DESERT RESEARCH INSTITUTE
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ABSTRACT

This report documents almost 30 years of research on soil moisture movement and recharge at the Department of Energy, Nevada Test Site. Although data is scarce, three distinct topographic zones are represented: alluvial valleys, inundated terrains, and upland terrain. Recharge in alluvial valleys was found to be very small or negligible. Ponded areas such as playas and subsidence craters showed significant amounts of recharge. Data in the upland terrains is very scarce but one area, Rainier Mesa, shows active recharge of up to three percent of the annual average precipitation in fractured volcanic tuff. The report summarizes the results.

ACKNOWLEDGEMENTS

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SECTION I

INTRODUCTION

Since 1963, all U.S. nuclear weapons testing has been conducted underground, with a majority of these tests being held at the U.S. Department of Energy (DOE), Nevada Test Site (NTS) in southern Nevada.

By conducting each detonation in the subsurface, the likelihood of immediate release of radioactivity to the environment is greatly reduced. Subsurface detonation, however, does not negate all of the potential environmental pathways for radionuclide release. One of the most likely pathways for release to the accessible environment from testing is through the ground water. Since many of the tests are conducted above the zone of ground-water saturation, partially saturated flow or soil water flow must be understood if these pathways are to be fully evaluated.

In addition, other waste materials, both hazardous and radioactive, are stored or disposed of at NTS. An understanding of soil water flow is also critical to risk assessment from these practices.

At first glance, NTS appears to offer little, if any, areas for deep soil water movement. The area is one of the driest areas in the continental United States (Winograd and Thordarson, 1975). Mean daily maximum temperatures may range from 13 to 40°C. Combining the low precipitation and the high potential evapotranspiration into a water budget model, it has been generally thought that little or no ground-water recharge can occur. Recent studies (Gee and Kirkham, 1984 and Tyler et al., 1986) have shown, however, that simple water balance approaches to soil water movement and ground-water recharge may be insensitive in arid regions. These insensitivities arise from the conflict between the long time scales used in water budget models and the short time frames over which precipitation, evaporation, and soil water movement occur in coarse-grained surface soils or fractured rock found in many arid regions. These time scales may be on the order of minutes to a few hours, while most modeling approaches use daily, weekly, or even monthly estimates. In addition, studies by Clebsch (1961), Thordarson (1965), and Tyler et al. (1986), have suggested that deep soil water movement (recharge) is occurring in selected areas of the NTS. These studies indicate that areas such as mesa tops, fractured bedrock surfaces, wash bottoms, and man-made depressions may allow deep soil water migration. It is interesting to note the two similarities of each of these study areas. In the first, each locale receives or concentrates precipitation in small areas (ponds, channels, or fractures). In the second, each locale allows for the rapid migration of potential recharge below the depth of active evaporation and transpiration because the surficial materials are highly permeable. These two criteria, source water and rapid transport, are crucial to understanding the potential for recharge in arid areas.

Although many of the studies already mentioned have dealt with aspects of soil water movement, none have been reviewed in terms of generating an overall recharge picture at NTS. The goal of this study is to review the current data base regarding soil water movement on or near the NTS. The results of this study will provide a clearer understanding of the potential recharge areas, an estimate of the magnitude of recharge, and directions for future studies. These results may also be used to design controls to prevent radionuclide migration to the ground-water system.

In Section 2 of this report, the general hydrologic and climatological conditions of the NTS are described. In Section 3, the results of soil moisture-related recharge studies are described in detail. The section describes three methodologies used by previous investigations to estimate recharge and flux. In addition, a discussion is presented of studies conducted at Rainier Mesa, an area of fractured tuff used for nuclear weapons testing. In Section 4, the results are summarized.

Although not included in this review, a considerable research effort on soil moisture flux is presently being conducted for the Nevada Nuclear Waste Storage Investigation. These studies are focused on characterization of a potential high level nuclear waste repository in fractured, partially saturated, tuffaceous rock. The repository site is located on the western boundary of NTS. Much of the data generated from this study have not been formally published; although, preliminary results (DOE, 1984) indicate that moisture flux at the Yucca Mountain Site is small or negligible. Since this project has only recently begun, it will not be included in this review. It is hoped that in the near future, data from this intensive effort will shed considerable light on the processes of moisture movement in fractured rock.

SECTION II

GENERAL RECHARGE CONSIDERATIONS

Various aspects of water flow through the unsaturated zone at NTS have been investigated for the past 25 years. Over 20 technical reports on the subject appear in this report's bibliography. Due to the wide variety in terrain and scope of studies, these reports indicate a wide variety of soil moisture conditions. This report describes the key studies, which may be related to soil water movement, and analyzes the results and suggests ways to determine recharge potential at NTS.

Recharge to ground water can come from numerous sources: infiltration and percolation of natural precipitation; seepage from canals and streams; and artificial infiltration through wells or surface ponding (Freeze and Cherry, p. 211, 1979). The primary source for recharge in the testing areas will be meteoric water percolating through the soils and rock. In other areas, disposal of wastewater may provide an additional source of recharge.

GEOGRAPHY AND SURFICIAL CONDITIONS

The NTS encompasses 3500 km^2 of Basin and Range topography in southwestern Nevada. The eastern part of the NTS is characterized by parallel Cenozoic topography and structural elements generally associated with the Basin and Range province (U.S.G.S., 1976). The range and ridge tops consist of either bare rock or thin soil mantling fractured bedrock. The basins are characterized by thick sequences of Quaternary alluvium. (Soil pedogenesis in both locales is limited due to the scarce rainfall.)

The western part of the NTS is made up of late Miocene and early Pliocene volcanism whose topographic and structural effects partly cover the typical Basin and Range topography (U.S.G.S., 1976).

As in the eastern half, soils are thin in most highland areas while thick sequences of Quaternary alluvium fill the valleys. Soils and sediments are generally derived from volcanic rocks with little derived from the carbonate bedrock. Throughout the NTS, however, it is typical to find calcic horizons either near the surface or as buried soil horizons.

CLIMATE

Precipitation in the form of intense convective summer storms and winter frontal storms are the common weather patterns for the NTS. Mean annual precipitation ranges from 7 to 15 cm on the valley floors to 25 to 40 cm on the mesa tops. The potential annual evaporation from lake and reservoir surfaces in the area was estimated by Meyers (1962) to range from 150 to 200 cm or roughly 5 to 25 times the annual precipitation. The mean daily maximum temperature at Las Vegas (station alt. 665 m) ranges from 13°C in January to 40.5°C in July. The mean daily minimum temperature for the same two months ranges from 0.5 to 24.5°C. The higher valleys, such as central Yucca Flat (1254 m), are as much as 3 to 8.5°C lower.

Variations in precipitation and temperature cause marked differences in plant life. Creosote bush, burro bush, and a variety of yuccas dominate the basins below 1200 m. These give way to blackbrush and joshua trees at slightly higher altitudes. Juniper, pinyon pine, and sagebrush dominate above 1800 m and are, in turn, replaced by white fir and yellow pine above 2300 m (Bradley, 1964).

Winter precipitation originating in the west is usually associated with transitory low pressure systems and, therefore, moves over large areas (Quiring, 1965). The summer precipitation occurs predominantly as convective storms, which can be intense over a few square kilometers and which vary in location from one storm to the next. Summer moisture usually originates from the southeast or south (Winograd and Thordarson, 1975).

HYDROGEOLOGIC SETTING

Data collected by Winograd and Thordarson (1975) indicate up to 10 separate hydrostratigraphic units that are present in various locations in the saturated zone underlying the NTS. The units range from fractured carbonates and clastic sediments to clastic volcanic and sedimentary rocks, each with different and variable hydrologic properties.

From a vadose zone standpoint, the NTS also contains some of the thickest unsaturated zones in the United States. Depth to water in certain locales may exceed 600 meters (Winograd, 1980).

The great depth to the water table in these areas is a combination of the following: areas of moderate to high relief; relatively permeable strata with the saturated zone; regional aquifers with topographically low discharge points; and little recharge. These thick unsaturated zones can be made up of any of the hydrostratigraphic units, but are typically made of layered Tertiary volcanics and Quaternary alluvial sediments.

SUMMARY

The climatic and hydrologic conditions found at the NTS indicate that water movement through the unsaturated zone should be slight. The lack of perennial streams and the small number of springs found in the area tend to support this conclusion. In any other locale, there would be little incentive to study soil moisture movement and recharge. At NTS, however, the activities conducted require a reasonable knowledge of soil water flux to assess its impacts on radionuclide transport. In the next section, reviews of studies conducted for DOE and its predecessor agencies will be used to assess the magnitude of water flow in the unsaturated zone of the NTS.

SECTION III

RESULTS OF MOISTURE FLUX STUDIES AT NTS

The measurement of water movement in the unsaturated zone has received significant attention in the last few years. The need to estimate the impact of man's activity on ground-water resources has driven this effort. At NTS, at least three methodologies have been applied to this end.

In the first method, soil hydraulic properties have been combined with measured soil water energy data in Darcy's equation to estimate fluid flux and velocity. This technique assumes that the moisture conditions remain constant with time. Environmental tracers, such as tritium or chlorine-36, have also been used to estimate the velocity of soil water. These tracers, introduced during atmospheric testing of nuclear weapons, are assumed to move as discrete packets with each precipitation event. By knowing their position in the soil profile and their first appearance in the precipitation, the soil water velocity may be estimated.

Direct measurement of soil water movement is, of course, the optimal technique for understanding ground-water recharge. In arid environments, however, this methodology encounters many difficulties. The difficulties arise from estimation of the small net volume of water which may be moving downward below the root zone. Several studies of this nature have been conducted at NTS and provide detailed information on soil water movement.

A fourth, but not entirely independent, methodology has been applied to estimate the magnitude of water flux in fractures in the unsaturated zone. These studies, centered at Rainier Mesa, have utilized a combination of fracture discharge measurements, environmental tracers, and geochemical data to understand the complex phenomenon of water flow in partially saturated fractured rocks.

In each of the following sections, a detailed review of the results of each methodology will be presented. The conclusions reached in these studies will be critically reviewed and alternative conclusions will be presented. By reviewing all the studies at once, general conclusions and comparisons on the rate and magnitude of soil water flux at NTS can be drawn.

It is the intent of this document to show the applicability and accuracy of various methodologies for measuring soil water flux. As will be shown, most of the techniques produce similar conclusions as to the magnitude and location of soil water flux at NTS.

FLUX ANALYSIS USING SOIL HYDRAULIC PROPERTIES

The use of soil hydraulic data may be used in an indirect method to calculate soil water migration. Soil water, under most deep soil conditions, is driven by two forces, capillarity and gravity. In the near surface soils, thermal forces may affect the movement both by inducing vapor transport and through thermal convection. For deep migration, we shall assume that soil water is unaffected by thermal gradients, gradients are vertically downward, and the soil water obeys Darcy's equation for flux:

flux = hydraulic conductivity x hydraulic gradient.

In order to calculate the flux, the hydraulic conductivity (a function of the soil texture and water content) and the driving forces, capillarity and gravity, must be known.

Field and laboratory measurements of these properties have been reported by several authors (Mehuys et al., 1975; Kearl, 1982; Romney et al., 1973; and Tyler et al., 1986). Figure 3.1 shows the approximate locations where hydraulic property data has been collected.

In each of these studies, soils used in the analyses were taken from near the surface (<50 m) and were collected in the alluvial basins. Alluvial thicknesses may exceed 300 m in some of these basins. No soil samples have been reported from the upland areas where thin soils mantle the fractured bedrock. Core data from unsaturated fractured rock have also been reported by Peters et al. (1984) and Weeks and Wilson (1984) from the Yucca Mountain area.

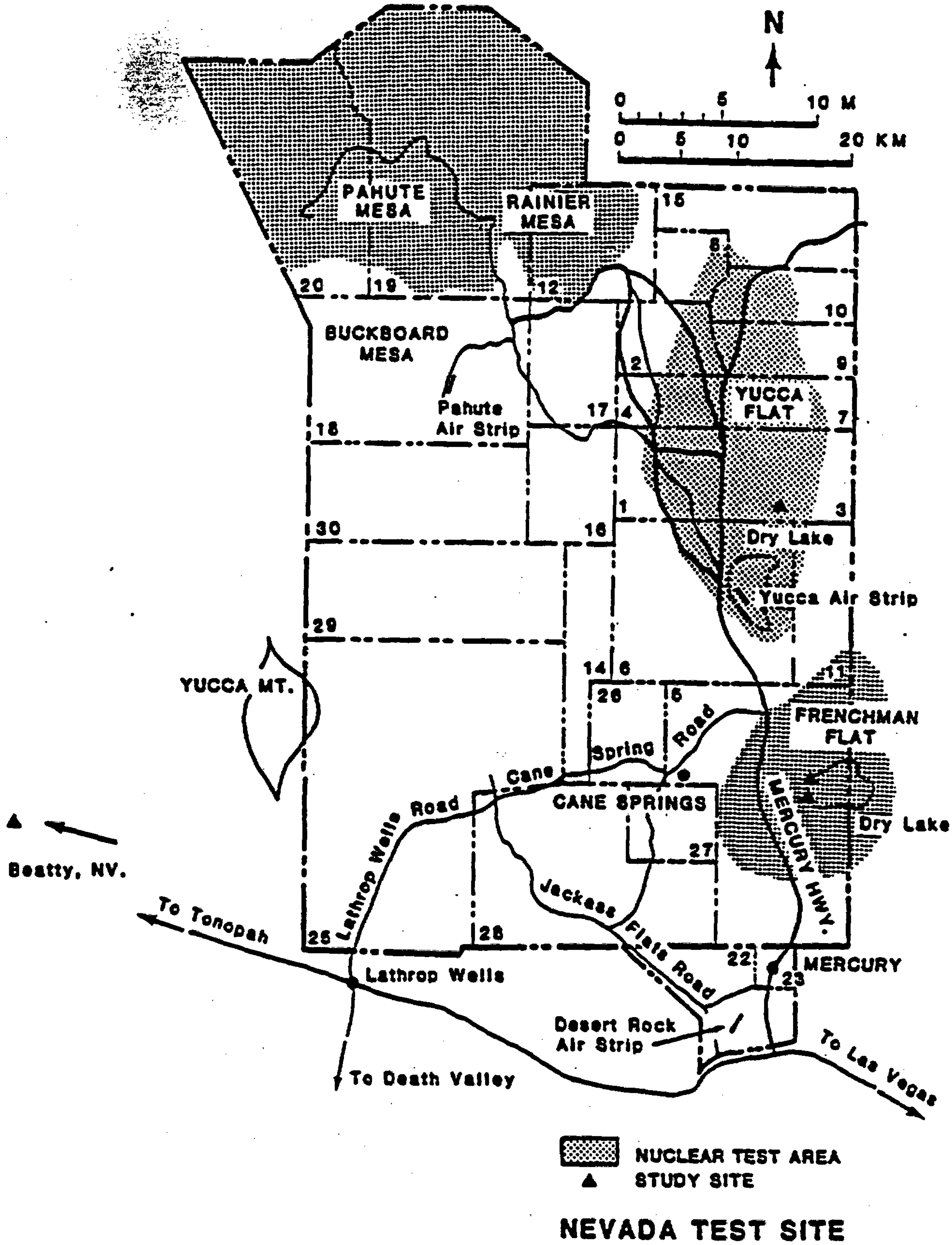

FIGURE 3.1. Soil Hydraulic Property Study Sites on NTS.

