Geohydrology of the Unsaturated Zone at the Burial Site for Low-Level Radioactive Waste Near Beatty, Nye County, Nevada

United States Geological Survey Water-Supply Paper 2312

Geohydrology of the Unsaturated Zone at the Burial Site for Low-Level Radioactive Waste Near Beatty, Nye County, Nevada

By WILLIAM D. NICHOLS

U.S. GEOLOGICAL SURVEY WATER-SUPPLY PAPER 2312

DEPARTMENT OF THE INTERIOR
DONALD PAUL HODEL, Secretary

U.S. GEOLOGICAL SURVEY
Dallas L. Peck, Director

UNITED STATES GOVERNMENT PRINTING OFFICE: 1987

For sale by the Books and Open-File Reports Section, U.S. Geological Survey,
Federal Center, Box 25425, Denver, CO 80225

Library of Congress Cataloging in Publication Data

Nichols, William D.
Geohydrology of the unsaturated zone at the burial site for
low-level radioactive waste near Beatty, Nye County,
Nevada.

(U.S. Geological Survey water-supply paper ; 2312)
Bibliography: p.
Supt. of Docs. no.: I 19.13:2312
1. Geology—Nevada—Nye County. 2. Hydrology—
Nevada—Nye County. 3. Zone of aeration—Nevada—
Nye County. 4. Hazardous waste sites—Nevada—Nye
County—Zone of aeration. 5. Radioactive waste
disposal in the ground—Nevada—Nye County.
I. Title. II. Series.
QE138.N9N53 1987 557.93'34 86-600331

CONTENTS

PLATE

FIGURES

TABLES

Geohydrology of the Unsaturated Zone at the Burial Site for Low-Level Radioactive Waste Near Beatty, Nye County, Nevada

By William D. Nichols

Abstract

Low-level radioactive solid waste has been buried in trenches at a site near Beatty, Nev., since 1962. In 1976, as part of a national program, the U.S. Geological Survey began a study of the geohydrology of the waste-burial site to provide a basis for estimating the potential for radionuclide migration in the unsaturated zone beneath the waste-burial trenches. Data collected include meteorological information for calibration of a long-term water-budget analysis, soil-moisture profiles, soil-water potentials, and hydraulic properties of representative unsaturated sediment samples to a depth of about 10 meters (m).

The waste-burial facility is in the northern Amargosa Desert about 170 kilometers (km) northwest of Las Vegas, Nev. The region is arid; mean annual precipitation at Lathrop Wells, 30 km south of the site, is only 7.4 centimeters (cm). The mean daily maximum temperature at Lathrop Wells in July, the hottest month, is 37 °C. The site is underlain by poorly stratified deposits of gravelly or silty sand and sandy gravel, and thick beds of clayey sediments. The total thickness of valley-fill deposits beneath the site is about 175 m; the unsaturated zone is about 85 m thick. Volumetric soil moisture to depths of 4 m ranges from 4 to 10 percent but commonly is in the range of 6 to 8 percent. Soil-water potential, measured to depths of 3 to 10 m, ranged from −10 to −70 bars. Unsaturated hydraulic conductivity computed from laboratory analyses of representative samples ranges from 10^{-13} to 10^{-4} centimeters per day (cm/d).

Evaporation studies over a 2-year (yr) period were used to calibrate a numerical procedure for analyzing long-term precipitation data and estimating annual water budgets during the 15-yr period 1962–76. This analysis (1) demonstrated that a potential exists for deep percolation (greater than 2 m), despite high annual evaporation demands, and (2) provided predictions of the time of year and the antecedent conditions that enhance the probability of deep percolation. Soil-moisture profiles obtained monthly over an 18-month (mo) period demonstrate that deep percolation does occur. Soil-moisture conditions antecedent to an observed deep-percolation event, and the time of year when the percolation occurred, support the interpretations based on long-term meteorological records.

Calculation of downward moisture movement through the waste-trench backfill material, on the basis of simplified assumptions, suggests that moisture could have penetrated as much as 6 m below land surface from 1963, when the oldest trenches were closed, to 1980, but that the moisture requirement for such penetration far exceeded the amount of moisture actually available. Steady-state downward movement of moisture at depths greater than 10 m and beneath the waste-burial trenches would be on the order of 4 cm per 1,000 yr, assuming a steady flux rate of 1×10^{-5} cm/d.

INTRODUCTION

The disposal of radioactive waste has been a problem for more than 30 years (yr). Disposal methods until 1962 included both land burial at federally operated facilities and sea disposal by several privately owned companies. Opposition to sea disposal led the Atomic Energy Commission in the late 1950's to designate several land-disposal sites for burial of low-level radioactive solid waste[1] generated by private industry. The first of these commercially operated burial grounds opened near Beatty, Nev., in 1962, and by 1971 a total of six sites (four east of the Mississippi River and two in the west) had been licensed.

Earth containment (burial) has been and still is considered the most viable method for disposing of radioactive solid waste. In general, however, the acceptability of any disposal method depends on its effectiveness in preventing radioactivity from becoming a public hazard. The effectiveness of burial as a disposal method thus depends on the chemical and physical form of the waste, the waste

[1] The term "low-level radioactive waste" has carried a changing and imprecise definition over the years. Currently, it generally means waste that does not fit the definition of high-level waste and in which the concentration of transuric elements is less than 10 nanoCurie per gram. It consists, in part, of miscellaneous solid materials that have been irradiated and contaminated through use as well as products of reactors and fuel reprocessing plants.

containers, the engineered containment mechanisms, the character of surrounding earth materials, and the hydrologic and geologic environment. Although burial removes the radioactive waste from the surface environment, it subjects the waste to possible influences of water infiltration and movement, erosion, plant uptake, animal penetration, and human activity. Probably the greatest threat to burial-ground integrity is water infiltration and movement, because radionuclides can migrate from the burial location either by dissolution in soil water or ground water, or through exposure by erosion and dissolution in surface water.

On the basis of the recognized threat posed to buried radioactive waste by water infiltration and movement, it has been suggested that certain areas of the arid west could provide locations where little or no water would move into or out of buried waste and, thus, maximum reliance could be placed on the natural system to provide containment (National Research Council, 1976, p. 67). It also has been suggested that more latitude in waste form might be possible and that reliance on engineered containment could be minimal at these locations (Battelle Memorial Institute, 1976, p. 24.48). Although these may be valid assumptions, insufficient data were available to reasonably demonstrate the effectiveness of geologic and hydrologic conditions in the arid zone to isolate buried radionuclides from the environment for the long period of time required for some of them to decay to innocuous levels.

Purpose and Scope

The U.S. Geological Survey in 1975 began a new national program in the area of low-level-radioactive-waste disposal. The general purpose of the program, designed to be a 5-yr endeavor, was to develop geohydrologic guidelines that can be used to establish technical criteria for selecting, evaluating, licensing, and operating new waste-burial sites. The commercial burial facility for low-level radioactive solid waste operated by U.S. Ecology, Inc. (formerly Nuclear Engineering Company), near Beatty, Nev., was one of five sites to be studied. The study at this site began in October 1976. The specific purpose of the investigation at this waste-burial facility was to determine, for current climatic conditions, the potential for downward movement of soil water in the unsaturated zone, thus providing a means for estimating the potential for and rate of downward transport of radioactive solutes or leachates. Additionally, actual movement of radionuclides was to be determined, if possible, by obtaining sediment samples from the zone directly beneath the waste-burial trenches into which contaminants might have migrated.

The investigation included the following activities:

1. Collection of meteorological data for site-specific evaporation studies, to be used in turn to estimate long-term relations between precipitation, evaporation, and deep percolation on the basis of National Weather Service data;
2. Monitoring of soil-moisture profiles for evidence of deep percolation;
3. Monitoring of soil-water potential to determine the magnitude of this potential at depth and the depth at which transient soil-water changes are dampened out;
4. Determination of unsaturated hydraulic conductivity of representative soil samples in the laboratory; and
5. Estimation of the rate and magnitude of deep soil-water percolation.

Detailed plans were also developed to obtain sediment samples from beneath waste-burial trenches for laboratory determination of radionuclide content and calculation of migration rates after the waste-burial trenches were closed. These plans were suspended indefinitely after analysis of the data contained in this report indicated that in the past 17 yr, infiltrating precipitation has not percolated to the reported depth of the older waste-burial trenches.

Location

The waste-burial facility is on the Amargosa Desert 17 kilometers (km) southeast of Beatty and 169 km northwest of Las Vegas in Nye County, Nev. (fig. 1). It lies about 32 km east of Death Valley, Calif., in the northern half of section 35, T. 13 S., R. 47 E., Mount Diablo baseline and meridian. The eastern border of the radioactive-waste burial area is about 900 meters (m) west of U.S. Highway 95.

Geographic Setting

The Amargosa Desert in the area of the waste-burial site is a northwest-trending valley about 13 km wide (figs. 1, 2; pl. 1). It is bounded on the northeast by Bare Mountain and on the southwest by the Grapevine Mountains and the Funeral Mountains. The head of the valley, about 19 km northwest of the waste-burial site, is formed by the Bullfrog Hills. The desert extends from the Bullfrog Hills about 80 km southeast to the Spring Mountains and about 80 to 90 km south-southeast to the Greenwater and Resting Spring Ranges. The altitude of the valley floor decreases from about 1,100 m above sea level in the northwest to nearly 600 m at the southeastern end near Death Valley Junction. The waste-burial facility is 847 m above sea level.

The floor of the northern Amargosa Desert is a sparsely vegetated, seemingly flat surface. Actually, it is moderately dissected by abandoned or little used shallow dry washes, all draining to the southeast. These washes have led to the development of an irregular and gently undulating surface that is not obvious when viewed from ground level. The apparent flatness of the desert floor is caused by the general accordance of the tops of low ridges separating the shallow dry washes.

Immediately southeast of the waste-burial site, and west of U.S. Highway 95, is a low southeast-trending ridge that extends for a distance of about 3 km (fig. 2). The northeast-facing slope of the ridge is steeper and more deeply dissected by washes and rills than the southwest-facing slope, which gradually descends westward to the general level of the desert floor within a distance of about 0.8 km from the ridge crest. Part of the northeast-facing slope has been destroyed or modified by construction of U.S. Highway 95 and by a secondary drainage system of unknown age that may have developed in historical times because of the presence of either the highway or the railroad that occupied the same position before the highway was constructed. Erosional remnants northeast of both the highway and the secondary drainage channels indicate that the northeast-facing slope descended to the level of the alluvial fans bounding Bare Mountain over a distance of about 0.4 km from the present ridge crest (figs. 2, 3). Detailed examination of this anomalous feature strongly suggests that it is an erosional remnant of an older depositional surface that is being supported by a locally developed caliche layer about 1 m below the surface of the ridge crest.

Previous Work and Acknowledgments

The only previous report dealing specifically with the waste-burial site is a report prepared by the U.S. Geological Survey (Clebsch, 1962) at the request of the Atomic Energy Commission at the time the facility was being established. Geologic investigations of a general nature in the northern Amargosa Desert include studies by Cornwall and Kleinhampl (1961, 1964), Cornwall (1972), and Byers and others (1976a, 1976b). A study of the hydrogeologic framework of the south-central Great Basin by Winograd and Thordarson (1975) marginally includes the area of the waste-burial facility. Walker and Eakin (1963) discuss the geology and ground water of the Amargosa Desert, but most of the data are for the southern part of the desert.

The author received the cooperation and assistance of many people and organizations during the course of the study. The cooperation of the Bureau of Consumer Health Protection Services, Nevada State Health Division, whose inspectors control activities at the waste-burial facility, was appreciated. The cooperation of U.S. Ecology, Inc., operators of the facility, is gratefully acknowledged. The author wishes to specifically thank William Jones and Steven Carpenter, site managers, and the other members of the work crew at the waste-burial site for their assistance and cooperation during the study.

Many other individuals helped at various stages of the investigation, and without their assistance the project would not have been completed. Mr. and Mrs. John Lisle and Patricia Thayer, of Beatty, served as observers for the meteorological instrument station at the study site and diligently serviced the equipment every other day. Donald H. Schaefer, U.S. Geological Survey, supervised installation of the instrument shaft and neutron probe access tubes. Other U.S. Geological Survey personnel, including Douglas K. Maurer, R. Nyle Pennington, Susan J. Mathews, and David B. Wood, provided field assistance during the course of the study; Robin G. Brown assisted full time during the last 15 mo of the study and largely managed and controlled the acquisition, processing, correction, and publication of the meteorological and related data collected for the investigation; Alex M. Sturrock, Jr., provided invaluable assistance and guidance on the collection and interpretation of meteorological data for evaporation calculations; both he and Henry M. Moore also provided equipment and field repair expertise when required; John B. Robertson provided timely and much needed support during the latter stages of the study; technical assistance on unsaturated zone hydrology was provided by E.P. Weeks, C.D. Ripple, Jacob Rubin, and E.G. Lappala; and, finally, Emily L. Mathews, student aide, digitized about 21 mo of multichannel daily meteorological data on analog charts comprising more than 17,000 data values per day; her persistence and perseverance are gratefully acknowledged.

GEOLOGIC SETTING

Consolidated Rocks

The Amargosa Desert is bounded, in large part, by mountain ranges composed of lower Paleozoic carbonate and clastic sedimentary and metasedimentary rocks (pl. 1). The valley floor is presumably underlain at depth by rocks of these same types. Rocks of Precambrian and Cambrian age crop out in part of the Funeral Mountains along the western side of the valley (Chapman and others, 1973; Streitz and Stinson, 1974). The Bullfrog Hills at the north end of the valley and the Grapevine Mountains on the northwest are composed mostly of Tertiary sedimentary and volcanic rocks but include small outcrops of Precambrian schist and gneiss (Cornwall and Kleinhampl, 1964). Tertiary volcanic rocks also are present in several of the ridges between the southern end of Bare Mountain and Lathrop Wells on the east side of the valley.

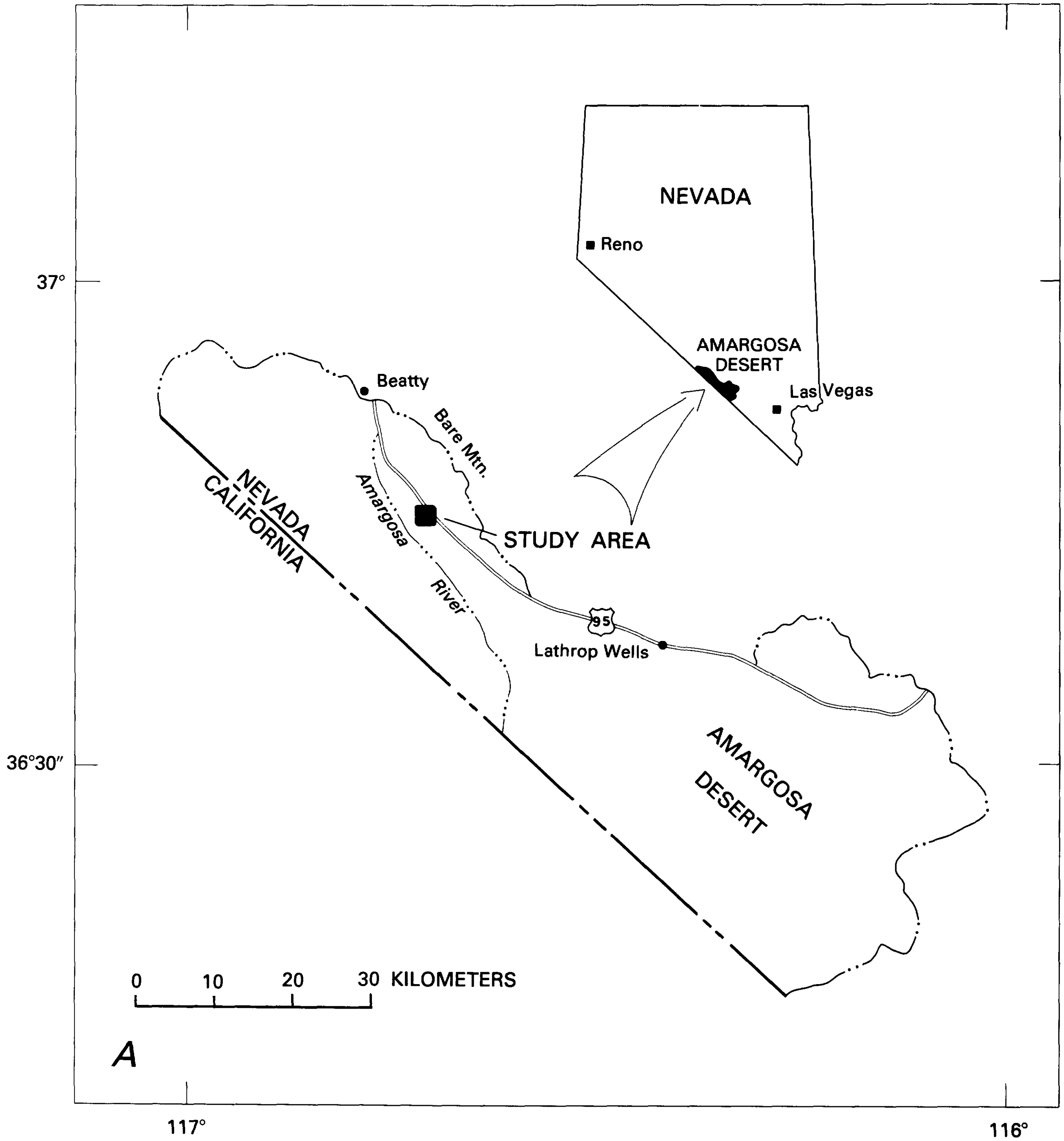

Figure 1*A*. Location of study area.

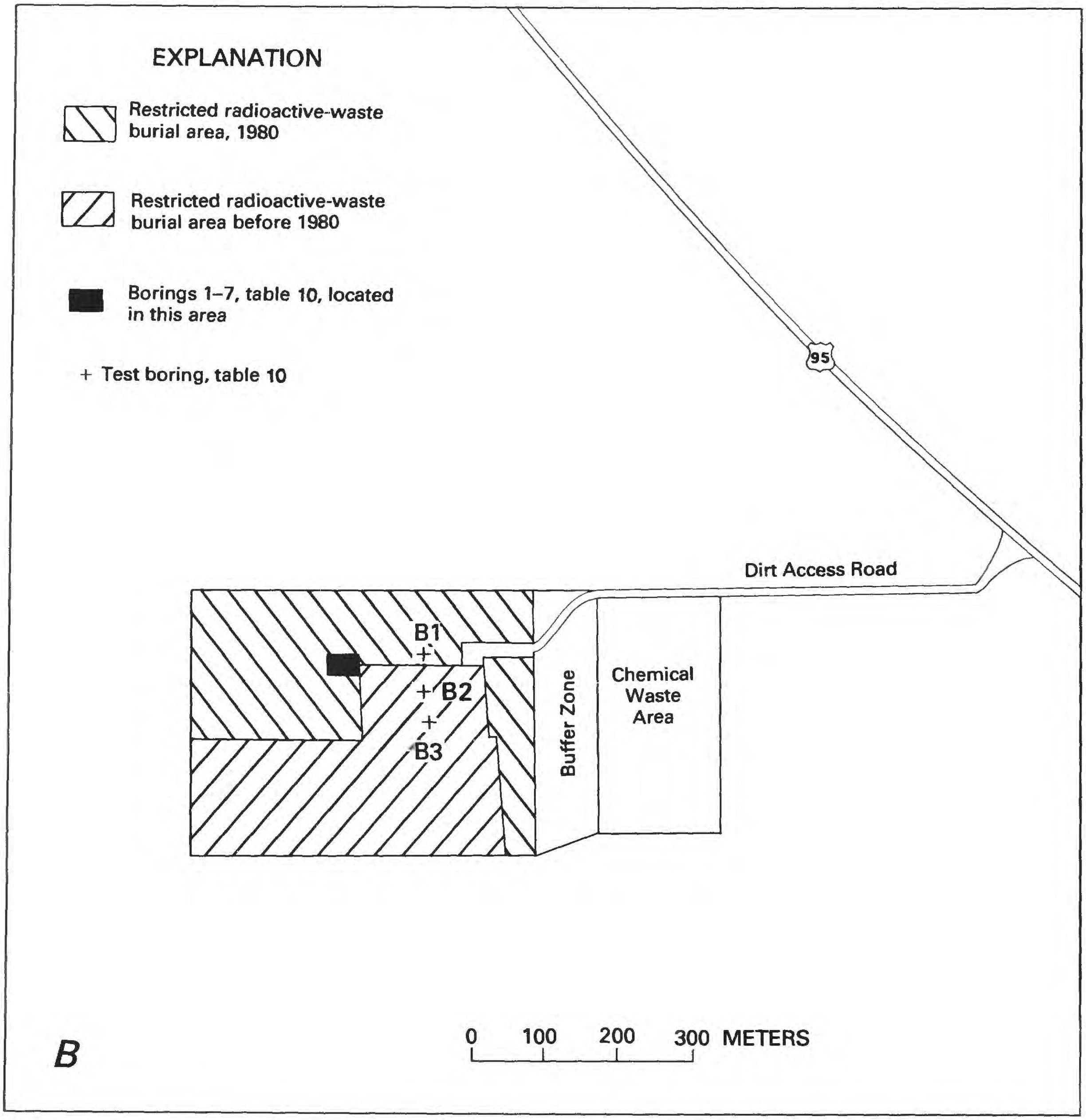

Figure 1*B*. Detail of waste-burial site.

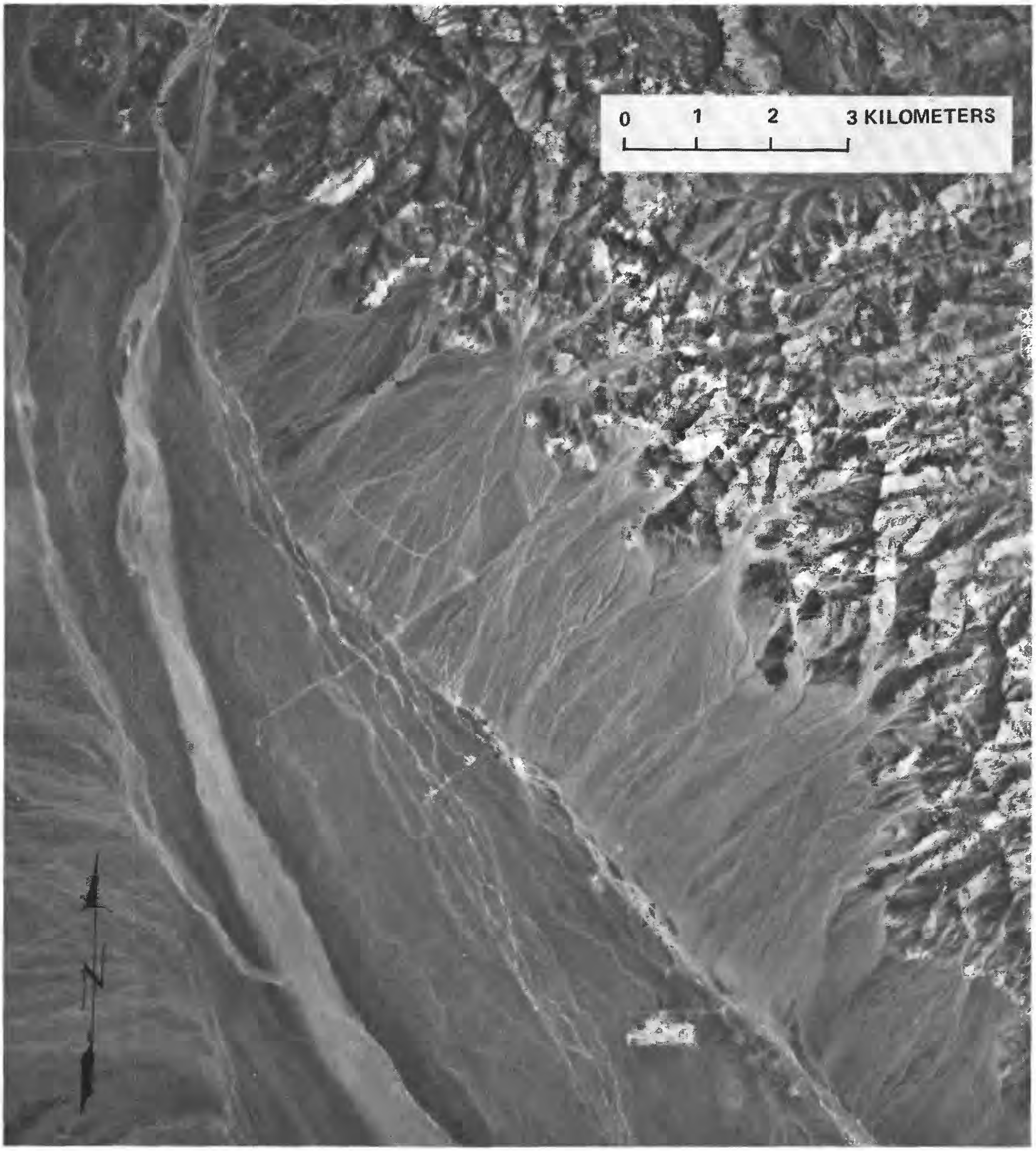

Figure 2. Aerial photograph of part of the northern Amargosa Desert, showing Bare Mountain (right), dry channel of the Amargosa River (light band from top left to bottom center), Amargosa Narrows (top left), and waste-burial site (light area to right of center near bottom). (Photograph taken June 6, 1976.)

Figure 3. Aerial photograph of the waste-burial site, September 24, 1980. (U.S. Department of Energy photograph, northern Amargosa Valley, no. 297.)

The geologic structure of the region surrounding the Amargosa Desert is complex. The major structural features include large-scale normal and thrust faults. Many of the surrounding mountain ranges are bounded by normal faults producing the typical Basin and Range structure shown by the topography of the area. Within the surrounding ranges the rocks are folded and for the most part intensely faulted by small-scale thrust, tear, normal, and strike-slip faults. Superimposed on this highly complex pattern of folding and faulting are several shear zones, including the Las Vegas Valley shear zone which extends northwestward to Mercury, Nev., just southeast of the Amargosa Desert, and shear zones in Death Valley and the Amargosa Desert (Winograd and Thordarson, 1975).

More detailed discussion of the geology in the area of the northern Amargosa Desert can be found in reports by Cornwall (1972) and Byers and others (1976b).

Unconsolidated Deposits

The Amargosa Desert is underlain by unconsolidated to weakly indurated deposits of Tertiary and Quaternary age. These include alluvial-fan deposits, fluvial deposits of sand and gravel, and freshwater or brackish-water playa deposits. Fluvial sediments, playa deposits, and dune sand of Pleistocene and Holocene age are present locally. The unconsolidated sediments are at least 170 m thick in the northern part of the desert, more than 295 m thick farther south near Lathrop Wells, and 240 m thick in the vicinity of Death Valley Junction (Walker and Eakin, 1963).

Stratigraphy

The best information available on the subsurface stratigraphy of the valley-fill deposits beneath the waste-burial site is a driller's log and sample descriptions for a well drilled at the site. The log and sample descriptions from a report by V.P. Gianella (consulting geologist, written commun., 1961) are given in tables 16 and 17 at the end of this report. The log and descriptions indicate that the materials penetrated by the well are, for the most part, a poorly sorted mixture of boulders, gravel, sand, silt, and clay. The driller's log (table 16), which is summarized in figure 4, is not entirely in agreement with the geologist's sample descriptions (table 17). Some of the unit boundaries are taken from the driller's log and are not noted or otherwise indicated on the geologist's log.

