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Wilson, 1985

United States Department of the Interior

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IN REPLY REFER TO:

December 24, 1985

Dr. D. L. Vieth, Director
Waste Management Project Office
Nevada Operations Office
U.S. Department of Energy
P. O. Box 14100
Las Vegas, Nevada 89114

THROUGH: W. W. Dudley, Jr. W W Dudley Jr

Dear Dr. Vieth:

Attached as a part of this letter is a discussion of unsaturated-zone moisture flux at Yucca Mountain and vicinity. A rationale is presented for using 0.5 mm/yr as a reasonable and conservative value of flux beneath the repository horizon at the primary repository area. This value could appropriately be used in calculating pre-waste-emplacement ground-water travel times from the disturbed zone to the water table. This information was formally requested by Max Blanchard in a letter to Bill Dudley, September 18, 1985.

If you have any questions in this matter, please call me at FTS 776-5044.

Very truly yours,

William E. Wilson

William E. Wilson

Attachment

cc: M. Blanchard, DOE/WMPO
J. Younker, SAIC
M. Spaeth, SAIC
T. Hunter, SNL
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UNSATURATED-ZONE FLUX AT YUCCA MOUNTAIN, NEVADA

by

William E. Wilson[1]

December, 1985

Introduction

Calculations of pre-waste-emplacement ground-water travel time from the disturbed zone to the accessible environment at Yucca Mountain, Nevada, require estimates of water flux in both the unsaturated and saturated zones. In the unsaturated zone, the value needed is the flux between the disturbed zone and the water table beneath the primary repository area. The purpose of this document is to estimate and support a reasonable and conservative value of this flux.

The primary repository area at Yucca Mountain is that area beneath which a repository would be constructed. This area occupies only a part of the physiographic feature called Yucca Mountain. The northern half and southern tip of Yucca Mountain and the fault zone that bounds the area along the eastern side are not part of the primary repository area. The range of land-surface altitudes of Yucca Mountain is about 3,500-5,900 ft; the range for the primary repository area is about 4,000-5,000 ft. Much of Yucca Mountain forms a topographic divide between two hydrographic basins, Crater Flat and the western part of Jackass Flats (Rush, 1970, pl. 1).

In the following discussion, "flux" is defined as the volumetric rate of moisture flow across a unit cross-sectional area. "Net infiltration rate" is the flux of water that enters the soil or rock below the interface with the atmosphere and that does not remain in shallow storage nor is rapidly returned to the atmosphere via evapotranspiration or shallow lateral flow to washes. "Recharge rate" is the flux of water that enters the saturated zone from the unsaturated zone. "Discharge rate" is the flux of water in the saturated zone that leaves a ground-water basin as underflow, spring discharge, or evapotranspiration. At the primary repository area at Yucca Mountain, unsaturated-zone flux beneath the repository horizon (needed for travel-time calculations) is assumed in this analysis to be equal to recharge rate.

Estimates of unsaturated-zone flux beneath the repository horizon are based on two lines of evidence: 1) calculations of flux in the proposed host rock, based on field and laboratory evidence; and 2) an estimate of the recharge rate beneath the Yucca Mountain area, based on regional relationships developed among precipitation, altitude, and recharge rate. Field and laboratory evidence from the site provides the most direct basis for estimating flux below the repository horizon. The estimate of the regional recharge rate probably is conservatively large, on the basis of comparisons with estimates of recharge rates that have been made for arid and semi-arid sites from around the world.

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Flux in the Topopah Spring Welded Unit

Various estimates have been made of flux in the Topopah Spring welded unit, on the basis of field and laboratory data from investigations at Yucca Mountain. Because this unit is the proposed host rock, these results provide the most direct evidence of flux beneath the repository horizon.

Weeks and Wilson (1984) estimated a moisture flux of 0.003 to 0.2 mm/yr in the matrix of the Topopah Spring welded unit. The results were obtained from analyses of core from test hole USW H-1. A range of values of effective permeability and an assumed unit hydraulic gradient were applied to Darcy's equation. Effective permeabilities were estimated from mercury porosimetry data, and the in situ potential gradients were extrapolated from water-content measurements and moisture-characteristic curves of core samples. Weeks and Wilson (1984) concluded that the flux values are extremely approximate but probably bracket the actual matrix flux at Yucca Mountain.