Our data base for review is biased toward soil moisture movement in thick alluvial sediments. Flux estimates obtained from this data are only valid for regions where it has been collected, but may be used to provide ranges of the values of recharge over the entire NTS. Flux in areas of periodic flooding, such as washes and playas, may be much higher than those predicted in this section using the interfluvial data.

The most complete set of soil hydraulic data was published by Mehuys et al. (1975) on soil samples from Rock Valley (area 25). In their study to determine the effects of stone content on hydraulic conductivity, conductivity measurements on gravelly sandy loam using the transient outflow method (Weeks and Richards, 1967) were collected over the range of -0.05 to -50 bars of capillary pressure. In addition, water retention data was also collected. This data is shown in Figures 3.2 and 3.3.

Figure 3.2 shows the steep drop in hydraulic conductivity as the capillary pressure decreases by seven orders of magnitude over the range of pressures tested. As expected, little difference was observed with and without the stony fraction when conductivity was plotted against capillary pressure. This indicates that the fine soil fraction was controlling the flow under partially saturated conditions.

In order to estimate a range of fluxes using the Rock Valley soil, the conductivity data must be combined with hydraulic gradient data. Unfortunately, no in situ matric potential or gradient data was presented by Mehuys et al. (1975). Other studies to be discussed later in the report (Case et al., 1984; and Tyler et al., 1986) on similar textured soils report in situ matric potentials of between -5 and -35 bars. Using the data presented in Figure 3.2, this corresponds to a conductivity range of 10^{-6} to 10^{-7} cm/hr. Hydraulic gradients estimated from these other studies ranged from 0.5 to 30 m/m.

To estimate the flux, these data may be combined in Darcy's equation under the simplifying assumptions that all flow is downward and steady. The four possible data combinations may be combined to produce a range of fluxes and velocities as shown in Table 3.1.

Although the results presented above may not truly represent the actual field conditions, the least conservative estimate is a flux of 0.26 cm/year, and an average pore water velocity of 2.9 cm/year, indicating that flux through these sediments assuming steady-state conditions may be quite small. In later

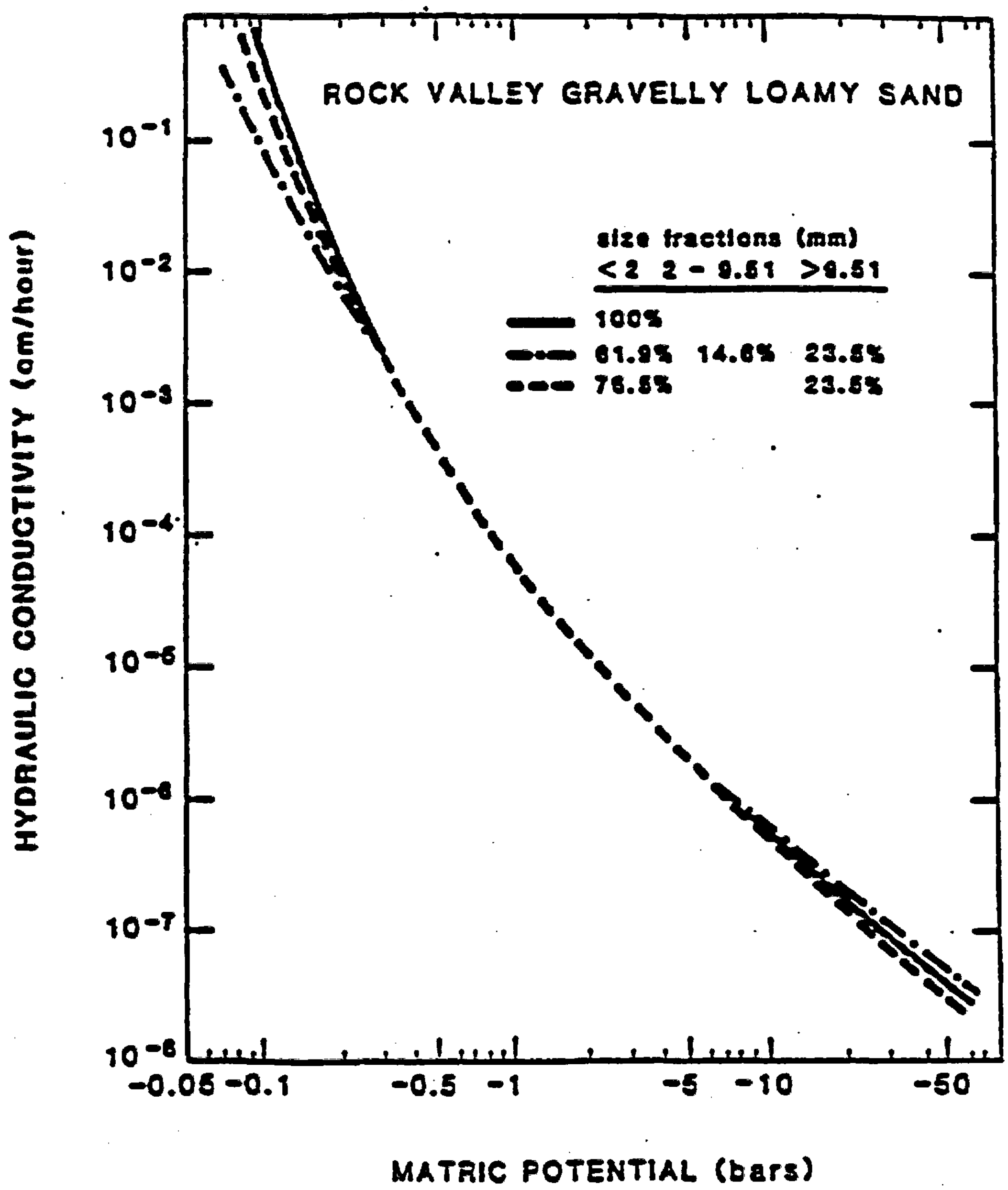

FIGURE 3.2. Conductivity and Pressure Head Data for Rock Valley Alluvium (after Mehuys et al., 1975).

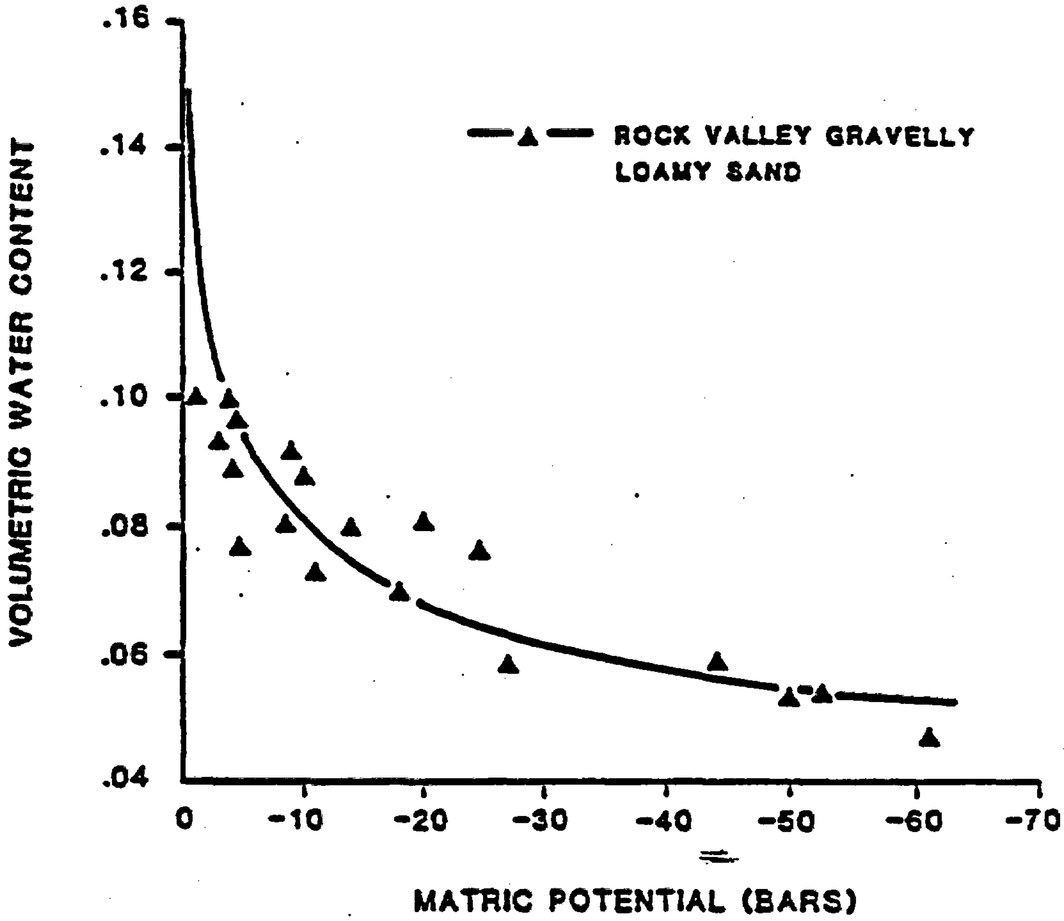

FIGURE 3.3. Water Retention Data for Rock Valley Alluvium (after Mehuys et al., 1975).

TABLE 3.1. ESTIMATED FLUX AND VELOCITY FROM ROCK VALLEY SOIL.

Vol. Water** Content	Potential (bars)	K (cm/hr)*	dh/dz***	Flux (cm/hr)	Flux (cm/yr)	Velocity (cm/yr)
0.09	-5	10^{-6}	0.5	5×10^{-7}	4.4×10^{-3}	4.9×10^{-2}
0.09	-5	10^{-6}	30	3×10^{-5}	2.6×10^{-1}	2.9×10^{0}
0.06	-35	10^{-7}	0.5	5×10^{-8}	4.3×10^{-4}	7.3×10^{-3}
0.06	-35	10^{-7}	30	3×10^{-6}	2.6×10^{-2}	4.9×10^{-1}

* estimated from Mehuys et al., 1975
** estimated from Figure 3.3
*** Tyler et al., (1986) and Kearl (1982)

sections, we shall see that these results agree quite closely with flux values derived from other methods.

Kearl (1982) presents an analysis of fluid movement adjacent to the radioactive waste management area (Area 5). Kearl reports a mean saturated hydraulic conductivity value of 4×10^{-4} cm/sec from cores in shallow sandy loam in Area 5. Another study in the area (Case et al., 1984) indicates that the area is underlain by sand and loamy sand. In addition to the saturated hydraulic conductivity results, moisture retention data presented by Romney et al. (1973) were used to construct a partially saturated hydraulic conductivity curve using the method of Mualem (1976). Although Kearl (1982) presents these calculated conductivities, the range of capillary pressures and water contents reported is not great enough to estimate the conductivities at the capillary pressures found at the site. Kearl suggests that at these capillary pressures, vapor transport may dominate over liquid transport and Darcy's equation may not be valid.

A particularly interesting set of soil data from the NTS is reported by Romney et al. (1973). Romney et al. (1973) presents water retention data at several capillary pressures (0, -0.33 bar, -1 bar, and -15 bar) from near-surface soil samples collected from Yucca Flat, Jackass Flat and Frenchman Flat. In Frenchman Flat, 52 soil samples were analyzed in detail. In a similar approach to that of Kearl (1982), an estimate of the hydraulic conductivity may be made following the approach of Campbell (1974). Campbell suggests the following relationships for the water retention curve and conductivity:

$$\psi = \psi_e \left(\frac{\theta}{\theta_s}\right)^{-b} \quad (3.1)$$

$$K = K_s \left(\frac{\psi}{\psi_e}\right)^{(-2 - 3/b)} \quad (3.2)$$

where ψ is the capillary pressure head; ψ_e is the air entry pressure; θ is the volumetric water content at ψ; θ_s is the saturated volumetric water content; K and K_s refer to the partially saturated and saturated hydraulic conductivity, respectively; and b is an empirical pore geometry factor.

This approach was applied to the mean water content presented in Romney et al. (1973) from Frenchman Flat to estimate the partially saturated conductivity. A linear least squares fit of the data to equation 3.1 yields:

$$\psi = 6.8\times10^{-3} \left(\frac{\theta}{\theta_s}\right)^{-4.93} \quad (3.3)$$

Unfortunately, Romney et al. (1972) does not present data on the saturated conductivity needed for equation 3.2. For this analysis, the saturated conductivity presented by Kearl (1982) ($K_s = 4.0\times10^{-4}$ cm/sec) will be used as a first approximation. Equation 3.2 then becomes:

$$K(\theta) = 4\times10^{-4} \left(\frac{\psi}{\psi_e}\right)^{-2.61} \quad (3.4)$$

With this set of soil data, Darcy's equation may be used to once again estimate fluid flux and velocity assuming steady downward flow. Table 3.2 shows these results.

TABLE 3.2 FLUX ESTIMATES.

Water* Content	Matric Pot. (bars)	K** (cm/sec)	dh/dz	Flux (cm/sec)	Flux (cm/yr)	Velocity (cm/yr)
0.066	-5	1.3×10^{-11}	0.5	6.5×10^{-12}	2.0×10^{-4}	3×10^{-3}
0.066	-5	1.3×10^{-11}	30	3.9×10^{-10}	1.2×10^{-2}	1.8×10^{-1}
0.046	-35	9×10^{-14}	.5	4.5×10^{-14}	1.4×10^{-6}	3×10^{-5}
0.046	-35	9×10^{-14}	30	2.7×10^{-12}	8.5×10^{-5}	1.8×10^{-3}

* calculated from eq. 3.3
** calculated from eq. 3.4

Although these velocities are smaller by at least an order of magnitude than those using the data of Mehuys et al. (1975), the results are encouraging since they are quite similar considering two different soils from differing locales are compared.

For the purposes of comparison, it appears that this simple approach yields consistent results and further shows that fluid velocities may not exceed 4 cm/year and may, in fact, be significantly lower.

CONCLUSIONS

Although simplistic, steady flow assumptions have been applied to the available soil data; fairly consistent results were obtained. Values of potential flux calculated, although independent of climatic variations, indicate that less than one percent of the average annual precipitation is moving downward through these soils. No values were calculated that approached significantly high velocities. In the areas where these samples were taken and the conditions assumed in the analysis, the depth to the saturated zone exceeds 300 meters. Using the highest velocity estimated (2.9 cm/year), the travel time to the saturated zone under steady flow conditions may exceed 10,000 years. It is important to note, however, that these estimates represent Mohave desert soils subject only to natural precipitation and plant cover. It will be shown in a later section that desert soils subject to periodic flooding (such as wash bottoms or ponds) will have much higher rates of soil water velocity.