Generally, the sediments penetrated by the well can be divided into thick sequences of poorly sorted coarse-grained and fine-grained materials, probably representing fanglomerate and debris flows, interbedded with sequences of clay and clay with gravel. There also are several intervals of clayey limestone or calcareous clay.

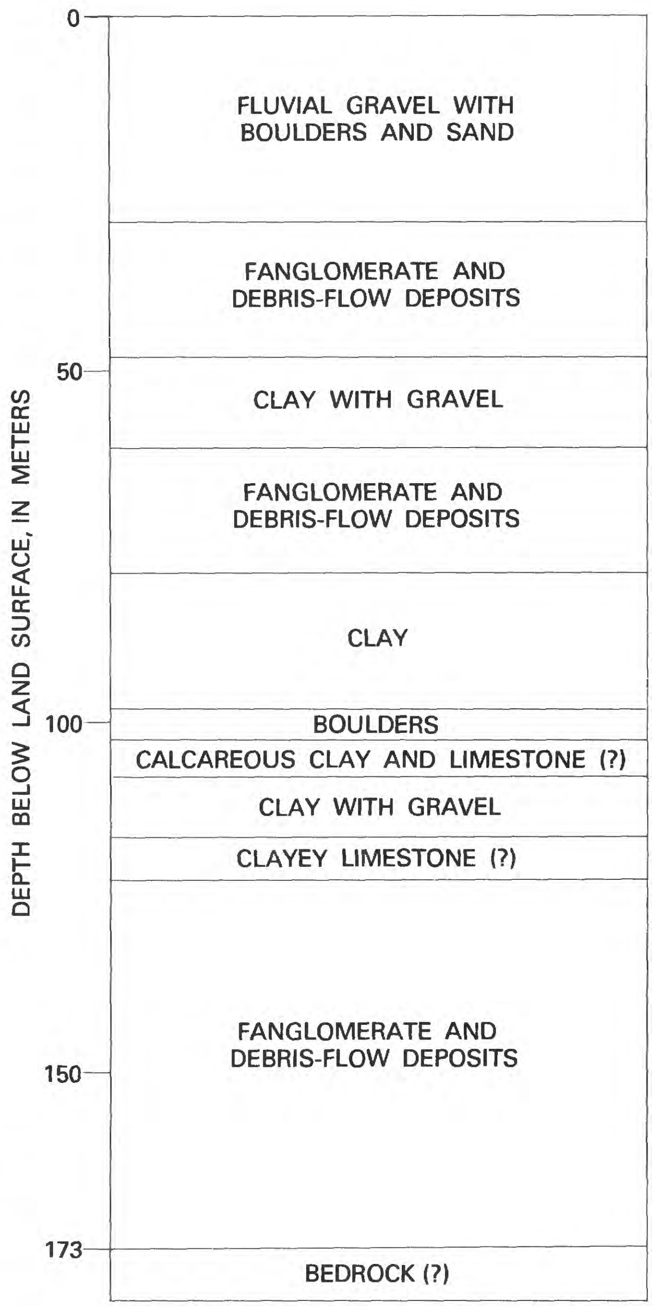

Figure 4. Summary log of U.S. Ecology, Inc., well at waste-burial site.

Descriptions of the samples collected from the well (table 17) strongly suggest that deposition of clastic sediments in this part of the valley has long been influenced principally by down-valley surface-water movement rather than by lateral infilling by extension of the bounding alluvial fans. Sample descriptions of material to a depth of 30 m suggest that the sediments are largely fluvial deposits associated with the Amargosa River. Below 30 m, lake- and debris-flow deposits predominate and volcanic gravel is less pervasive. Quartzite and schist are referred to more frequently in this part of the log, suggesting greater influence of lateral infilling by the building of alluvial fans. Nevertheless, the dominance of gravel derived from volcanic rocks throughout the section indicates that the most likely source of inflow to the valley was somewhere along the northern boundary of the desert or farther upstream in the upper reaches of the Amargosa River or its ancestral drainage.

Surface drainage appears to have ponded several times in the northern Amargosa Desert. The intervals of clay or clay and gravel are too thick to represent debris flows. Additionally, the clay and gravel at 49 m underlie a large part of the northern end of the desert (see below). The sequences of calcareous clay and limestone also represent a lacustrine depositional environment.

The areal extent of the fine-grained deposits shown in figure 4 has not been determined by test drilling. The thickness of clay and gravelly clay intervals on the driller's log suggests that these units may be traceable over a considerable area. A reconnaissance seismic reflection survey was made over part of the northern Amargosa Desert to determine the areal distribution of the clay and gravel bed in the interval 49 to 62 m. The results of the survey are shown in figure 5. The thickness of a deeper clay bed (80 to 99 m below land surface) suggests that it too may be an areally extensive deposit and of more than local significance. The calcareous clay or clayey limestone(?) (marl?) at 103 and 117 m may also be areally extensive and may represent deposition in freshwater or brackish-water lakes.

Thickness

The well drilled at the waste-burial site may have penetrated bedrock at about 173 m, so the unconsolidated deposits are at least that thick. A reconnaissance gravity survey made during this study, together with gravity data given by Healey and Miller (1962, 1965), provide some indirect information on possible thickness of the valley fill in the northern part of the Amargosa Desert. A gravity anomaly map (fig. 6) based on all available data suggests that bedrock is relatively shallow under the waste-burial site and for some distance northwest and southeast of the site. Two profiles across the Amargosa Desert, one near the burial site and one about 6.4 km northwest (fig. 7), were drawn to show the thickness of valley fill on the basis of the gravity data. A maximum thickness of about 600 m is suggested for the deeper parts of the basin. The interpretation of the relatively shallow depth to bedrock at the burial site on the basis of gravity data is supported partly by the well log discussed above and partly by the presence of a small bedrock knoll 1.6 km east-southeast of the waste-burial site and just west of U.S. Highway 95. This knoll is about 2.5 km west of the nearest outcrop on Bare Mountain. Several other bedrock knolls are present, about 5 km southeast of the waste-burial site and west of the highway. These outcrops are also within the area of the interpreted bedrock high.

Structure

The alluvial fans along the west side of the north end of Bare Mountain have been cut by faulting (fig. 2, pl. 1), probably during the late Quaternary. The fault, which is a sinuous to arcuate normal fault, can be traced from near the south boundary of Beatty through the Amargosa Narrows and southward for about 9.5 km. It lies to the east of and parallel to U.S. Highway 95 (fig. 2). The greatest offset seems to be at a point about 1.7 km south of the narrows, where the fault-scarp height is about 22 m.

Recent studies suggest that movement along the fault is older than 10,000 yr but younger than 50,000 yr (W.J. Carr, U.S. Geological Survey, oral commun., 1980). The fault scarp cuts alluvial-fan deposits that are considered to be 50,000 yr old and in places does not cut, or is covered by, alluvial-fan deposits that are considered to be not more than about 10,000 yr old. Additional studies, using the approximate relationship between fault-scarp slope angle and scarp age as developed by Wallace (1977), produced conflicting results (A.J. Gordon, consultant, written commun., 1980). At one location, the slope angle is consistent with an approximate age of 10,000 yr; at several other locations, the slope angle suggests an age of about 5,000 yr. The younger age is not consistent with the local Quaternary geology and may be the result of caliche layers retaining the slope at a steep enough angle to imply an erroneously young age.

Nowhere does the fault exhibit composite or multiple scarps. This suggests that movement occurred as a single event, or as a series of smaller events over a geologically short time. Composite or multiple scarps, in contrast, would suggest mean recurrence intervals of movement on individual faults on the order of thousands of years (Wallace, 1977).

The fault probably extends along the entire southwest side of Bare Mountain and is probably the main bounding fault for the mountain block. About 1 km east of the waste-burial site, some type of tectonic disruption of the unconsolidated sediments is suggested by interrupted, but not offset, older erosional surfaces, truncated depositional surfaces, and disarranged minor drainages. However, little to no surface evidence of vertical movement exists, except for the bedrock knob about 1.6 km east-southeast of the waste-burial site.

This bedrock knob lies west of the southeastward extension of the fault trace projected from its last surface expression about 8 km to the northwest. At this point the bedrock exposure is immediately west of U.S Highway 95,

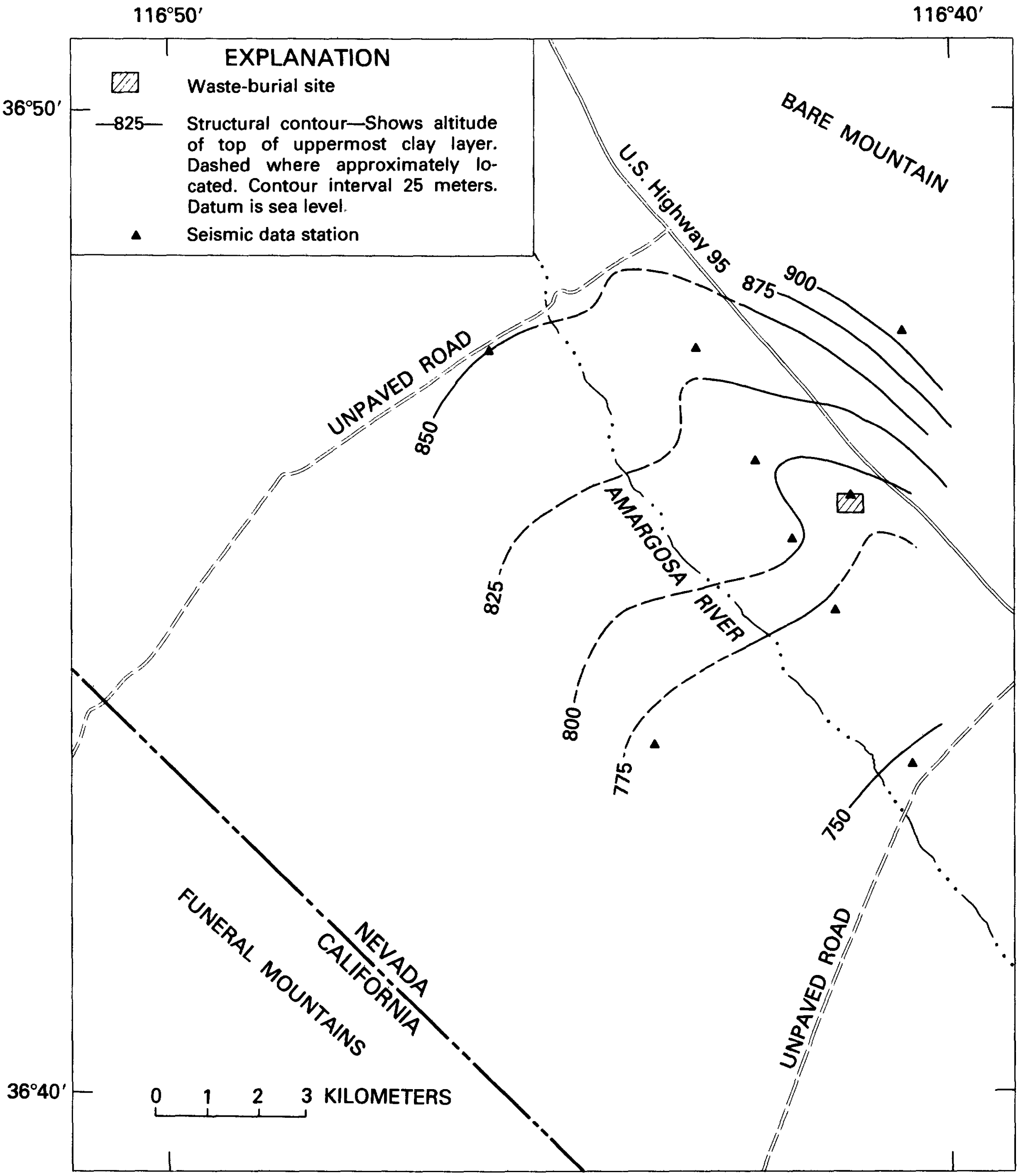

Figure 5. Approximate altitude of top of uppermost clay layer, northern Amargosa Desert.

and the projected fault trace would be about 300 m east of the highway. This implies a relative movement on the fault in this area opposite to that at the north end of Bare Mountain, where the downdropped area is to the west. Faulting along this segment of Bare Mountain probably is more complicated than farther north and requires more detailed field studies.

HYDROLOGIC SETTING

The waste-burial site is located in the drainage basin of the Amargosa River, which is part of the Death Valley hydrographic area. The terminus of the dry channel of the Amargosa River is at the southern end of Death Valley, but no flow has been observed along that part of the river in historic times. The ground-water system beneath the site probably flows toward Ash Meadows, to the southeast, but may also flow toward the south and southwest beneath the Funeral Mountains and into Death Valley. Ground water in the Ash Meadows area also eventually discharges toward Death Valley. Thus, both the surface-water and ground-water systems beneath the waste-burial site eventually terminate in Death Valley.

Table 1. Annual maximum discharge at U.S. Geological Survey gaging station on Amargosa River south of Beatty, calendar years 1964–79[a]

Date	Discharge (m^3/s)
July 26, 1964	~0.71
September 7, 1965	~.57
1966	No flow
August 30, 1967	120
February 10, 1968	2.6
February 24, 1969	453
August 15, 1970	~.002
1971	No flow
1972	No flow
February 11, 1973	.51
1974	No flow
September 10, 1975	12
February 1976	~2.8
June 1977	~.05
March 1, 1978	~18
1979	No flow

[a] No flow during most or all of each year.

Surface-Water Runoff

Precipitation is sparse in the area, averaging less than 10 cm a year, but surface runoff is even more rare. No perennial streams exist within about 16 km of the waste-burial facility. The dry bed of the Amargosa River is the principal drainage channel. Perennial flow in this channel is maintained by springs in the upper reaches of the Amargosa River north of Beatty, and the flow usually has disappeared beneath the surface within about 3 km downstream from Beatty. The dry channel of the Amargosa passes about 3 km west of the waste-burial site.

No records or observations of flow in the Amargosa River at the latitude of the waste-burial site are available. Records of flow about 3 km south of Beatty since 1964 are available and are summarized in table 1. Commonly, these flows last for only a few days following a major storm over the drainage basin upstream from the gaging station; there is no flow most of the year. Most measurements on the Amargosa River south of Beatty record peak flow from a crest-stage gage or from slope-area measurements. Several of the events recorded at this gage probably produced sufficient discharge for surface flow to have reached as far south as the latitude of the waste-burial site, a distance of about 14 km along the river channel from the gage south of Beatty. On March 1, 1978, a flow of about 18 cubic meters per second (m^3/s) was recorded at the gage south of Beatty. On the same day, flow was also observed by the author about 8 km south of the gage, at a road crossing in the SW¼ of sec. 18, T. 13 S., R. 47 E.; the estimated flow there was in the range of 1–3 m^3/s. The southern extent of this flow was not determined, but it may have continued the additional 6 km required to reach the latitude of the waste-burial site. Two previous events recorded at the gage near Beatty probably provided flow opposite the waste-burial site: On August 30, 1967, a discharge of about 120 m^3/s was determined from slope-area measurements at the gage, and on February 24, 1969, a discharge of about 450 m^3/s was determined, also from slope-area measurements.

Secondary drainage features that may be of some significance are two dry streambeds that trend roughly parallel to U.S. Highway 95 (figs. 2, 3). Both drainages split from the main channel of the Amargosa about 4 km south of the Amargosa Narrows. One dry channel trends south-southeast and passes about 0.6 km west of the waste-burial site between the waste-burial site and the main channel of the Amargosa. It rejoins the main channel of the Amargosa about 6 km south of the site. The other dry channel trends southeast along the east side of the highway, passes about 1 km east of the waste-burial site, and has several small tributary channels that appear to drain the southwest slope of Bare Mountain. This channel largely disappears on the desert floor about 13 km southeast of the site. Both channels are probably overflow bypass channels developed during a high discharge event of the Amargosa River.

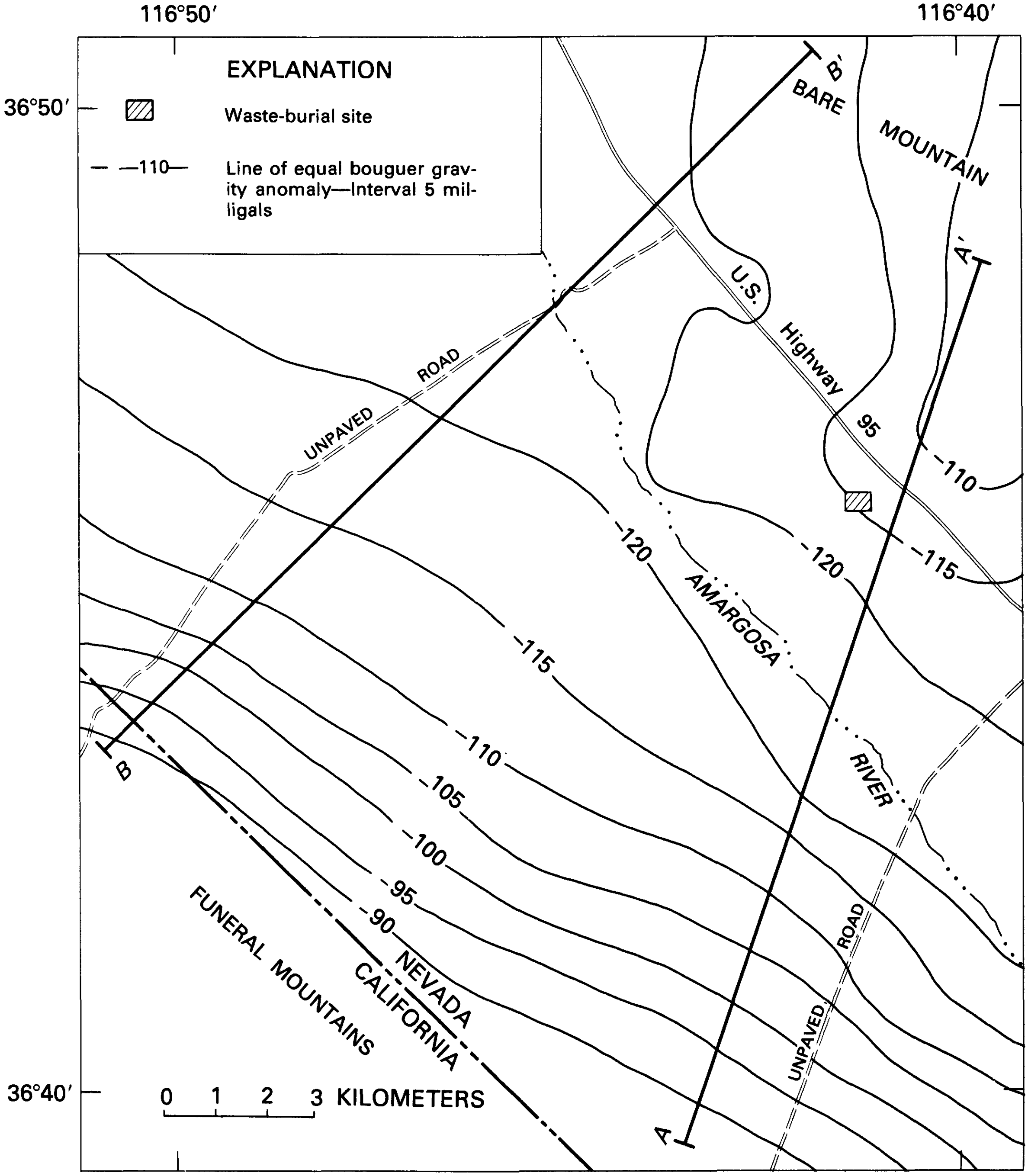

Figure 6. Bouguer gravity anomalies of the northern Amargosa Desert. Data from Douglas K. Maurer (U.S. Geological Survey, written commun., 1979). Shows location of profiles *A–A′* and *B–B′* (fig. 7).

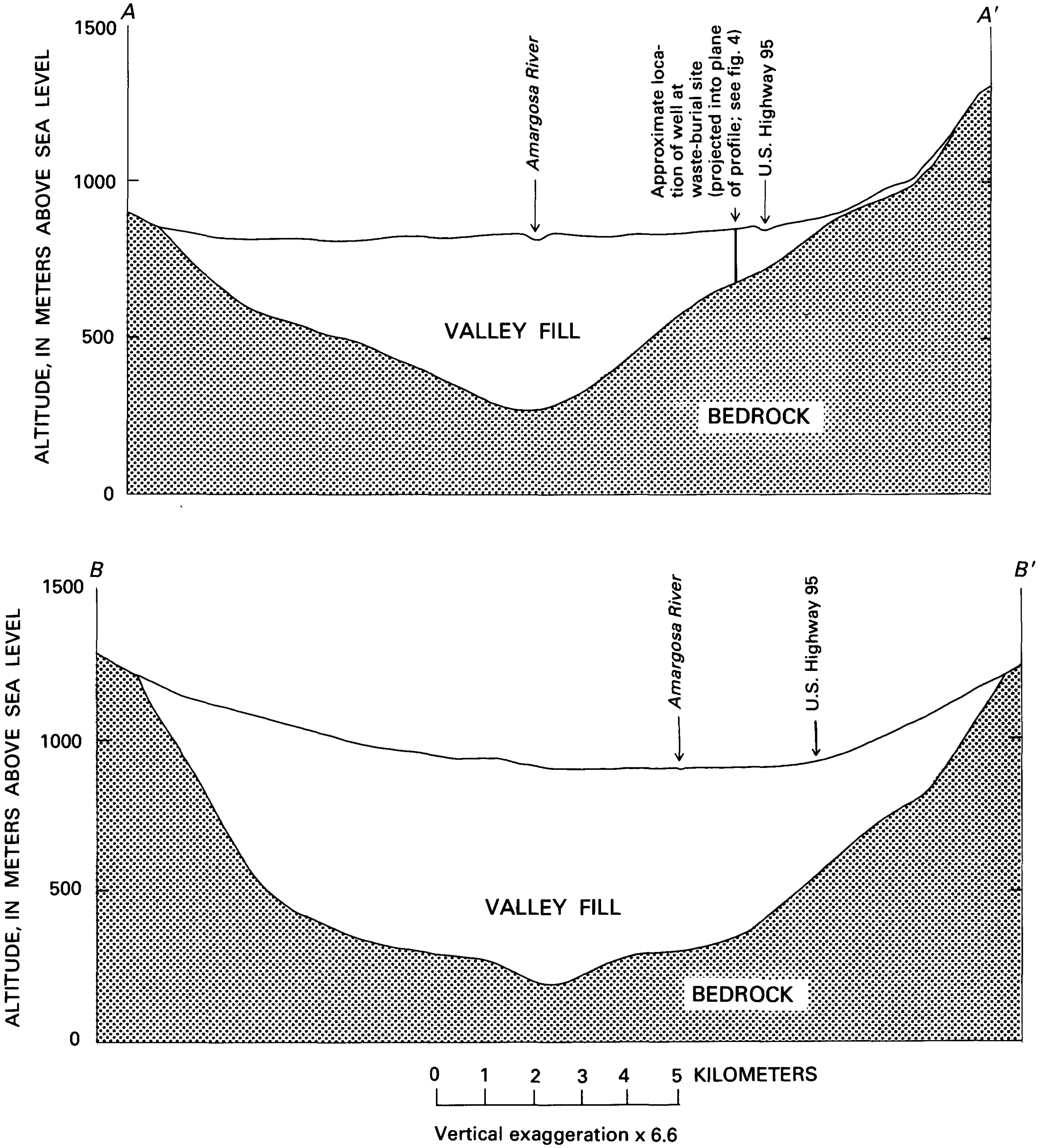

Figure 7. Profiles along lines *A–A′* and *B–B′* in figure 6, showing approximate depth to bedrock on the basis of gravity data.

Table 2. Water-level data for wells in vicinity of waste-burial site

Site number (pl. 1)	Name	Altitude of land surface (meters above sea level)	Well depth (meters)	Depth to water	
				Meters	Date
1	Nuclear Eng. Co.[a]	850	175	85.9	7-12-62
2	W. Dale[a]	795	147	77.1	7-12-62
3	Rose's Station[b]	775	--	63.4	1905

a From Walker and Eakin, 1963.
b From Ball, 1907.

On aerial photographs, minor local surface-drainage channels appear to pass through the area occupied by the waste-burial site. However, no surface runoff was observed or reported during the course of the study.

Unsaturated Zone

The unsaturated zone is of special significance in this study because it is through this zone that any radionuclides leached from the waste-burial trenches must pass before reaching the saturated zone; only then can the radionuclides be transported elsewhere (unless they are exhumed by erosion). The unsaturated zone in this part of the Amargosa Desert is at least 60 m thick and locally is nearly 90 m thick.

The soil-moisture content and soil-water potential of the unsaturated zone are not generally known. Data collected during this study at the waste-burial site suggest moisture contents of 4 to 10 percent by volume in the upper 6 m, except during the winter months when the moisture content of the top 0.5 to 1 m may be as high as 15 to 18 percent following a heavy rain. Studies of similar alluvial material at Jackass Flats, 32 km east of the waste-burial site, indicated moisture contents of 5 to 8 percent by volume (Clebsch, 1962). Infiltration experiments at Jackass Flats suggested that downward movement of soil moisture below the top 0.5 m did not occur until the soil attained about 50 percent saturation; this requires a volumetric soil-moisture content of between 15 and 20 percent.

The magnitude and range of soil-water potential is even less well known. Some measurements were made at the waste-burial site during the course of this study and are discussed in detail later in this report. Measured potentials ranged from a few millibars negative pressure in the near-surface sediments following rainfall events to several bars negative pressure in the same sediments during the dry summer months. At depths of 3 to 10 m, soil-water potential is in the range of 20 to 60 bars negative pressure. These values are consistent with laboratory soil-water potentials determined for these types of sediments and the observed moisture-content range (Mehuys and others, 1975).

Ground-Water System

Few wells have been drilled in the northern Amargosa Desert, and, consequently, the occurrence of ground water in the area is poorly known. Based on studies at the Nevada Test Site and in the southern Amargosa Desert, two major aquifers probably underlie the area: a valley-fill aquifer and an aquifer in the underlying Paleozoic bedrock, which together constitute the ground-water system. Three wells, located in Tps. 13 and 14 S., R. 47 E., Mount Diablo baseline and meridian, are the only sources of subsurface data northwest of Lathrop Wells. These wells are listed in table 2 and shown on plate 1.

Knowledge of the ground-water system beneath the waste-burial site is based almost solely on the information obtained from the drilling and testing of a well at the waste-burial site in 1961. The data obtained from this well suggest the presence of a principal water-bearing zone in the valley-fill deposits in the depth interval 99 to 103 m below land surface (fig. 4). Another, less productive zone exists from 132 to 173 m. This zone may be in hydraulic continuity with the water-bearing bedrock aquifer that is presumed to underlie the valley fill.

The deepest aquifers beneath the study area are those in the bedrock underlying the valley fill. No data are available for these aquifers beneath this part of the Amargosa Desert. Considerable information on the bedrock aquifers has been developed for large areas east and southeast of the disposal site, including the southern Amargosa Desert (Winograd and Thordarson, 1975). The most widespread bedrock aquifer is in the Cambrian to Devonian carbonate-rock sequence, which is presumed to underlie the study area because of its presence in Bare

Mountain. Less widespread and occasionally of only local significance are aquifers in Tertiary welded and bedded tuffs, several of which may underlie the valley fill of the northern Amargosa Desert. Water in these aquifers moves primarily through fractures and, in the carbonate-rock aquifer, through solution openings. Recharge to these aquifers probably is supplied by underflow from outside the Amargosa drainage basin. The source area of this recharge is not known.