Montazer and Wilson (1984) calculated flux in the matrix of the Topopah Spring welded unit, on the basis of preliminary analyses of 1) the in situ potential gradient measured in test hole USW UZ-1, and 2) effective permeabilities of core from an adjacent borehole (USW G-1). The results showed that downward flux ranges from 1×10^{-7} to 1×10^{-4} mm/yr. Montazer and Wilson (1984) concluded that the flux in the Topopah Spring welded unit is extremely small, probably 1×10^{-7} to 0.2 mm/yr but no greater than the saturated hydraulic conductivity of the matrix of the unit (1.0 mm/yr).

Montazer and others (1985) further evaluated data from borehole USW UZ-1. They observed a relatively constant matric potential in the depth interval 122-244 m, within the Topopah Spring welded unit. On the assumption that a constant matric potential with depth indicates that a unit hydraulic gradient exists (Weeks and Wilson, 1984), Montazer and others (1985) calculated a downward matrix flux of 0.1-0.5 mm/yr. A range of relative permeability of 0.1 to 0.5 (Peters and others, 1984) was applied to a saturated matrix hydraulic conductivity of 1.0 mm/yr (Montazer and Wilson, 1984) to obtain this range of flux values.

Upward (negative) water fluxes in the fractures of Topopah Spring welded unit have been estimated from geothermal data (Montazer and Wilson, 1984; Montazer and others, 1985). Montazer and Wilson (1984) applied geothermal-gradient data from Sass and Lachenbruch (1982) to the unsaturated zone and calculated a water flux of -1.5 mm/yr. From geothermal data in USW UZ-1, Montazer and Wilson (1984) estimated a flux of about -1 to -2 mm/yr in the Topopah Spring welded unit. Because of the preliminary nature of the data and complexities involved, both sets of estimates were considered preliminary by Montazer and Wilson (1984).

A more detailed analysis of geothermal data from USW UZ-1 was conducted by Montazer and others (1985). Long-term temperature measurements within this borehole indicated that the geothermal gradient was slightly convex upward within the Topopah Spring welded unit (Montazer and others, 1985). The quantity of water in vapor form that could be transported upward by the calculated air flux was estimated to be 0.025 to 0.05 mm/yr; probably this flux would occur through the fractures of the welded tuff.

In summary, various lines of field and laboratory evidence indicate that the downward moisture flux in the matrix of the Topopah Spring welded unit probably is less than 0.2 mm/yr. In addition, an upward component of flux probably occurs in the fractures of this unit.

Recharge Rate in the Yucca Mountain Area

On a regional scale, average annual recharge rate can be considered equivalent to flux in the lower part of the unsaturated zone. Thus, an estimate of recharge rate for the Yucca Mountain area provides another basis for evaluating flux needed for travel-time calculations at the primary repository area at Yucca Mountain. The regional value can appropriately be used only as a guide, however, because recharge rates at specific sites may differ considerably from regional rates.

Estimates of recharge rates for areas that include Yucca Mountain have been made using a technique developed by Maxey and Eakin (1949) and described further by Eakin and others (1951). The technique, referred to as the Maxey-Eakin method (Watson and others, 1976), provides a basis for estimating average annual recharge rates in basins in Nevada. The method applies relationships that were developed among altitude, precipitation, and percentage of precipitation that infiltrates to become recharge. These relationships were developed by equating recharge rates to discharge rates in 13 basins in east-central Nevada where the discharge rates could be measured or estimated with reasonable confidence (Eakin and others, 1951). The relationships that were developed for the Maxey-Eakin method and that were later applied to the Yucca Mountain area are shown in table 1. In the actual calculations using the Maxey-Eakin method, the recharge rate that results from average precipitation that is less than 152 mm/yr is considered to be zero.

Table 1.--Relationships among altitude, precipitation, and percent of precipitation that becomes recharge

Altitude (thousands of ft)	Precipitation (mm/yr)		Percent of precipitation that becomes recharge
	Range	Average	
6-7	305-381	335	7
5-6	203-305	244	3
<5	<203	152	Minor

Using the Maxey-Eakin method, Rush (1970) estimated an average annual recharge rate of 1.0 mm/yr for western Jackass Flats and Crater Flat, two hydrographic basins that have Yucca Mountain as a mutual boundary. Czarnecki (1985) applied Rush's (1970) results to a smaller area (herein called the Yucca Mountain area) that included all of Yucca Mountain but that excluded those parts of the two basins north of Yucca Mountain where altitudes are greater than 6,000 ft. For the Yucca Mountain area, Czarnecki (1985) calculated a recharge rate of 0.7 mm/yr; he adjusted this value to 0.5 mm/yr.