FLUX ESTIMATES USING TRITIUM TRACERS

Since 1952, atmospheric testing of nuclear weapons has produced concentrations of tritium in precipitation that have been well above levels that existed prior to 1952. Relatively few reliable measurements on natural tritium levels in the atmosphere were made before the atmospheric test of a thermonuclear device in 1952 injected artificial tritium into the atmosphere. These early measurements sufficed, however, to establish natural tritium levels in precipitation, ranging for different locations from about 4 to 25 TU (1 TU = 1×10^{-18} atoms of tritium per atom of hydrogen or 3.2×10^{-3} pCi/ml). Details of the distribution in time and space are sketchy and the picture of natural tritium geophysics relies, to a large extent, on additional information from the post-1952 era, based on the assumption that the atmospheric fate of cosmic-ray and bomb-produced tritium was similar.

The pattern of tritium levels in precipitation at Ottawa, Canada (the station with the longest continuous record), is essentially repeated at other northern hemisphere stations, with varying amplitudes and some significant phase shifts. Figure 3.4 shows the average northern hemisphere values and the notable feature of this curve is a yearly cycle of maximum concentrations in spring and summer and a winter minimum, with typical concentration ratios of 2.5-6 between maximum and minimum values. The annual cycle is superimposed upon long-term changes which have ranged over three orders of magnitude since 1952.

The changing tritium inventory of the stratosphere of recent years reflects the massive injections by weapon tests in 1954, 1955, 1958, and again during 1961-1962, mostly in the northern hemisphere. At any time, the inventory decreases by 5.5 percent per year through radioactive decay and some of the tritium leaks into the troposphere from where it is lost into the ocean or ground waters, both of which can be considered a sink for the stratospheric tritium (Fritz and Fontes, p. 24, 1980).

Historic data on tritium levels in precipitation at NTS unfortunately, are not available. The result of this dramatic increase in tritium levels in precipitation has been used extensively for dating of both soil and ground water in other areas, however. Since tritium levels dramatically increased after 1952, waters containing elevated tritium levels are believed to have had contact or come exclusively from post-1952 precipitation.

In soils work, this tritium "pulse" has been used to detect the depth of migration of post-1952 infiltration (Isaacson et al., 1974; Anderson and Sevel, 1974). In ground-water systems, existence of elevated tritium levels indicates that some post-1952 recharge has been introduced into the aquifer.

At NTS, both of these approaches have been used to determine the rate of infiltration and areas of rapid ground-water recharge. Figure 3.5 shows the locations of studies where tritium tracing has been used.

SOIL MOISTURE TRITIUM

At least two published reports describe tritium migration in soils from natural precipitation on NTS. In a Master's thesis, Hansen (1978) describes the results of soil coring and soil water tritium analysis from several areas of the NTS. Samples were collected in alluvial and playa sediments of both Yucca and Frenchman Flat. Tritium analysis of borings from Forty Mile Wash in

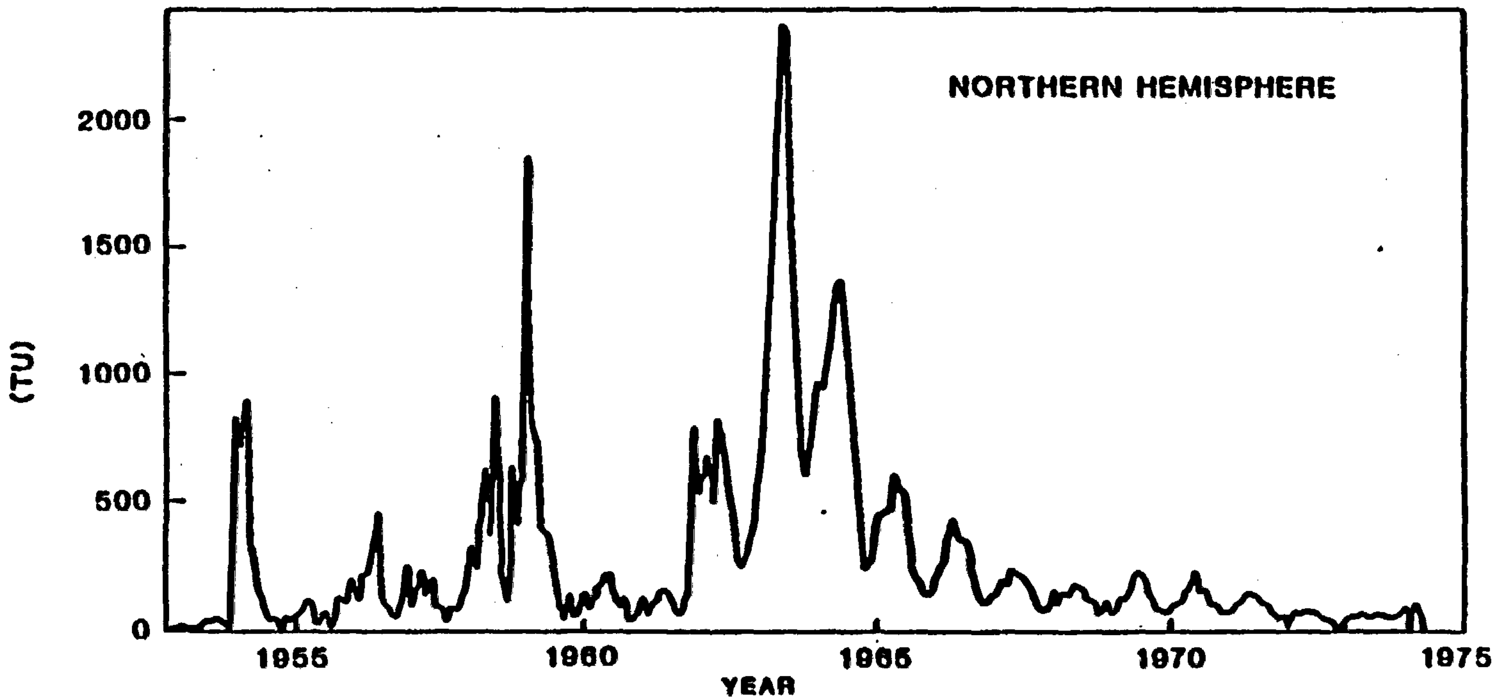

FIGURE 3.4. Distribution of Tritium in Precipitation in Ottawa, Canada (after Fritz and Fontes, p. 545, 1980).

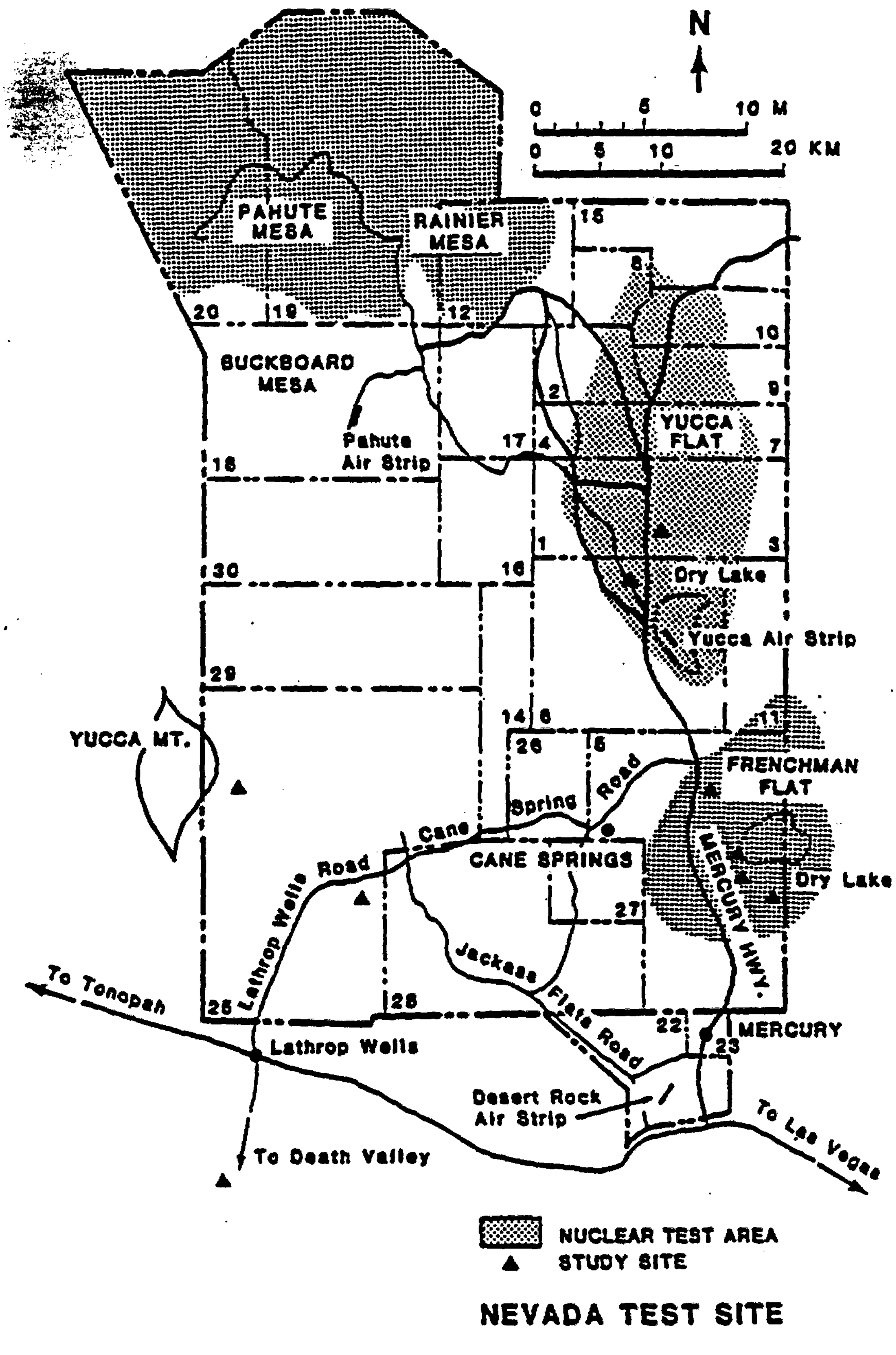

FIGURE 3.5. Locations of Soil Tritium Sampling Studies at NTS.

Jackass Flat are also presented. Unfortunately, the tritium analysis techniques used in Hansen's work have high errors associated with any samples containing less than 100 TU ($3.2x10^{-1}$ pCi/ml).

As a result, samples containing less than 100 TU ($3.2x10^{-1}$ pCi/ml) may be interpreted as either old (pre-1952) or younger water. In each of his shallow borings (<1 meter), tritium in excess of pre-1952 levels and well above the 100 TU ($3.2x10^{-1}$ pCi/ml) experimental error level were found throughout the profile. Maximum tritium levels were generally found at or near the soil surface. These results indicate that recent (less than 26 years old) precipitation had migrated to at least one meter below the soil surface. Since no pre-1952 levels were detected in these shallow sites, no estimates of soil moisture velocities may be made except that the velocity was greater than 1 meter in 26 years or 3.8 cm/year.

Hansen also presents data from three deep boreholes. Borehole YF-10 completed in playa sediments in Yucca Flat, showed elevated tritium levels to a depth of 5 meters. Below this depth, tritium levels appear to be at pre-1952 levels (2-15 TU or $6.4-48x10^{-3}$ pCi/ml). Figure 3.6 shows the measured soil water tritium levels. Figure 3.7 shows the soil water tritium from borehole FFI-A1. This borehole, drilled to a depth of 3 m in alluvial fan sediments of Frenchman Flat, shows a decline in soil water tritium from the surface to 3 m. The tritium levels in FFI-A1 are slightly higher than those of YF-10, indicating that recent moisture may have penetrated to at least 3 m. The uncertainties in analytical techniques may, however, mask the actual tritium distribution at the bottom of the borehole. Data from borehole UE2 ce, part of an emplacement hole augered in alluvial soils in Yucca Flat to a depth of 26 m, are also presented. Tritium levels in soil water from these cores at UE2 ce were elevated above pre-1952 levels in most of the sampled interval. Two depths (20 and 26 m) showed less than 2 TU, however.

The data from these deeper boreholes is quite enlightening. Using the data presented from YF-10, post-1952 water had migrated to a depth of 5 meters. Assuming that recharge occurred uniformly from 1952, the average soil moisture velocity (V) may be estimated from the following simple mass balance equation.

V = Depth of Penetration/Date of Sample-1952

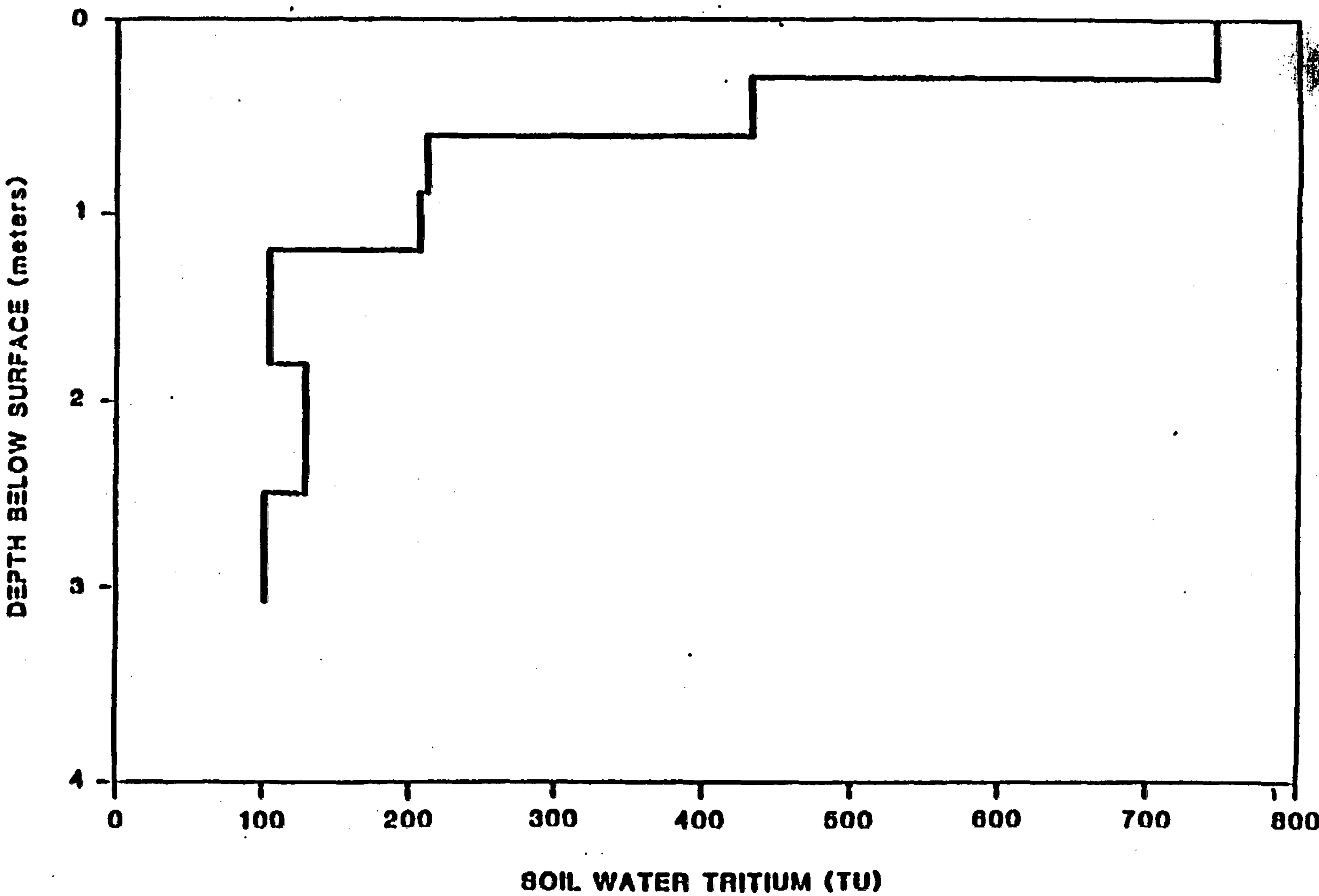

FIGURE 3.6. Soil Water Tritium Profile from Yucca Flat #YF-10 (from Hansen, 1978).