The deepest aquifer in the valley fill, extending from 132 to 173 m below land surface, is assumed to immediately overlie the bedrock aquifer. The well drilled at the waste-burial site was originally perforated only in the interval from 138 to 173 m. The water level was 93 m below land surface; this is 39 m above the presumed top of the aquifer, suggesting confined conditions for the aquifer in this area.

The upper aquifer in the valley fill between 99 and 103 m also may be confined and is directly beneath the well-defined confining layer that extends from 62 to 99 m below land surface (fig. 4). Following a brief test of the deepest valley-fill aquifer, the well casing was slotted from 91 to 136 m depth so that it is now open to the entire interval from 91 to 173 m. The water level in the well rose to 86 m below land surface, which is 13 m above the presumed top of the upper aquifer. This represents a composite head for the whole thickness of valley-fill aquifers beneath the waste-burial site and indicates that the head in the upper aquifer is higher than that in the lower one.

Plate 1 shows the generalized configuration of the potentiometric surface for valley fill beneath the northern and central Amargosa Desert. The contours, slightly modified from those of Walker and Eakin (1963, pl. 3), are based on the assumption that ground-water flow beneath the northern part of the desert is to the southeast—that is, downvalley toward the Ash Meadows area. A similar interpretation was made by Winograd and Thordarson (1975, pl. 1). The basic assumption of downvalley flow is, however, not necessarily correct. The location of the three wells (pl. 1, wells 1, 2, and 3) used as altitude control for water-level contours in the northern part of the desert is such that the wells do not really define the direction of the gradient. It is possible that the gradient is toward the south or even the southwest.

The present interpretation of the direction of ground-water flow implies a recharge area to the north and northwest, perhaps the Sarcobatus Flat-Pahute Mesa area (see pl. 1). Some water in the valley-fill aquifer discharges to Alkali Flat, near Death Valley Junction; the rest may enter the carbonate-rock aquifer and eventually discharge to Death Valley, possibly along the Furnace Creek fault zone bounding the Funeral Mountains on the west. Hunt and others (1966) noted the similarity in chemical composition between ground water in the Ash Meadows area and spring discharge along the northeast side of Death Valley.

CLIMATE

Radioactive waste is buried at the facility near Beatty at depths of 6 to 15 m in an unsaturated zone that is about 85 m thick. A number of geologic and hydrologic processes that govern and affect the movement of water into and through this zone must be recognized and understood if we are to understand the potential for radionuclide migration beneath the site. Among these are the hydrologic processes controlled by the climate in the area of the waste-burial site.

The climatic factors of rainfall, temperature, solar radiation, and evaporation interact under bare-soil conditions, such as those that exist at the waste-burial site, in a complex manner with the geohydrologic factors of soil moisture, soil-water potential, and unsaturated hydraulic conductivity to determine the amount and movement rate of water percolating through the unsaturated zone. The only water that might come in contact with, leach, and transport radionuclides from the buried waste is that derived from precipitation falling directly on the backfill in the waste-burial trenches. The amount of water that infiltrates and percolates downward, and the depth and rate at which it moves, depend largely on the amount and intensity of precipitation, evaporation demand, and preexisting soil-moisture conditions. To clarify the hydrologic processes in the shallow unsaturated zone at the waste-burial site, each of the controlling parameters is examined in considerable detail. The following discussion defines the areal climatic factors of precipitation, temperature, and evaporation, which in turn characterize recharge-inducing rainfall events and set an upper limit on the potential recharge from local sources. Transpiration demands are not considered in the following analysis and discussion of significant precipitation because the waste-burial site is kept cleared of vegetation; only the evaporation losses from bare soil are applicable. If plant-growth requirements are added to bare-soil evaporation, deep percolation of precipitation would be doubtful. Site-specific conditions of soil moisture and soil-water potential are discussed in a later section of this report.

Precipitation

The waste-burial site is situated in one of the most arid parts of the United States. Mean annual precipitation in the area varies from 11.4 centimeters (cm) at Beatty (altitude, 1,005 m), 17.4 km north of the site, to 7.4 cm at Lathrop Wells (altitude, 817 m), 30 km southeast of the site.

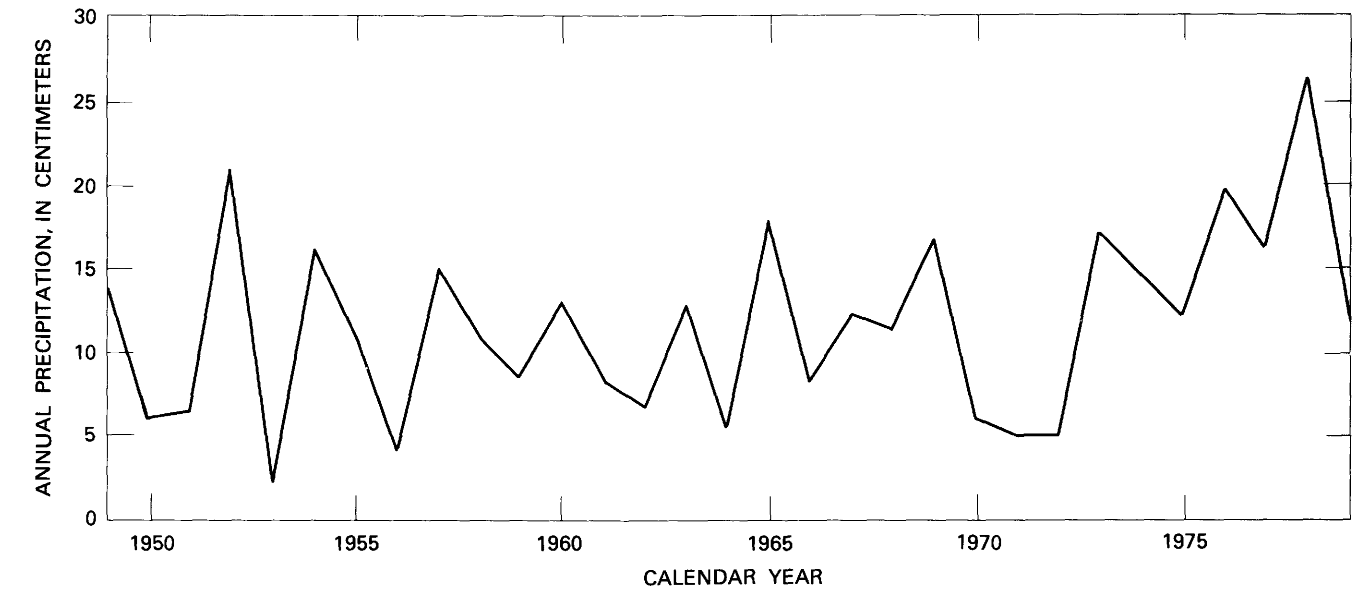

Figure 8. Annual precipitation at Beatty, 1949–79.

Annual precipitation varies considerably from one year to the next. During the time period 1949–79 at Beatty (fig. 8), it ranged from 1.8 cm in 1953 to 26.3 cm in 1978. During the same time period at Lathrop Wells, recorded annual precipitation (the record is discontinuous) ranged from 2.4 cm in 1962 to 13.4 cm in 1957.

Precipitation can occur during all months of the year, but the amount varies considerably with season; most falls during the winter months. Mean monthly precipitation at Beatty and Lathrop Wells during the period 1949–79 is shown in figure 9. Winter precipitation originates from the west and is commonly associated with transitory low-pressure systems that usually cover large areas. It is almost always in the form of rain. Snow is uncommon at Beatty and rare on the Amargosa Desert, and it persists on the ground for no more than a few hours. Summer rainfall occurs predominantly during convective storms that may yield intense rainfall over small areas. On several occasions during late August or in September, tropical storms have come inland from the Pacific Ocean, crossing the California coast between San Diego and Los Angeles, and moved northeast across southern Nevada. Such a storm in August 1977 produced nearly 5 cm of rain in 24 hours (hr) at Beatty.

More important than total or mean annual rainfall as a source of potential recharge to the unsaturated zone is the magnitude, intensity, and timing of a single precipitation event. For a given precipitation event to have potential recharge significance, it must exceed evaporative demands during the following days and also be able to satisfy and exceed the existing soil-moisture deficit. Precipitation events during summer months, when evaporative demands are high and surface soils are extremely dry, are unlikely to result in recharge. Alternatively, precipitation may occur when evaporative demands are low, such as during the cool winter months, and when the soil-moisture deficit is small, as would be the case following a series of closely spaced rainfall events. Precipitation intensity is also a factor influencing infiltration. High-intensity rainfall commonly results in less infiltration and more runoff. Rainfall intensity is not considered in this analysis because (1) the necessary data were not available, and (2) winter storms, which are of greatest importance to deep percolation, are generally of low intensity (but long duration) compared with high-intensity summer convective-storm precipitation.

An analysis of single-rainfall-event magnitude and frequency has been made using data from the National Weather Service stations at Beatty and Lathrop Wells. Conditions at Lathrop Wells are more like those at the waste-burial site because of similarities in topographic setting and altitude, but the precipitation record there is shorter and much less complete than the record at Beatty. The major undesirable feature of the Beatty weather-station site with respect to the waste-burial site is the difference in altitude—1,005 m at Beatty versus 847 m at the waste-burial site. Nevertheless, most of this analysis relies on the more complete record from the station at Beatty; data from the station at Lathrop Wells is compared

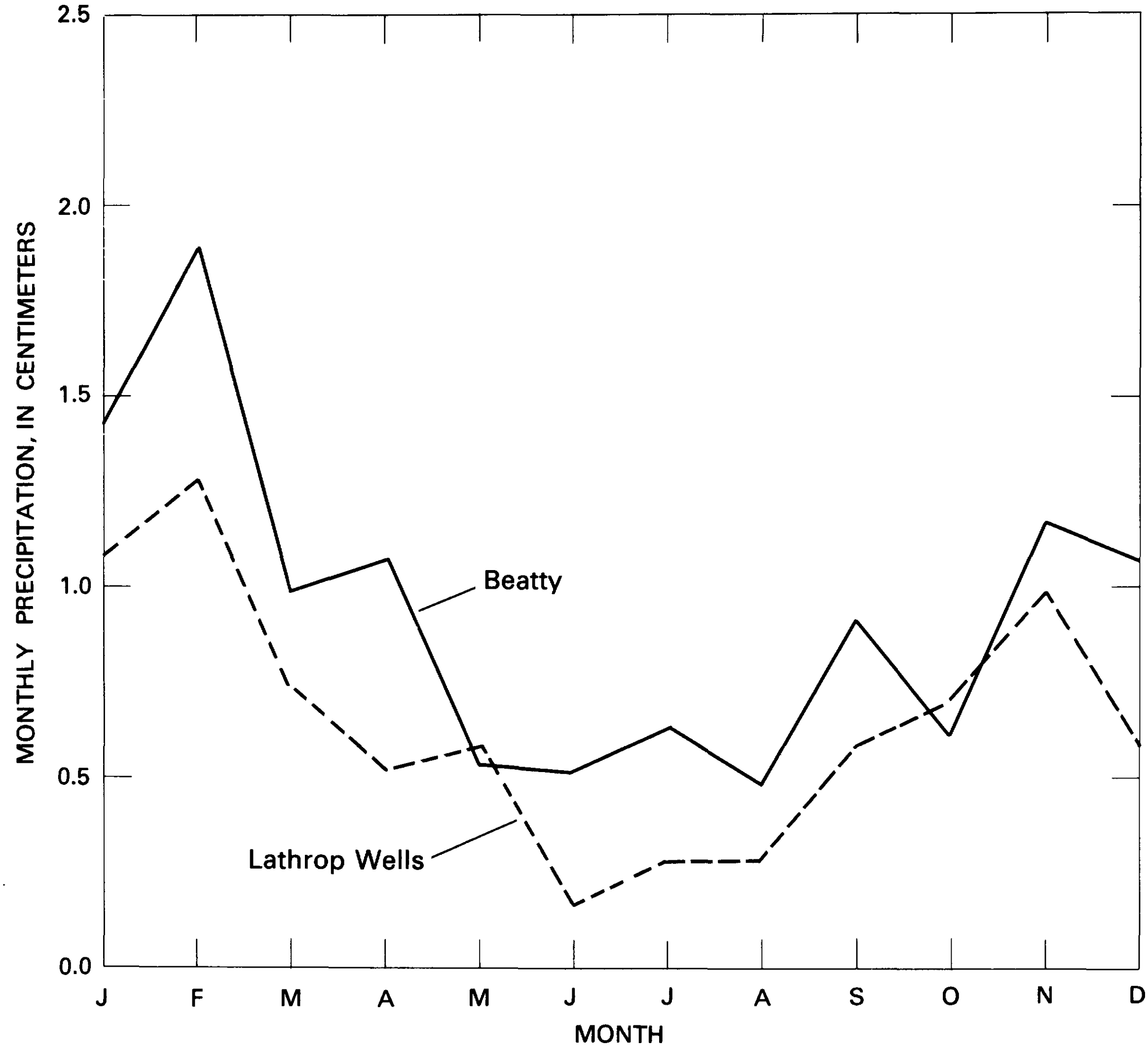

Figure 9. Mean monthly precipitation at Beatty and Lathrop Wells, 1949–79. Data for Lathrop Wells are based on incomplete record.

and contrasted with that from Beatty for those years for which the record is complete.

Analysis of the frequency and magnitude of individual precipitation events in southern Nevada is complicated by a number of factors. Studies by Weedfall (1963) and Quiring (1965) demonstrated that precipitation in the region is a function of both altitude and longitude. The weather station at Beatty was 158 m higher in altitude than the waste-disposal site during the period 1948–72. In 1972, the station was moved to a new location that is 234 m higher than the previous location. The station at Lathrop Wells is 190 m lower in altitude than the waste-burial site. Much of the record at Lathrop Wells for the period 1949–77 is missing, thereby complicating any analysis dealing with number of events. Years with partial record are not included in the following analysis; thus,only 16 yr of complete record could be compared with the data from the Beatty station.

The number of precipitation events in different magnitude categories is given in table 3 for Beatty and in table 4 for Lathrop Wells. The amount of rainfall recorded during a 24-hr period is considered to represent a discrete rainfall event, which is not strictly correct because a given storm may span more than 1 day. The potential effect of this approach to defining rainfall events would be to reduce the number of large rains and increase the number of smaller rains. Examination of the dates and magnitudes of daily precipitation, however, suggests that this approach has not significantly affected the analysis.

Daily precipitation at Beatty producing 2.5 cm or less accounted for 98 percent of the total number of daily events recorded from 1949 to 1979. Daily precipitation of

Table 3. Classification of 24-hr precipitation data at Beatty, 1949–79, by magnitude of event
[cm, centimeters]

Calendar year	Total precipitation (cm)	Cumulative precipitation (cm)	Number of events in each class: Class 1 (0.01 to 0.60 cm)	Class 2 (0.61 to 1.25 cm)	Class 3 (1.26 to 2.50 cm)	Class 4 (2.51 to 3.75 cm)	Class 5 (3.76 to 5.0 cm)
1949	13.79	13.79	32	1	2	1	0
1950	6.04	19.83	9	3	1	0	0
1951	6.60	26.43	14	5	0	0	0
1952	21.23	47.66	21	15	1	1	0
1953	1.75	49.41	13	0	0	0	0
1954	16.36	65.77	16	0	6	0	1
1955	10.95	76.72	16	6	2	0	0
1956	4.24	80.96	8	0	1	0	0
1957	15.01	95.97	25	6	3	0	0
1958	10.74	106.71	18	4	2	0	0
1959	8.61	115.32	9	4	2	0	0
1960	13.00	128.32	11	7	0	1	0
1961	8.36	136.68	12	4	1	0	0
1962	6.78	143.46	18	2	1	0	0
1963	12.70	156.16	13	3	4	0	0
1964	5.36	161.52	17	2	0	0	0
1965	18.62	180.14	25	4	5	0	0
1966	8.18	188.32	14	1	2	0	0
1967	12.39	200.71	17	5	2	0	0
1968	11.30	212.01	8	4	2	0	1
1969	16.59	228.60	10	5	4	1	0
1970	7.62	236.22	7	3	0	1	0
1971	5.03	241.25	2	1	2	0	0
1972	5.18	246.43	3	0	1	1	0
1973	17.07	263.50	30	9	2	0	0
1974	14.73	278.23	20	6	3	0	0
1975	12.29	290.52	28	1	0	0	1
1976	19.86	310.38	14	8	2	2	0
1977	16.36	326.74	16	4	1	1	1
1978	26.34	353.08	31	8	7	0	0
1979	11.96	365.04	34	4	2	0	0
Total	365.04	--	511	125	61	9	4
Percentage of total events	--	--	71.9	17.7	8.6	1.3	0.5
Average annual	11.77	--	16	4	2	<1	<1

0.6 cm or less is by far the most common size of event, accounting for nearly 72 percent of the total. The potentially significant storms (from a recharge standpoint) that produced more than 2.5 cm accounted for about 2 percent of the events during the period of analysis—only 13 events in 31 years. Of those, nine produced rainfall of 2.51 to 3.75 cm and four produced rainfall of 3.76 to 5.0 cm. Interestingly, 5 of the 13 major precipitation events occurred after the station was moved in 1972. Table 5 gives the date and magnitude of each of the major events.

A noticeable increase in precipitation was recorded at the Beatty weather station following 1972 when the station was moved to a location 76 m higher than the previous site. The increase in both cumulative precipitation and cumulative number of events of 0.6 cm or less after 1972 is shown in figures 10 and 11. The probable effect of moving the station to a higher altitude is suggested by the data shown on both graphs.

The seasonal distribution of daily precipitation events of several different magnitudes that are less than or equal to 2.5 cm at Beatty is shown in figures 12 and 13. These storms typically account for 70 to 90 percent of the annual rainfall. Exceptions to this arise when a large storm occurs during a year of low annual rainfall such as

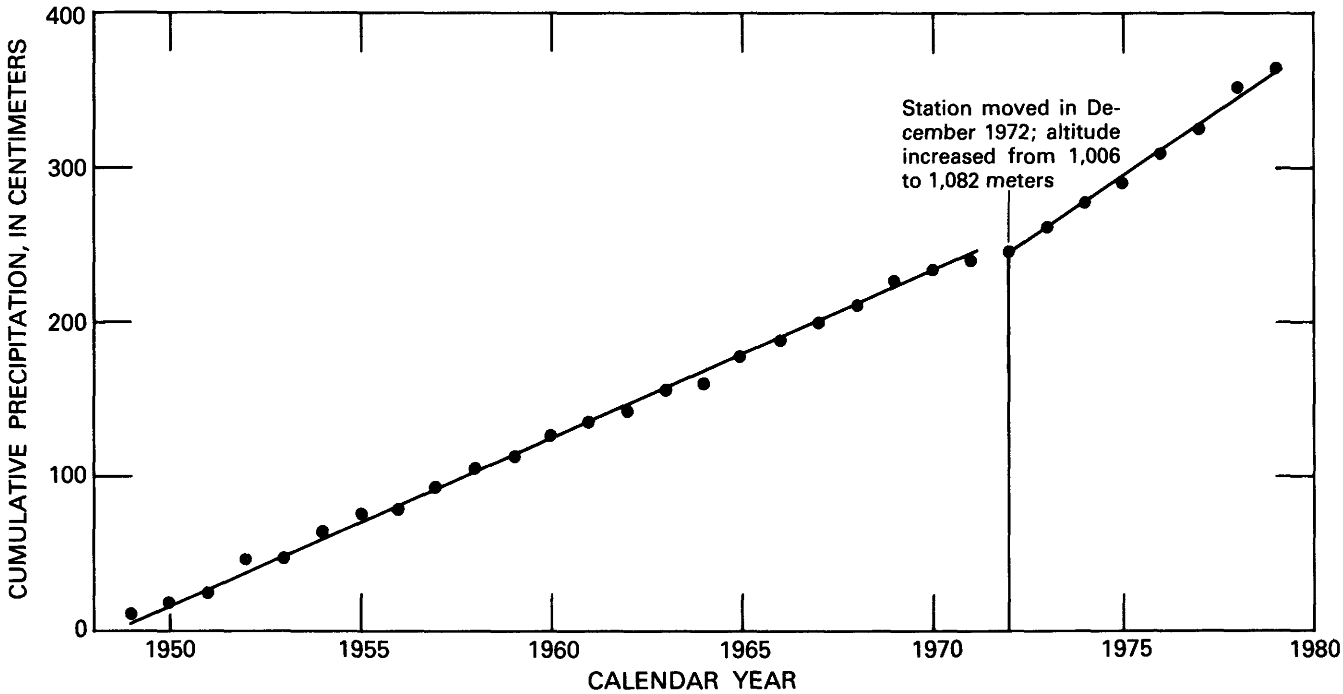

Figure 10. Cumulative precipitation at Beatty, 1949–79.

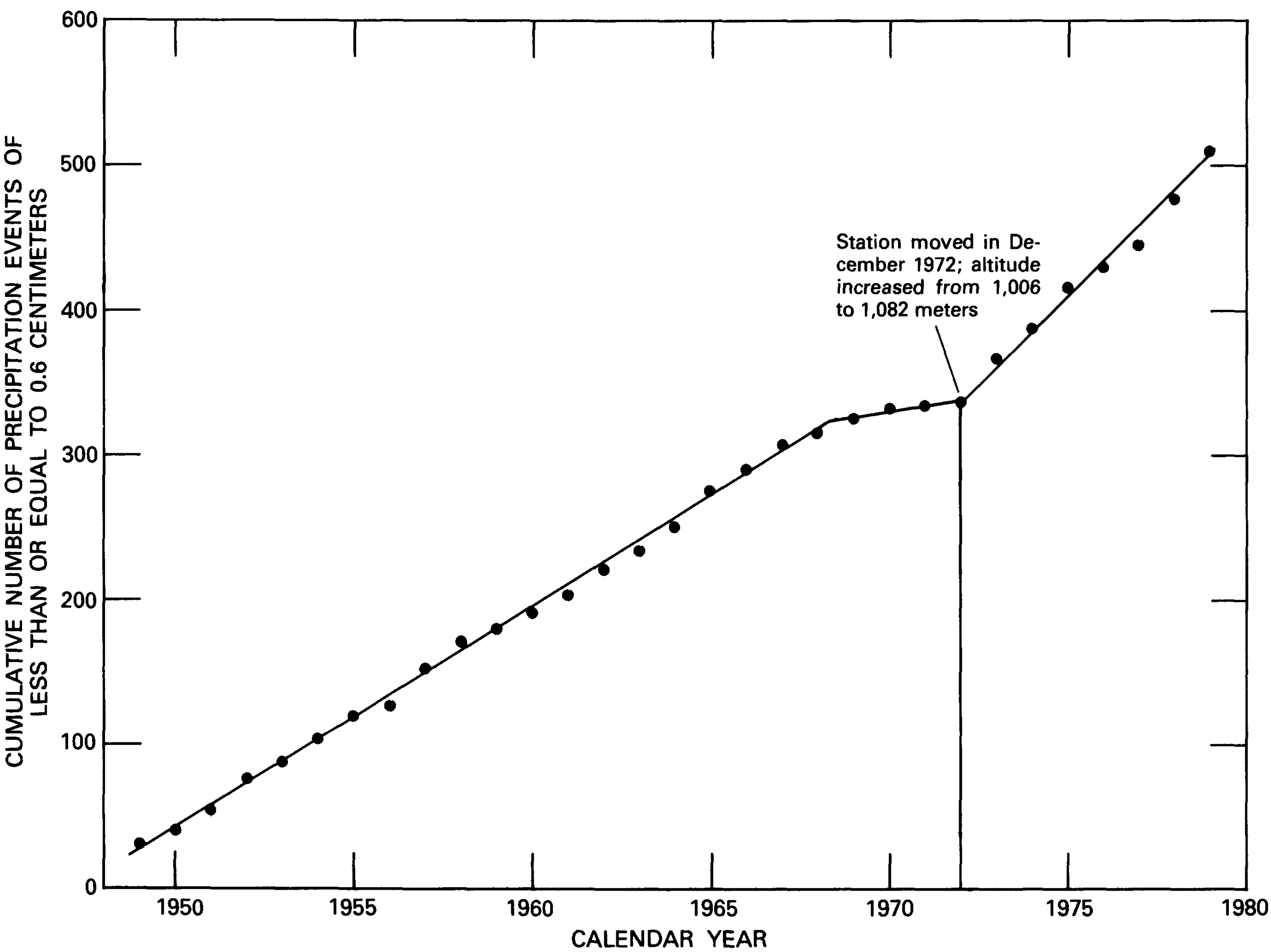

Figure 11. Cumulative number of precipitation events of 0.6 cm or less at Beatty, 1949–79.

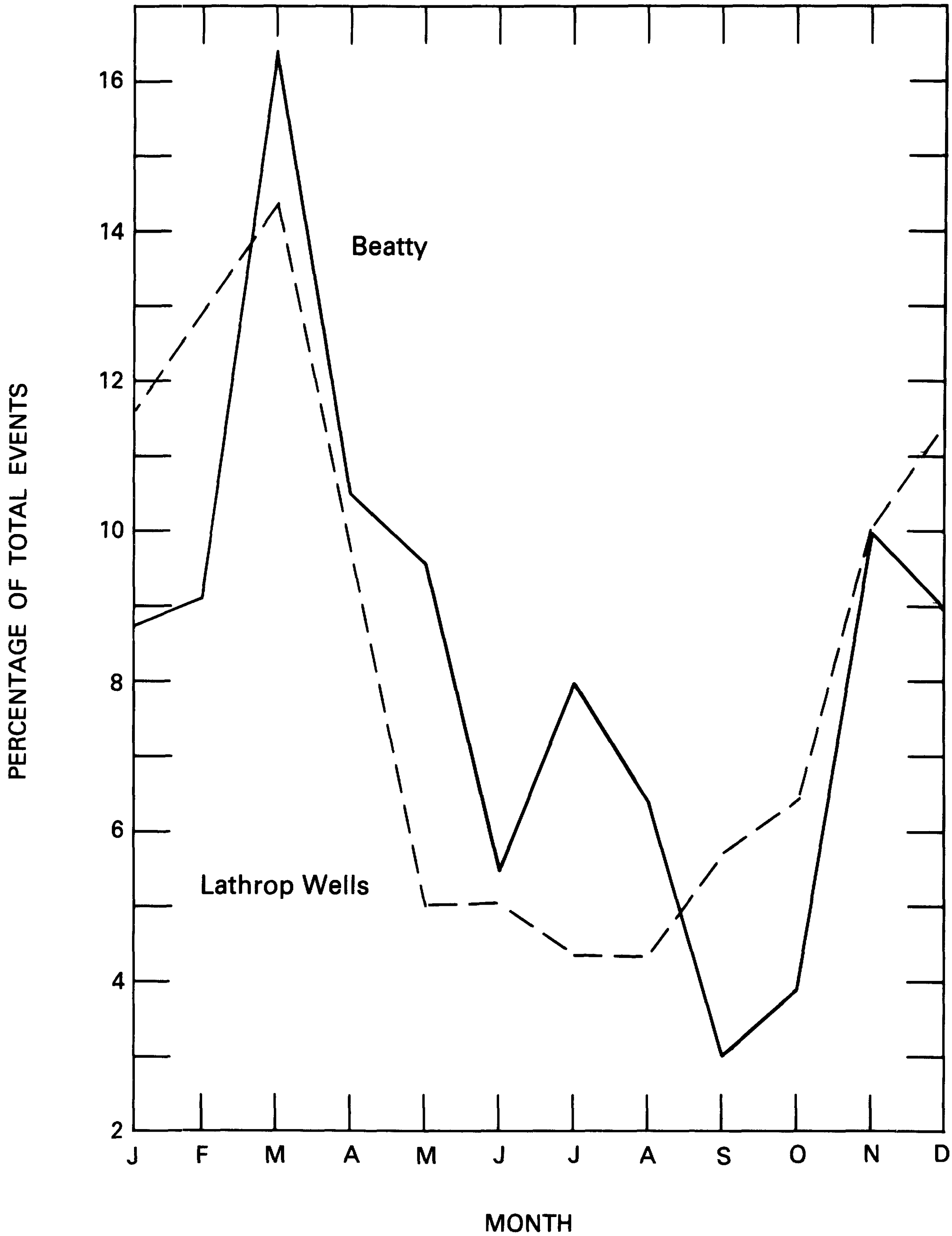

Figure 12. Monthly distribution of precipitation events of 0.6 cm or less at Beatty and Lathrop Wells, 1949–76.