Although the Maxey-Eakin method has been widely used to estimate recharge rates in basins in Nevada and Utah, the technique provides only an approximation of recharge rate. Czarnecki (1985) described some of the limitations: the method ignores local variations in topographic slope and aspect, only indirectly includes rock lithology and vegetative type and density, and treats drainage channels the same as other areas. The method assumes that general hydrologic equilibrium exists for the flow system, a condition that may not prevail where thick unsaturated zones and long flow paths may result in substantial lag times between net infiltration, recharge, and discharge. Furthermore, the relationship between precipitation and altitude developed for applying the technique was based on a very generalized precipitation map of Nevada (Hardman, 1936). Despite these many limitations, Watson and others (1976), in an evaluation of the Maxey-Eakin method, concluded that it is the only practical method available for estimating recharge rates in Nevada.

Average annual precipitation at the various altitude zones in the Yucca Mountain area probably is less than would be estimated from the Maxey-Eakin method (table 1). This difference is indicated by precipitation maps that have been developed for the Nevada Test Site and vicinity (Winograd and Thordarson, 1975, fig. 3; Quiring, 1983, fig. 1). These maps are based on longer records and more data points than were available to Hardman (1936) and, therefore, they probably are more accurate.

Czarnecki (1985) used the map of Winograd and Thordarson (1975) to estimate a precipitation range of about 3-6 in/yr (or about 75-150 mm/yr) for the Yucca Mountain area, where altitudes range from about 3,000-6,000 ft. From Quiring's (1983) map, a precipitation-to-altitude ratio at Yucca Mountain was interpolated to be about 1.36 in/thousand ft. This ratio gives a precipitation range of about 140-175 mm/yr for Yucca Mountain, where altitudes are about 4,000-6,000 ft. These precipitation values are generally less than those for corresponding altitudes shown for the Maxey-Eakin method in table 1.

Rush (1970) and Czarnecki (1985) both used in their analyses the precipitation-altitude relationships defined by the Maxey-Eakin method. Because actual precipitation in the Yucca Mountain area probably is less than the values used in the application of the Maxey-Eakin method, actual recharge rates probably are less than the calculated values. Thus, Czarnecki (1985) probably was justified in revising downward his calculated value of 0.7 mm/yr to an estimated value of 0.5 mm/yr for recharge rate in the Yucca Mountain area.

Another regional estimate of recharge rate was made by Winograd and Thordarson (1975); they estimated that about 3 percent of the precipitation falling on upland carbonate outcrop areas at the Nevada Test Site and vicinity becomes recharge to the regional carbonate aquifer. Montazer and Wilson (1984) applied this percentage to an estimated average annual precipitation of 150 mm/yr at Yucca Mountain to calculate an upper bound of 4.5 mm/yr for the recharge rate at the mountain. This value is very approximate, because of the uncertainties associated with applying regional results to specific sites. Based on Maxey-Eakin considerations, the value of 3 percent probably is too large to apply to Yucca Mountain, because precipitation for most of the mountain probably is considerably less than 203-305 mm/yr, the precipitation range for which 3 percent applies (table 1).

On the basis of the preceding analyses, an estimate of 0.5 mm/yr probably is reasonable for the recharge rate in the Yucca Mountain area, as determined by using the Maxey-Eakin method. The value probably is also conservatively large, on the basis of a comparison with recharge rates estimated by various investigators for arid and semi-arid regions throughout the world.

Average annual precipitation and recharge rates expressed as a percentage of precipitation are shown in figure 1 for 14 world-wide study areas, for the Yucca Mountain area, and for the various precipitation zones that are considered when applying the Maxey-Eakin method to estimate recharge rates. The value for the Yucca Mountain area was calculated to be 0.3 percent of precipitation, on the basis of an average annual precipitation of 150 mm/yr and an estimated recharge rate of 0.5 mm/yr. Data and references for the 14 study areas are shown in table 2. Results from all 14 study areas that were reviewed are presented, despite significant experimental or conceptual differences in study methods, and despite significant environmental differences among the sites.

Environmental differences reflected in these measurements, in addition to annual precipitation, include seasonal rainfall distribution, magnitude and seasonal distribution of potential evapotranspiration, type and extent of vegetative cover, depth to ground water, and soil characteristics. For example, the large recharge rates from studies at Hanford (points 9 and 10) are largely due to a greater-than-average precipitation during the test period, the presence of coarse-textured soils, the absence of vegetation or the occurrence of only sparse shallow-rooted grass, and also to possible experimental and conceptual modeling errors. The large recharge value from the Sahara (point 7) may be due in part to the large percent of coarse-textured soils and to the fact that reported recharge apparently is infiltration to a depth of 5 m rather than actual recharge. Points 8a and 8b are based solely on hydrologic budget models with virtually no experimental data. A wide variety of soil factors was sampled at sites represented by points 5a and 5b, ranging from vegetated dunes (small value) to a sinkhole (large value) in a recent collapse feature related to solution of underlying fractured limestone.