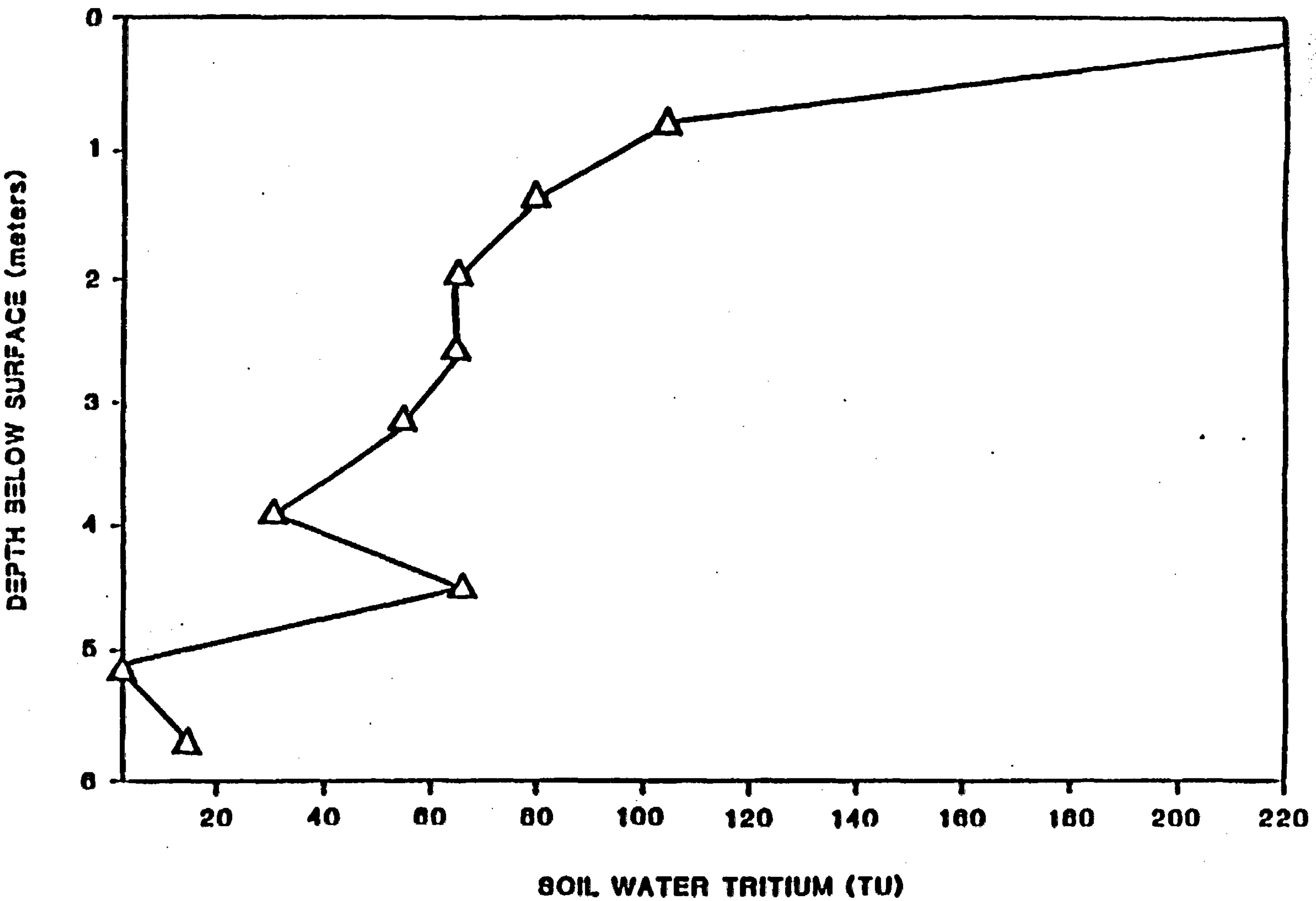

FIGURE 3.7. Soil Water Tritium Profile from Frenchman Flat #FFI-A1 (from Hansen, 1978).

This simple approach neglects dispersion and diffusion phenomenon and assumes steady flow. For the purpose of this review, however, this approach is adequate. Using the data provided in Hansen, the soil water velocity at YF-10 may be calculated at 0.2 m/year. From the same approach, if one assumes a uniform water content with depth, the recharge flux may also be calculated by multiplying the velocity term by the average volumetric water content. Using an estimated bulk density of 1.6 g/cm^3 and the gravimetric water content reported by Hansen of approximately 10%, the flux is calculated as approximately 3 cm/year. This represents approximately 20% of the average yearly precipitation at Yucca Flat. Although this may seem rather high, the site is in playa sediments and is periodically inundated by ponded water.

An alternative hypothesis often suggested for desert moisture transport is also possible at YF-10. In this scenario, the soil system is not under steady flow conditions. Precipitation falling on the soil is incorporated as soil water storage in the top 5 m. Following precipitation events or periods of low evapotranspiration, this stored soil water is evaporated and transpired by plants and is removed from the system. At borehole YF-10, this maximum storage depth would be estimated to be 5 m.

The data collected from borehole UE2 ce and reported by Hansen is difficult to interpret. If tritium migration is considered to be piston-like, there should exist a sharp distinction between pre- and post-1952 soil water. Data from UE2 ce, however, is erratic showing layering of both tritiated and non-tritiated soil water. This layering may be a result of the sampling procedures used at UE2 ce, which was augered with a 3 m diameter bucket auger. Cross contamination of cuttings samples may have occurred during this process. In light of this, these results are not unexpected but shed no light on tritium migration.

In a recent study by Buddemeier and Isherwood (1984), tritium profiles in soil are presented from Frenchman Flat. Two hollow stem auger holes were drilled to depths of 6 m adjacent to the Cambric RNM site in 1983. Borehole #1 was drilled 15 m from an unlined ditch containing high levels of tritiated water while borehole #2 was drilled 30 m from the same ditch. This site is underlain by alluvial soils classified as sand to sandy loams. Coarse cobble layers were also encountered during drilling. The results of soil water tritium are presented in Table 3.3.

TABLE 3.3. TRITIUM PROFILES FROM AREA 5 SURFACE SOILS (after BUDDEMEIER, 1984).

Borehole ID	Interval Sampled (m)	Tritium Concentration (T.U.)	(pCi/ml)
1	0-0.6	1750±344	5.6±1.1
1	0.6-1.2	750±312	2.4±1.0
1	2.5-3.1	63±63	0.2±0.2
1	5.5-6.1	19±19	0.07±0.07
2	0.0-0.6	1543±312	4.9±1.0
2	2.5-3.1	<19	<0.07
2	5.5-6.1	<19	<0.07

Figure 3.8 graphically shows the tritium levels in the soil water. From this data, it appears that post-1952 precipitation had migrated no deeper than 2.5 m in the sandy alluvial soils at Frenchman Flat. Using the same flux approach as applied to Hansen's data, the soil moisture velocity at this site is estimated to be 0.08 m/year. Assuming a soil volumetric water content of 10 percent, the average downward flux is estimated to be 0.008 m/year or less than 1 cm/year. An alternative hypothesis for this distribution indicates that 2.5 meters is the maximum depth of storage of precipitation. Precipitation, held in storage in the upper 2.5 m of soil, is evaporated and transpired at a rate equal to yearly flux into the soil surface. Hence, the 2.5 meter depth may represent a soil moisture flow divide.

In addition to soil tritium, tritium in aquifers has been used to delineate post-1952 recharge. Due to underground testing at NTS, however, the question of contamination of many recently collected ground-water samples is of concern. A relatively "virgin" suite of samples was published by Clebsch (1961) from various wells and springs at the NTS. These values are shown in Table 3.4.

Five wells were sampled in 1958-59 and contained ground water with less than 0.5 TU ($1.6x10^{-3}$ pCi/ml), indicating residence times of greater than 50 years. Three of the wells were completed in alluvium; the remaining two in fractured volcanic rocks.

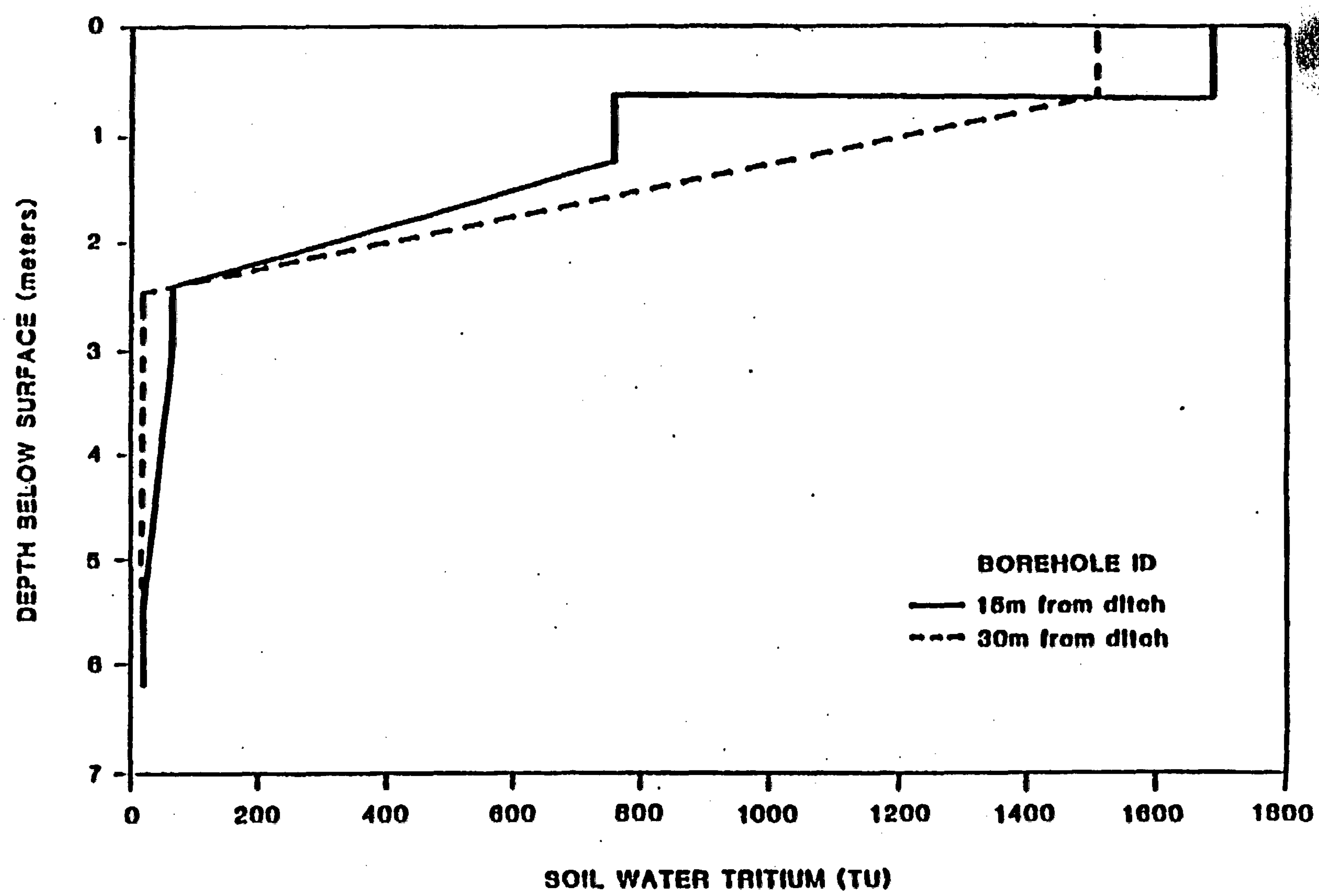

FIGURE 3.8. Soil Water Tritium Profiles from Cambric RNM Site (after Buddemeier and Isherwood, 1984).

TABLE 3.4. TRITIUM IN NTS GROUND WATERS (after CLEBSCH, 1961)

Sample Location	Aquifer	Date of Sampling	Tritium Concentration (T.U.)	(pCi/ml)
Well #3 (Yucca Flat)	Tuff	8/7/58	<0.5	$<1.6\times10^{-3}$
Well #3	Tuff	4/21/59	<0.5	"
Well #5A (Frenchman Flat)	Alluvium	2/26/59	<0.5	"
Well #5C (Frenchman Flat)	Alluvium	2/26/59	<0.5	"
Well #J-11 (Forty Mile)	Tuff	8/7/58	<0.5	"
Well #J-11 (Forty Mile)	Tuff	4/21/59	<0.5	"
Well 15S/49-14aa1 (Forty Mile)	Alluvium	1/28/59	<0.5	"
White Rock Spring (Rainier Mesa)	Tuff	8/7/58	34	0.11
Tunnel U12e.05 (Rainier Mesa)	Tuff	9/12/58	36	0.12

Two 'perched' flow systems were also sampled in this study. A sample from White Rock Spring, a small spring located northeast of Rainier Mesa and discharging from zeolitized tuff, contained 34 TU (0.11 pCi/ml), leading Clebsch to conclude that this spring had a hydraulic residence time of less than 6 years. Clebsch also reports a value of 36 TU (0.12 pCi/ml) from a sample taken at a seep in E-tunnel at Rainier Mesa. Since several underground nuclear tests had been conducted in the vicinity of the sample point, the "purity" of this sample is in question. Since the tritium level is very similar to that found at White Rock Spring, which was believed to be far enough from testing areas to be unaffected, it is possible that this sample also represents recent recharge from post-1952 precipitation.

Following the same reasoning as at White Rock Spring, Clebsch suggests a residence time of less than 6 years in this area of E-tunnel. Since the unsaturated zone above E-tunnel is approximately 400 m thick, this indicates very high recharge velocities (70 m/year) through the fractured rocks. This result, as well as other more recent data from Area 12, will be presented in a later section devoted strictly to Rainier Mesa.