Table 4. Classification of 24-hr precipitation data at Lathrop Wells, 1949–77, by magnitude of event
[cm, centimeters]

Calendar year[1]	Total precipitation (cm)[2]	Cumulative precipitation (cm)	Number of events in each class: Class 1 (0.01 to 0.60 cm)	Class 2 (0.61 to 1.25 cm)	Class 3 (1.26 to 2.50 cm)	Class 4 (2.51 to 3.75 cm)	Class 5 (3.76 to 5.0 cm)
1949	11.99	11.99	4	3	1	2	0
1950	3.40	15.39	1	0	2	0	0
1951	2.79e	18.18	4	1	1	0	0
1954	11.61	29.79	8	3	2	1	0
1955	6.78	36.57	4	4	1	0	0
1956	3.05	39.62	4	2	0	0	0
1957	13.39	53.01	6	5	4	0	0
1958	11.43	64.44	12	8	1	0	0
1962	2.44	66.88	5	0	1	0	0
1971	3.58	70.46	9	2	0	0	0
1972	7.95	78.41	15	2	0	1	0
1973	11.10	89.51	25	3	2	0	0
1974	8.00	97.51	15	2	2	0	0
1975	5.26	102.77	7	3	1	0	0
1976	10.97	113.74	9	2	1	0	1
1977	11.3e	125.04	--	--	--	--	--
Total	125.04	--	128	40	19	4	1
Percentage of total events	--	--	66.7	20.8	9.9	2.1	0.5
Annual average	7.82	--	8	2	1	<1	<1

1 Period of full-year record only.
2 Estimated values indicated by "e."

1972. A greater frequency of occurrence of small events (less than or equal to 0.6 cm) in July and August as compared with June, September, and October (fig. 12) probably reflects increased convective-storm activity during these 2 mo.

Precipitation frequency and magnitude at Lathrop Wells is more nearly like that at the waste-burial site than is the frequency and magnitude at Beatty. Missing records at Lathrop Wells between 1949 and 1977 have resulted in only 16 yr of usable data for the 30-yr period, and the longest span of continuous record is the 6 yr from 1971 through 1976. These 16 yr of data are compared with the same 16 yr of record from Beatty.

Precipitation events of 0.6 cm or less are the most common type at Lathrop Wells, as they are at Beatty, accounting for 67 percent of the events recorded during the 16 yr of record (table 4). Daily precipitation of 2.5 cm or less accounted for 97 percent of the total number of rainfall events during the 16 yr being considered. The seasonal distribution of daily precipitation events of 2.5 cm or less at Lathrop Wells is shown in figures 12 and 13. In most years, these rains account for all the precipitation recorded at Lathrop Wells. The pattern is similar to that at Beatty, but there are fewer small rainfall events (0.6 cm or less) in July and August and more rainfall events producing 0.61 to 2.5 cm in March and April.

The total precipitation at Lathrop Wells amounted to 69 percent of the total recorded at Beatty during the 16 yr of concurrent record. The number of small storms (0.6 cm or less) at Lathrop Wells amounted to only 51 percent of the number of small storms at Beatty. The number of events producing 0.6 to 2.5 cm of rain at Lathrop Wells was 74 percent of the number of events of the same size at Beatty. The number of potentially significant precipitation events, those producing more than 2.5 cm of rain, was nearly the same at the two stations during the 16 yr being examined—five at Lathrop Wells and six at Beatty. Table 5 gives the date and magnitude of these events at Lathrop Wells. The event on November 6, 1960, is not included in table 4 because the records for that year are incomplete, but it is included in table 5 for comparison with events of similar size at Beatty.

Table 5. Date and magnitude of 24-hr precipitation events exceeding 2.5 cm at Beatty and Lathrop Wells, 1949–79

Date	Precipitation, in centimeters	
	Beatty	Lathrop Wells
February 27, 1949	3.71	3.56
May 18, 1949	(a)	3.25
March 15, 1952	2.54	(b)
November 11, 1954	4.06	2.67
November 6, 1960	3.25	2.85
February 10, 1968	4.19	(b)
November 7, 1969	2.54	(b)
February 21, 1970	2.69	(b)
October 4, 1972	3.05	3.30
September 9, 1975	4.39	(c)
February 7, 1976	3.23	4.85
February 9, 1976	(c)	4.85
September 10, 1976	3.07	(c)
May 9, 1977	3.33	(c)
August 17, 1977	4.45	5.72

a Missing record.
b Station not in operation.
c Precipitation less than 2.5 cm.

Temperature

Temperature is an indicator of the evaporative demands in the area at any given time and provides a guide to potential evaporation. Temperature also tends to show more areal uniformity over longer periods of time than precipitation, so that average temperature values have greater meaning than do average values of precipitation.

The seasonal distribution of mean monthly temperature at Beatty is shown in figure 14. The mean annual maximum daily temperature for the period 1949–79 is 25 °C. The mean annual minimum daily temperature is 6 °C, and the mean annual mean daily temperature is 15 °C. The mean daily maximum temperature exceeds 32 °C from June through September. The hottest month is July, with a mean daily maximum temperature of 37 °C; the mean daily minimum temperature for this month is 17 °C. Average daily minimum temperatures fall below 0 °C during December, January, and February. The coldest month is January, with a mean daily minimum temperature of −3 °C; several days in early January have long-term mean daily minimum temperatures below −5 °C.

The temperature distribution and ranges at Lathrop Wells (fig. 15) are similar to those at Beatty (fig. 14). The mean annual maximum daily temperature is 27 °C, the mean annual minimum is 8 °C, and the average annual mean daily temperature is 18 °C. The warmest month is July, having a mean daily maximum temperature of 39 °C and a mean daily minimum of 20 °C. The mean daily maximum temperature exceeds 32 °C from June through September. The coolest month is January, with a mean daily minimum temperature of −2 °C and a mean daily maximum of 14 °C. The average daily minimum temperatures drop below 0 °C during December, January, and February.

These temperature distributions and extremes are significant from the standpoint of evaporation demands. The warmest temperatures occur in the summer months, when precipitation is sparse and small rainfall events dominate. Evaporation demands are greatest during these months. The coolest months are the winter months, when much of the yearly rainfall occurs and when most of the major potentially significant precipitation events take

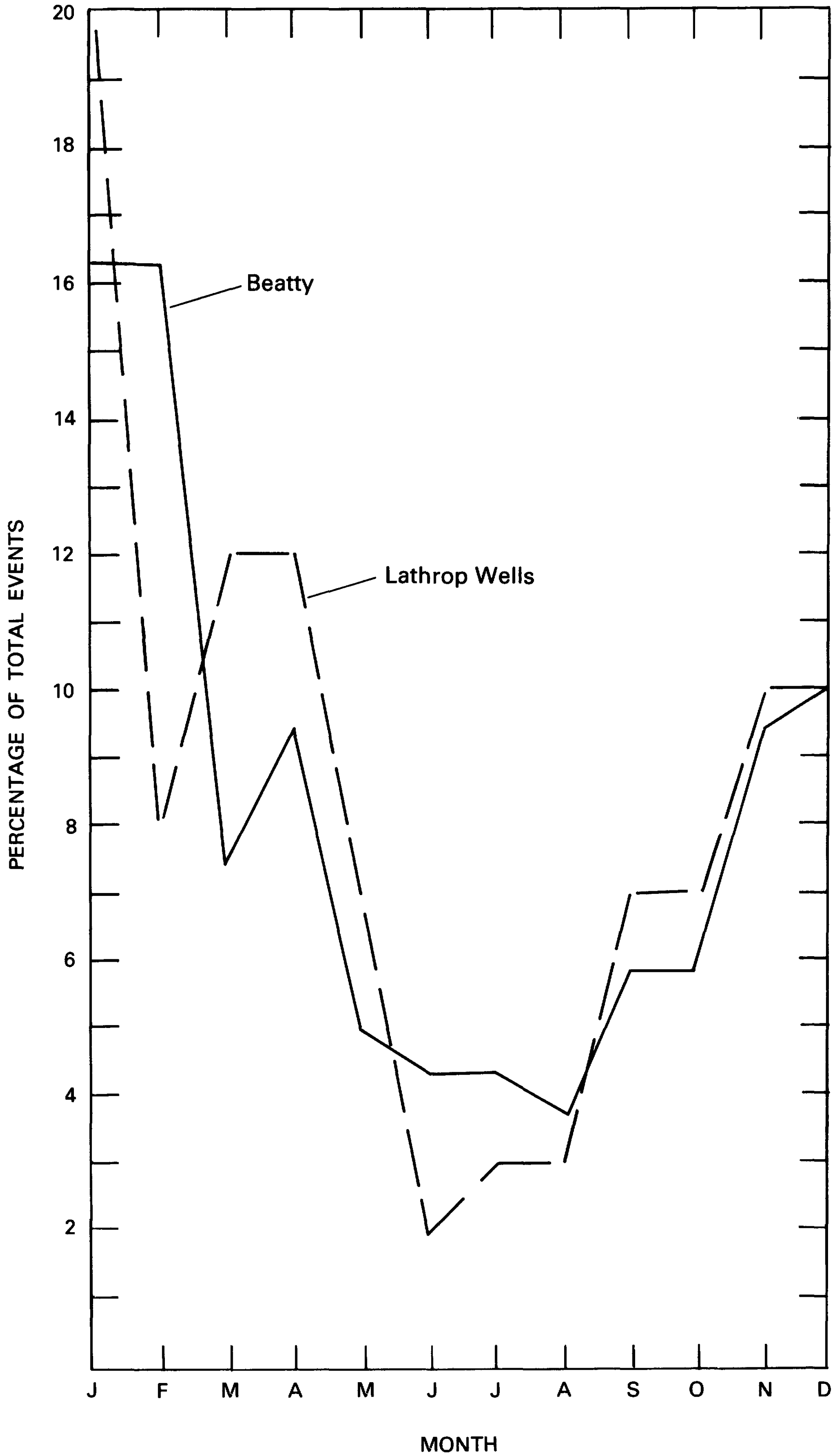

Figure 13. Monthly distribution of precipitation events of between 0.61 and 2.5 cm at Beatty and Lathrop Wells, 1949–76.

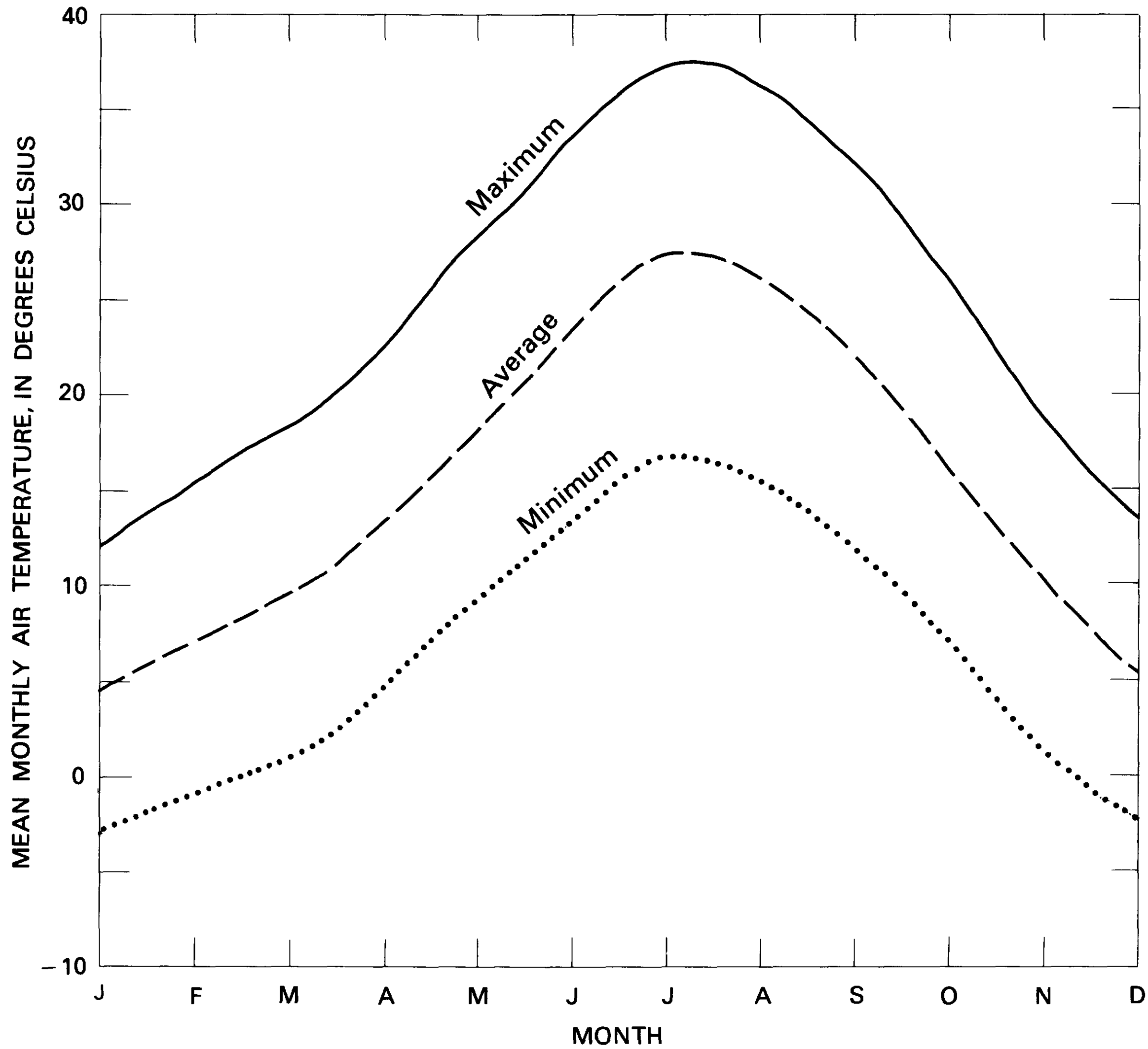

Figure 14. Mean monthly maximum, average, and minimum air temperatures at Beatty, 1949–76.

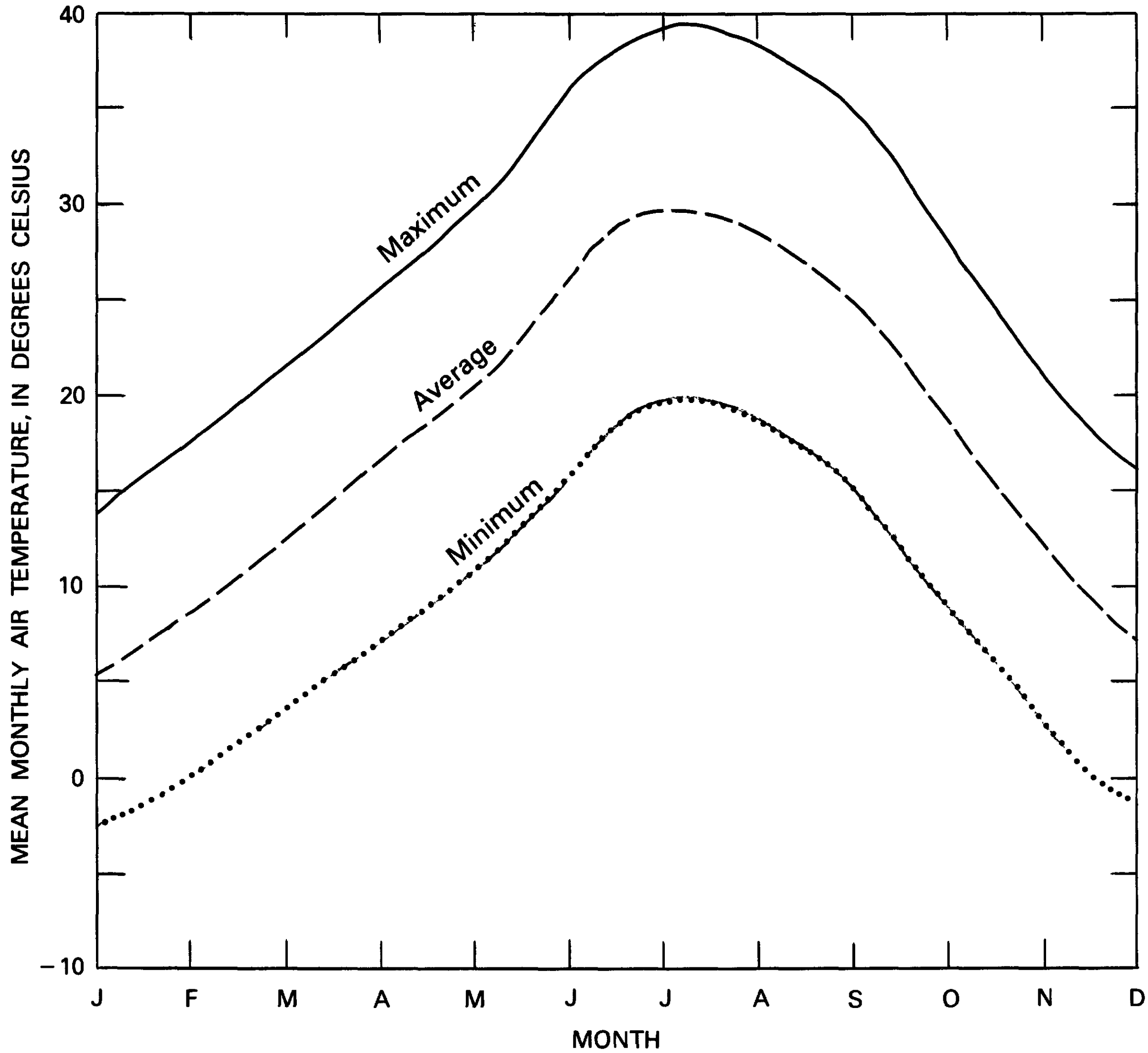

Figure 15. Mean monthly maximum, average, and minimum air temperatures at Lathrop Wells, 1949–76.

place. Evaporative demands are low during these months, and if enough precipitation falls to satisfy the soil-moisture deficit built up during the preceding summer, there is the potential for deep percolation.

Evaporation

Evapotranspiration, rather than just evaporation, is more commonly considered in investigations of this type because of the need to consider not only water lost directly from the soil by evaporation, but also moisture lost by plants through transpiration. Only evaporation is considered here, however, because the waste-burial site is kept cleared of vegetation and water is lost to the atmosphere only through evaporation from bare soil.

Many discussions of evaporation consider only pan evaporation or potential evaporation, usually because actual evaporation data are not available. Pan-evaporation and potential-evaporation rates can be useful guides to actual evaporation in some instances, but they are poor indicators in such an arid climate. Pan evaporation occurs at the potential, or energy-limiting, rate. As long as water is available, evaporation at this maximum rate will continue, and the purpose of the evaporation pan is to provide a continuous supply of water. Potential evaporation also is a measure of evaporation at the energy-limiting rate, but, rather than being measured directly, it is computed using climatic data. Pan evaporation in this part of Nevada probably exceeds 250 cm a year. Measured pan evaporation at Boulder City, 183 km southeast of the waste-burial site, is about 280 cm per year.

A number of equations have been developed to compute potential evaporation and potential evapotranspiration using a variety of meteorological or climatic data. Most equations have been developed to compute potential evapotranspiration from cropped surfaces using readily available meteorological data. Those equations developed for calculating potential evaporation from bare soil commonly require meteorological data that are not readily available, particularly in remote areas. Equations to estimate actual evaporation also require data that commonly are not available.

During the course of this investigation, meteorological data (described below) were collected at the study site for use in evaporation studies. Several equations were used to calculate actual evaporation for selected time periods of 5 to 15 days. Several other equations were employed to estimate long-term potential and actual evaporation on the basis of 28 yr of precipitation and temperature data from the Beatty weather station. The details of these computational procedures are discussed later in this report. The intent of an in-depth study of evaporation is not to calculate a precise annual total for a particular year or an accurate water balance for the area for an extended period, but rather to screen the available climatic data for the area since 1949 for potential "recharge-inducing" events on the basis of reasonable long-term estimates of evaporation. Because virtually no runoff occurs at the waste-burial site, the difference between precipitation and evaporation, once the soil-moisture deficit is satisfied, is considered to be the recharge that can percolate deep into the unsaturated zone. This approach to estimating long-term evaporation allows a reasonable upper limit to be set on the amount of recharge that might have occurred since the waste-burial facility was established in 1962, and it also identifies the times and conditions under which the recharge would have taken place. This approach is discussed in greater detail later in this report.

Mean monthly potential evaporation at Beatty from 1961 to 1976 is shown in figure 16. It ranges from 4 cm in December to 33 cm in July. The seasonal distribution can be compared with that of precipitation (fig. 9). Annual potential evaporation at Beatty for 1961 through 1976 is shown in figure 17. It ranges from 132 cm to 214 cm and averages 190 cm over the 16 yr. A comparison of the evaporation data in figure 17 and precipitation data in figure 8 clearly demonstrates the limited usefulness of potential-evaporation computations in constructing a water balance. In contrast to the monthly potential evaporation, estimated monthly actual evaporation from bare soil at the waste-burial site ranges from 0.4 cm in December to slightly less than 1.1 cm in February (fig. 18). The pattern of estimated actual evaporation is significantly different from that of potential evaporation. Maximum estimated actual evaporation occurs in February, when rainfall is most common and water is most readily available, and it generally declines through the rest of the year to a minimum in December. Mean annual estimated actual evaporation is 9 cm and ranged from 2 to 16 cm for the 16-yr period.

The precipitation record upon which these evaporation estimates were based is a modification of the record from the Beatty station. Comparison of the records from Beatty and Lathrop Wells indicates significantly fewer rainfall events in the size category 0.6 cm or less at Lathrop Wells than at Beatty, but Beatty has the more complete record as required for the analysis. Accordingly, the number of precipitation events recorded at Beatty that were equal to or less than 0.6 cm was reduced by 33 percent by arbitrarily deleting every third rainfall event of that size, which in turn resulted in a mean annual precipitation of 10 cm for the 16 yr of analysis, a reasonable average for the location of the waste-burial site. For the 16-yr period, the cumulative amount of estimated actual evaporation equaled 97 percent of cumulative precipitation. Likewise, the mean annual value for estimated actual evaporation equaled 97 percent of the

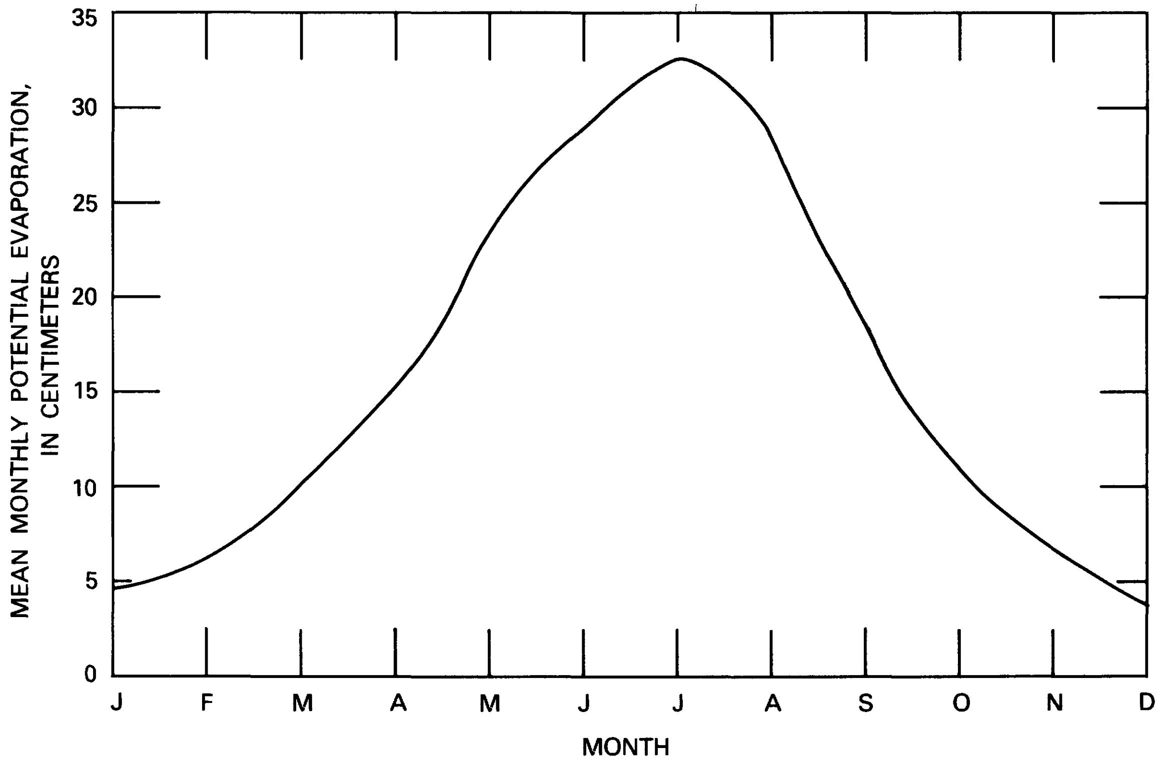

Figure 16. Mean monthly potential evaporation at Beatty, 1961–76.

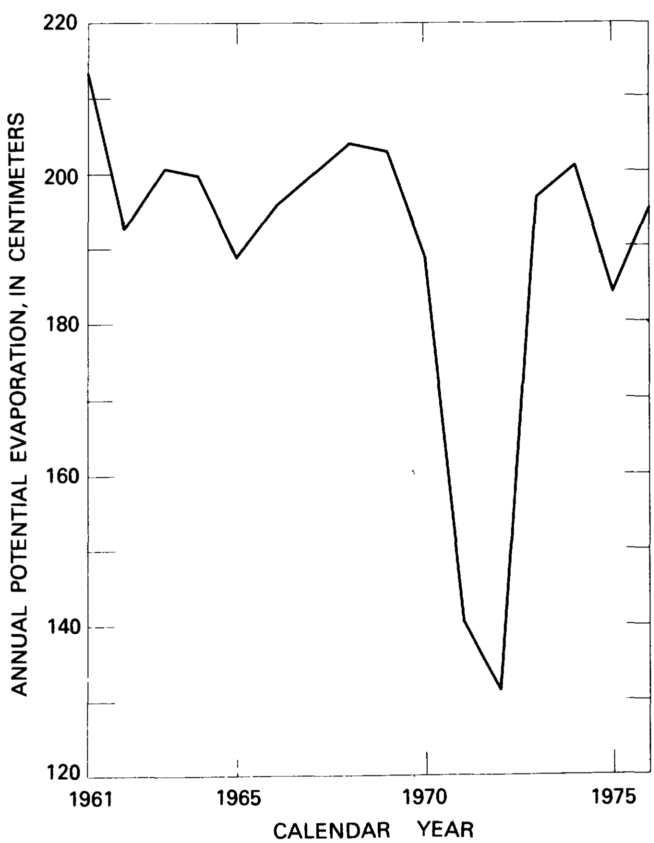

Figure 17. Annual potential evaporation at Beatty, 1961–76.