In figure 1, many points are to the right of the trendline established by the points for the Maxey-Eakin method and the Yucca Mountain area. Especially significant are the five points representing measurements of recharge rates that are less than 0.5 percent of precipitation. Each of these points is from an area receiving precipitation greater than that at Yucca Mountain, and, disregarding experimental errors, they appear to support the value of 0.3 percent of average annual precipitation (or 0.5 mm/yr) for recharge at the Yucca Mountain area as a conservative estimate.

Table 2--Worldwide recharge estimates

Site No.	Location	Annual precipitation (mm/yr)	Recharge rate (mm/yr)	Recharge as percent of precipitation (%)	Reference
1	Cyprus	420	50	12	Kitching and others, 1980
2	New Mexico	200	0.02[1]	0.01	Phillips and others, 1984
3	Botswana	250 to 550	<0.5	0.12	DeVries, 1984
4a 4b	North Dakota	440	10 33	2.3 7.5	Rehm and others, 1982
5a 5b	Australia	300	0.06 100	0.02 33	Allison and others, 1985
6a 6b	Australia	335	0.07 4	0.02 1.2	Allison and Hughes, 1983
7	Saudi Arabia	82	20	24	Dincer and others, 1974
8a 8b	Saudi Arabia	165 155	15 3	9.1 1.9	Caro and Eagleson, 1981
9	Washington	160[2]	50	31	Kirkham and Gee, 1983
10a 10b	Washington	160	11 56	6.9 35	Gee and Heller, 1985
11	Arizona	229 to 330	2.5	0.9	Huntoon, 1977
12	Arizona	234	0	0	Sammis and Lloyd, 1979
13a 13b	Australia	800	4.6 86	0.6 11	Sharma and others, 1983
14[3]	Australia	1100	550	50	Viswanathan, 1984

[1]Infiltration to 5 m depth
[2]240 mm during year of test
[3]Not shown in figure 1