Clebsch's work indicates that active and rapid soil water movement may be occurring in certain locales of NTS. Specifically, these areas are upland areas where soils are thin to non-existent and where winter precipitation often falls as snow. The unsaturated zone in these areas consists of sequences of highly fractured and permeable volcanic tuff. Areas underlain by thick alluvial sediments (all wells sampled by Clebsch were overlain by alluvium) showed no input from recent soil waters.

CONCLUSIONS

The results of tritium tracing methods at NTS indicate that the soil water movement in alluvial soils is slow or negligible in most areas tested. In the studies presented, soil moisture velocities ranged from 0.03 to 0.08 m/year. These conclusions are supported by both soil moisture and ground-water studies.

As expected, the depth of recent soil water penetration was significantly greater in those areas where periodic ponding or flooding has occurred. The areas where data supports this conclusion are the playa areas but it is expected that other sites receiving periodic inundation, such as washes and man-made depressions (including subsidence craters and waste pits), will also show evidence of rapid soil water movement. A detailed discussion of the implications of recharge through man-made structures will be presented at the conclusion of this report.

Based upon the analysis of Clebsch (1961), rapid recharge (and hence, soil water movement) appears likely in at least one perched ground-water system (White Rock Spring). This conclusion is reasonable, since the unsaturated zone above this system is highly fractured and permeable.

IN SITU MEASUREMENTS/MONITORING

Long term direct monitoring of soil moisture movement is extremely difficult in arid environments, due to very small rates of fluid movement. Errors associated with input signals (precipitation), evaporation, transpiration, and the small changes in soil moisture storage, are each potentially larger than the magnitude of the flux term. Nevertheless, several authors: (Kearl, 1982; Case et al., 1984; Morgan and Fischer, 1984; and Tyler et al., 1986) have reported data on in situ moisture and flux measurements at or near the NTS. These authors provided valuable data on:

- Quantifying the energy state of soil moisture;
- Quantifying soil moisture storage changes; and
- Development of field instrumentation technology.

Figure 3.9 shows the locations of these studies. Each of the studies presents data which may be applied to a hydraulic analysis approach to estimate soil water flux. Unfortunately, no studies have been performed to quantify, in a direct way, the mechanism and magnitude of soil water flux using weighing

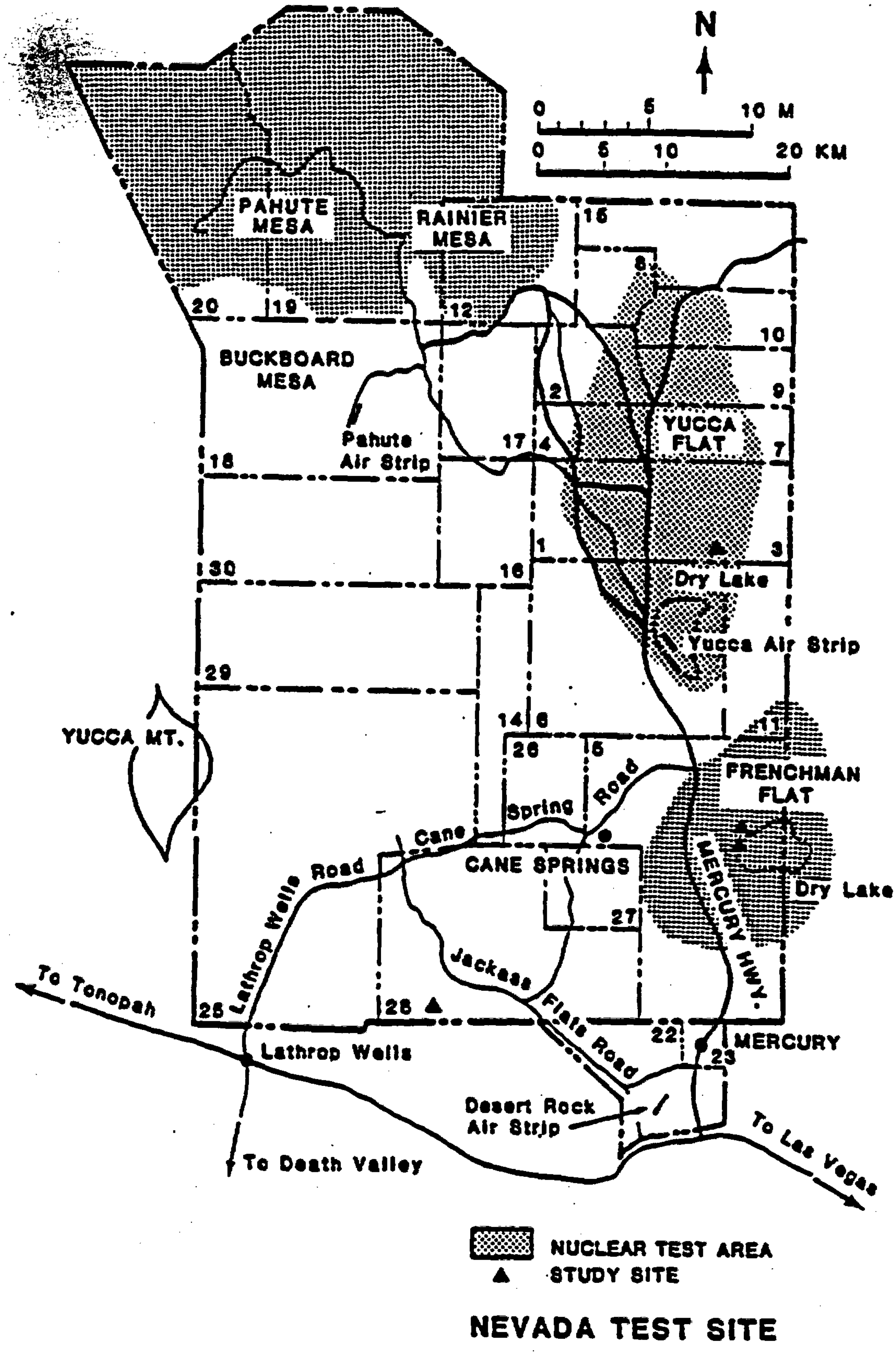

FIGURE 3.9. Location of In-Situ Study Areas on or near NTS.

lysimeters. Gee and Heller (1984) report that weighing lysimeters are the most effective methodology for the measurement of soil water storage. These devices measure the weight change and fluid flux through large masses of isolated soil. Direct evaluation of evaporation and transpiration, as well as the flux through the bottom of the lysimeter, may be used to measure directly the relative magnitude of each of these parameters. Tracer experiments may also be conducted within a lysimeter to determine the radionuclide migration potential in various soils.

The work of Kearl (1982) and Case et al. (1984) provides a complete data set on the energy state (matric potential) of a field site in Frenchman Flat. Baseline monitoring of matric potential for approximately two months to a depth of 5 m is shown in Figure 3.10, as reported by Kearl. The data shows that below 1 m, a relatively uniform set of potential values between -35 and -40 bars are present. As expected, much lower potentials were observed near the soil surface indicating the extreme evaporation and transpiration occurring in the desert soils. Also reported is a neutron log to a depth of 5.5 m, shown in Figure 3.11. The data shows a slight decrease in moisture content from 9 to 7 percent below the first meter. It is not reported, however, if the neutron log was calibrated for the site soils; hence, the absolute value of the water contents reported may not be exact.

Case et al. (1984) conducted a more detailed investigation of Frenchman Flat Site. Their work provides a much longer data set (1 year). Using psychrometer data from 1.9 and 3.1 m below land surface, Case et al. (1984) indicate that the gradients of matric potential ranged from approximately +25 to -30 m/m over the one year period. These results are shown in Figure 3.12. Interpretation of Figure 3.12 surprisingly indicates that matric gradients (hence, fluid driving gradients) are conducive to upward flow between September and February while downward flow would be dominant the rest of the year. Although gravity gradients were neglected in the analysis, their magnitude (+1) allows the use of matric gradients alone to calculate flux except at those times when the matric gradients are near zero. These results are rather surprising as upward flow would be expected to dominate during the hot summer months when evaporation and transpiration effects are highest. Extreme summer precipitation events may account for the downward flow during these periods and thermal gradient effects may also be a significant factor.

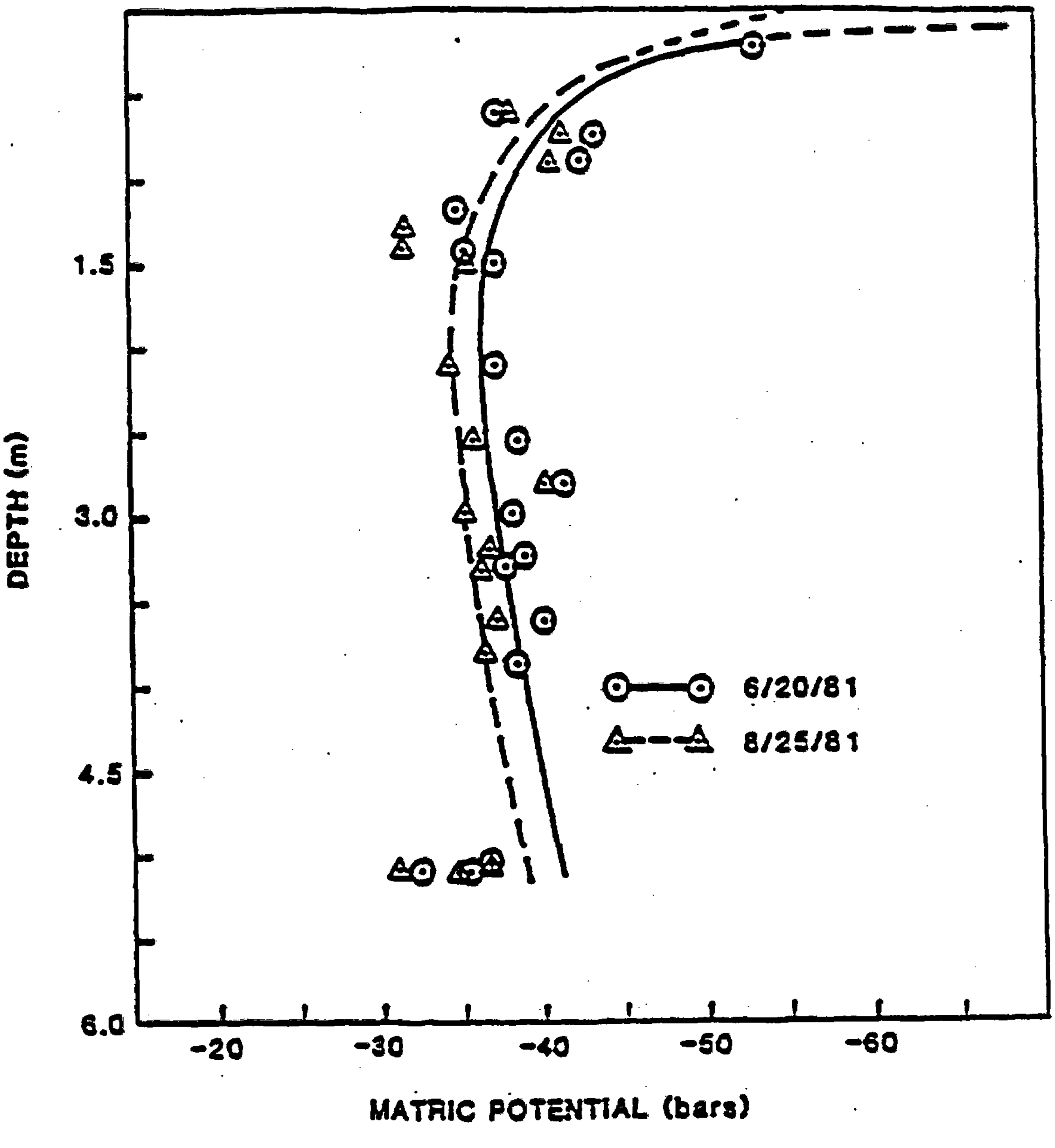

FIGURE 3.10. Matric Potential Profile from Frenchman Flat (after Kearl, 1982).

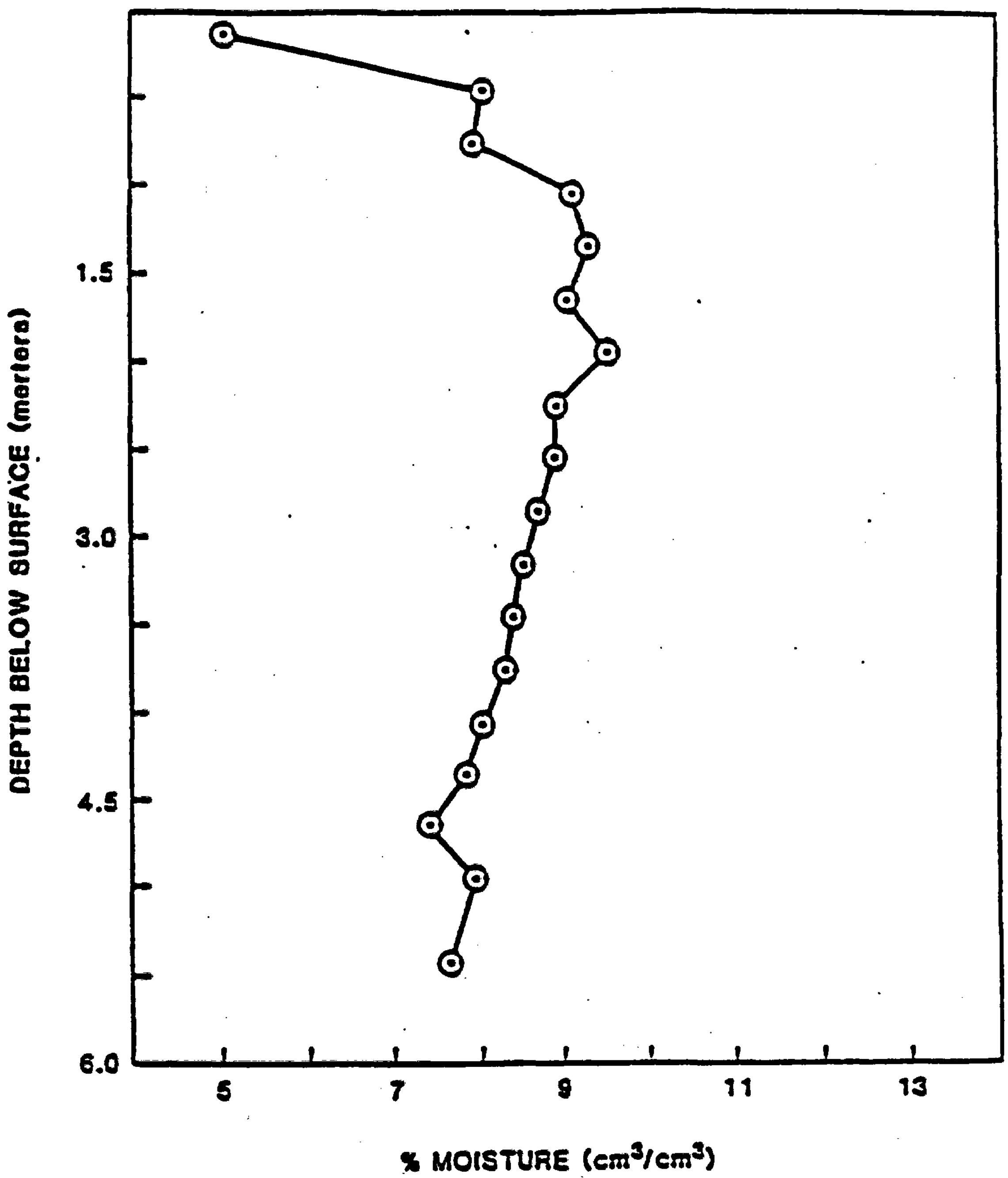

FIGURE 3.11. Neutron Water Content Log from Frenchman Flat (after Kearl, 1982).