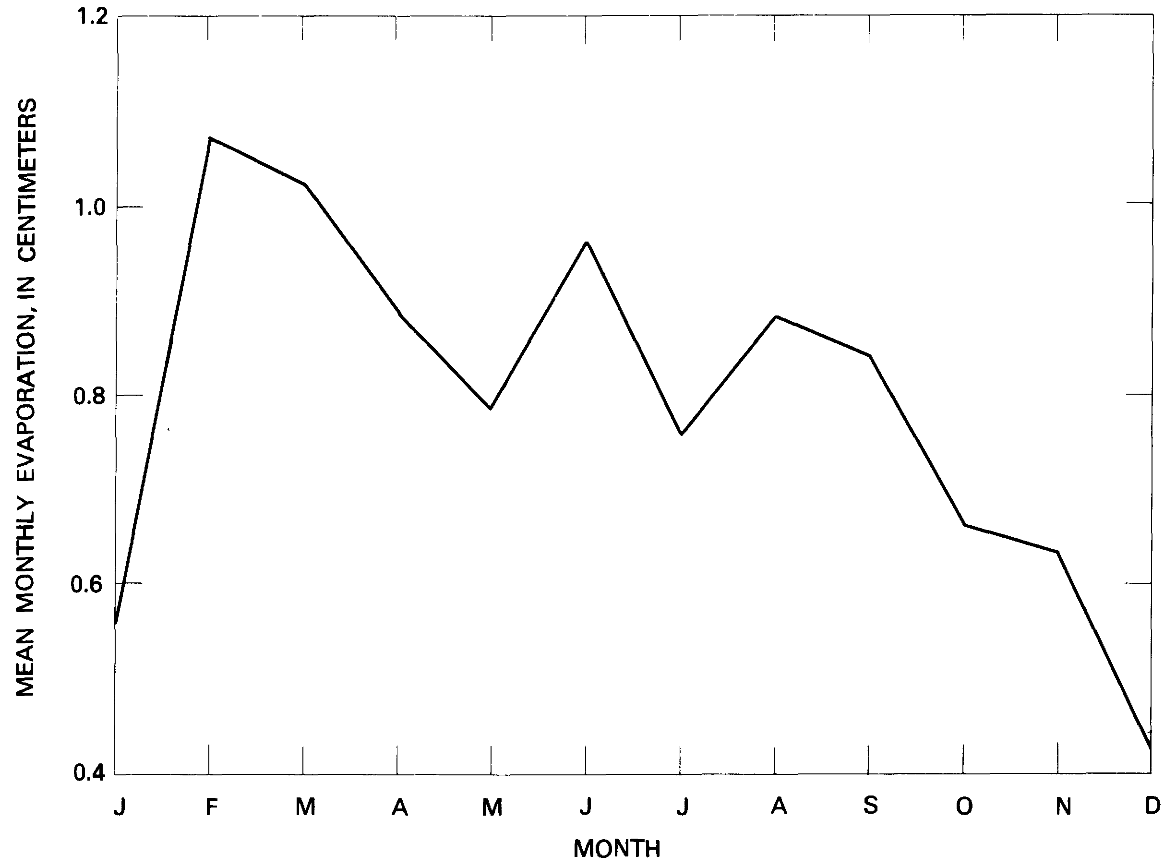

Figure 18. Estimated mean monthly actual evaporation from bare soil at waste-burial site, 1961–76.

mean annual rainfall. The remaining 3 percent (or 0.3 cm), which is within the limits of accuracy of the estimate, would represent potential mean annual recharge.

GEOHYDROLOGY OF THE UNSATURATED ZONE AT THE WASTE-BURIAL SITE

Geohydrologic studies at the waste-burial site have been confined to a detailed investigation of the top 10 m of the unsaturated zone. The intent is to provide a better basis for determining the potential for infiltration and deep percolation of precipitation; only deeply percolating rainfall can leach and transport radionuclides from the buried waste. Micrometeorological data (R.G. Brown, U.S. Geological Survey, written commun., 1985) were collected to better characterize the precipitation and evaporation conditions at the site. Soil-moisture profiles to a depth of 3.5 m were obtained monthly for a 15-mo period. Soil-water potential and soil temperature to a depth of 10 m were obtained over a 37-mo period.

Evaporation and the Potential for Recharge

Evaporation Studies

Micrometeorological data collected at the waste-burial site include (1) short-wave incoming solar radiation, (2) net radiation, (3) air and wet-bulb temperature at 1 and 0.5 m above land surface, (4) soil-heat flux, (5) soil temperature, and (6) precipitation. Data on windspeed and wind direction and reflected short-wave radiation were collected for a short time. The micrometeorological data were originally intended for use in calculating a rigorous water budget for the study site, but instrument failures leading to significant record gaps and the relatively short period of data collection (2 yr) for such a variable climate necessitated the use of other methods. Consequently, the data were used to calibrate a water-balance model developed by E.P. Weeks (U.S. Geological Survey, written commun., 1980) for estimating a long-term water budget.

Briefly, the model is used to compute, on days with precipitation, a value for daily potential evaporation which in turn is subtracted from the precipitation value. Precipitation in excess of potential evaporation is then assumed to replenish soil-moisture depletion; when the soil-moisture deficit is satisfied, the remaining moisture from precipitation is considered to be recharge. On days without precipitation, or when precipitation is less than the computed daily potential evaporation, the computed "actual" evaporation is subtracted from soil-moisture storage and the deficit increases accordingly. The major problem, then, is in computing a daily "actual" evaporation. An approach reported by Ritchie (1972) is used in the water-balance model for this application.

Estimated actual evaporation from bare soil is calculated in two stages. The first is a constant-rate stage in which evaporation is limited only by the supply of energy to the soil surface (termed the "energy-limiting" stage). The second stage is a falling-rate stage in which evaporation is limited by hydraulic properties of the soil and by climatic conditions (the "soil-limiting" stage). This approach allows evaporation to proceed at the energy-limiting, or potential, rate until the water content of the near-surface soil has decreased below a threshold value, at which time evaporation takes place at the soil-limiting rate.

Potential evaporation in the model is computed by the Jensen-Haise equation (Jensen, 1973, p. 73, 74), which was developed for well-watered crops with full cover in the Western United States; although not strictly applicable to the present situation, the equation is believed to give the best approximation for the available data. Potential evaporation, using the Jensen-Haise equation, is given by

$$E_{TP}=C_T\,(T-T_x)\,R_s, \qquad (1)$$

where

E_{TP}= potential evapotranspiration as defined for alfalfa, in centimeters per day,
C_T= temperature coefficient (see below),
T= mean air temperature, in degrees Celsius,
T_x= intercept of the temperature axis (see below), and
R_s= solar radiation, in calories per square centimeter per day.

The temperature coefficient is given by the equation

$$C_T=\frac{1}{C_1+C_2C_H}, \qquad (2)$$

where

C_1= 38−2(A/305), in degrees Celsius,
A= altitude, in meters above sea level,
C_2= 7.6 °C, and
$C_H=\frac{50 \text{ millibars}}{e_2-e_1}$, in which e_2 is the saturation vapor pressure at mean maximum temperature for the warmest month and e_1 is the saturation vapor pressure at mean minimum temperature for the warmest month, both in millibars.

The temperature-axis intercept is given by

$$T_x=-2.5-[0.14(e_2-e_1)T/P]-A/550, \qquad (3)$$

where

T= temperature, in degrees Celsius, and
P= pressure, in millibars.

Long-term data on daily temperature from the National Weather Service station near Beatty and long-term average solar radiation from Las Vegas (fig. 19), 185 km southeast of Beatty, are used to solve the Jensen-Haise equation. The equation may underestimate potential evaporation from bare soil because it was developed to estimate potential evapotranspiration from an alfalfa reference crop. The leaf canopy of alfalfa is sufficiently dense to absorb most of the solar radiation before it reaches the soil surface. This is not especially critical in the present application because evaporation at the potential rate is considered to occur only on days when there is precipitation, and at Beatty this happens, on average, 20 days/yr. Evaporation on nonprecipitation days is the dominant factor. Use of the term "evaporation" henceforth should be understood to mean actual evaporation.

Estimated evaporation from bare soil on days without precipitation was calculated at the soil-limiting rate, provided the water available for energy-limiting evaporation, assumed to be 1 cm, had been exhausted. Following Black and others (1969), Ritchie (1972) computed the cumulative evaporation since the beginning of soil-limiting, or stage 2, drying with the following equation

$$\Sigma E_{s_2}=Ct^{1/2}, \qquad (4)$$

where

E_{s_2}= evaporation rate from bare soil during stage 2 drying, in centimeters per day,
C= coefficient dependent on climate and the hydraulic properties of the soil, in centimeters, and
t= time since the beginning of stage 2 drying, in days.

Black and others (1969) defined the coefficient C as

$$C=2(\theta_i-\theta_0)(D/\pi)^{1/2}, \qquad (5)$$

where

θ_i= initial water content at time t=0, in centimeters,
θ_0= water content at the surface at t>0, in centimeters, and
D= soil-water diffusivity, in square centimeters per day.

Ritchie (1972) assumed that C is independent of climate and is a function of soil hydraulic properties only, but

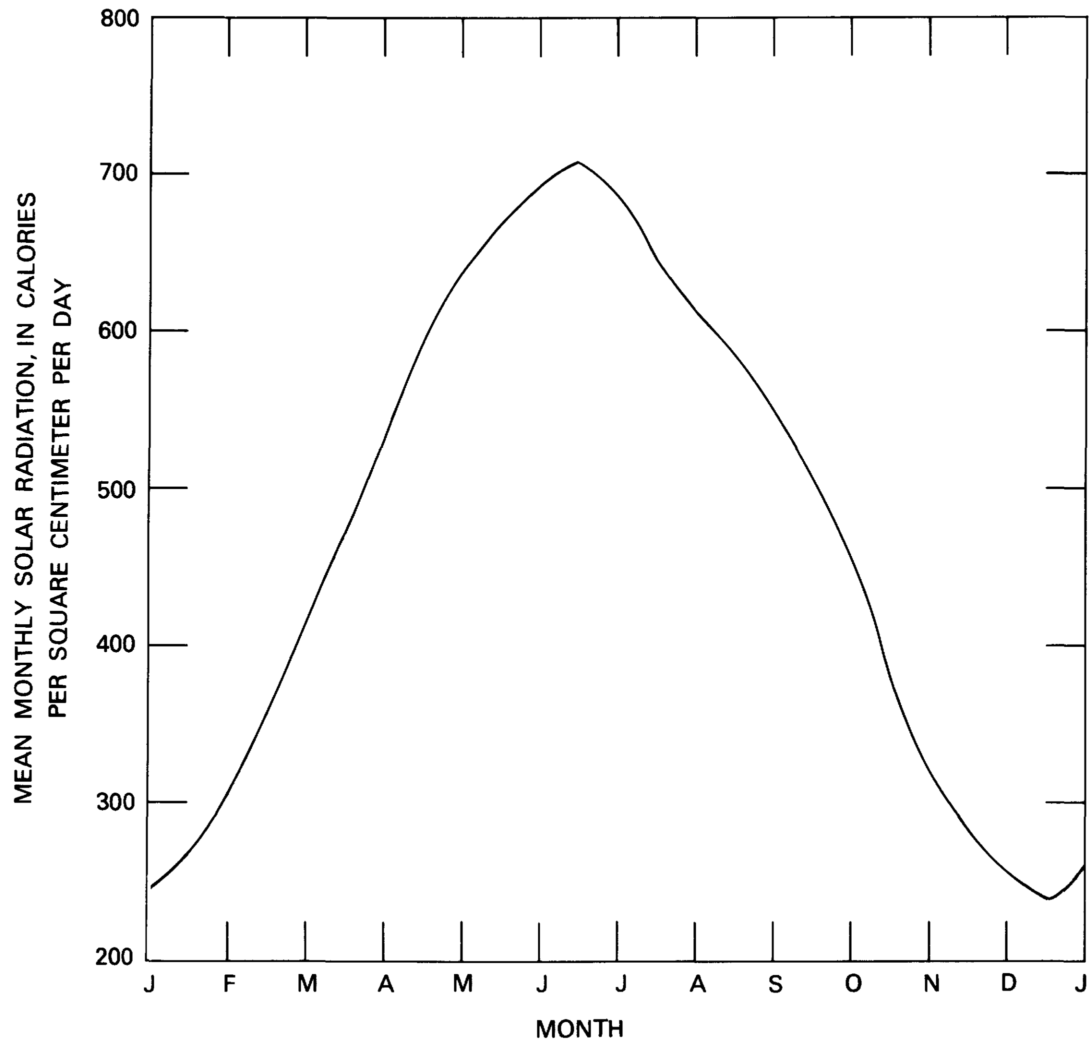

Figure 19. Mean monthly solar radiation at Las Vegas, 1955–75.

Jackson and others (1976) show that *C* also can be correlated with temperature using the normalized temperature dependence of water-vapor diffusion in soil, and thus is a function of climate (represented by temperature) as well as soil properties. Analysis of the parameter *C*, using data collected at the waste-burial site during this investigation, is in accord with the conclusions of Jackson and others (1976), as is shown below.

Data were selected for two time periods to investigate the parameter *C*. The periods July 21 through August 2, 1979, and January 31 through February 13, 1980, were selected for their representation of seasonal extremes. In both periods, rainfall occurred on the first day. The data are given in table 6.

Daily evaporation rates were computed using the energy-balance equation

$$LE = R_n - H - G, \qquad (6)$$

where

LE = the latent heat flux, in calories per square centimeter per day (E=evaporation rate, in centimeters per day, and L=latent heat of vaporization, in calories per gram),

R_n = net radiation,

H = sensible heat flux, and

G = soil-heat flux, all in calories per square centimeter per day.

Rearranging terms (Wilson and Rouse, 1972) so that H is divided by LE, gives

$$LE = (R_n - G)/(1 + H/LE), \qquad (7)$$

where $H/LE = \beta$, which is the Bowen ratio. Both R_n and G can be readily measured, and β can be determined by

$$\beta = \gamma(\Delta T/\Delta e), \qquad (8)$$

Table 6. Meteorological data for waste-burial site during July 21 through August 2, 1979, and January 31 through February 13, 1980

[R_n=net radiant energy of all wavelengths, in calories per square centimeter per day; T_1=air temperature at 1 meter, T_{w1}=wet-bulb temperature at 1 meter, T_2 = air temperature at 0.5 meter, and T_{w2}=wet-bulb temperature at 0.5 meter, all in degrees Celsius; G=soil-heat flux, in calories per square centimeter per day]

Date	R_n	T_1	T_{w1}	T_2	T_{w2}	G
1979[a]						
July 21	313.8	25.3	19.3	25.6	19.5	6.0
22	285.6	28.2	18.0	28.7	18.3	37.8
23	286.2	31.1	17.9	32.2	18.5	48.0
24	258.6	31.3	17.0	32.1	17.0	40.8
25	253.8	32.2	16.9	33.0	17.3	32.4
26	228.6	32.5	15.9	33.4	16.3	27.0
27	221.8	32.3	15.6	33.0	15.9	18.0
31	228.6	30.5	14.4	31.4	14.8	18.6
Aug. 2	208.8	31.6	14.1	32.2	14.4	15.0
1980						
Jan. 31	37.2	6.8	4.0	7.0	3.9	-9.6
Feb. 1	98.4	9.3	5.2	9.4	4.9	21.0
2	79.2	11.4	6.7	11.5	6.7	19.8
3	33.0	11.0	6.8	10.9	6.6	-1.2
4	78.0	12.7	7.0	12.8	6.8	18.6
5	40.8	11.7	6.0	11.8	6.0	7.2
6	67.8	14.0	6.0	13.9	5.9	18.6
7	1.8	9.9	3.6	10.1	3.5	-6.6
8	72.0	10.0	3.0	10.1	3.1	2.4
9	74.4	6.3	0.9	6.2	0.5	4.2
10	57.0	6.0	0.8	6.0	0.3	5.4
11	81.0	6.5	1.0	6.4	0.8	13.8
12	-37.8	5.5	0.5	5.6	0.6	-36.6
13	-96.0	5.5	3.3	5.4	2.5	-15.0

[a] No data available for July 28-30 and August 1.

where

γ= psychrometric constant, in millibars per degree Celsius,

ΔT= difference in air temperature between two vertical measurements at a given time, in degrees Celsius, and

Δe= difference in vapor pressure between two vertical measurements at a given time, in millibars.

The temperature difference, ΔT, between two levels is measured. Δe is calculated from wet-bulb temperature measurements as follows (Wilson and Rouse, 1972):

$$\Delta e=(S'+\gamma)\Delta T_w-\gamma\Delta T \qquad (9)$$

where

S'= slope of the curve for saturation vapor pressure versus wet-bulb temperature at the mean wet-bulb temperature (that is, de_s/dT at $\overline{T}_w$), and

ΔT_w= difference in wet-bulb temperature, in degrees Celsius.

Finally, the evaporation rate, E, is determined by dividing the energy-balance equation by the latent heat of vaporization, L, which leads to

$$E=(R_n-G)/L\rho_w(1+\beta), \qquad (10)$$

where

L= 595.9−0.545T (T=air temperature, in degrees Celsius),

E= evaporation rate, in centimeters per day,

L= latent heat of vaporization, in calories per gram, and

ρ_w= density of water, in gram per cubic centimeter.

Evaporation computed by this equation is given in table 7.

Table 7. Evaporation at waste-burial site during July 21 through August 2, 1979, and January 31 through February 13, 1980
[All values in centimeters]

Date	Evaporation: Bowen-ratio equation	Evaporation: Best fit curve, figures 20 and 21	Cumulative evaporation from best fit curve, figures 22 and 23
1979			
July 21	0.2526	0.2440	0.2440
22	.1808	.1850	.4290
23	.1670	.1600	.5890
24	.1348	.1385	.7275
25	.1232	.1225	.8500
26	.1102	.1085	.9585
27	.0997	.0960	1.0545
28	--	.0860	1.1405
29	--	.0780	1.2185
30	--	.0700	1.2885
31	.0603	.0640	1.3525
Aug. 1	--	.0580	1.4105
2	.0519	.0530	1.4635
1980			
Jan. 31	.1598	.1600	.1600
Feb. 1	.1497	.1420	.3020
2	.0063	.1260	.4280
3	.0442	.1140	.5420
4	.1196	.1020	.6440
5	.1050	.0920	.7360
6	.0839	.0840	.8200
7	.0260	.0720	.8920
8	.0782	.0650	.9570
9	.1034	.0590	1.0160
10	.0865	.0540	1.0700
11	.0977	.0485	1.1185
12	--	.0440	1.1625
13	.0426	.0420	1.2045

Calculated daily evaporation was plotted (figs. 20, 21) and a smooth curve fitted, by eye, to the data points. Revised (or estimated) daily evaporation was obtained from this curve (table 7). Stage 2 evaporation was assumed to have begun on the first day of each of the periods analyzed. In fact, even though rain preceded the period of analysis, stage 1, or energy-limiting, evaporation may not have taken place. The transition from stage 1 to stage 2 evaporation as described by Ritchie (1972) was not observed in the plot of cumulative evaporation as a function of time (figs. 22, 23).

The cumulative evaporation values were then plotted as a function of the square root of time (figs. 24, 25), following the example of Ritchie (1972, fig. 4), and a straight line was fitted to the data; in fitting the line, greatest weight is given to cumulative evaporation values toward the end of the selected time period. The slope of this straight line is equal to *C* in Ritchie's equation. The value for the June–August period is equal to 0.41 cm, and the value for the January–February period is equal to 0.32 cm. These are well within the range of values for *C* reported by Ritchie (1972) but higher than the temperature-dependent values suggested by Jackson and others (1976, fig. 2). Jackson and his coworkers (1976) calculated *C* values for five sets of evaporation data and plotted them as a function of temperature. The data

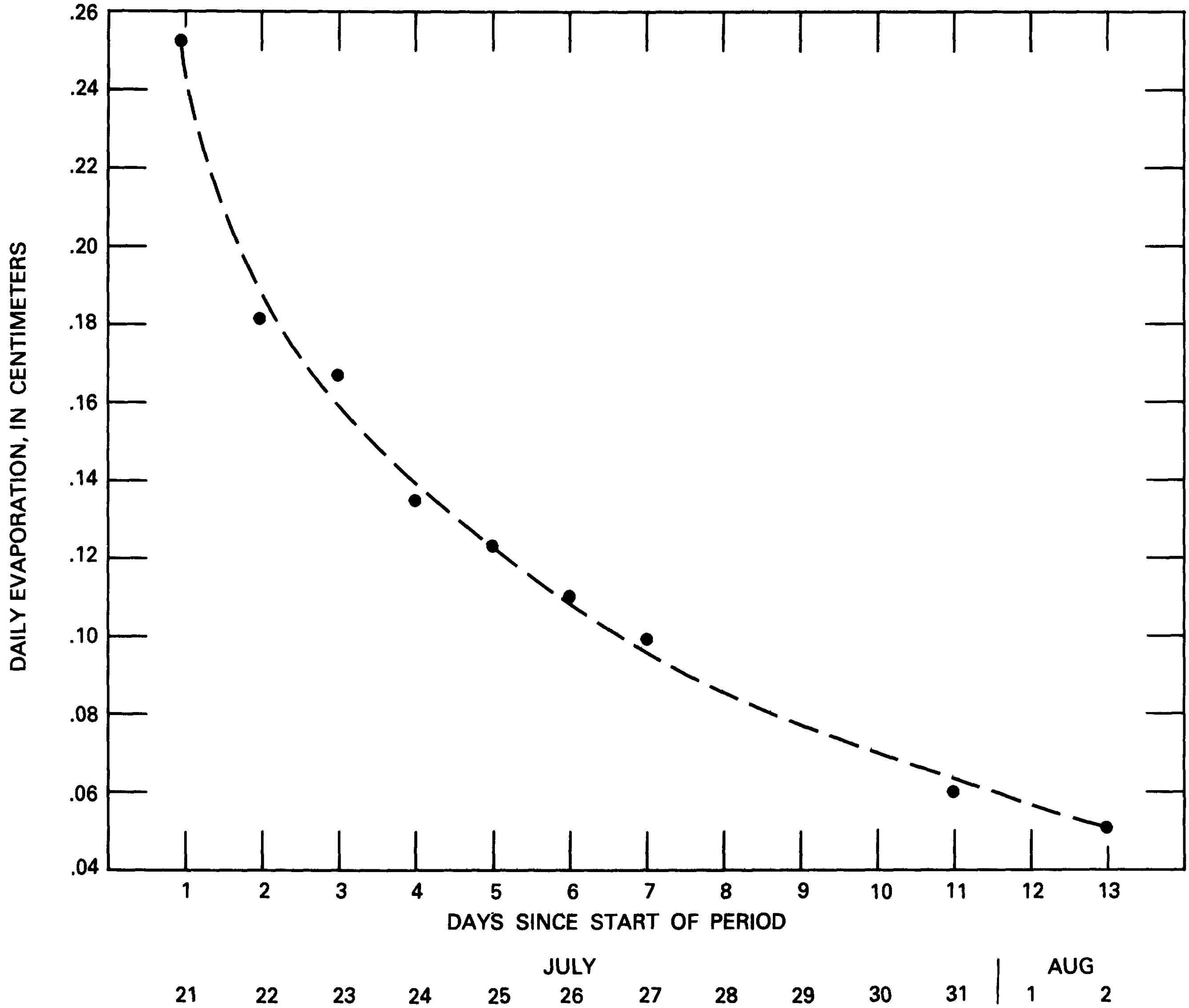

Figure 20. Calculated daily evaporation at waste-burial site, July 21 through August 2, 1979. Dashed line is "visual best fit."

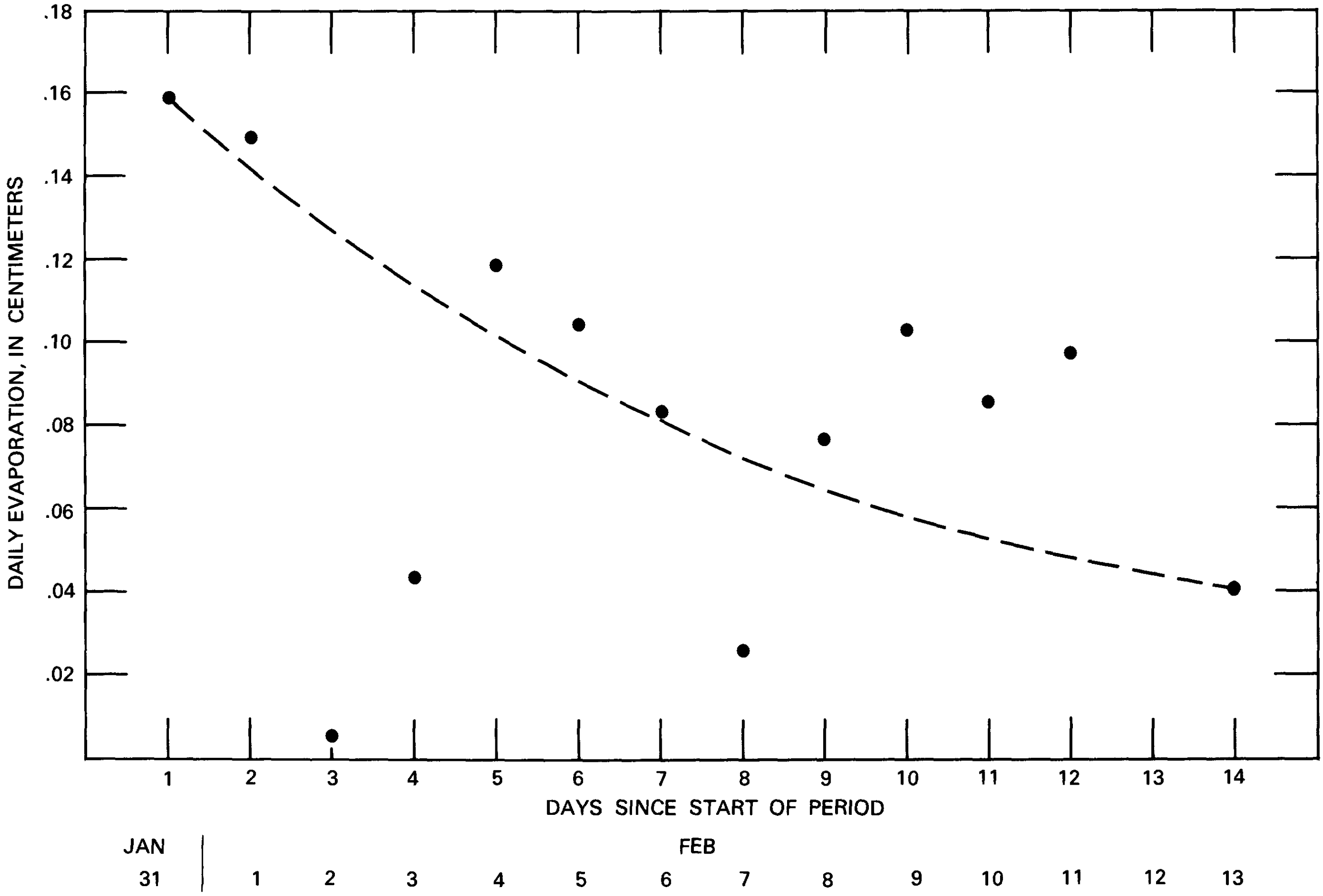

Figure 21. Calculated daily evaporation at waste-burial site, January 31 through February 13, 1980. Dashed line is "visual best fit."

points all fall very close to the curve of the calculated normalized temperature dependence of water-vapor diffusion in soil. This curve is shown in figure 26, and the *C* values calculated from data collected at the waste-burial site are plotted for comparison.