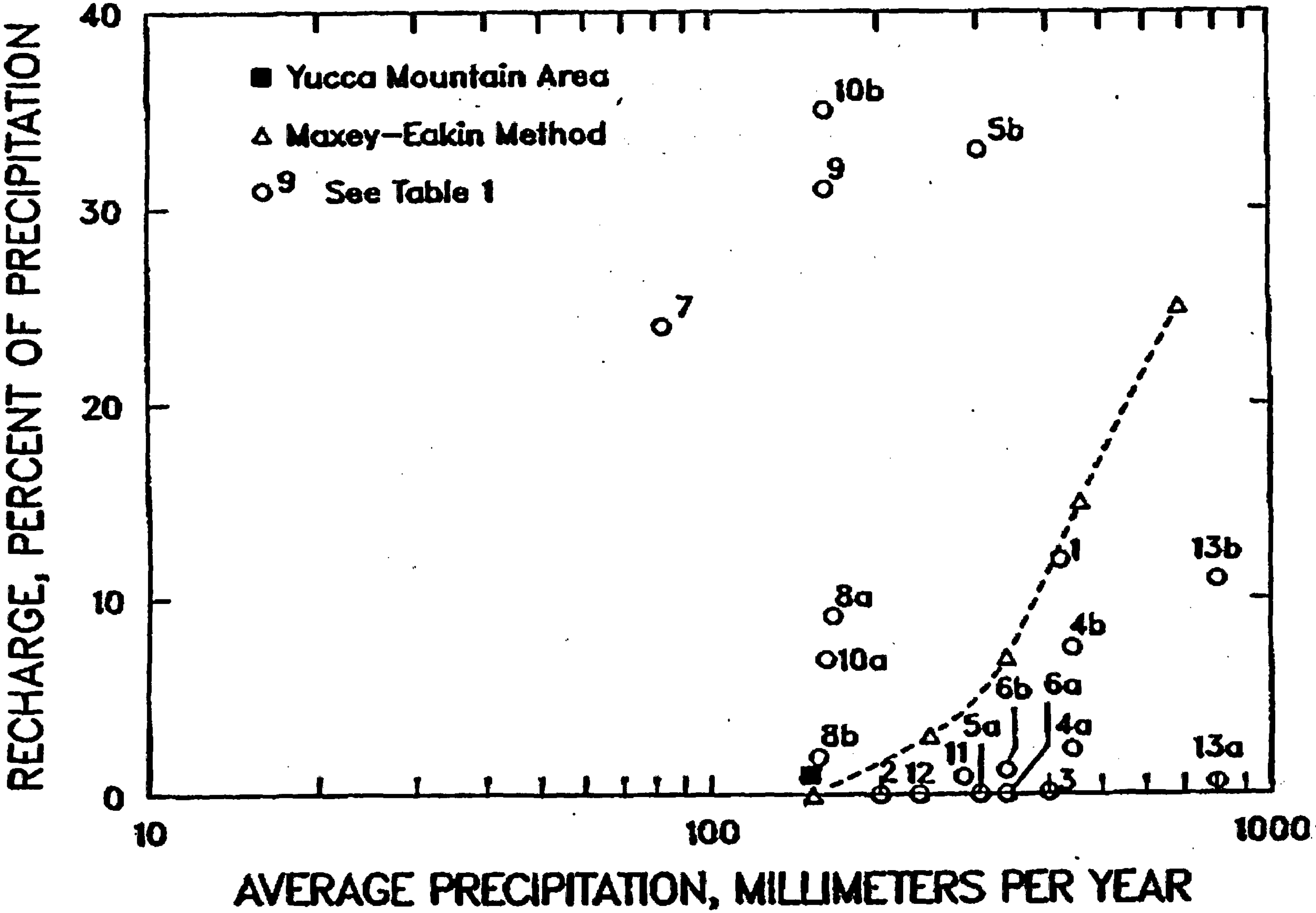

Figure 1.—Relationship between recharge and average precipitation

Conclusions

A value of 0.5 mm/yr probably is a reasonable and conservative value for flux below the repository horizon at the primary repository area of Yucca Mountain. Calculations from field evidence at Yucca Mountain provide the most direct basis for this conclusion; estimates of downward flux in the matrix of the host rock range from 1 x 10^{-7} to 0.2 mm/yr, and geothermal evidence indicates that little or no downward flux probably occurs in the fractures of this unit.

Estimates of the regional recharge rate for the Yucca Mountain area provide supporting evidence for the flux rate below the repository horizon at Yucca Mountain. From the Maxey-Eakin method of estimating recharge rates in Nevada basins, a conservative recharge rate of 0.5 mm/yr was estimated for the Yucca Mountain area. The conservative aspect of this value was determined from a comparison with recharge rates estimated by various methods for 14 arid and semi-arid sites from around the world. Thus, 0.5 mm/yr is a reasonable and conservative flux to use for unsaturated-zone travel-time calculations.

References

Allison, G. B., and Hughes, M. W., 1983, The use of natural tracers as indicators of soil-water movement in a temperate semi-arid region: Journal of Hydrology, v. 60, p. 156-173.

Allison, G. B., Stone, W. J., and Hughes, M. W., 1985, Recharge in karst and dune elements of a semi-arid landscape as indicated by natural isotopes and chloride: Journal of Hydrology, v. 76, p. 1-25.

Caro, Rodrigo, and Eagleson, P. S., 1981, Estimating aquifer recharge due to rainfall: Journal of Hydrology, v. 53, p. 185-211.

Czarnecki, J. B., 1985, Simulated effects of increased recharge on the ground-water flow system of Yucca Mountain and vicinity, Nevada-California: U.S. Geological Survey Water-Resources Investigations Report 83-4344, 33 p.

DeVries, J. J., 1984, Holocene depletion and active recharge of the Kalahari groundwaters--A review and an indicative model: Journal of Hydrology, v. 70, p. 221-232.

Dincer, Turgut, Al-Mugrin, A., and Zimmermann, U., 1974, Study of the infiltration and recharge through the sand dunes in arid zones with special reference to the stable isotopes and thermonuclear tritium: Journal of Hydrology, v. 23, p. 79-109.

Eakin, T. E., Maxey, G. B., Robinson, T. W., Fredericks, J. C., and Loeltz, O. J., 1951, Contributions to the hydrology of eastern Nevada: Nevada Department of Conservation and Natural Resources Water Resources Bulletin 12, 171 p.

Hardman, George, 1936, Nevada precipitation and acreages of land by rainfall zones: Nevada Experiment Station, Reno, Nevada, Mimeographed Paper, 10 p.