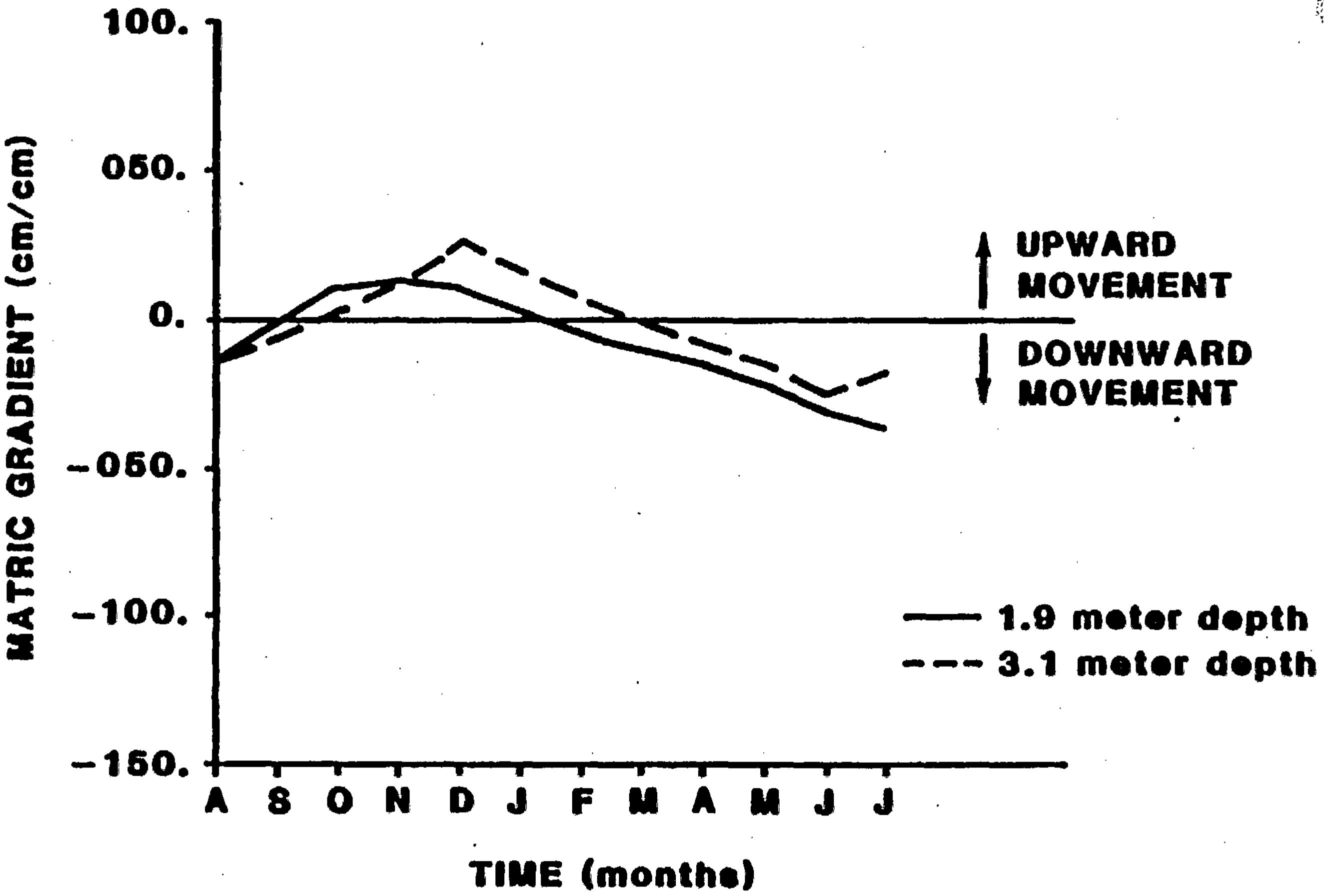

FIGURE 3.12. Matric Gradients Measured at Frenchman Flat (after Case et al., 1984).

Case et al. (1984) combined this gradient data with the hydraulic conductivity data presented by Kearl (1982), to estimate the magnitude and direction of water velocity at both the 1.9 and 3.1 m depths. The results of this analysis are shown in Figure 3.13. The resulting velocities range from 12 cm/year downward to 25 cm/year upward at the 1.9 m depth to 2 cm/year downward to 4 cm/year upward at the 3.1 m depth. Figure 3.13 shows a cyclic behavior indicating that net yearly velocities may be near zero at this site. (The reader should note that Figure 3.13 has been corrected by including the estimated volumetric water content instead of the soil porosity.)

Although not within the boundary of NTS, Morgan and Fischer (1984) present preliminary data on a large scale in situ study near Beatty, Nevada adjacent to a commercial low-level radioactive waste disposal site. At the site, a 1.5 m diameter monitoring shaft was installed to a depth of 14 m in silty sand and gravelly alluvium. The intent of the study is to determine the state of moisture flux and to estimate the potential for radionuclide release to the saturated zone. Data presented in the report covers both the shaft design and soil conditions encountered during shaft construction as well as data from a 42 m deep borehole adjacent to the site.

The shaft design is quite unique. After installation, thirty-three lateral drill holes were extended 4 m from the shaft. Specially designed, serviceable, thermocouple psychrometers were installed and recorded automatically.

Matric potential measurements from the shaft indicate very dry conditions ranging from -10 to -70 bars in the upper 10 m of the profile. Moisture contents in the upper 4 m of soil were also quite dry ranging from 4 to 10 percent by weight. Data from a deep (42 m) borehole indicate that the moisture contents remain low, ranging from 4 to 17 percent by volume.

Although this project has only been in operational mode for a short time, valuable data has already been accumulated. The range of moistures and energy states agree with data collected at other sites on NTS, indicating relative consistency in alluvial sediments and hydrology. As more data is collected, this project will provide a unique opportunity to study deep soil moisture flux.

Tyler et al. (1986), in an investigation of potential downward soil moisture movement from ponded water in subsidence craters in Yucca Flat, presents data from two deep (>30 m) boreholes. The first borehole (N-1) was completed

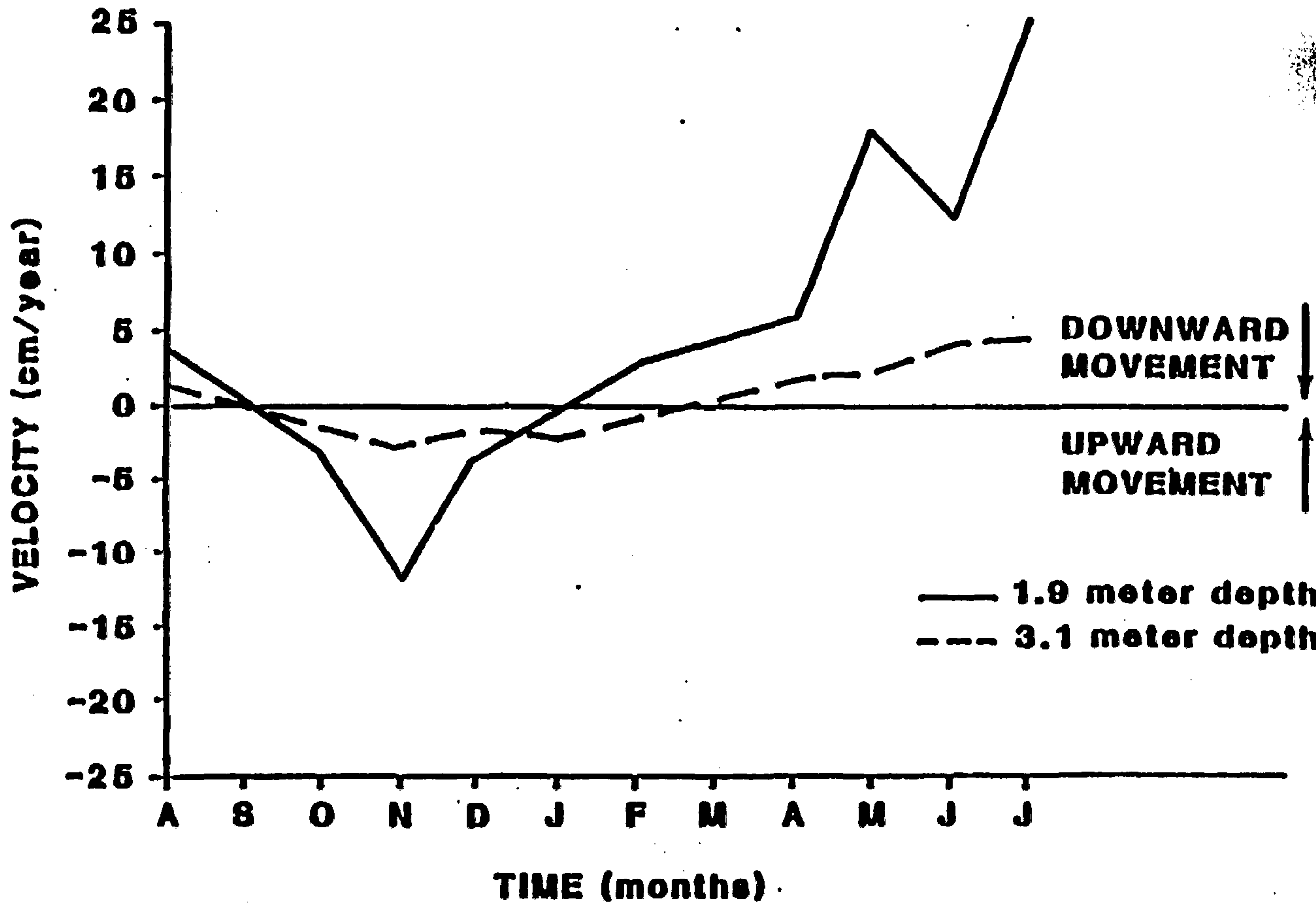

FIGURE 3.13. Soil Water Velocities at Frenchman Flat (after Case et al., 1984).

within a subsidence crater while the second hole (N-2) was completed in nearby undisturbed alluvial sediments.

Core analysis from borehole N-1 indicated high moisture contents and very low capillary pressures (>-0.1 bar). A unit hydraulic gradient was observed throughout the borehole. Using core data at downward flux of at least 5.4×10^{-1} m/year and a minimum average pore water velocity of 4.4 m/year was calculated. In the undisturbed area, core data showed much lower moisture contents and matric potentials of between -8 and -36 bars. Potentials are shown for both boreholes in Figure 3.14. Gradients calculated in the undisturbed zone were erratic with depth, indicating both upward and downward flow. These conditions are typical of soils receiving little or no recharge (Gee and Heller, 1984). No soil moisture flux estimates were made for the core data in the undisturbed environment, due to the conflicting gradient measurements.

Calibrated neutron logs were run on both boreholes and indicated a significantly higher stored moisture content in the soils below the crater, further indicating the theory of enhanced recharge in the crater environment. In the undisturbed borehole, 50 percent lower moisture storage was observed as well as much lower variability in moisture content.

Although simplified methods were used to determine the infiltration below the crater environment, it is clear that this environment significantly increased the recharge potential. Data from the undisturbed soils showed little or no detectable soil water movement.

By assuming that the infiltrating water moves vertically downward below the crater bottom, the velocity of the wetting front is at least 4.4 m/year. By using an average precipitation value of 0.168 m/year, a minimum of 13 percent of the precipitation falling on the crater catchment results in deep percolation.

CONCLUSIONS

Several _in situ_ experiments have been used to estimate the magnitude of soil moisture movement in the alluvial filled valleys of NTS and surrounding areas. In all but one case, soil moisture movement was very slow with fluxes and velocities less than several centimeters per year. Only one area, where precipitation has been concentrated and ponded due to weapons testing (subsidence craters), was there significant downward movement detected. In general,

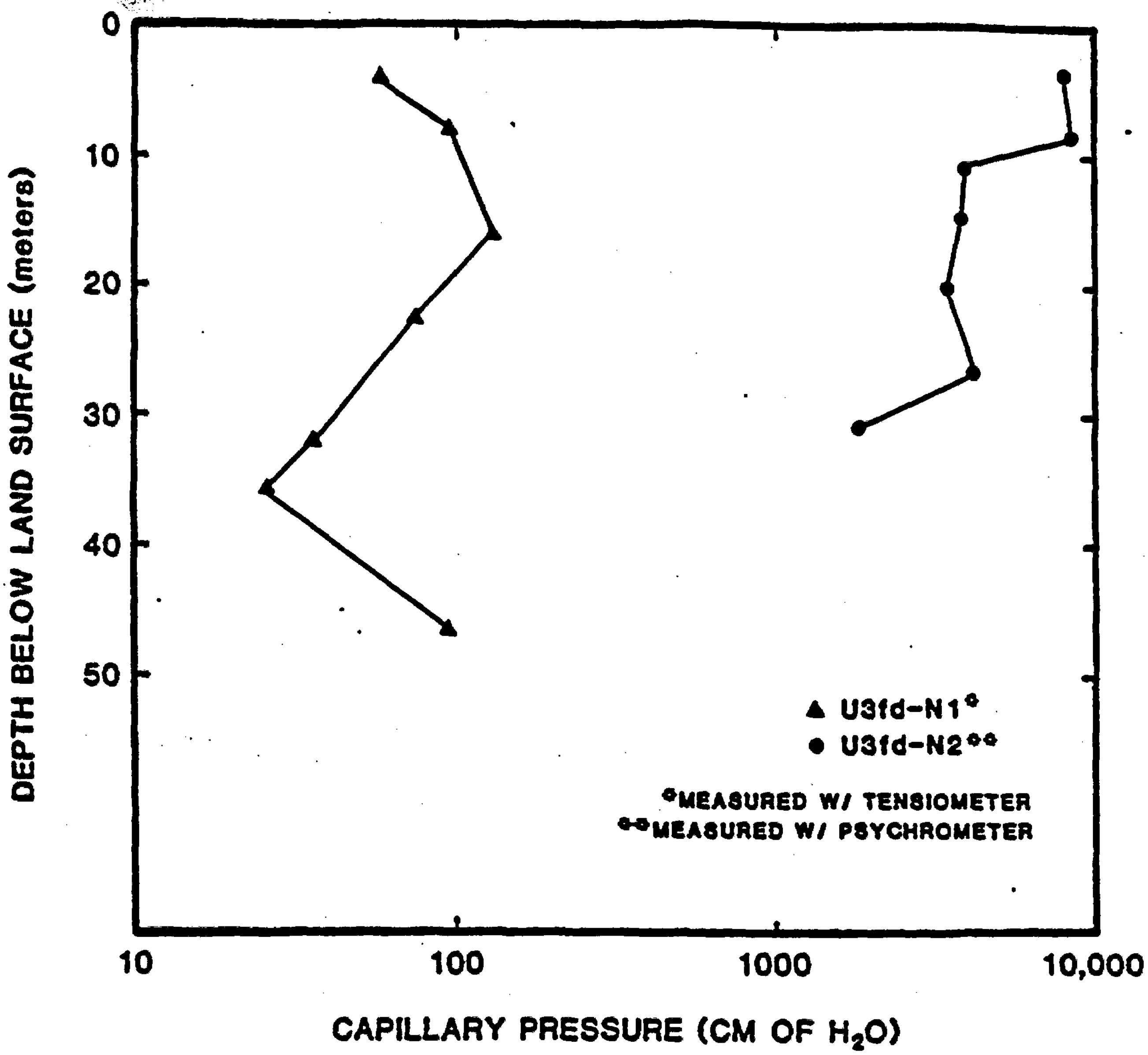

FIGURE 3.14. Capillary Pressure from Core Samples at Yucca Flat. (after Tyler et al., 1986).

measured matric potentials were less than -2 bars with most considerably lower. Field moisture content ranged from 4 to 17 percent by weight in the low flux areas, while the average volumetric moisture content at the active flow site (subsidence crater U3fd) ranged from 20 to 37 percent. It is clear from this data therefore, that very dry soils with slow moisture fluxes extends over much of the natural terrain of the NTS.