Estimates of Long-Term Evaporation

Long-term evaporation was calculated with the water-balance computer program using several different values for the coefficient *C*. None of the solutions was entirely satisfactory. The program was then modified to allow for the seasonal variation of *C* as a function of mean daily temperature. An equation determined for the curve in figure 26 from Jackson and others (1976) was used initially. The coefficients computed with this equation-calculated too little evaporation and a maximum soil-moisture deficit that was considered too small on the basis of available soil-moisture field data. A new equation was obtained by an upward shift of the curve of Jackson and others (1976) toward the range of *C* values obtained from field data at the waste-burial site. This curve is shown by the dashed line in figure 26.

The water-balance model, like the procedures of Ritchie (1972) and Jackson and others (1976), has been tested only for agricultural conditions and has not been applied to an arid area such as the Amargosa Desert. In this investigation, the model is not used to calculate a precise annual evaporation and water budget for the area, but rather to screen the available climatic data for the area since 1961 for potential recharge events. By varying the value of *C* and the threshold soil-moisture deficit within reasonable limits, the precipitation events that might lead to recharge can be identified and their possible significance with respect to potential radionuclide migration can be assessed.

Table 8 gives the computed annual evaporation for three different values of *C*. The "low" estimate of evaporation is for the low values of *C* from Jackson and others (1976), as indicated by the solid line in figure 26. The "high" and "intermediate" estimates of evaporation are for the high and intermediate values of *C* based on the dotted and dashed curves, respectively, in figure 26. The *C* values obtained from data collected at the waste-burial site are closer to the curve used in obtaining the high estimates. The major difference between the high and intermediate estimates is in the evaporation calculated for 1968 and 1976.

Implications Regarding Recharge

The analysis suggests that recharge could have occurred in February 1968, March 1973, and February 1976. The 1968 event seems to have been the result of two factors: (1) above-average and frequent rainfall in 1967 and (2) a heavy storm in February 1968. The pattern and magnitude of precipitation in 1967 (table 9) kept soil-moisture depletion at a moderate level throughout 1967 and into early 1968, so that when intense rain (5.46 cm at Beatty) fell on February 9 and 10, 1968, a great potential existed for deep percolation. The computed potential recharge in 1968 was about 2.2 cm.

A different sequence of events in 1972 and 1973 led to computed potential recharge in March 1973. Very little rain fell throughout 1972, resulting in a fairly significant soil-moisture deficit by year's end. However, a series of storms, which produced an estimated 2.2 cm of rain in January, 4.6 cm in February, and 4.5 cm in March 1973, resulted in a computed potential recharge of 0.5 cm.

Conditions in 1975–76 leading to potential recharge were similar to those for 1967–68. Moderate rains during the last 4 mo of 1975 held the soil-moisture deficit to an intermediate level. Then, a series of storms extending from February 6 through February 10 produced an estimated 7.5 cm of rain, including 3.2 cm on February 7. These rains were enough to satisfy the soil-moisture deficit and still provide a computed potential recharge of about 2.6 cm.

These calculations of long-term evaporation and recharge, though only estimates, strongly suggest that the potential for recharge, or deep percolation, exists in the area of the waste-burial facility. The calculations also define the types of events and conditions that might eventually lead to deep percolation. Obviously, such a simplistic approach does not accurately simulate the interrelation of precipitation, evaporation, infiltration, and deep percolation, but it does provide a reasonable qualitative framework for further theoretical studies. Note, however, that if vegetation is present, recharge is unlikely. Filled and decommissioned waste-burial sites commonly are landscaped with native or other vegetation that, under the conditions at the site near Beatty, would provide a major buffer to deep percolation.

Water Content and Soil-Moisture Profiles

Detailed field investigations of soil-moisture content and soil-water potential were made at the site from 1978 to 1980. These studies concentrated on the upper 4 to 10 m of the undisturbed stratigraphic sequence. Similar studies on a disturbed sequence of material representative of trench backfill were not made because of the lack of a suitable site.

The shallow subsurface stratigraphy is relatively uniform beneath the area covered by the waste-burial site. Briefly, a thin gravel pavement on the ground surface is underlain by a very fine silty sand that extends from land surface to a depth of about 0.75 m. This is underlain by a coarse sandy gravel, with cobbles, from 0.75 m to about 2.5 m, which is in turn underlain by a dense, poorly

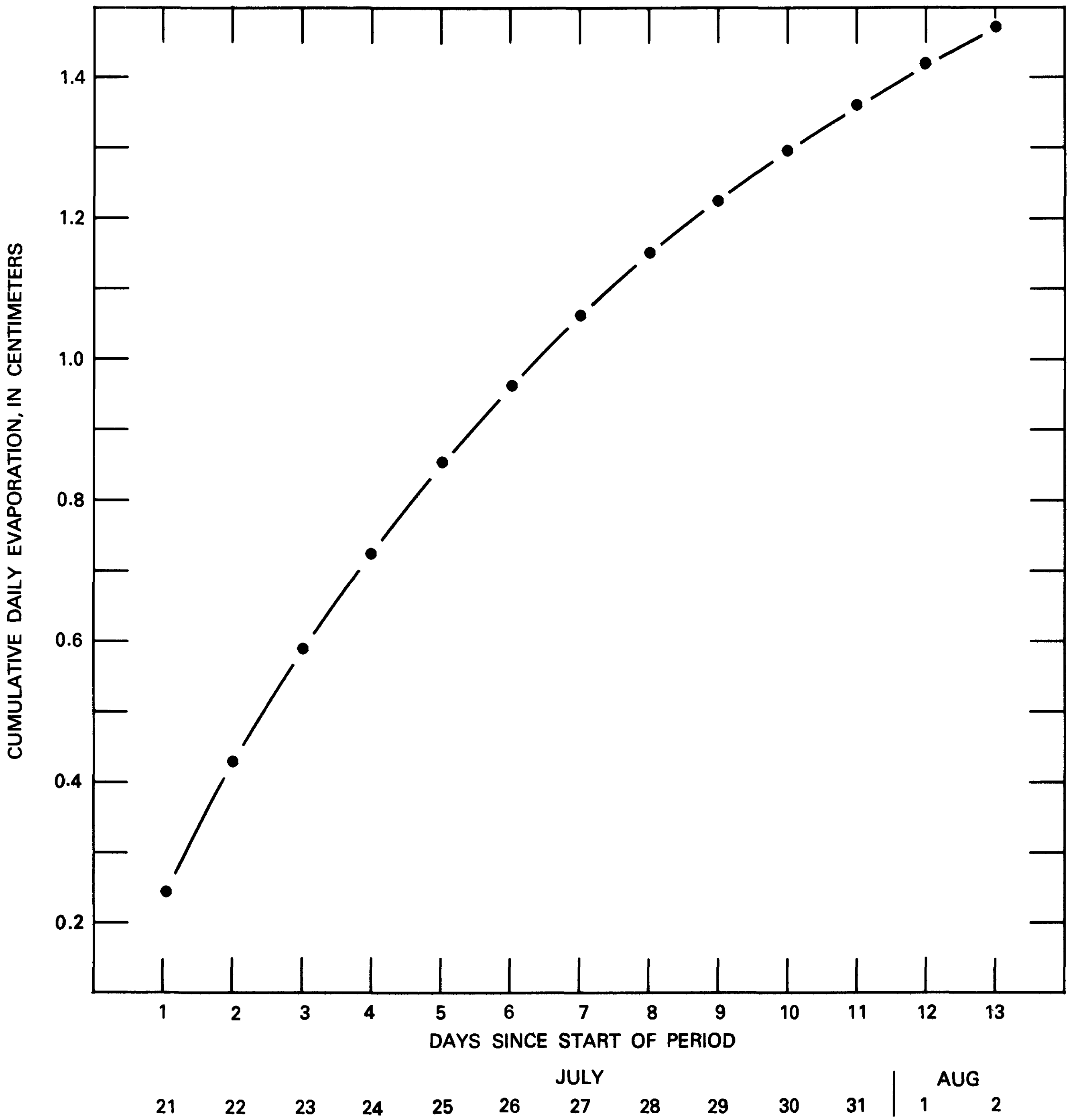

Figure 22. Cumulative daily evaporation at waste-burial site, July 21 through August 2, 1979.

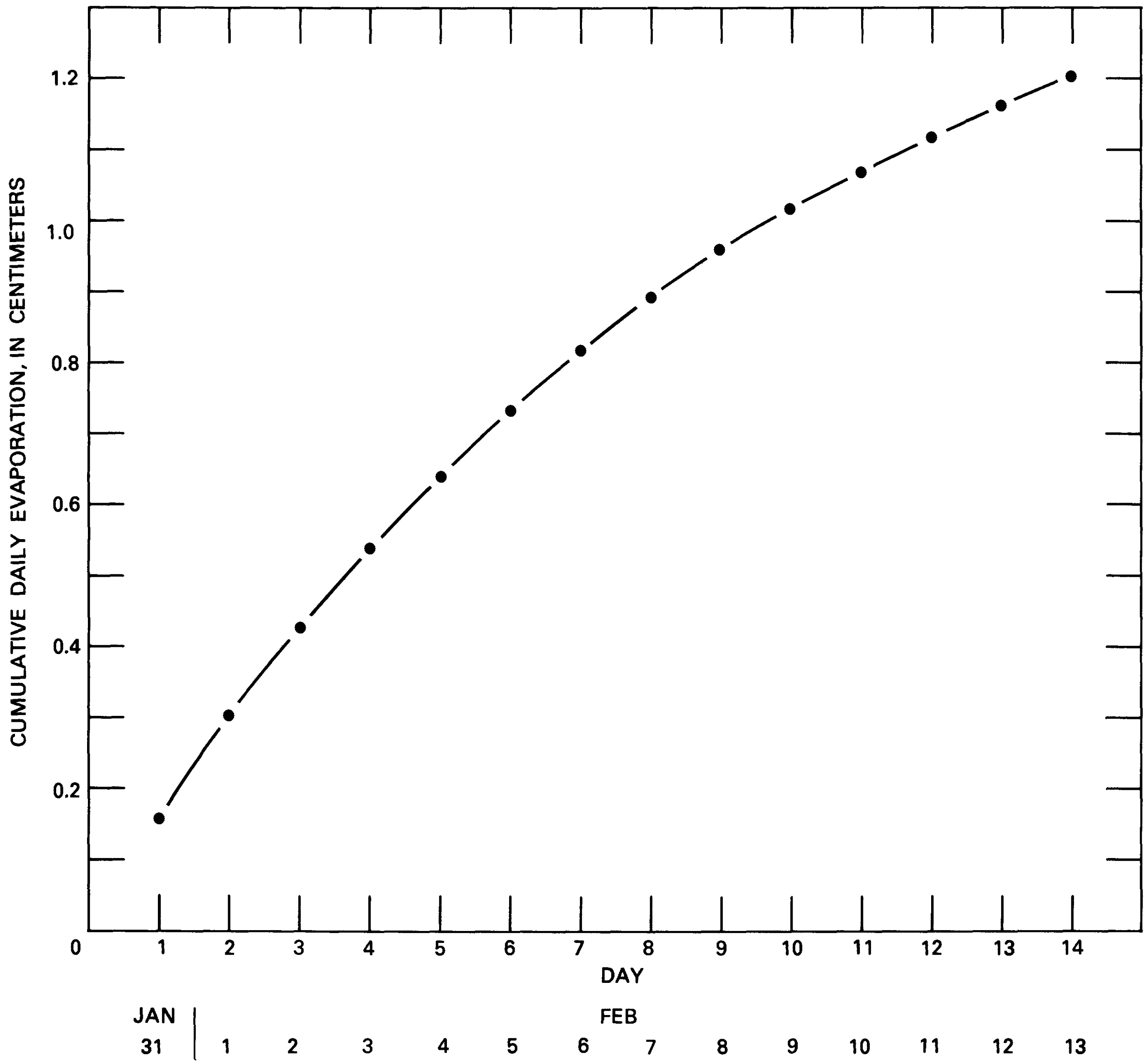

Figure 23. Cumulative daily evaporation at waste-burial site, January 31 through February 13, 1980.

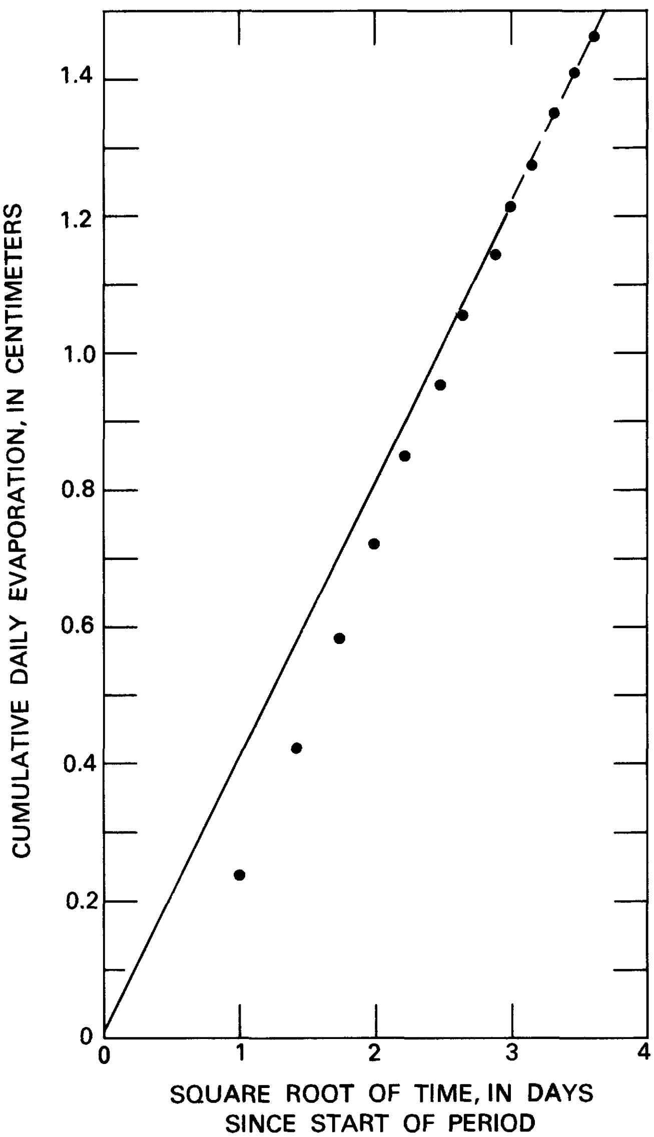

Figure 24. Cumulative daily evaporation versus square root of time, in days since start of period, July 21 through August 2, 1979.

cemented sand to silty sand, with some gravel, cobbles, and a few boulders, from 2.5 m to about 10 m. The stratigraphy below this depth is uncertain, but observations in one trench excavated to 15 m indicate a 1-m-thick layer of coarse sandy gravel, similar to that seen from 0.75 to 2.5 m, underlain by the same type of sediments seen in the interval from 2.5 to 10 m. This sequence is shown diagrammatically in figure 27.

Volumetric water content has been determined for core samples collected to depths of 11 m (table 10), and neutron soil-moisture profiles have been obtained to depths of 3.8 m (fig. 28). Water content to a depth of 0.5 m ranged from 4.5 percent, following lengthy dry spells, to 18 percent after heavy winter rains. The water content of the sediments below 0.5 m is fairly constant, ranging from about 6 to 10 percent. There was no change observed in water content of sediments below 2 m from February 1979 to May 1980.

Cores were collected during the drilling of a deep instrumentation shaft and neutron access holes. The cores were used to determine volumetric water content, using standard oven-drying techniques, to obtain general information on moisture content, and to calibrate the neutron moisture-meter (Troxler, model 104A[2]) used in obtaining moisture profiles. Water content of the samples is given in table 10.

Thin-walled aluminum access tubes for the neutron probe were installed to a depth of 10 m in August 1977. Attempts to obtain moisture-profile logs from these holes

---

[2] The use of trade names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

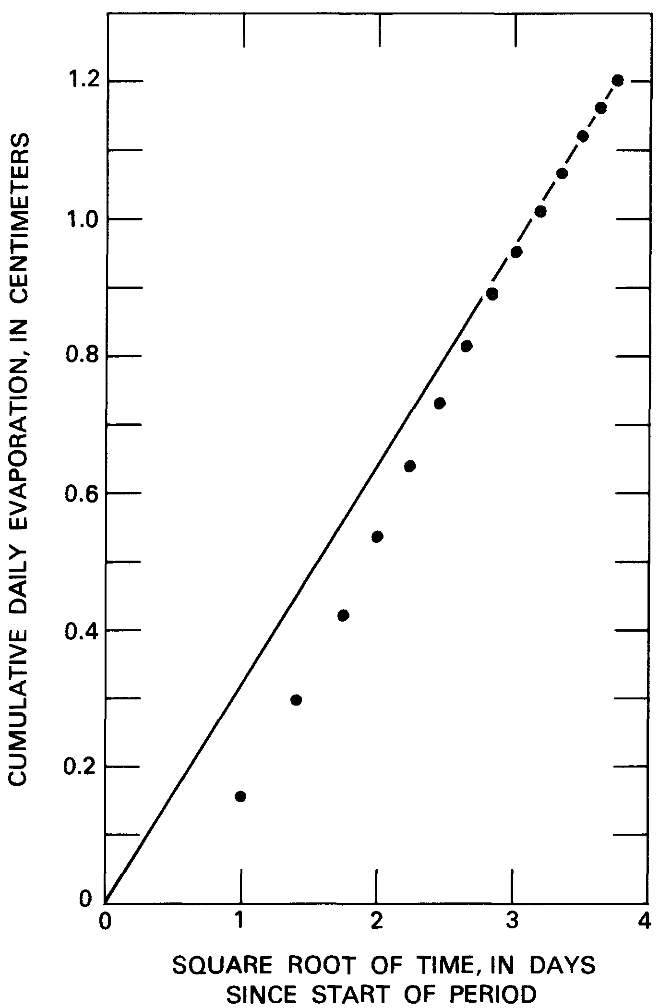

Figure 25. Cumulative daily evaporation versus square root of time, in days since start of period, January 31 through February 13, 1980.

in February 1978 disclosed that all three tubes had been damaged during installation. Replacement tubes to a depth of 3.5 m were installed in January 1979. Profiles were obtained on a nearly monthly schedule until May 1980. Selected profiles are shown in figure 28.

Comparison of the profiles for February 27, 1979, and February 26, 1980 (fig. 28*D*), indicate a downward redistribution of moisture to a depth of about 2 m—nearly to the base of the coarse sandy gravel layer (fig. 27). The change in moisture content between 0.9 and 2.4 m is equivalent to about 0.9 cm of water and represents a total change in water content of 7.9 percent. Examination of several pairs of moisture-content profiles for shorter time periods (not shown) indicates that most of the downward redistribution had occurred by May 1979 (fig. 28*A*) and that the greatest change took place between April 12 and May 23. Additional downward movement took place between May 23, 1979, and February 26, 1980 (fig. 28*B*). However, between February 26 and May 28, 1980, the moisture profile changed little if any below 0.6 m (fig. 28*C*), the approximate depth to the top of the coarse sandy gravel layer. No change of water content below 2.4 m was observed from February 1979 to May 1980.

Considered in the light of the precipitation record from January 1979 to May 1980 (R.G. Brown,

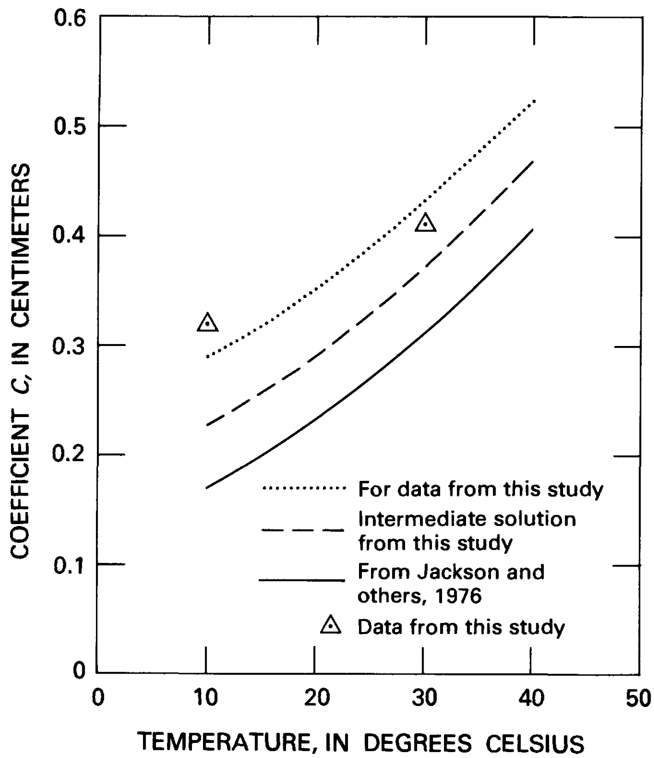

Figure 26. Temperature dependence of the coefficient *C*.

Table 8. Estimates of annual evaporation and potential annual recharge at waste-burial site for three ranges of the coefficient *C* (fig. 26)
[All values in centimeters]

		Low			Intermediate			High		
Year	Annual precipitation	Annual evaporation	Annual recharge	SMD[1]	Annual evaporation	Annual recharge	SMD[1]	Annual evaporation	Annual recharge	SMD[1]
1961	6.91	8.86	1.17	4.19	8.19	0.00	4.83	6.68	0.00	4.77
1962	6.07	7.11	.00	5.23	8.20	.00	6.96	8.26	.00	6.96
1963	12.24	9.94	.00	2.93	9.77	.00	4.49	10.16	.00	4.87
1964	3.05	5.37	.00	5.25	5.05	.00	6.95	5.47	.00	7.30
1965	13.39	9.40	.00	1.26	9.23	.00	2.79	10.43	.00	4.34
1966	7.21	6.97	.54	1.56	6.86	.00	2.43	7.15	.00	4.28
1967	11.10	12.57	.00	3.02	11.27	.00	2.60	12.97	.00	6.15
1968	11.30	10.54	1.79	4.05	11.77	2.18	5.26	10.36	.00	5.20
1969	14.53	11.84	1.56	2.92	13.17	.00	3.89	13.97	.00	4.65
1970	6.71	7.85	.07	4.14	6.61	.00	3.08	5.80	.00	3.37
1971	2.24	1.45	.00	3.35	2.32	.00	3.89	2.25	.00	3.74
1972	.61	2.79	.00	5.53	2.06	.00	5.34	2.88	.00	6.01
1973	16.33	13.66	.78	3.65	15.26	.50	4.77	15.90	0.40	5.98
1974	12.60	11.15	.30	2.50	12.12	.00	4.29	12.74	.00	6.12
1975	9.37	7.90	.00	1.02	8.63	.00	3.55	9.00	.00	5.74
1976	18.75	14.71	5.23	2.21	16.26	2.57	3.64	17.70	.29	4.99

[1] SMD = Soil-moisture deficit at end of calendar year.

Table 9. Estimated monthly precipitation for selected years at waste-burial site

[All values in centimeters]

Month	1967	1968	1972	1973	1975	1976
January	0.89	0.00	0.00	2.21	0.00	0.00
February	.00	6.27	.00	4.65	.20	7.54
March	.00	.91	.00	4.55	1.32	.00
April	2.41	.86	.00	.00	.56	.84
May	1.37	.00	.00	1.47	.03	.05
June	.74	1.80	.00	.36	.00	.58
July	.00	.56	.00	.00	.20	3.68
August	1.83	.13	.38	.86	.00	.00
September	1.24	.00	.00	.00	5.54	4.42
October	.00	.63	.00	1.04	.43	1.60
November	2.62	.00	.23	.89	.58	.03
December	.00	.13	.00	.30	.51	.00

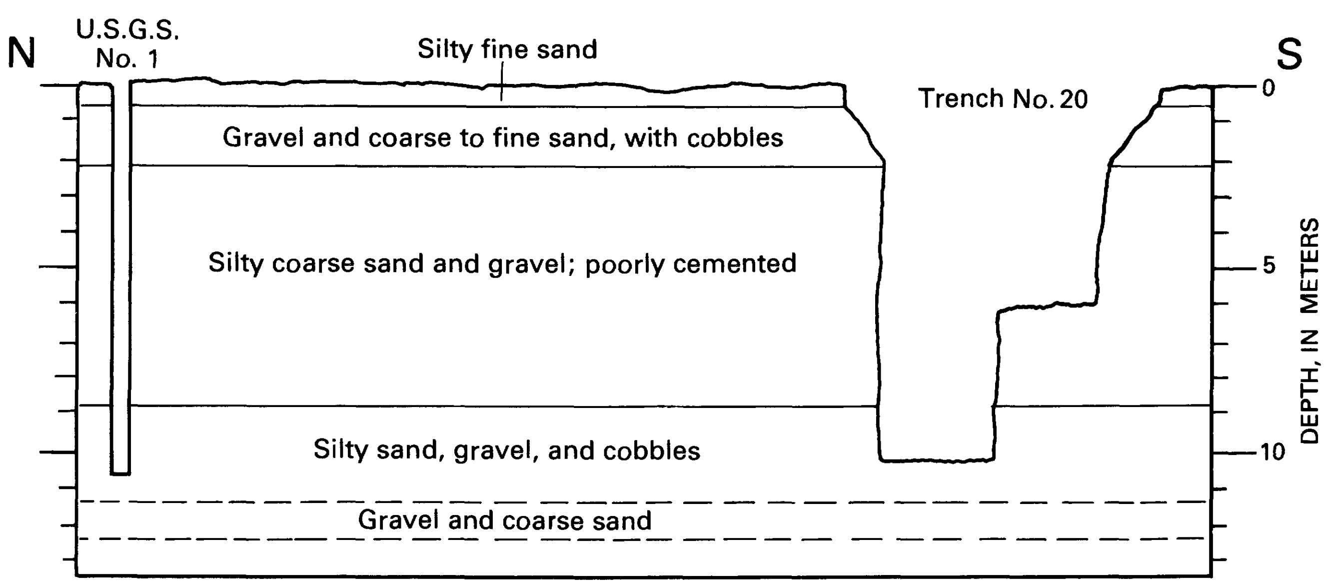

Figure 27. Diagrammatic geologic section of shallow unconsolidated deposits at waste-burial site. Vertical exaggeration=7×.

U.S. Geological Survey, written commun., 1985), the deep percolation that had occurred by May 1979 resulted from the following sequence of events: precipitation in January 1979 restored much of the antecedent soil-moisture deficit, so that the heavier rainfall of late March, which exceeded the seasonal evaporation demands, produced percolation below 0.6 m. Enough moisture was available from these rains to permit downward movement from the fine-grained near-surface sediments into the coarser sediments below 0.6 m. Additional downward redistribution continued from May 1979 to February 1980.

