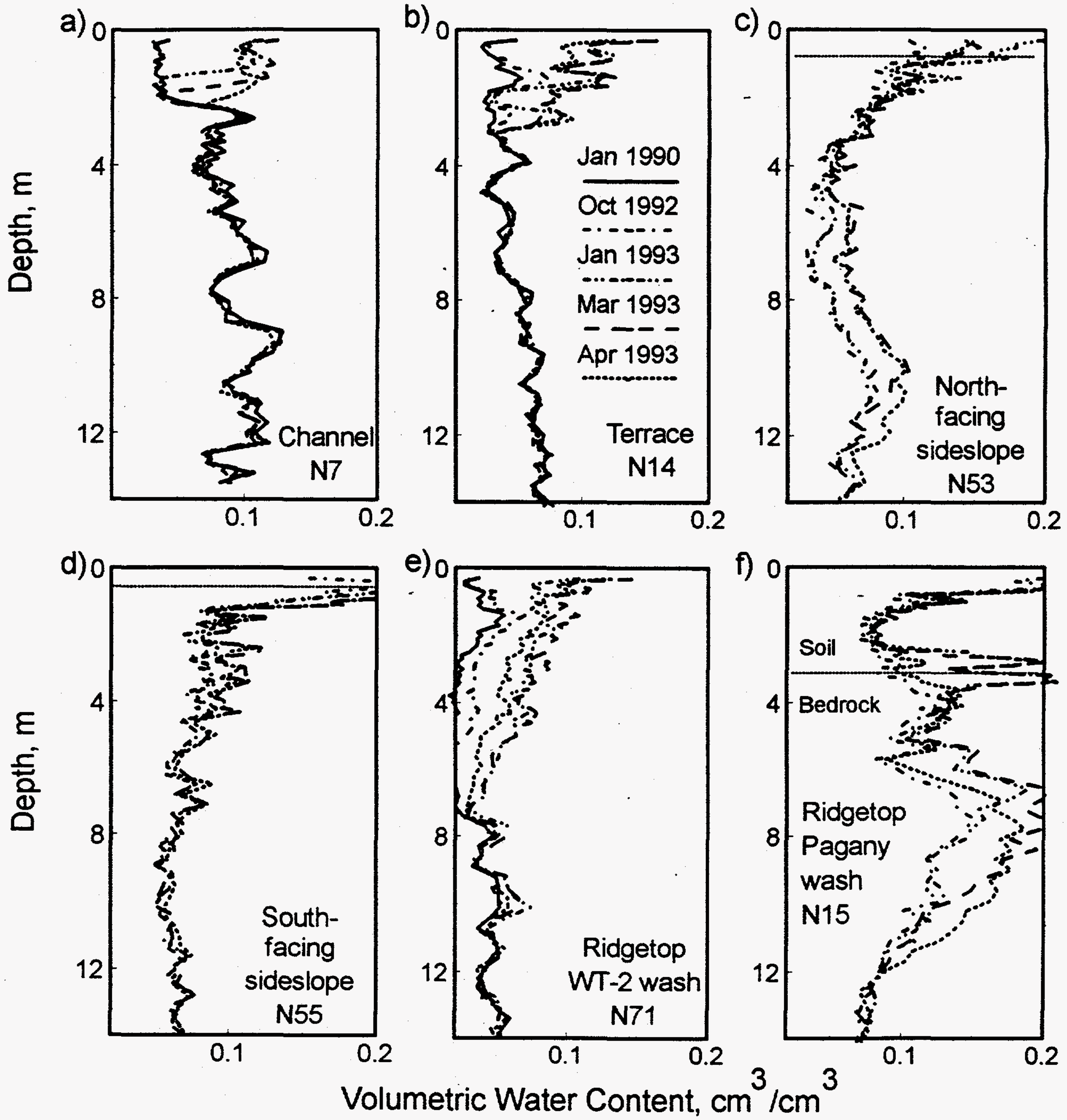

Figure 3. Water-content profiles from boreholes in each of the topographic positions: ridgetop, sideslope, terrace, and channel from 1/90 through 4/93.