RECHARGE STUDIES IN FRACTURED TERRAIN

Fractured rock has recently received attention as a potentially safe disposal medium for radioactive waste. Studies of unsaturated fracture flow are, however, very limited. Two such areas on NTS have been studied in detail: Rainier Mesa and Yucca Mountain. This review limits discussion to Rainier Mesa since much of the Yucca Mountain data has not yet been published on field studies of partially saturated fluid flow. It is expected, however, that in the next several years, studies at Yucca Mountain will greatly enhance our knowledge of fracture flow under partially saturated conditions. In the interim, there exists quite a great deal of information on fractured flow on Rainier Mesa. Since the understanding of fracture flow is in its infancy, a review of the Rainier Mesa data may provide valuable guidance for future research.

Studies of geology and moisture movement at Rainier Mesa were begun in 1958. The work of Clebsch (1961) and Thordarson (1965) stand as the major works on Rainier Mesa.

Rainier Mesa is the highest of a group of mesa ridges and low mountains that border the northwestern part of Yucca Flat. The mesa trends north-south and is 5 km long and 2.5 km wide. The altitude of the mesa caprock is roughly 2300 m above sea level (Thordarson, 1965). Due to its high elevation, the mesa top receives in excess of 30 cm of precipitation yearly (French, 1985) and supports a large stand of pinyon pine and juniper. The mesa top is characterized by relatively gentle topography with several well-developed drainage networks. Soils are thin over much of the mesa top.

The mesa is underlain by sequences of welded tuff, bedded tuff, and zeolitized bedded tuff. The caprock is hydraulically characterized by high fracture permeability and low matrix permeability. Underlying the caprock lies a friable non-welded tuff. Figure 3.15, from Thordarson (1965), shows the general hydrostratigraphic units at Rainier Mesa.

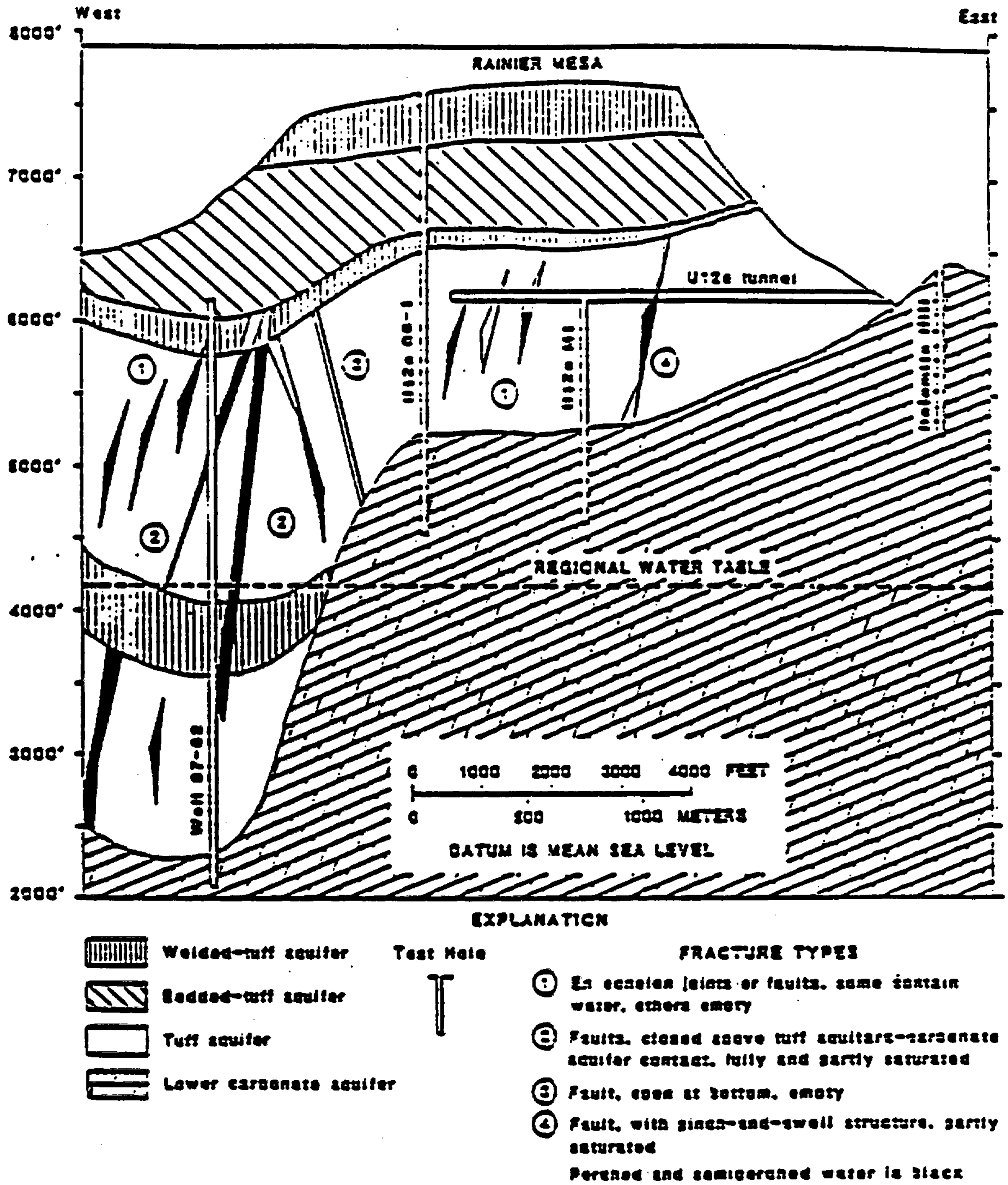

FIGURE 3.15. Hydrostratigraphy of Rainier Mesa (from Thordarson, 1965).

In order to conduct nuclear weapons testing activities, numerous adits, boreholes, and drifts have been constructed within the zeolitic tuff units 300 to 400 m below the mesa top. Although the regional zone of saturation lies 600 m below the adit portals, water has been intercepted in many areas of the tunnels. The existence of this water combined with the unique opportunities to examine, in three dimensions, the flow characteristics of partially saturated fracture flow make Rainier Mesa a very attractive study area.

Clebsch (1961), and Clebsch and Barker (1960) present data on water chemistry from tunnel seeps and drill holes at Rainier Mesa. In addition, Clebsch (1961) presents tritium data from several wells on NTS. As has been discussed earlier in this report, Clebsch (1961) interpreted tritium levels in a seep in E-tunnel to indicate that the water was introduced into the soil and traveled through the fractured rock above the tunnel in less than 6 years but greater than 0.8 years. At E-tunnel, the thickness of the unsaturated zone is approximately 400 m.

Assuming that the water originated at the surface in 1952 and was sampled 6 years later, the minimum travel velocity through the fractured tuff and friable tuff was 66 m/year. Such high rates are not surprising, since the effective fracture porosity may be very low allowing for rapid migration downward. Unfortunately, underground testing prior to Clebsch's sampling may also have contributed to the higher tritium levels in E-tunnel. Clebsch and Barker (1960) report chemistry data from 24 seeps and drill holes in B and E-tunnels, however, tritium data is not reported directly. They report background beta activity (presumably caused by cosmically-produced tritium) to be less than 25 pCi/l (8 TU). Of the 24 samples, 16 were at or below the assumed background level. Due to the nuclear testing at Rainier Mesa concurrent to sampling, it is impossible to determine if the remaining 8 samples contained precipitation tritium or locally derived tritium.

Thordarson (1965) presented a detailed report of data on perched ground water at Rainier Mesa. According to Thordarson, the zeolitic tuff at the tunnel level has very limited hydraulic conductivity and is fully saturated at the tunnel level. The low conductivity causes the perching of recharging water from the mesa top. The only free flowing water is found in fractures and fault zones intercepted by tunnels. No major springs or seeps appear at the mesa sides.

Although Thordarson does not dwell on the mode of transport from the surface to the tunnel levels, he suggests that water is moving vertically downward through the zeolitic tuff at the tunnel level based upon hydraulic gradients in wells penetrating this unit. Gradients from head measurements in packed off boreholes range from 0.3 to 1.0 m/m downward.

Thordarson also suggests that water in the fractures has a considerably lower fluid conductivity, at least 25 to 35 times lower than the interstitial fluid, indicating a much shorter residence time.

Several other more recent studies have dealt with the moisture flux at Rainier Mesa. Benson (1976) presents data on rock water interactions as does Henne (1982). Henne also presents data on soil water chemistry from the mesa top, and time series discharge measurements from three seeps in N-tunnel. He reports mean flow rates are 8, 6.5, and 6.5 l/m from these seeps.

A very interesting "back of the envelope" recharge calculation may be made using some of this data. If one were interested in recharge estimates, combining Henne's flow data with the recharge catchment area would yield the approximate annual flux through the system and indicate the percent of precipitation contributing to recharge. Several simplifying assumptions must be made:

- all seep water is recharge water and not water released from storage;
- the catchment area is known; and
- the tunnel seeps intercept 100 percent of the recharge water.

For simplicity's sake, we will assume that the tunnel recharge catchment is a circular area whose diameter is equal to the length of the tunnel (approximately 2000 m).

Figure 3.16 shows the conceptual model of the catchment area as well as the outline of the caprock area.

The recharge is calculated as follows:

recharge flux = yearly flow from seeps/catchment area

From this simple analysis, the recharge flux is approximately 0.3 cm/year. Based upon French (1985), the estimated yearly precipitation for Rainier Mesa is 30 cm. Therefore, this "simple" recharge estimate indicates that 1 percent of the total precipitation at the Rainier Mesa top becomes recharge. A slightly more realistic area of estimated recharge is obtained by assuming a circular area of recharge equal in diameter of the tunnel length underlying the mesa cap rock, since little recharge is expected to occur on the steep side slopes of the mesa. This area is also shown in Figure 3.16 and is approximately $1.2x10^6 M^2$. Using the same simplified recharge model, the estimated recharge flux is 1 cm/year or 3 percent of the average annual precipitation. Eakin et al. (1951) in qualitative estimate of recharge, suggest that 7 percent of the annual precipitation would be recharging areas with similar precipitation to Rainier Mesa.

Of course, this exercise is only for example and order of magnitude estimates. If for example, recharge were uniform over the mesa caprock, each tunnel would produce an amount of water proportional to the square of its length. As reported by Fernandez and Freshley (1984), G-tunnel, located at the southern end of Rainier Mesa, produces only 20 m^3/year of fluid, well below that which would be estimated by its length. Certain other factors, such as fracture density, tunnel elevation, and surface topography, may all contribute to the variability of fluid discharge. In addition, it is not possible to rule out the possibility that all water produced in the tunnels is being released from storage only. Thordarson (1965) suggests that the rapid decline in discharge from many fractures following intersection may be the result of local dewatering of the perched water system. In this scenario, it is not necessary for recharge to be actively occurring at Rainier Mesa. Instead, all the fluid produced was recharged during a more pluvial period.

CONCLUSIONS

Evidence collected over the last 28 years has not conclusively proven the sources and mechanisms for recharge in the Rainier Mesa area. It appears most likely that some recharge is actively moving through the fractured units above the tunnel elevation. Using simplistic calculations, 1 to 3 percent of the average annual precipitation may be transformed into recharge. In addition, hydraulic gradient data suggests that fluid is moving through the tunnel levels and into the saturated zone below. Both the rate and velocity of this recharge is unknown at this time. It is quite likely, however, that weapons testing in the tunnels will significantly increase the fracture permeability of the perching zeolitic tuff. The resulting increase in flux may also increase the

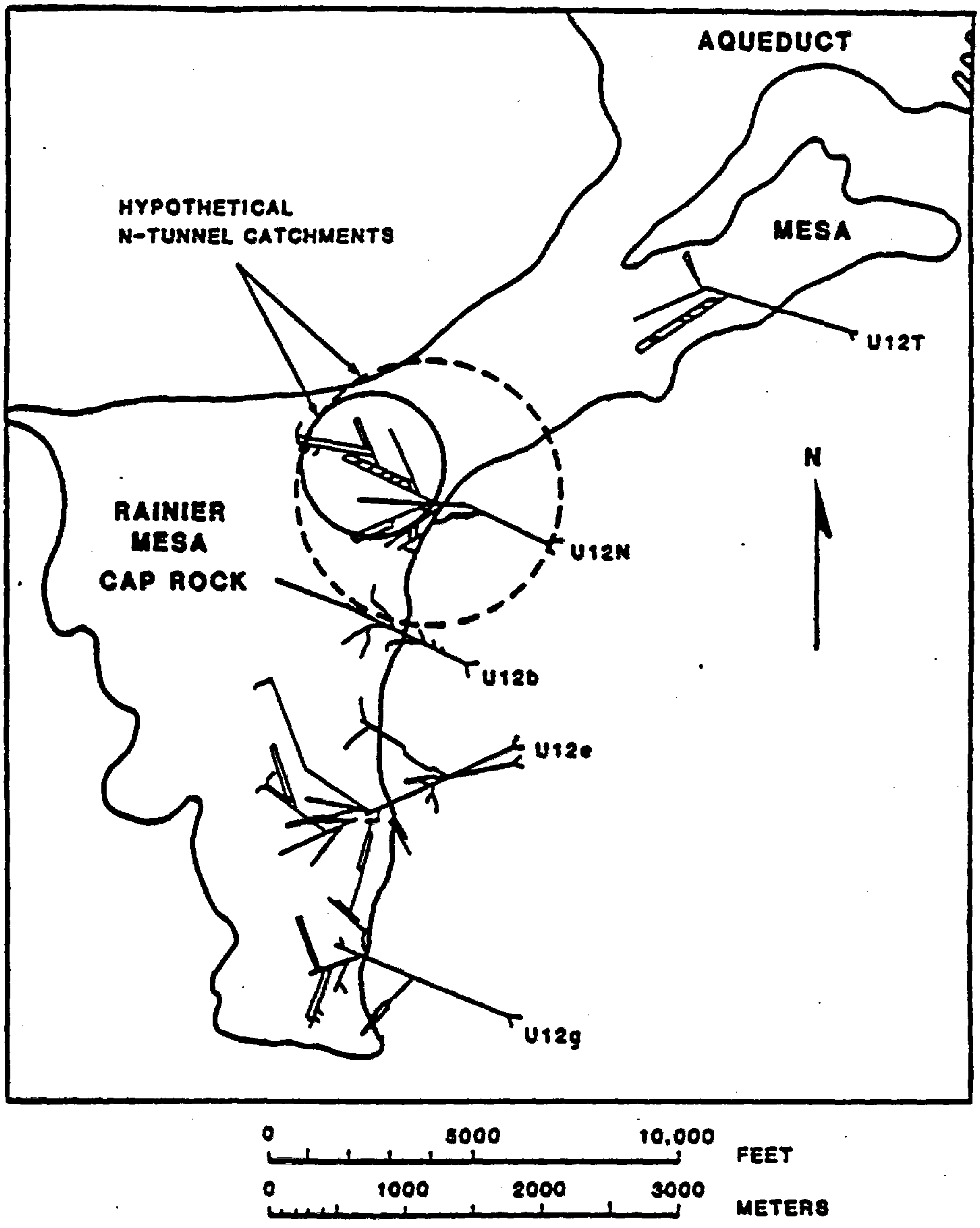

FIGURE 3.16. Rainier Mesa Showing Potential Catchment Areas for N-Tunnel Complex.

potential for radionuclide migration from the tunnel levels to the underlying ground water.