The results of soil-moisture studies made at the waste-burial site support the conclusions of the long-term evaporation studies, namely that given the correct circumstances of precipitation occurrence, evaporation demands, and soil-moisture deficit, deep percolation can take place. The sequence of events leading to the observed deep percolation is not unlike that postulated from long-term evaporation modeling. Precipitation in 1978 was 26.34 cm at Beatty and 23.35 cm at the waste-burial site, more than twice the long-term annual average. This was followed by a significant storm in January 1979 (4.62 cm) and several significant storms in late March 1979 (2.52 cm). The net result was that the March precipitation provided enough moisture to allow downward percolation during the succeeding months.

Soil-Water Potential

Attempts were made during the investigation to obtain in-place measurements of soil-water potential using thermocouple psychrometry. A vertical shaft, 1.5 m in diameter and 10 m deep, was drilled and cased with steel pipe. Windows measuring about 20 by 40 cm were cut into the casing at 1-m intervals to provide access to sediments along the shaft sidewall. The shallowest window was cut at 3 m because slumping and collapse of the upper 2.5 m during drilling of the shaft caused too much ground disturbance to permit collection of reliable data for undisturbed conditions.

The theoretical basis for the psychrometric measurement of soil-water potential has been discussed by Rawlins (1966, 1972) and by Van Haveren and Brown (1972). The measurement of soil-water potential in soil samples in the laboratory using psychrometers has been discussed by Campbell and Wilson (1972), and their field use in a desert environment has been described by Moore and Caldwell (1972). Porous-cup thermocouple psychrometers used during this study were implanted in the sidewall of the 10-m shaft. An access hole 1.3 cm in diameter was drilled horizontally into the sidewall sediments a distance of 45 to 50 cm. Once the psychrometer was emplaced, the access hole was backfilled. Drilling

Table 10. Volumetric water content of core samples from waste-burial site[1]
[Moisture contents in percent; "--" indicates lack of data]

Boring number	Depth, in meters														
	1.0	1.2	1.5	2.0	2.4	2.7	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0
1	--	--	--	7.3	--	--	7.1	7.9	7.9	8.8	6.6	4.9	5.4	8.5	7.6
2	--	--	--	9.7	--	--	7.3	8.2	6.5	7.9	9.4	6.0	--	9.0	--
3	4.1	--	--	--	--	--	8.4	--	--	--	9.4	--	--	--	--
4	--	--	--	7.8	--	--	--	6.6	--	8.9	--	5.1	--	--	--
4A	--	--	6.3	--	--	10.7	11.6	8.3	9.0	--	--	--	--	--	--
5	--	--	6.7	--	--	7.7	8.5	8.2	7.0	--	--	--	--	--	--
6	--	--	5.9	--	--	--	9.5	9.1	--	--	--	--	--	--	--
7	--	7.6	--	--	7.6	--	9.7	--	--	--	--	--	--	--	--
B1	--	--	8.0	--	--	--	9.3	--	6.1	3.9	--	--	--	--	--
B2	--	--	6.7	--	--	--	7.1	--	5.7	4.8	--	--	4.6	--	--
B3	--	--	--	--	--	--	6.9	--	--	7.2	--	--	--	--	--
Average	4.1	7.6	6.7	8.2	7.6	9.2	8.5	8.0	7.0	6.9	8.4	5.3	5.0	8.7	7.6

[1] Measurements made by W. D. Nichols and D. H. Schaefer.

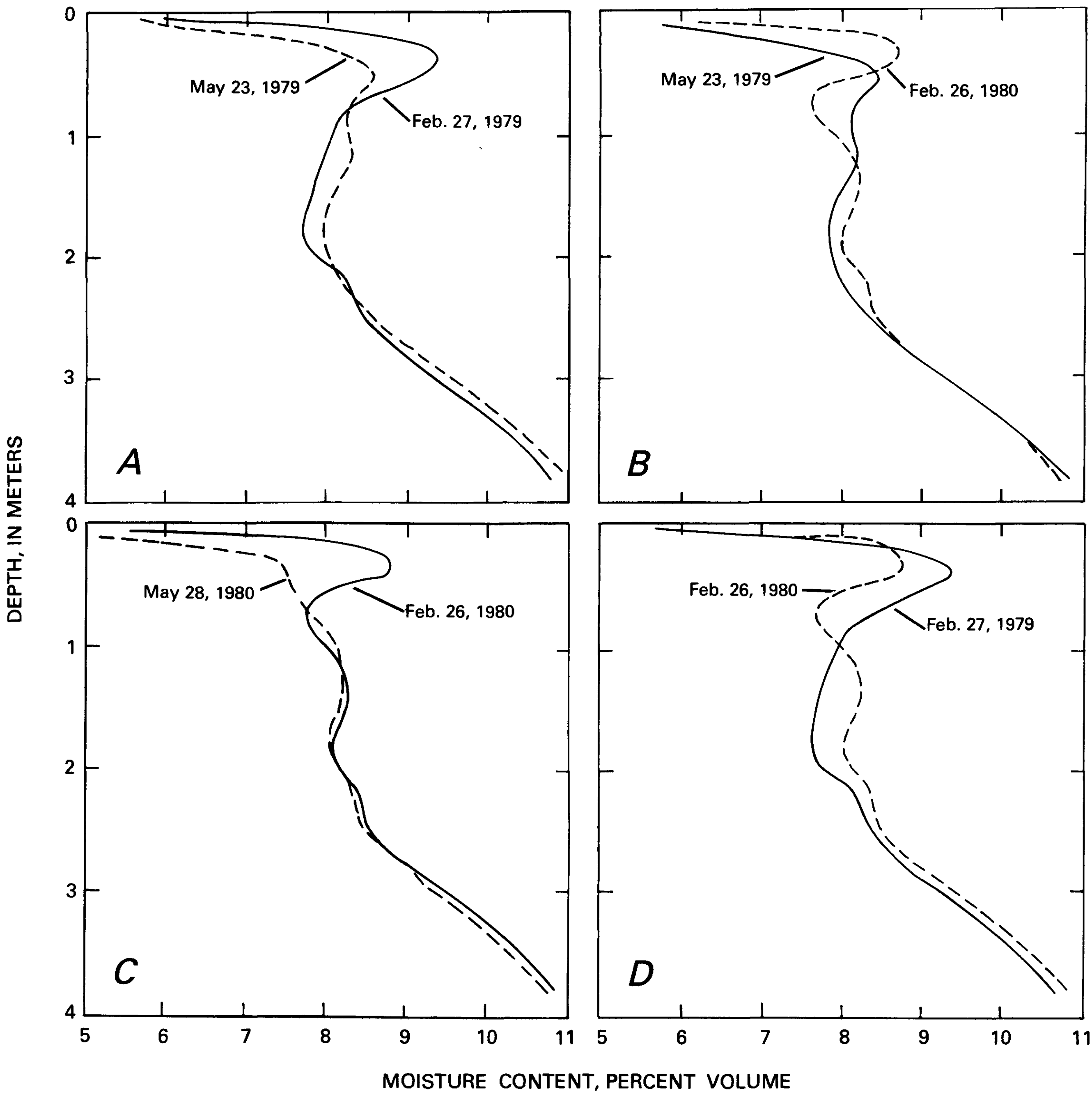

Figure 28. Comparative soil-moisture profiles, showing net changes in moisture content between the following dates: (*A*) February 27 and May 23, 1979; (*B*) May 23, 1979, and February 26, 1980; (*C*) February 26 and May 28, 1980; and (*D*) February 27, 1979, and February 26, 1980.

farther than about 50 cm was difficult because of the large gravel (diameters as great as 3 cm) commonly encountered at all locations. In fact, psychrometers could not be emplaced at depths of 8 and 9 m because of the coarseness and unstable character of the materials there.

The most reliable data were obtained from the psychrometers at 3, 6, and 10 m. Plots of these data are shown in figure 29. Cyclical fluctuations are indicated at depths of 6 and 10 m. The soil-water potential at 6 m also exhibits a trend of decreasing potential during the period of measurement, whereas at 10 m an increase is suggested. The soil-water potential at 3 m shows a slight increase over the period of measurement but does not exhibit a clear pattern of cyclical fluctuations.

Of particular interest is the magnitude of soil-water potential at all three depths. The soil-water potential generally was in the range of −40 to −60 bars, except for late 1979 to early 1980 at the 10-m depth, when the soil-water potential was in the range of −10 to −15 bars. Even this decrease in soil-water potential does not imply any significant change in moisture conditions. A change in soil-water potential from −50 to −15 bars can occur with an increase in volumetric water content of less than 1 percent, and probably less than 0.5 percent.

Hydraulic Properties of Sedimentary Deposits

Determination of the hydraulic properties—specifically the unsaturated conductivity—of sedimentary materials such as those at the waste-burial site was difficult, and the results are questionable. The very coarse deposits encountered make sample collection difficult and nearly preclude collection of representative samples. Laboratory methods and instrumentation for determining unsaturated conductivity versus water content or unsaturated conductivity versus matric potential, particularly in the range of very low moisture content and at potentials more negative than −5 bars, generally have not been applied to such coarse heterogeneous materials. Nevertheless, an attempt was made to determine the relationship among matric potential, water content, and unsaturated conductivity for the three major stratigraphic units found at the waste-burial site (that is, the very fine silty sand from 0.0 to 0.75 m, the coarse sandy gravel and some cobbles from 0.75 to about 2.5 m, and the dense silty sand with some gravel and cobbles below 2.5 m.

Undisturbed core samples were collected at 0.15, 4.0, and 9.0 m, and disturbed bulk samples were collected at 1.0 and 2.75 m. Two cores were collected at each of the cored sample depths, but the materials from each of the two cores (except at 9.0 m) were combined to provide sufficient quantities for analysis. Analyses could not be accomplished on whole samples because of the presence of gravel (table 11). The method of Mehuys and others (1975) was used to determine the hydraulic properties for the fraction of the sample smaller than 2 millimeters (mm) in diameter and then corrected to a "whole-soil" basis. The analyses were made by Gaylon S. Campbell of Washington State University, and the following discussion is based largely on his report (written commun., 1980).

An approximate moisture-release curve was determined for each soil depth sampled. Emphasis was given to the very dry end of the curve because hydraulic properties in the range of −20 to −50 bars are most closely related to conditions at the waste-burial site. Multiple samples for a single depth were combined for these measurements because of the difficult and time-consuming nature of the technique. The total soil-water potential of each composite sample was measured using a thermocouple psychrometer (Campbell and others, 1966). Water content

Table 11. Mass of grain-size fractions greater than and less than 2 mm for soil samples from waste-burial site

[Data from Gaylon S. Campbell, Washington State University, written commun., 1980]

Depth (meters)	Sample number	Fraction >2 mm (grams)	Fraction <2 mm (grams)	Percentage >2 mm[1]
0.15	1	10.5	106.8	9
.15	2	1.3	96.3	1
1.0	1	2,087	2,393	47
1.0	2	2,616	1,757	60
2.75	1	2,572	1,096	70
2.75	2	1,814	1,298	58
4.0	1	56.9	58.2	49
4.0	2	25.1	74.3	25
9.0	1	269.7	343.3	56

[1] Calculated as follows: 100(>2 mm)/[(>2 mm)+(<2 mm)].

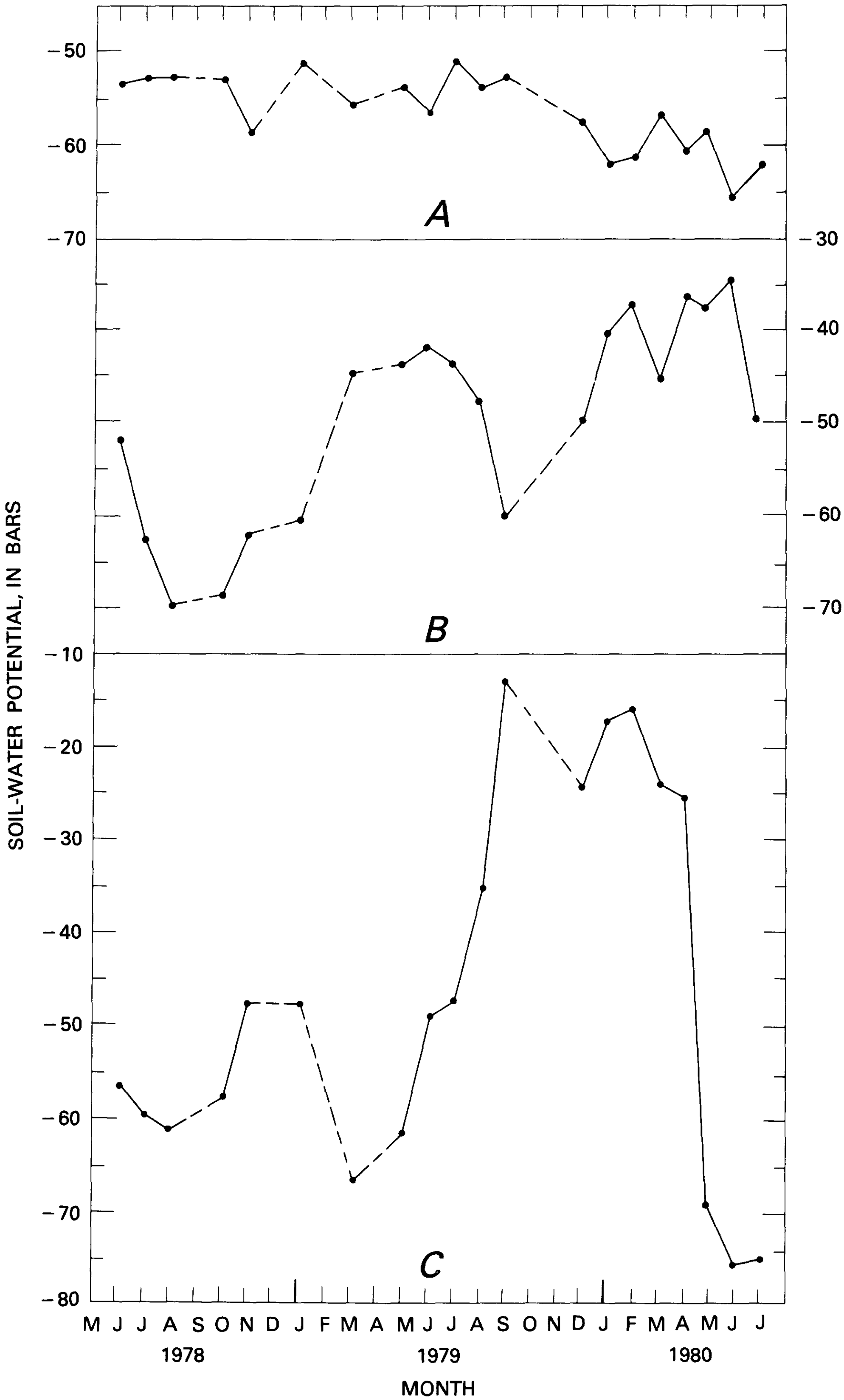

Figure 29. Measurements of soil-water potential, May 1978 to June 1980, for depths of (*A*) 3, (*B*) 6, and (*C*) 10 m. Data points more than 1 mo apart are connected by dashed line.

Table 12. Laboratory-measured moisture characteristics of soil samples from waste-burial site[1]

[cm, centimeters. Data from Gaylon S. Campbell, Washington State University, written commun., 1980]

Depth (meters)	W_1	h_1 (cm) [see footnote 2]	W_2	h_2 (cm) [see footnote 2]	Osmotic water potential at saturation (cm)
0.15	0.030	41.6×10^3	0.065	0.8×10^3	0.3×10^3
1.0	.032	35.9×10^3	.053	3.6×10^3	1.3×10^3
2.75	.030	48.0×10^3	.049	3.9×10^3	$.8 \times 10^3$
4.0	.079	9.1×10^3	.143	1.3×10^3	1.6×10^3
9.0	.075	24.3×10^3	.117	1.3×10^3	—

1 W_1 and W_2 indicate gravimetric water content of size fraction less than 2 millimeters at potentials h_1 and h_2.

2 All potentials are negative.

was determined gravimetrically by drying for 24 hr at 105 °C. Initial measurements indicated that salts were present in the samples in sufficient concentration to affect measurements of matric potential at low water content, so the samples were leached with distilled water before the final measurements were made. Electrical conductivity of the leachate from each sample was measured to provide an estimate of the osmotic component of the soil-water potential. Table 12 gives the results of water-content and water-potential measurements made on the sample fraction smaller than 2 mm in diameter.

The data given in table 12 were used to find the constants a and b for the following equation (Hillel, 1971, p. 63):

$$h = aW^{-b}, \tag{11}$$

where h is the matric potential, in centimeters of water, and W is the gravimetric water content, in grams per gram (g/g), at the given potential. These constants computed for the less-than 2-mm fraction, together with the corrected value of the constant a for the "whole soil," are given in table 13. Values of air-entry potential were calculated for each sample. By assuming that the bulk density of the less-than-2-mm fraction was about 1.2 grams per cubic centimeter (g/cm^3), a value of saturated water content (for the <2 mm fraction) of 0.42 g/g was determined. Combining the following equation (Campbell, 1974):

$$h = h_e(W/W_s)^{-b}, \tag{12}$$

where

h_e = air-entry potential, in centimeters,
h = matric potential, in centimeters,
W = water content at h, in grams per gram,
W_s = saturation water content, in grams per gram, and
b = constant,

with equation 11, we obtain

$$h_e = aW_s^{-b}, \tag{13}$$

from which the air-entry potential is obtained. The values of air-entry potential used are not the actual values that would be observed for the whole-soil sample; instead, they represent extrapolated values for the finer-than-2-mm fraction. Similarly, the whole-soil values for saturation water content do not represent the actual saturation water content of these gravelly soils. Values of h_e and W_s are given in table 13.

Unsaturated hydraulic conductivity at a given water content or at a known matric potential can be determined from the following equations (Campbell, 1974):

$$k = k_s\ (W/W_s)^m \tag{14}$$

and

$$k = k_s\ (h_e/h)^n, \tag{15}$$

where

k = unsaturated hydraulic conductivity and
k_s = saturated hydraulic conductivity, both in centimeters per day,
n = 2+3/b, and
m = 2b+3.

Both equations require that the saturated hydraulic conductivity be known. It can be measured in a conventional

Table 13. Calculated moisture-characteristic parameters for soil samples from waste-burial site[1]

[mm, millimeters; cm, centimeters; g/g. gram per gram. Data from Gaylon S. Campbell, Washington State University, written commun., 1980]

Depth (meters)	a (centimeters) Fraction <2 mm [see footnote 2]	Whole sample [see footnotes 2, 3]	b	h_e (cm) [see footnote 2]	W_s for whole sample (g/g) [see footnote 4]
0.15	6.9×10^{-4}	5×10^{-4}	5.1	0.06	0.40
1.0	5.5×10^{-3}	2×10^{-4}	4.6	.3	.19
2.75	7.8×10^{-4}	4×10^{-6}	5.1	.07	.15
4.0	2.2	5×10^{-1}	3.3	38	.26
9.0	9.5×10^{-4}	4×10^{-6}	6.6	.3	.18

[1]Symbols: a and b, constants in equation $h = aW^{-b}$; h_e, air-entry potential; W_s, gravimetric water content at saturation.

[2]All values are negative.

[3]Calculated as follows: a(whole sample) = a(<2 mm fraction) x $(1-WR)^b$, where WR is the mass ratio of stones to total sample.

[4]Calculated as follows: W_s (<2mm fraction) x $(1-WR)$, where WR is as defined in footnote 3.

manner or can be calculated by measuring the rate of advance of a wetting front in the dry soil. Bresler and others (1978) have shown that

$$k_s = 0.27 f^4, \qquad (16)$$

where

k_s = saturated hydraulic conductivity, in centimeters per second, and

$f = dx/d(t^{1/2})$, which is the slope of the line relating the wetting-front position and the square root of time.

The results of both methods are given in table 14. The sample from 9 m was from a cemented layer for which the conductivity was measured by shaping a sample to fit a 5-cm tube and sealing the sample in the tube for a conventional permeameter measurement.

The principal interest in the present application is in estimating an approximate value of unsaturated conductivity for the materials below 2 m in the soil-water potential range of −20 to −50 bars. Combining equations 13 and 14, a single expression,

$$k = k_s \{[(h_e/a)^{-1/b}] / W_s\}^m, \qquad (17)$$

can be used to calculate unsaturated conductivity at any selected value of soil-water potential. Values of unsaturated conductivity in the range of −5 to −50 bars of soil-water potential, based on the data given in tables 14 and 15 and equation 17, are listed in table 15 and shown in figures 30, 31, and 32.

The computed values of unsaturated hydraulic conductivity appear to be too small, but few other data for stony soils at such low water contents and large negative potentials are available for comparison. The study by Mehuys and others (1975) is one of the few to consider stony soils in arid environments. Their experiments included samples of stony soil from Rock Valley in southern Nevada, and their calculated values of unsaturated conductivity for this soil are in the range of 10^{-4} to 10^{-6} centimeters per day (cm/d) at potentials of −5 to −50 bars. This is up to seven orders of magnitude larger than the values computed by Campbell (written commun., 1980) for materials at the waste-burial site (figs. 30–32). Direct comparison of values may be difficult, however, because only 38 percent of the Rock Valley soil was greater than 2 mm in diameter, whereas most of the samples from the waste-burial site contained more than 49 percent of the coarse-grained fraction. The higher percentage of coarse-grained material will result in smaller unsaturated conductivity values for the whole soil. Consequently, the values of unsaturated conductivity obtained during this study will be considered reasonable until more data for these types of soils become available.

Table 14. Measured and calculated values of saturated hydraulic conductivity and other parameters for soil samples from waste-burial site[1]
[Data from Gaylon S. Campbell, Washington State University, written commun., 1980]

Depth (meters)	Sample number	Centimeters per day: k_s [see footnote 2]	k_s [see footnote 3]	k_s, corrected [see footnote 4]	n	m
0.15	1	$1.7x10^2$	$1.7x10^1$	$1.7x10^1$	2.6	13
.15	2	$8.5x10^1$				
1.0	1	$3.4x10^2$				
1.0	2	$2.5x10^2$	$1.7x10^2$	$8.5x10^1$	2.7	12
2.75	1	$2.5x10^3$				
2.75	2	$6.8x10^3$	$4.2x10^3$	$1.7x10^2$	2.6	13
4.0	1	$6.8x10^2$	$5.9x10^2$	$4.2x10^2$	2.9	10
9.0	1	$1.7x10^0$	--	$1.7x10^0$	2.5	16

[1]Symbols: k_s, saturated hydraulic conductivity; n and m, exponents in equations $k = k_s(W/W_s)^m$ and $k = k_s(h_e/h)^n$, where k is the unsaturated hydraulic conductivity.

[2]Measured using standard permeameter techniques.

[3]Inferred from rate of wetting-front advance.

[4]Computed as follows: (k_s) x (mass ratio for fraction <2 mm).

Table 15. Unsaturated hydraulic conductivity for depths of 2.75, 4.0, and 9.0 m at waste-burial site
[Hydraulic conductivities in centimeters per day. Data from Gaylon S. Campbell, Washington State University, written commun., 1980]

Potential (bars)	Depth, in meters: 2.75	4.0	9.0
-5	$5.47x10^{-11}$	$2.18x10^{-4}$	$1.20x10^{-10}$
-10	$9.35x10^{-12}$	$2.56x10^{-5}$	$2.24x10^{-11}$
-15	$3.32x10^{-12}$	$7.81x10^{-6}$	$8.37x10^{-12}$
-20	$1.59x10^{-12}$	$3.27x10^{-6}$	$4.17x10^{-12}$
-25	$9.05x10^{-12}$	$1.66x10^{-7}$	$2.43x10^{-12}$
-30	$5.86x10^{-13}$	$9.57x10^{-7}$	$1.56x10^{-12}$
-35	$3.84x10^{-13}$	$6.00x10^{-7}$	$1.07x10^{-12}$
-40	$2.73x10^{-13}$	$4.00x10^{-7}$	$7.77x10^{-13}$
-45	$2.02x10^{-13}$	$2.80x10^{-7}$	$5.83x10^{-13}$
-50	$1.54x10^{-13}$	$2.03x10^{-7}$	$4.52x10^{-13}$

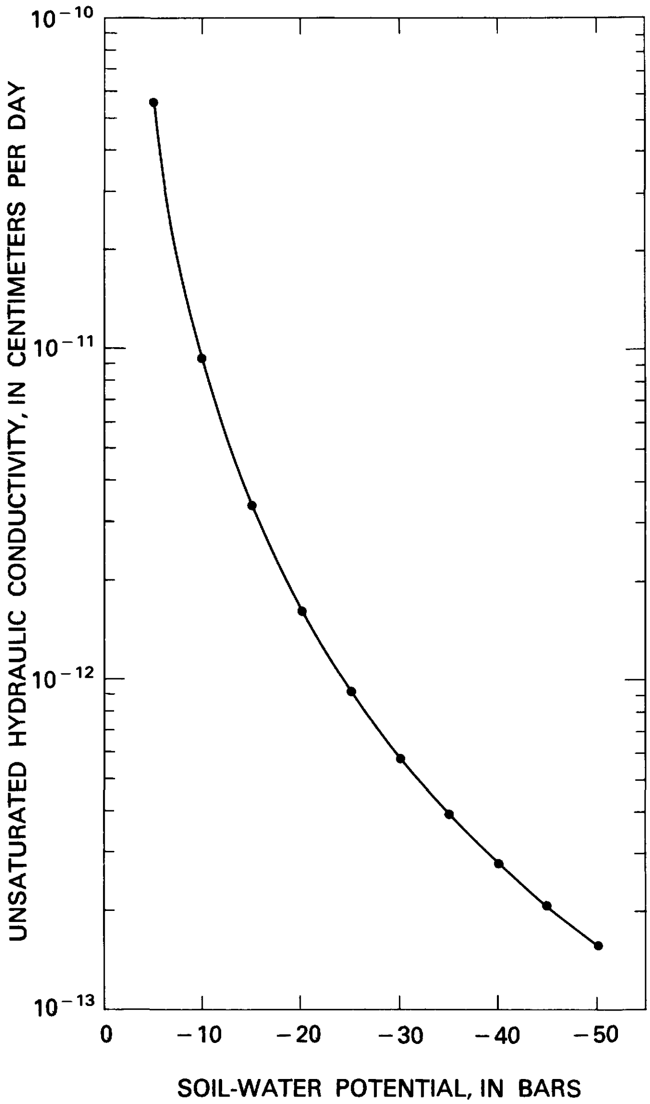

Figure 30. Calculated unsaturated hydraulic conductivity versus soil-water potential for sample from 2.75 m.