Gee, G. W., and Heller, P. R., 1985, Unsaturated water flow at the Hanford Site--A review of literature and annotated bibliography: Richland, Washington, Pacific Northwest Laboratory PNL-5428, UC-70, 42 p.

Huntoon, P. W., 1977, Cambrian stratigraphic nomenclature and ground-water prospecting failures on the Hualapai Plateau, Arizona: Ground Water, v. 15, no. 6, p. 426-433.

Kirkham, R. R., and Gee, G. W., 1983, Measurement of unsaturated flow below the root zone at an arid site, in Nielson, D. M., and Curl, Mary, eds., Proceedings of the NWWA/U.S. EPA Conference on Characterization and monitoring of the vadose (unsaturated) zone, Las Vegas, Nevada, December 8-10, 1983: National Water Well Association, p. 917-935.

Kitching, R., Edmunds, W. M., Shearer, T. R., Walton, N. R. G., and Jacovides, J., 1980, Assessment of recharge to aquifers: Hydrologic Sciences Bulletin, v. 25, no. 3, p. 217-244.

Maxey, G. B., and Eakin, T. E., 1949, Ground water in White River Valley, White Pine, Nye, and Lincoln Counties, Nevada: Nevada Department of Conservation and Natural Resources Water Resources Bulletin 8, 59 p.

Montazer, Parviz, and Wilson, W. E., 1984, Conceptual model of flow in the unsaturated zone, Yucca Mountain, Nevada: U.S. Geological Survey Water-Resources Investigations Report 84-4345, 55 p.

Montazer, Parviz, Weeks, E. P., Thamir, Falah, Yard, S. N., and Hofrichter, P. B., 1985, Monitoring the vadose zone in fractured tuff, Yucca Mountain, Nevada: in Proceedings, National Water Well Association Conference on Characterization and Monitoring of the Vadose (Unsaturated) Zone, Denver, Colorado, November 19-21, 1985 (in press).

Peters, R. R., Klavetter, E. A., Hall, J. J., Blair, S. C., Heller, P. R., and Gee, G. W., 1984, Fracture and matrix hydrologic characteristics of tuffaceous materials from Yucca Mountain, Nye County, Nevada: Sandia Report SAND 84-1471, 63 p.

Phillips, F. M., Trotman, K. N., Bentley, H. W., and Davis, S. N., 1984, The Bomb-36Cl pulse as a tracer for soil-water movement near Socorro, New Mexico, in Stone, W. J., compiler, Selected papers on water quality and pollution in New Mexico: New Mexico Bureau of Mines and Mineral Resources Hydrologic Report 7, p. 271-280.

Rehm, B. W., Moran, S. R., and Groenewold, G. H., 1982, Natural groundwater recharge in an upland area of central North Dakota, U.S.A.: Journal of Hydrology, v. 59, p. 293-314.

Rush, F. E., 1970, Regional ground-water systems in the Nevada Test Site area, Nye, Lincoln, and Clark Counties, Nevada: Nevada Department of Conservation and Natural Resources, Water Resources-Reconnaissance Series Report 54, 25 p.

Sammis, T. W., and Gay, L. W., 1979, Evapotranspiration from an arid zone plant community: Journal of Arid Environments, v. 2, p. 313-321.

Sass, J. H., and Lachenbruch, A. H., 1982, Preliminary interpretation of thermal data from the Nevada Test Site: U.S. Geological Survey Open-File Report 82-973, 30 p.

Sharma, M. L., Farrington, P., and Fernie, M., 1983, Localized ground-water recharge on the "Gnangara Mound", western Australia, in Papers of the International Conference on Groundwater and Man, Volume 1, The investigation and assessment of groundwater resources, Sydney, December 5-9, 1983: Department of Resources and Energy, Australian Water Resources Council, Conference Series 8, p. 293-302.

Watson, P., Sinclair, P., and Waggoner, R., 1976, Quantitative evaluation of a method for estimating recharge to the desert basins of Nevada: Journal of Hydrology, v. 31, p. 335-357.

Weeks, E. P., and Wilson, W. E., 1984, Preliminary evaluation of hydrologic properties of cores of unsaturated tuff, test well USW H-1, Yucca Mountain, Nevada: U.S. Geological Survey Water-Resources Investigations Report 84-4193, 30 p.

Winograd, I. J., and Thordarson, William, 1975, Hydrogeologic and hydrochemical framework, south-central Great Basin, Nevada-California, with special reference to the Nevada Test Site: U.S. Geological Survey Professional Paper 712-C, 126 p.