The water content continued to increase in all boreholes over the next year and a half. The increase in water content varied between boreholes in different topographic positions, primarily by the volume of water, and by the depth of the infiltrating pulses. The moisture profiles in the channel and terrace boreholes (Figs. 3a and 3b) are similar. The water does not penetrate very deep (about 2-3 m) over this 3 year period, and most of the water is held close to the surface in the soils that have large storage capacity. These positions are similar during this period because borehole N7 was not exposed to any runoff events. The boreholes in sideslope positions that have shallow soils (Figs. 3c and 3d), permit deeper penetration of the water. Smaller volumes of water are held in the upper portions of these profiles because of the lower porosity, and the penetration of water is especially deep

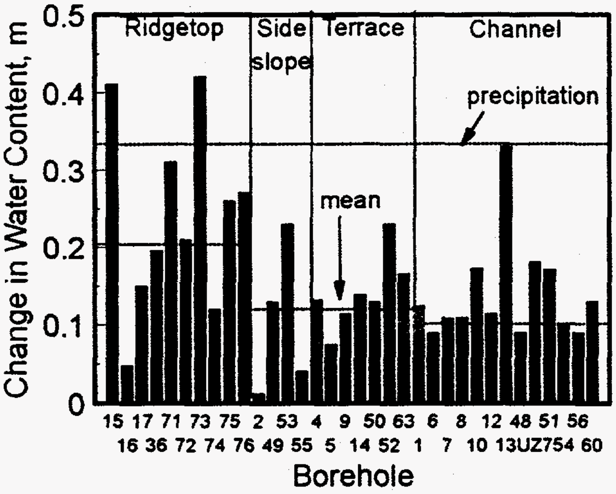

Figure 4. Change in volumetric water content for entire borehole from 10/92 through 3/93 for 34 boreholes. Included is the mean for each topographic location and total precipitation for 5 month period of time.

(about 13 m) in the north-facing slope because of the lower ET, which is due to the low available solar radiation load for much of the year. Infiltration of water in the ridgetop boreholes (Figs. 3e and 3f), whether or not the boreholes have soil cover, is greater in volume than all the other locations and especially in N71 at the surface and at depth in N15, a borehole located in a small ridgetop channel. In the boreholes that have thick soils and large storage, the volume of water may be the same as for boreholes located along the ridgetops, but it is stored higher in the profile. Where there is little storage capacity near the surface, water is observed to infiltrate deeper. In addition, the shallow infiltration in the washes may be due, in large part, to low-porosity restricting layers. If boreholes N7 and N15 are compared (Figs. 3a and 3f), both having surface soil, the penetration in N15 is deep because of relatively high-porosity bedrock and high-conductivity fractures, as well as runoff from winter snow melt. N15 differs from N7 for two reasons: 1) N7 generally receives less snow than the ridgetop; and 2) the infiltration is stored shallower because of subsurface restricting layers that have porosities of less than 15 percent.

Change in Water Content

The total change in water content over a 5-month period from October 1992 through March 1993 (Fig. 4) calculated for all 34 boreholes indicates that the mean change is higher for the ridgetop boreholes than for the boreholes in other topographic positions. Mean precipitation for that period was 0.34 m. It can be estimated that boreholes having an increase in water content close to or greater than 0.34 m probably received run-on or concentrated surface water, whereas boreholes having total changes in water content less than the precipitation had runoff or higher evapotranspiration. As an example, runoff was observed during this time at boreholes N13 and N15. This exercise is qualitative, as total precipitation does differ somewhat at the various locations; however it