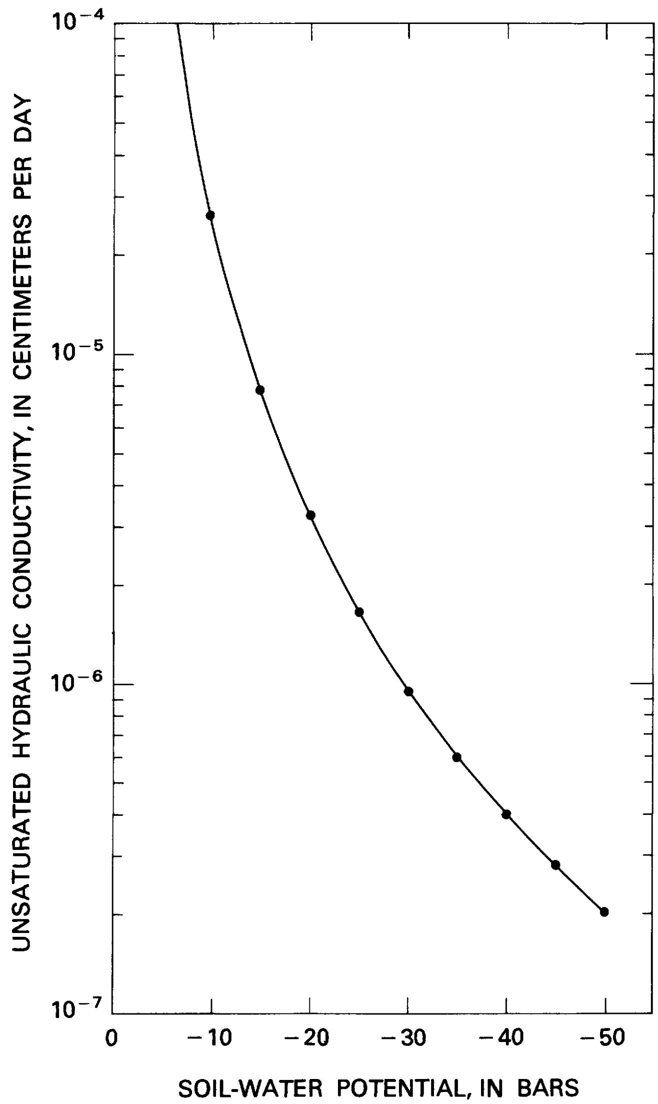

Figure 31. Calculated unsaturated hydraulic conductivity versus soil-water potential for sample from 4.0 m.

IMPLICATIONS REGARDING RADIONUCLIDE MIGRATION

Detailed studies of meteorological data and soil-moisture movement in the natural stratigraphic sequence at the waste-burial site demonstrated that deep percolation can occur, given the required antecedent conditions. The depth of downward moisture movement observed from February 1979 to February 1980 was controlled largely by the coarse-grained layer from about 0.75 to about 2.5 m. This layer served as a natural capillary barrier to unsaturated flow (Corey and Horton, 1969; Frind and others, 1976; Rancon, 1980). A capillary barrier is formed when unsaturated fine-grained sediments overlie unsaturated coarse-grained sediments. The downward movement of soil moisture is retarded at the contact between the two layers. Movement into the coarse sediments does not occur until the saturation level in the overlying fine-grained sediments becomes such that gravitational forces exceed interstitial tension forces. Such a barrier does not exist in the backfill material encompassing the radioactive-waste containers in the waste-burial trenches. The trench backfill is a heterogeneous mixture of the sediments removed during trench construction. It still is considered a stony soil, but the hydraulic characteristics are a composite of the characteristics given in tables 12 and 13. Regardless of the exact character of the backfill material, no capillary barrier overlies the existing trenches and nothing is present to retard moisture movement to depths greater than the 2.4 m observed during this study.

The hydraulic properties of the trench backfill are expected to vary from place to place, but they probably are not too different from the properties of the samples listed in tables 12 and 13 or the properties reported by Mehuys and others (1975) for the Rock Valley stony soil. A reasonable range of unsaturated hydraulic conductivity for matric potentials in the range of −5 to −50 bars might be from about 1×10^{-3} cm/d to perhaps as little as 1×10^{-8} cm/d. Volumetric water content might be somewhat greater at depth in the trench backfill; in the absence of field or laboratory data, an estimated range of water content of 5 to 12 percent might be reasonable. Soil-water potential in the backfill is not known, but, on the basis of the measurements shown in figure 29, it is expected to be in the range of −5 to −25 bars.

Conditions of steady-state unsaturated flow are unlikely in the trench backfill material. Large potential gradients are likely near the wetting fronts of successive deep percolation events. Such fronts are not expected to occur more frequently in the trench backfill than in the undisturbed sediments, but the depth of percolation likely will be greater because of the absence of a natural capillary barrier. (Even this infrequent deep percolation could be reduced by constructing capillary barriers over

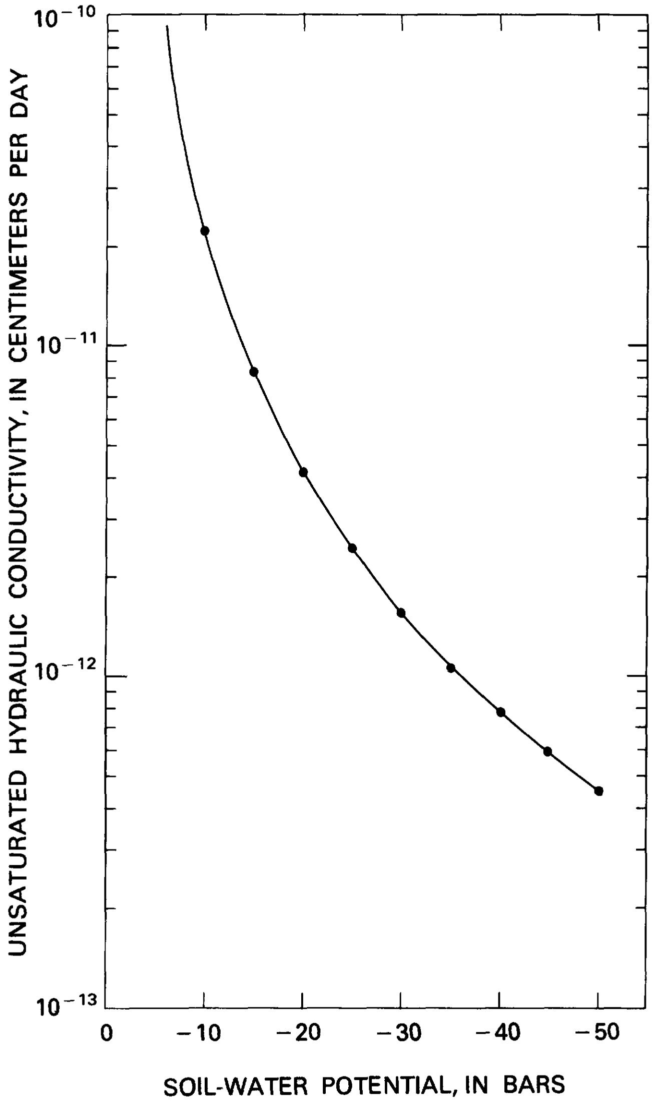

Figure 32. Calculated unsaturated hydraulic conductivity versus soil-water potential for sample from 9.0 m.

the waste trenches.) Under the circumstances, an estimation of unsaturated flow rates in the trench backfill is speculative at best. The rate might be as high as 10 cm/d near wetting fronts, where potential gradients are steep, but such rates would not continue to significant depths, or for significant lengths of time.

A detailed analysis of the hydrodynamics of transient flow in the trench backfill is complicated not only by lack of knowledge regarding hydraulic characteristics of the backfill but also by uncertainty regarding discontinuities introduced by the presence of waste containers. Other hydrologic discontinuities that either promote or inhibit the movement of moisture include settling fractures that extend to land surface, settling fractures that do not extend to land surface, void spaces that originate during the backfill process, and void spaces that develop from collapse of waste containers at some time following burial. Given all these complications and uncertainties, a simplified analysis that assumes ideal conditions is useful to the extent that it could provide a means for estimating possible limiting conditions.

An unsaturated hydraulic conductivity of 1×10^{-5} cm/d and a soil-water potential gradient, $\partial\psi/\partial Z$, of 10,000 cm/cm would give a transient flux rate of 0.1 cm/d. Assuming that (1) this condition was imposed at land surface when the oldest trenches were closed in 1963 and 1964 and (2) the supply of moisture at land surface was sufficient to allow for the continued downward movement of a wetting front at the rate of 0.1 cm/d, the wetting front would have reached a depth of about 6 m during the 18-yr period 1963–80. This depth of penetration is comparable to the reported depth of the older trenches. The volume of water needed to sustain such a flux is not easily determined without more information on the material and hydraulic properties of the trench backfill. Even the minimum volume of water, based on the flux rate of 0.1 cm/d, totals 120 cm^3/cm^2, an amount far in excess of the deep percolation that can reasonably by expected on the basis of the analysis presented earlier in this report. This would suggest that precipitation infiltrating through the trench caps since 1963 has not yet percolated deep enough to reach the bottom of the waste-burial trenches.

Movement of moisture in the region of steady unsaturated flow is expected to be extremely slow in the area of the waste-burial facility. The depth at which steady flow finally occurs is not known; soil-water potential data collected for this study indicate that transient effects may still exist at a depth of 10 m. The steady flux rate is speculative, but a value on the order of 1×10^{-5} cm/d in undisturbed sediments may be reasonable. This implies a moisture movement rate of about 4 cm per 1,000 yr, which in turn would represent the maximum rate of radionuclide transport (disregarding diffusion and dispersion) in the liquid phase in the zone of steady unsaturated flow beneath the waste-burial trenches.

SUMMARY OF ANALYSIS AND CONCLUSIONS

Detailed analysis of climatic conditions and precipitation patterns in the northern Amargosa Desert from 1949 to 1976 demonstrates that most of the precipitation falls in the cool winter months when evaporative demands are at a minimum. Meteorological data collected at the waste-burial site during the present study were used to calibrate a long-term water-balance model based on National Weather Service data. The model was then used to determine when and under what conditions, between 1962 and 1976, deep percolation might have occurred. This approach suggests that deep percolation—that is, percolation to a depth greater than 2 m—might have occurred in 1968, 1973, and 1976. Examination of the precipitation record for the 12 to 16 mo before each occurrence of predicted deep percolation defined the necessary antecedent conditions.

A similar sequence of precipitation events and soil-moisture conditions occurred in 1978 and early 1979. Soil-moisture profiles collected from February 1979 to June 1980 provided documentation of deep percolation to a depth of about 2 m during the late spring of 1979, as a result of these events. These data provide conclusive evidence of deep percolation in areas of bare soil. Considering the small volume of water involved (only 0.9 cm in 1979), deep percolation is not likely if vegetation is present.

Soil-water potential was monitored with thermocouple psychrometers to a depth of 10 m. The most reliable data were obtained at depths of 3, 6, and 10 m. Seasonal-type fluctuations were observed at all three depths but are most pronounced at 6 and 10 m. Measured soil-water potential ranged from −10 to −60 bars. These large changes in potential do not imply any significant change in moisture content; a decrease in negative potential from −50 bars to −15 bars can result from an increase in volumetric water content of less than 1 percent.

The unsaturated hydraulic conductivity of representative samples of the shallow subsurface sediments was determined using laboratory data and empirical relationships given by Hillel (1971) and Campbell (1974). The computed values of unsaturated hydraulic conductivity range from 10^{-13} to 10^{-4} cm/d. These values appear to be too small, but few other data for stony soils at such low water contents and large negative potentials are available for comparison.

A simplified analysis of transient unsaturated flow in the trench backfill material demonstrates the probable slow rate of migration of radionuclides in response to the movement of water under natural conditions. The analysis assumes an unsaturated hydraulic conductivity for the backfill of 10^{-5} cm/d and a gradient of 10^4 cm/cm; the resulting transient flux rate would be 0.1 cm/d. Assuming that (1) this flux condition was imposed when the oldest trenches were closed in 1963 and 1964 and (2) the flux rate was maintained at land surface, the wetting front would have reached a depth of 6 m in the 18-yr period 1963–80. This depth of penetration is comparable to the reported depth of the oldest trenches. However, the volume of water needed to sustain this flux rate, while not easily determined, is estimated to be several orders of magnitude greater than the volume of water expected to be available for deep percolation on the basis of long-term water-balance determinations. Steady flux rates in the unsaturated zone beneath the waste-burial trenches and below a depth of 10 m may be on the order of 10^{-5} cm/d, which implies a moisture movement rate of about 4 cm per 1,000 yr. Disregarding transport by diffusion and dispersion, this value would represent the maximum rate of radionuclide movement in the liquid phase, under steady, unsaturated conditions.

REFERENCES CITED

Ball, S.H., 1907, A geologic reconnaissance in southwestern Nevada and eastern California: U.S. Geological Survey Bulletin 308, 218 p.

Battelle Memorial Institute, 1976, Alternatives for managing wastes from reactors and post-fission operations in the LWR fuel cycle: U.S. Energy Research & Development Administration Report ERDA-76-43, v. 4, 199 p.

Black, T.A., Gardner, W.R., and Thurtell, G.W., 1969, The prediction of evaporation, drainage, and soil water storage for a bare soil: Soil Science Society of America Proceedings, v. 33, p. 655–660.

Bresler, E., Russo, D., and Miller, R.D., 1978, Rapid estimate of unsaturated hydraulic conductivity function: Soil Science Society of America Journal, v. 42, p. 170–172.

Byers, F.M., Jr., Carr, W.J., Christiansen, R.L., Lipman, P.W., Orkild, P.P., and Quinlivan, W.D., 1976a, Geologic map of the Timber Mountain caldera area, Nye County, Nevada: U.S. Geological Survey Miscellaneous Investigations Map I-891.

Byers, F.M., Jr., Carr, W.J., Orkild, P.P., Quinlivan, W.D., and Sargent, K.A., 1976b, Volcanic suites and related cauldrons of Timber Mountain-Oasis Valley caldera complex, southern Nevada: U.S. Geological Survey Professional Paper 919, 70 p.

Campbell, G.S., 1974, A simple method for determining unsaturated conductivity from moisture retention data: Soil Science, v. 117, no. 6, p. 311–314.

Campbell, G.S., and Wilson, A.M., 1972, Water potential measurements of soil samples, *in* Brown, R.W., and Van Haveren, B.P., eds., Psychrometry in water relations research: Symposium on Thermocouple Psychrometers, Logan, Utah, March 17-19, 1971, Proceedings, p. 142–149.

Campbell, G.S., Zollinger, W.D., and Taylor, S.A., 1966, Sample changer for thermocouple psychrometers: Construction and some applications: Agronomy Journal, v. 58, p. 315–318.

Chapman, R.H., Healey, D.L., and Troxel, B.W., 1973, Bouguer gravity map for California, Death Valley sheet: California Division of Mines and Geology.

Clebsch, Alfred, Jr., 1962, Geology and hydrology of a proposed site for burial of solid radioactive waste southeast of Beatty, Nye County, Nevada, *in* Morton, R.J., 1968, Land burial of solid radioactive wastes—Study of commercial operations and facilities: Atomic Energy Commission, NTIS Report WASH-1143, p. 70–100.

Corey, J.C., and Horton, J.H., 1969, Influence of gravel layers on soil moisture content and flow: Du Pont Corporation, Savannah River Laboratory Report DP-1160.

Cornwall, H.R., 1972, Geology and mineral deposits of southern Nye County, Nevada: Nevada Bureau of Mines and Geology Bulletin 77, 49 p.

Cornwall, H.R., and Kleinhampl, F.J., 1961, Geology of the Bare Mountain quadrangle, Nevada: U.S. Geological Survey Geologic Quadrangle Map GQ-157.

———1964, Geology of the Bullfrog quadrangle and ore deposits related to Bullfrog Hills caldera, Nye County, Nevada, and Inyo County, California: U.S. Geological Survey Professional Paper 454-J, 25 p.

Frind, E.O., Gillham, R.W., and Pickens, J.F., 1976, Application of unsaturated flow properties in the design of geologic environments for radioactive waste storage facilities, *in* Gray, W.G., Pinder, G.F., and Brebbia, C.A., eds.: International Conference on Finite Elements in Water Resources, 1st, Proceedings, Princeton, N.J., Princeton University, p. 3.133.

Healey, D.L., and Miller, C.H., 1962, Gravity survey of the Nevada Test Site and vicinity, Nye, Lincoln, and Clark Counties, Nevada—Interim report: U.S. Geological Survey Report TEI-827, 36 p.

———1965, Gravity survey of the Amargosa Desert area of Nevada and California: U.S. Geological Survey Technical Letter NTS-99, 32 p.

Hillel, Daniel, 1971, Soil and water: Physical principles and processes: New York, Academic Press, 288 p.

Hunt, C.B., Robinson, T.W., Bowles, W.A., and Washburn, A.L., 1966, Hydrologic basin, Death Valley, California: U.S. Geological Survey Professional Paper 494-B, 138 p.

Jackson, R.D., Idso, S.B., and Reginato, R.J., 1976, Calculation of evaporation rates during the transition from energy-limiting to soil-limiting phases using albedo data: Water Resources Research, v. 12, no. 1, p. 23–26.

Jensen, M.E., ed., 1973, Consumptive use of water and irrigation water requirements: American Society of Civil Engineers report, 215 p.

Mehuys, G.R., Stolzy, L.H., Letey, J., and Weeks, L.V., 1975, Effect of stones on the hydraulic conductivity of relatively dry desert soils: Soil Science Society of America Proceedings, v. 39, p. 37–42.

Moore, R.T., and Caldwell, M.M., 1972, The field use of psychrometers in desert soils, *in* Brown, R.W., and Van Haveren, B.P., eds., Psychrometry in water relations research: Symposium on Thermocouple Psychrometers, Logan, Utah, March 17–19, 1971, Proceedings, p. 165–169.

National Research Council, 1976, The shallow land burial of low-level radioactively contaminated solid waste: Washington, D.C., National Academy of Sciences, 150 p.

Quiring, R.F., 1965, Annual precipitation amount as a function of elevation in Nevada south of 38 degrees latitude: Las Vegas, Nev., U.S. Weather Bureau Research Station report, 14 p.

Rancon, D., 1980 Application de la technique des barrieres capillaires aux stockages entranchees, *in* Proceedings of the International Symposium on Underground Disposal of Radioactive Wastes, Helsinki, Finland, July 1979: International Atomic Energy Commission, v. 1, p. 241–265.

Rawlins, S.L., 1966, Theory for thermocouple psychrometers used to measure water potential in soil and plant samples: Agricultural Meteorology, v. 3, p. 293–310.

______1972, Theory of thermocouple psychrometers for measuring plant and soil water potential, *in* Brown, R.W., and Van Haveren, B.P., eds., Psychrometry in water relations research: Symposium on Thermocouple Psychrometers, Logan, Utah, March 17–19, 1971, Proceedings, p. 43–50.

Ritchie, J.T., 1972, Model for predicting evaporation from a row crop with incomplete cover: Water Resources Research, v. 8, no. 5, p. 1204–1213.

Streitz, Robert, and Stinson, M.C., 1974, The geologic map of California, Death Valley sheet: Sacramento, California Division of Mines and Geology.

Van Haveren, B.P., and Brown, R.W., 1972, The properties and behavior of water in the soil-plant-atmosphere continuum, *in* Brown, R.W., and Van Haveren, B.P., eds., Psychrometry in water relations research: Symposium on Thermocouple Psychrometers, Logan, Utah, March 17–19, 1971, Proceedings, p. 1–27.

Walker, G.E., and Eakin, T.E., 1963, Geology and ground water of Amargosa Desert, Nevada-California: Nevada Department of Conservation and Natural Resources Reconnaissance Report 14, 57 p.

Wallace, R.E., 1977, Profiles and ages of young fault scarps, north-central Nevada: Geological Society of America Bulletin, v. 88, p. 1267–1281.

Weedfall, R.O., 1963, An approach to the development of isohyetal maps for the Nevada and California deserts: Las Vegas, Nev., U.S. Weather Bureau Research Station report, 17 p.

Wilson, R.G., and Rouse, W.R., 1972, Moisture and temperature limits of the equilibrium evapotranspiration model: Journal of Applied Meteorology, v. 11, p. 436–442.

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.

TABLES 16 AND 17

Table 16. Driller's log for well at waste-burial site[1]

Depth (meters)	Material
0.0-0.6	Silt. Probably wind-blown dust.
.6-1.5	Coarse gravel with some silt.
1.5-9.1	Coarse gravel with some boulders.
9.1-13.7	Fine gravel with larga boulders. Boulder bed at 13.7 meters.
13.7-30.5	Coarse gravel with some boulders and sand.
30.5-31.0	Boulders in coarse gravel.
31.0-32.6	Bouldery clay.
32.6-35.6	Bouldery clay; about half clay.
35.6-44.8	Small gravel with brown sandy clay.
44.8-45.1	Boulders in brown sandy clay.
45.1-47.8	Boulders with some clay.
47.8-49.0	Boulders and gravel in orange clay.
49.0-52.1	Orange clay.
52.1-55.1	Reddish-orange clay.
55.1-60.6	Cored in bentonitic red and orange clay. No core recovery.
60.6-61.5	Cored. No core recovered. Brown clay from bit.
61.5-62.8	Cored. No core recovered. Considerable brown clay from bit.
62.8-71.6	Clayey gravel, with boulders, brown clay, and small gravel at 71.6 meters.
71.6-78.6	Fine clayey gravel. Pinkish clay.
78.6-80.8	Gravel and boulders with but little clay.
80.8-83.5	Brown and yellow clay with some gravel.
83.5-85.3	Cored. Recovered 1.8 meters of light brown clay.
85.3-92.0	Brown clay with occasional boulders.
92.0-93.9	White and brown bentonitic clay with layers of bright-yellow clay.
93.9-98.5	Brown swelling clay with some gravel. Mostly clay from 80.8 to 98.1 meters.
98.5-98.8	Boulders in brown sandy clay.
98.8-99.4	Yellow clay.
99.4-103.6	Boulders but with little clay. Possible water zone.
103.6-106.4	White to brown clay. White argillaceous carbonate rock altered to clay.
106.4-108.5	White carbonate rock. Largely altered to clay from 108.2 to 108.5 meters.
108.5-112.1	Bouldery brown clay.
112.1-112.8	White clay, brown clay, and small gravel.
112.8-117.0	Dark volcanic boulders with brown bentonitic sandy-clay.
117.0-123.7	White carbonate rock somewhat altered to clay.
123.7-129.5	Greenish-brown clay, some boulders.
129.5-132.6	White carbonate rock and white clay.
132.6-135.6	Boulders in red clay.
135.6-142.3	Hard boulders with gravel in dark-red clay. Volcanic rocks.
142.3-144.5	Boulders and clay. Red clay at 143.9 meters.
144.5-148.7	A variety of boulders with but little clay. A possible source of water.
148.7-153.0	Hard boulders in brown and red sandy clay.
153.0-161.2	Pinkish-brown clay with sand and occasional boulders.
161.2-166.1	Boulders in pink and light-brown clay. Some sericitic rock.
166.1-168.5	Boulders in clay. Some rounded gravels.
168.5-172.8	Boulders in brown clay. Yellow clay and small gravel at 171.0 meters.
172.8-175.0	Light gray metamorphic rocks. Large boulders or possibly basement rock.

[1] V. P. Gianella, consulting geologist, written communication, 1961.

Table 17. Description of samples obtained from well drilled at waste-burial site[1]

Depth (meters)	Description
0.0-0.6	Silt. Probably wind-blown dust.
1.5	Coarse gravels and silt. Volcanic rocks, andesite, basalt, and rhyolite.
3.0	Dominantly volcanic rocks, some quartz.
7.6	Volcanic gravel with some quartz and chalcedony.
20.4	Volcanic gravels. Somewhat altered and silicified.
30.5	Gravels of volcanic rocks.
32.6	Mostly gravels of volcanic rocks and some quartz.
35.6	Volcanic gravel, partly well-rounded.
44.2	Largely rhyolitic gravel. Some quartzite.
44.8-45.1	Gravels of volcanic rocks and quartzite.
48.7	Volcanic rocks, altered volcanic rocks, and some quartz.
52.1	Two-thirds volcanic rocks and about one-third schist, with some well-rounded pebbles.
55.2	Volcanic rocks, quartzite, schist, quartz, and chalcedony. A few well-rounded pebbles.
61.6	Pebbly orange clay from coring bit. Well-rounded pebbles of volcanic rocks. (Note change to volcanics with no sedimentary or metasedimentary rocks.)
62.8	Light brown clay from coring bit with about 5 percent sand.
68.3	Cuttings dominantly volcanic rocks with some quartzite and chalcedony.
76.2	Fine clayey gravel. Gravel chiefly of volcanic rocks with some quartzite, schist, and quartz.
81.4	Yellow to light-brown clay.
84.1-84.4	Light-brown clay from core barrel. Contains little sand.
85.3	Brown sandy clay from core barrel. Contains about 10 percent fine to coarse sand. Some grains are well rounded.
93.3	White, brown, and yellow bands of bentonitic clay. Contains a little gravel from volcanic rocks.
105.5	White to brown bentonitic clay with boulders. Cuttings are mostly white and pink silicified felsitic rock.
108.5	White altered rock with white clay--a carbonate rock, probably an impure freshwater limestone. Also cuttings of dark-colored limestone, volcanic rocks, and some quartzite.
117.0-117.3	White clayey rock continuous from 108.5 meters. Much white clay. Cuttings are from a white clayey-carbonate like that in sample No. 23.
135.6	Dark red sandy clay cuttings of dark volcanic rocks. Some small rounded pebbles of dark gray volcanic rock. Some gray schist, quartzite and occasional quartz. A marked change from sample No. 24.
142.3	Volcanic boulders in light-colored red clay. Cuttings of dark red volcanic rock and some gray quartzite. Some rounded gravels.
144.2	Cuttings of light- and dark-colored volcanic rocks. Very little red volcanic rocks as at 142.3 meters. Some schist and quartz. Many small rounded pebbles.
146.9	Cuttings of light and dark volcanic rock. Some light-colored volcanics, quartzite, and quartz. Rounded pebbles.
147.5	Cuttings like those from 146.9 meters.
153.0	Gravel and red clay. Mostly dark red volcanics, with some rhyolite and rounded pebbles.
155.7	Volcanic rocks, schist, and other metasediments. Fine gravel embedded in red clay.
158.2	Light-colored volcanic rocks with much schist and quartzite.
161.2	Dark pink clay recovered from bit. The clay contains about 5 percent fine sand grains of schist, quartzite, and quartz. Some grains are well-rounded.

Table 17. Description of samples obtained from well drilled at waste-burial site[1]—Continued

Depth (meters)	Description
161.5	Light and dark volcanic rock, quartzite, quartz, and some schist.
163.1	Cuttings are mostly quartzite and schist, with little volcanic rock.
166.4	Cuttings consist of about equal amounts of light and dark volcanic rocks, schist, and quartzite.
167.0	Light-brown clay with pebbles. Volcanic rocks, schist, and well-rounded pebbles.
168.2	Cuttings of light and dark volcanic rocks, schist, and quartzite.
172.2	Reddish clay with pebbles of schist and some volcanic rocks.
172.5	Schist and quartzite predominate, with some volcanic rocks.
174.9	Mostly sericitic schistose rock. Either large boulders or possible basement rock.

[1] V. P. Gianella, consulting geologist, written communication, 1961.

METRIC CONVERSION FACTORS

International System (metric) units of measure used in this report may be converted to "inch-pound" units by using the following factors:

Multiply	By	To obtain
Centimeters (cm)	0.3937	Inches (in)
Centimeters per day (cm/d)	0.3937	Inches per day (in/d)
Cubic meters per second (m^3/s)	35.31	Cubic feet per second (ft^3/s)
Grams	0.03527	Ounces
Grams per cubic centimeter (g/cm^3)	62.43	Pounds per cubic foot ($1b/ft^3$)
Kilometers (km)	0.6214	Miles (mi)
Meters (m)	3.281	Feet (ft)
Millimeters (mm)	0.03937	Inches (in)

For temperature, degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) by using the formula F=[(1.8)(°C)]+32.

ALTITUDE DATUM

The term "National Geodetic Vertical Datum of 1929" replaces the formerly used term "mean sea level" to describe the datum for altitude measurements. The geodetic datum is derived from a general adjustment of the first-order leveling networks of both the United States and Canada. For convenience in this report, the datum also is referred to as "sea level."

☆ U.S GOVERNMENT PRINTING OFFICE. 1987 - 201-933 - 226/60061