Further studies are ongoing at Rainier Mesa to study these effects. It is hoped that the next few years will provide the answers to some of these questions.

SECTION IV

CONCLUSIONS

The data collected at the NTS covers a wide range of conditions and terrains. In order to apply the results to test site activities, it is useful to divide the topographic conditions into three broad areas: alluvial basins, ponded or flooded terrain, and upland areas. Soil moisture flux conditions in each of these areas may then be summarized.

ALLUVIAL BASINS

In the alluvial basins, the studies have found that low water contents and low matric potentials dominate. These observations are a result of low precipitation, long periods of drying, and efficient extraction of soil water by plants. The following results support the conclusion that little, if any, deep soil moisture flux or recharge is occurring in these areas.

1) Estimates of fluid flux using hydraulic analysis are hampered by the lack of field data on hydraulic conductivity. However, simplified methods indicate that fluid flux is no greater than 0.3 cm/year in the areas studied. Assuming a 10 percent volumetric water content, maximum fluid velocities are less than 3 cm/year.
2) Tritium studies conducted in these areas shows that recent (post-1952 precipitation) has penetrated less than 2.5 m. Flux estimates, assuming steady-state flow, ranged from 0.3 to 0.8 cm/year. Fluid velocities ranged from 3.0 to 8.0 cm/year. These estimates agree quite well with the hydraulic analysis.

INUNDATED AREAS

Due to the nature of precipitation and topography, areas of the NTS are periodically flooded. These areas include washes, playas, and intermittent streams. In addition, ponding occurs in man-made structures, such as subsidence craters and runoff control structures. These topographic features occur throughout the site. Washes, in fact, are a subset of the alluvial basin topography.

The common features of these landforms are highly permeable soils and periods of saturated conditions at the soil surface. Playa sediments, although generally of low permeability, may contain deep desiccation fractures which allow for rapid infiltration of waters and are, therefore, included in this category. The following results support the conclusion that recharge may be significant in these areas.

1) Moisture content ranged from 20 to 40 percent by volume in areas receiving periodic inundation. Hydraulic gradients calculated from capillary pressure data showed a gravity-dominated drainage process was occurring in at least one subsidence crater.
2) Estimates of fluid flux at subsidence craters was limited by the lack of unsaturated hydraulic conductivity data; however, estimates indicated that as much as 13 percent of the average annual precipitation falling on the subsidence crater catchment was contributing to recharge.
3) Tritium profile data for playa sediments indicated moisture velocities as high as 20 cm/year. Using an estimated volumetric water content, the average soil water recharge may be as high as 20 percent of the annual precipitation.

UPLAND AREAS

At this time, the data base in the upland areas is very scarce and limited to Rainier Mesa. The area is characterized by high precipitation, much in the form of snow, flat lying topography, reduced potential evapotranspiration, and thin soils. These characteristics are typical of much of the northwestern portion of the NTS, including the Pahute Mesa area and comprise roughly 25 to 40 percent of the total upland areas of the NTS. The remaining 60 to 75 percent of the upland areas is characterized by lower precipitation, steep topography, and higher potential evaporation. It is anticipated that potential recharge over much of these areas is significantly reduced over the Rainier/Pahute Mesa area. Based upon the available data, the following conclusions may be made:

1) Tritium studies at Rainier Mesa indicate the active recharge may be occurring with water velocities in the fractured tuff exceeding 60 m/year. Contamination of the samples from nuclear testing leads to some questioning of these results, however.
2) Rainier Mesa tunnel discharge measurements appear to show some seasonal fluctuations, indicating possible rapid response of the perched system to precipitation. Simple mass balance calculations indicate that 1 to 3 percent of the average yearly precipitation on the mesa top may be contributing to recharge.
3) Data are not yet available to make estimates of recharge in upland areas other than Rainier Mesa, however, it is anticipated that as much as 10 percent of the average annual precipitation of areas such as Pahute Mesa becomes ground-water recharge.

SECTION V

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1804

GSAB Abstract WHITNEY 1986
p 787 V18, No6.

OUNDWATER HYDRAULICS OF SMALL CRITERIA FOR DETERMINING Y OF SEMI-INFINITE SOLUTION | Nº 107691

CRAFT, Stephen W., Desert Research Institute, University of System, P.O. Box 60220, Reno, Nv. 89506

are often the most important stresses in the groundwater sys- oceanic islands. Although in many cases it is important to take into account, many islands have hydrogeologic conditions that of horizontal flow assumptions. Analytical solutions to the flow aquifer tidal response can be used to evaluate hydraulic parame- aquifer and to assess the conceptual flow model envisioned for the island aquifer. For these islands, it is necessary to choose an analytic which is based on boundary conditions that are consistent with existing conditions (i.e., the conceptual flow model).

aquifers the tidal response decays exponentially inland from and the classical Ferris semi-infinite solution can be employed. For aquifers the tidal response comes from more than one side (the number depends on the island geometry). If the island is small enough, the tidal from two or more sides can meet in the middle and cause interference, the semi-infinite solution to be incorrect.

paper, a review of solutions for tidal responses on small islands is and the solutions are analyzed. Expressions are obtained from these which allow one to determine when an island is large enough to justify semi-infinite Ferris solution. Expressions are obtained for a number of geometries, but in general, they are a function of transmissivity, coefficient and a parameter related to the size of the island.

INCREASES IN THE $\delta^{34}S$ VALUES OF PYRITE, COAL BED, MARYLAND | Nº 103530

J. F., U.S. Geological Survey, MS 963, Denver, CO 80225; LYONS, T. C., U.S. Geological Survey National Center, MS 956, Reston, VA 22092

Bakerstown coal bed (Conemaugh Gp., Maryland) has total sulfur that range from 1.4 to 6.0 wt%, dominantly as pyritic sulfur. thick column sample of this coal contains ~3.3 wt% pyrite, pri- concentrated in the upper 30 cm. Early diagenetic pyrite in the occurs in a coal ball and as random scattered grains and thin dis- bands. The coal ball occurs at ~30 cm and constitutes ~75% total pyrite; it consists mainly of cell fillings of medullosan petioles genus Myeloxylon. Late diagenetic pyrite in the consists of a single tiny cleat just below the coal ball.

$\delta^{34}S$ values of early pyrite taken from eight depth intervals range from -3.1 to 23.7, generally increasing with depth. of the coal-ball pyrite have $\delta^{34}S$ values ranging only from 1.6. The cleat pyrite has a $\delta^{34}S$ value of 37.5. The increase of depth in the column sample is most likely the result of early bacterial reduction of aqueous sulfate introduced into the lignite from an overlying source. Within 10 km of our sample, bed is roofed by marine-fossil-bearing rocks, so seawater was sulfate source. Sulfate-reducing bacteria preferentially meta- thereby increasing the $\delta^{34}S$ of the remaining sulfate. reduction of sulfate percolating or diffusing into the peat is the probable cause of the top-to-bottom increase in sul- values. The distinctly high $\delta^{34}S$ of the cleat pyrite may re- reduction of the ^{34}S-enriched remnants of the early dia- sulfate, or later introduction of ^{34}S-enriched sulfate from an source, such as connate or formation waters.

OF THE VANDFALDSDALEN MACRODIKE, A GIANT GABBROIC DIKE ADJACENT TO THE SKAERGAARD, E. GREENLAND | Nº 95745

Craig M., Dept. of Geology and Geophysics, Boise St. Univ., Boise, ID 83725; GEIST, Dennis J., Dept. of Geology and Geo- physics, Univ. of Wyoming, Laramie, WY 82071.

aldsdalen macrodike is a funnel-shaped, layered and differen- roic dike approximately 3.5 km long and 200-400 m wide. It posed vertical section more than 500 m thick. The composition illed margin indicates the initial magma was a tholeiitic ilar the inferred initial Skaergaard magma.

acrodike can be divided into three structural divisions: a series adjacent to the walls; a central series in the inter- a felsic series at the top. The marginal series is 50-90 m contains gabbros that are modally layered parallel to the the dike. Differentiation is reflected in the compositions of solution minerals which vary serially to lower-temperature inward from the contacts with the country rock. Sample across the marginal series show plagioclase varies from An69 high-Ca pyroxene varies from En/En+Fs=80 to En/En+Fs=64.

A central series formed in the interior of the macrodike at higher stratigraphic levels, where the width of the dike is equal to or greater than its vertical thickness. Layering in the central series is synformal with dips ranging from 30° inward from the margins to hori- zontal along the axis. Mineral compositions vary upward through the central series in a manner analogous to the inward variation observed in the marginal series.

The felsic series occupies a zone up to 130 m thick above the gabbro of the central series and beneath the basaltic roof. It con- sists mainly of granophyric rocks with abundant inclusions of quartz- ite and quartz-feldspar hornfels. Petrographic, geochemical and isotopic data indicate the felsic series contains a large proportion of partially melted silicic crustal rocks.

TUFF RINGS AND MAARS OF THE HOPI BUTTES, NE ARIZONA | Nº 103583

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The Hopi Buttes volcanic field of northeastern AZ comprises Pliocene and alkalic basalts erupted into lacustrine and sandflat-playa environments represented by the lower Bidahochi Fm. Most surficial volcanic deposits are tuff rings (low height/rim width ratios, low-angle dips), which are best preserved where capped by later extrusive basalts. Vent-filling tuffs extend downward into fault-bound contact with underlying Mesozoic sedimentary rocks, some of which are aquifers. Rocks of the upper Bidahochi Fm. begin with reworked rhyolitic tuffs deposited from shallow, ephemeral streams. Tuff ring deposits are overlain by lava or lower Bidahochi sediment; intrabasinal volcanism was not directly re- sponsible for the transition from lacustrine to fluvial sedimentation.

Tuff ring deposits show abundant evidence of base-surge deposition, including sandwaves, planar to massive beds, and ballistic ejecta. Expanded, relatively dry surges may have developed despite the presence of surface water if initial contact with water and subsequent fragmentation began at depth (upon contact with aquifer). Superheated ("dry") steam could result from extended magma/water contact during vent transit, as well as from variations in initial magma/water ratios.

Many vents contain cinder and spatter deposits, suggesting cyclic phreatomagmatic/Strombolian eruption. Basalt dikes, sills and spatter are locally peperitic, indicating mixing of magma and wet sediment. Intra-vent lacustrine deposits are common among vents lacking basaltic caps. Different levels of exposure allow examination of both extra-vent ejecta and vent-filling sequences. Sandwaves and planar bedding are best developed beyond vent margins. Proximal tuff ring material makes up much of the subsided vent infilling at levels less than 100m below eruption surface. U-shaped channels carved and filled by surges are present in proximal tuffs. Deeper in the vents, blocks of country rock quarried from vent margins form one or more bouldery breccia layers interlayered with weakly bedded tuff breccia rich in juvenile material.

1804

RECURRENT QUATERNARY MOVEMENT ON THE WINDY WASH FAULT, NYE COUNTY, NEVADA | Nº 102850

WHITNEY, J. W., Shroba, R. R., SIMONDS, F. W., and HARDING, S. T., U.S. Geological Survey, MS 913 Box 25046, Denver Federal Center, Denver, CO 80225

The Windy Wash fault is a major north-trending fault on the west side of Yucca Mountain, about 5 km west of a proposed high-level nuclear waste repository site in southern Nevada. Detailed investigation of three trenches across the fault reveals several buried shear zones, offset stratigraphic units, and soil horizons that indicate a minimum of seven episodes of Quaternary movement along the Windy Wash fault. Trench CF-2 exposes evidence of at least three fault episodes that predate the emplacement of a basaltic ash along two fault planes during or shortly after a fourth fault episode. Fault episodes five, six, and seven are recorded in trenches CF-2.5 and CF-3; both trenches expose offset alluvial and eolian deposits younger than the basaltic ash in trench CF-2.

The basaltic ash is chemically similar to two nearby basalt cones that are K-Ar dated at 0.3 and 1.1 m.y. The ash is correlated with the younger cone because the uncemented ash occurs in open fractures in CF-2 that breach all stratigraphic units except the uppermost deposit, a Holocene silt. Uranium-trend ages of alluvial deposits in CF-3 indicate that the fifth faulting episode took place between 270 and 190 thousand years ago; the sixth episode between 190 and 40 thousand years ago; and the seventh and latest episode took place during the past 40 thousand years. The timing of the last episode is refined by thermoluminescence age determinations on the youngest faulted deposit (eolian silt); these age dates range from 6.5 to 3.0 thousand years ago, which indicates the last faulting episode probably took place during the last several thousand years. The fault has an average recurrence interval of 75 thousand years based on the occurrence of the last four episodes during the past 300 thousand years. Trenches CF-2.5 and CF-3 show an apparent vertical offset of about 40 cm on the 270 thousand-year-old gravel. This vertical component is considered to be a minimum indicator of net throw, because seismic reflection profiles across the fault reveal subsurface structures which suggest that the fault has a strike-slip component. Apparent vertical offset on the Holocene silt is less than 10 cm.