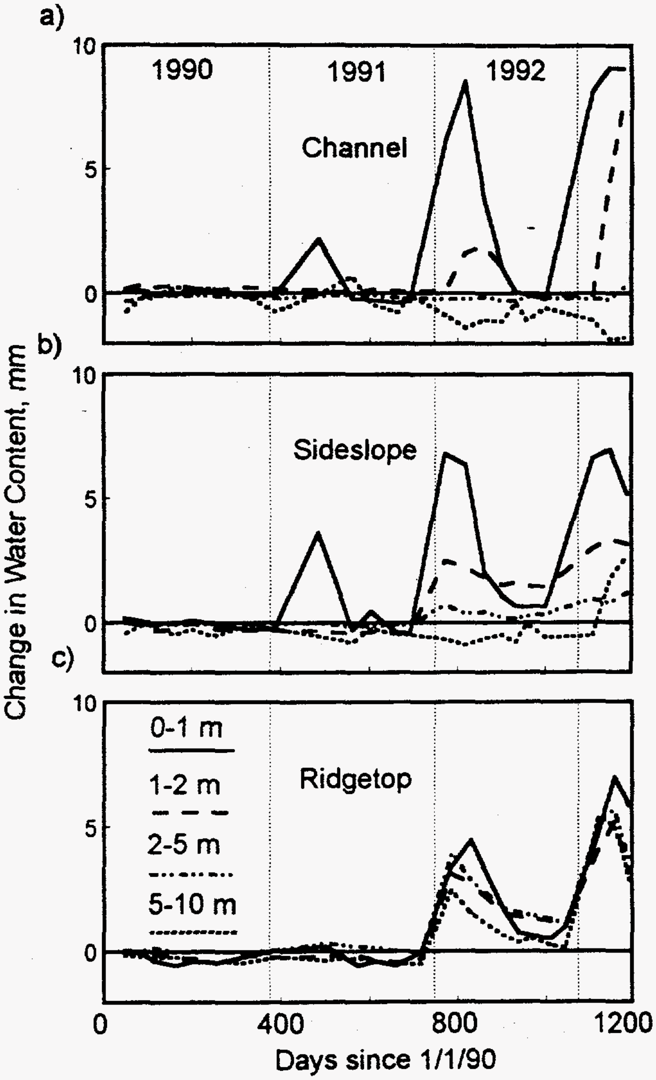

Figure 5. Change in volumetric water content for 4 depths over time for 3 boreholes from 3 topographic positions.

suggests the mechanisms causing these major differences.

A time series of water-content changes in boreholes in different positions provides information regarding rate and timing of infiltration for a 3-year period (Fig. 5). Changes in water content in the uppermost one meter occur with precipitation cycles, wetting in the winter and drying out in the summer. The second-meter depth lags behind the top meter in the channel hole by a few months, whereas there is no increase in water content deeper than 2 m. In the sideslope borehole, the same result is noted in the upper one-meter depth interval and in the second-meter-depth interval and, after 3 years, is beginning to be recorded in the lower depth intervals. The ridgetop borehole shows no increase in moisture until 1992 when the entire profile responds to the annual precipitation and indicates relatively deep infiltration. These changes with time and depth indicate different rates of infiltration for these three boreholes: water in the channel borehole penetrates more slowly than in the other two, and the ridgetop borehole increases in water content throughout its whole profile with no time lag.

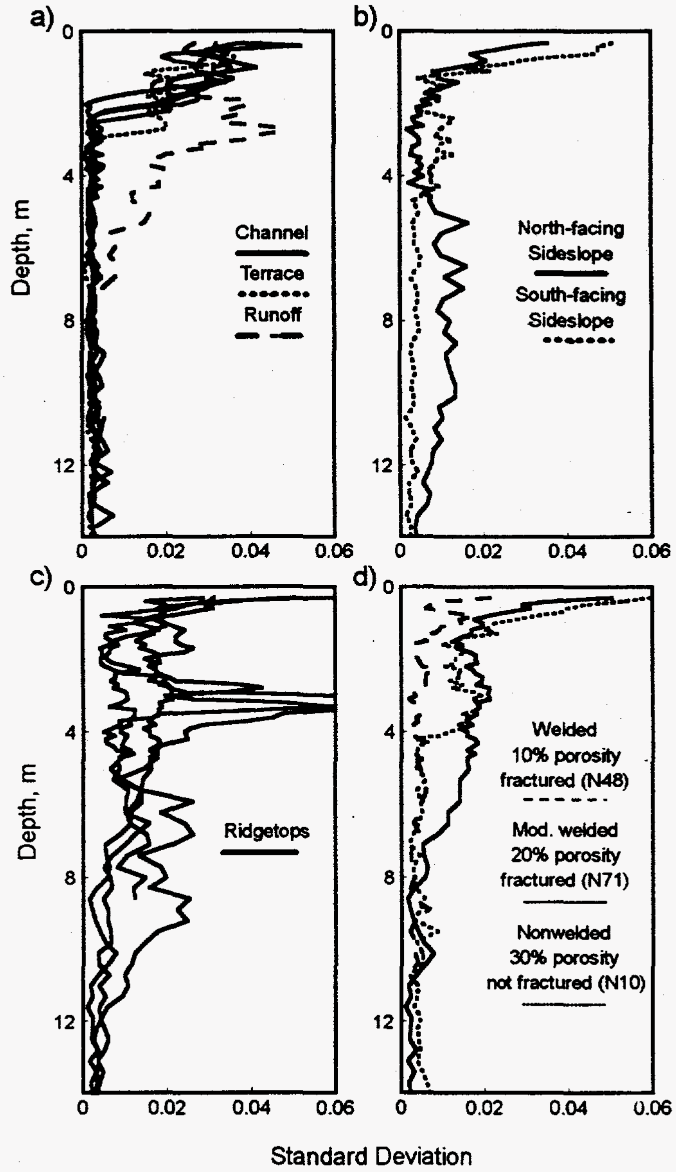

Figure 6. Standard deviation of volumetric water content from 7/92 through 4/93 for each depth interval for (a) channels, (b) sideslopes, (c) ridgetops and (d) boreholes in different porosity bedrock with no soil cover.

Variation and Depth of Penetration

The variation in moisture content with depth also can be used to analyse how deeply in a borehole moisture changes have occurred, suggesting a depth of infiltration. If an estimate can be made of a depth below which infiltration becomes net infiltration, then this depth of penetration is a useful parameter. Variation in moisture content with depth was determined for all boreholes by calculating the standard deviation of a series of measurements at every depth interval for a 10-month period from July 1992 through April 1993 (Figs. 6a-6d). The channel and terrace boreholes show variation to a depth of about 2.5 to 3 m except for N13 (shown as "runoff" in Fig. 6a) which received a large amount of runoff in 1993 that infiltrated to about 7 m. The sideslope holes had some variation in moisture content near the surface but also to depths of about 13 m. The ridgetop boreholes had large variability throughout the profile, probably because of flow in filled fractures. Examples of boreholes that have no soil cover but that are in bedrock that has different properties have different depths of penetration because of storage capacity and fracture density of the rock. The borehole in densely welded tuff, which is highly fractured, showed little variation throughout the profile. If the fractures are filled and the matrix has very low porosity (less than 10 percent), there is little imbibition of the water into the matrix. The borehole in nonwelded bedrock that has a high porosity (30 percent) looks similar to the channel and terrace boreholes in which there is a larger variation at the surface but, because of the high storage, does not penetrate deeply into the profile. In the borehole in the moderately welded, fractured tuff (porosity 20 percent), water can imbibe into the matrix, yet also reach a degree of saturation to initiate fracture flow and, therefore, penetrate more deeply into the profile.

A comparison of the depth of variation in all 34 boreholes with the depth of the overlying soil shows that the deeper the soil (or greater the surface storage), the shallower the variation in water content over this 10-

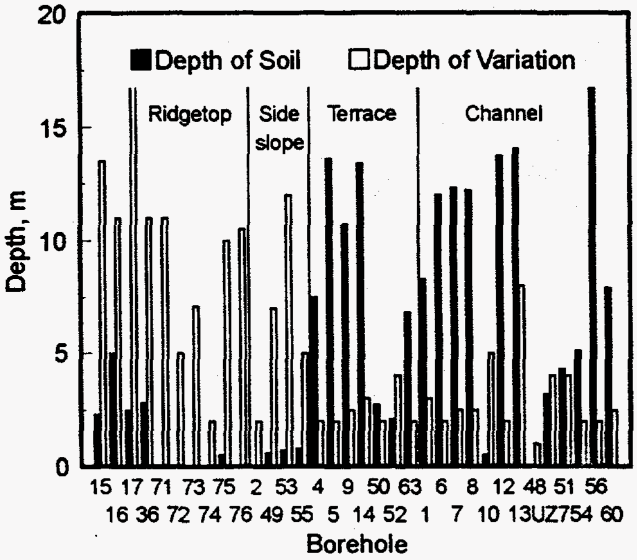

Figure 7. Depth of water content variation for 34 boreholes, compared to depth of soil cover.

month period (Fig. 7). The ridgetop boreholes had more variation, which was also much deeper than the boreholes in the wash, with the exception of sites influenced by runoff events. This depth of variation, especially if determined for several years, may suggest the depth below which infiltration becomes net infiltration. This depth may also change with time, climatic cycles, and plant cover but is probably fairly consistent for given topographic positions under today's climatic conditions. Ongoing work in this area is being done to incorporate data from a network of 99 boreholes to provide a statistical basis for the above analyses.

SUMMARY AND CONCLUSIONS

In general, the analysis of moisture profiles in boreholes from various topographic positions included both quantitative and subjective methods, based on the fact that only a limited number of boreholes were analyzed during a relatively short time. Analysis of the measured profiles indicated that the thinner the soil cover, i.e. storage capacity, the deeper the measured increase in water content, indicating greater net infiltration, which is especially evident when surface flow concentrates runoff at locations underlain by fractured bedrock. The more deeply the water penetrates the less likely that it will be lost to evapotranspiration. When surface flow is negligible, the deepest infiltration was found in the ridgetops, and the shallowest infiltration was observed in the washes, although there is little difference between the terrace and channel boreholes. Exceptions were observed following appreciable runoff events. For these cases, large volumes of water often infiltrated more than 5 m into the soil in the washes, which is below the estimated root zone. At these sites, however, conditions precipitating significant channel runoff occurred episodically and only in a few washes during any given event. In addition, the active channels where runoff occurs comprise less than 2 percent of the surface area of the watersheds, and therefore, is not considered a large contribution to the overall net infiltration in the watershed. More precipitation infiltrates during the winter when the evapotranspiration is low, which allows for larger volumes of water to penetrate below the root zone and escape the high evapotranspiration demands of summer. This effect may be increased on the ridgetops where snow exists for several weeks during the winter, slowly melting and reducing runoff.

A conceptual model of shallow infiltration processes at Yucca Mountain was developed to categorize the site into four zones that generally can be identified on the basis of the manner in which water contents change with depth and time. The zones are described as follows: 1) The ridgetop is flat to gently sloping, higher in elevation, and has thin soils mostly developed in place with clays and higher water-holding capacity that reduces rapid evaporation. The ridgetops are generally located where the bedrock is moderately to densely welded and, therefore, fractured. These conditions lead to deeper penetration than in the other topographic positions, and smaller volumes of water. In some locations, however, where runoff is channeled, there are also large volumes of water. 2) Sideslopes are steep and often have very shallow to no soil cover and are most often developed in welded, fractured tuff, which creates a situation for rapid runoff. The low storage capacity at the surface and fractures exposed at the surface can cause small volumes of water to infiltrate to greater depths, especially on slopes with north-facing exposures and, therefore, lower evapotranspiration demands. At the bases of the slopes there is shallow alluvium which can easily saturate and initiate flow into the underlying fractures. 3) Alluvial terraces are flat, broad deposits of layered rock fragments and fine soil that has large storage capacity. There is, therefore, little runoff and little movement of water to any depth in the profile before evapotranspiration removes it. Consequently, this zone contributes the least to net infiltration in the watershed. 4) Active channels differ little from the terraces but are located in a position to collect and concentrate runoff, which, though it occurs infrequently, can then penetrate deeply. This is not considered a major contributor to net infiltration because of the infrequency of precipitation resulting in runoff and because the channels encompass a very small percentage of the area of the watershed.

There are numerous heterogeneities and exceptions to this categorization. In general, however, changes in moisture profiles over time measured at a borehole tend to be characterized by the conceptual model zone in which the site is located. These locations can be used to identify the infiltration mechanisms and to aid in the estimation of the surface conditions, necessary for the development of large-scale watershed models. In conclusion, in an environment that has a high evaporative demand, it is more important to assess the depth of water penetration than the volume of water entering the profile in order to estimate *net* infiltration. This penetration is influenced by the potential for surface storage (depth of soils, layering and caliche, slope and aspect), the timing of the precipitation (winter or summer), the occurrence of fractures, and the saturation of the wetting front when it reaches fractured bedrock.

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[a] The use of brand, trade, or firm names in this paper is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

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