INFILTRATION TO THE NAVAJO SANDSTONE IN THE LOWER DIRTY DEVIL RIVER BASIN, UTAH, WITH EMPHASIS ON TECHNIQUES USED IN ITS DETERMINATION

By T. W. Danielson and J. W. Hood

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 84-4154

Prepared in cooperation with the

UTAH DEPARTMENT OF NATURAL RESOURCES,

DIVISION OF WATER RIGHTS

Salt Lake City, Utah

1984

UNITED STATES DEPARTMENT OF THE INTERIOR

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CONVERSION FACTORS

Values in the report are given in the unit system in which they were originally measured. Conversion from one system to another may be made using this table.

Inch-pound			Metric	
Unit (Multiply)	Abbreviation	(by)	Unit (to obtain)	Abbreviation
Acre-feet	acre-ft	0.001233	Cubic hectometer	hm^3
		1233	Cubic meter	m^3
Acre-feet per year	acre-ft/yr	0.001233	Cubic hectometer per year	hm^3/yr
		1233	Cubic meter per year	m^3/yr
Cubic feet per second	ft^3/s	.02832	Cubic meter per second	m^3/s
Feet	ft	.3048	Meter	m
Feet per year	ft/yr	.3048	Meter per year	m/yr
Inch	in.	25.40	Millimeter	mm
		2.540	Centimeter	cm
Mile	mi	1.609	Kilometer	km
Square mile	mi^2	2.590	Square kilometer	km^2

Water temperature is given in degrees Celsius (°C), which can be converted to degrees Fahrenheit (°F) by the following equation:

$°F=1.8(°C)+32$.

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ABSTRACT

An investigation was made to determine areas of infiltration and areas and amounts of recharge to the Navajo Sandstone in the lower Dirty Devil River basin in south-central Utah. Techniques used in the investigation are described.

Information gathered using neutron emitting and receiving equipment indicated that small quantities of water infiltrate sloping surfaces of the sandstone outcrop. Larger quantities infiltrate where the Navajo Sandstone underlies areas of ponding and alluvium-covered channels.

Moisture-retention curves were developed for cores obtained at outcrops of the Navajo Sandstone. The hydraulic conductivity of the rock was determined using data from these curves in empirical equations. Recharge values were computed for two areas using hydraulic conducitivity and in-situ rock-suction measurements. No recharge occurred on the sloping surface of the Navajo on Waterpocket Fold during the summer thunderstorm season of 1977. During the same period, 0.32 inch or 14 percent of the precipitation recharged the Navajo on Thousand Lake Mountain.

Deuterium and oxygen-18 concentrations in water samples of precipitation, streamflow, spring flow. and ground water indicate that the source of recharge to the Navajo is primarily precipitation that occurred in the fall, winter, and early spring. Ratios of carbon-14 and carbon-12 isotopes in samples of ground water indicate an unadjusted age of between 7,000 and 33,000 years. The "younger" water samples collected at the Waterpocket Fold indicate a recharge area nearby.

Statistical analyses of nine sets of discharge measurements on the Fremont River as it crosses the Navajo Sandstone outcrop at Waterpocket Fold show the loss or gain to be no greater than about 2 to 3 percent of the total flow.

Total recharge to the Navajo Sandstone outcrop in the study area is estimated to be about 4,000 acre-feet per year from precipitation and 2,000 acre-feet per year from streams.

INTRODUCTION

During 1975-77, the U.S. Geological Survey. in cooperation with the Utah Department of Natural Resources, Division of Water Rights, made a study of bedrock aquifers in the lower Dirty Devil River basin area, Utah (Hood and Danielson, 1979). One objective of that study was to determine the areas and amounts of recharge to the Navajo Sandstone of Triassic(?) and Jurassic age, a major aquifer in the study area. The purpose of this report is to describe the techniques used to accomplish that objective and to present the findings.

Some of the techniques described herein are not commonly used in areal ground-water studies. These techniques include the use of neutron probes to determine where infiltration has occurred and the use of soil-suction measuring equipment to determine how much of this infiltration can be considered recharge. Stable and radioactive isotopes, used to gain additional insight into the infiltration-recharge phenomenon, are discussed in the appendix.

The study area (fig. 1) encompasses about 3,200 miles in south-central Utah. It is incised by deep narrow canyons separated by benches, mesas, and broad desert flats. Altitudes in the area range from about 3,700 feet near the mouth of the Dirty Devil River to more than 11,000 feet in the mountains that border the area on the south and west.

Although the Navajo Sandstone underlies nearly the entire study area, it crops out only in about 200 square miles (pl. 1) mostly around the San Rafael Swell, along the Waterpocket Fold, in the canyon area of the Dirty Devil River southeast of Hanksville, and on Thousand Lake Mountain and the Henry Mountains where in many areas it is mantled by colluvium and glacial deposits. Ancient folding of the formation has caused the sandstone to be tilted at various degrees from horizontal. Where exposed. such as at the edge of the San Rafael Swell and at the Waterpocket Fold, these "sloping surfaces" of the outcrop allow rapid runoff of most precipitation.

Five perennial streams (pl. 1) traverse the Navajo in the study area. The Fremont River crosses the outcrop on the northern part of the Waterpocket Fold. Its average discharge is about 67 ft^3/s. Oak and Pleasant Creeks also cross the Waterpocket Fold, but average discharges probably are no more than 4 ft^3/s for Oak Creek and 8 ft^3/s for Pleasant Creek. Muddy Creek crosses the Navajo in two places on the San Rafael Swell. During the non-irrigation season, its average discharge is about 8 ft^3/s. The Dirty Devil River crosses the Navajo southeast of Hanksville; the average discharge there is about 95 ft^3/s. During the irrigation season, discharge across the formation from both Muddy Creek and the Dirty Devil River may be almost zero.

Except in the high bordering mountains, the study area is generally arid, characterized by hot, dry summers and cold, dry winters. Average annual precipitation ranges from about 5 inches at Hanksville to about 30 inches in the higher parts of the Henry Mountains and Thousand Lake Mountain (Covington and Williams, 1972). Most of the precipitation falls during late summer as shown by the record for Hanksville (fig. 2), which is representative of most of the study area. Summer precipitation generally results from local thunderstorms of short duration. Winter precipitation generally falls as snow; most accumulations are dissipated rapidly by evaporation and sublimation, except in the mountains.

Conditions favorable for deep infiltration and ground-water recharge to the Navajo are almost nonexistent in the study area. Potential evaporation in the area is significant, as indicated by Iorns, Hembree, and Oakland (1965, p. 19). This is coupled with a topography that causes rapid runoff and a seasonable distribution of precipitation that brings much of the area's annual water supply in the form of scattered, rapidly dissipated thunderstorms. Formations overlying the Navajo contain layers of almost impervious shales that virtually prevent any recharge via this route. The areas with the

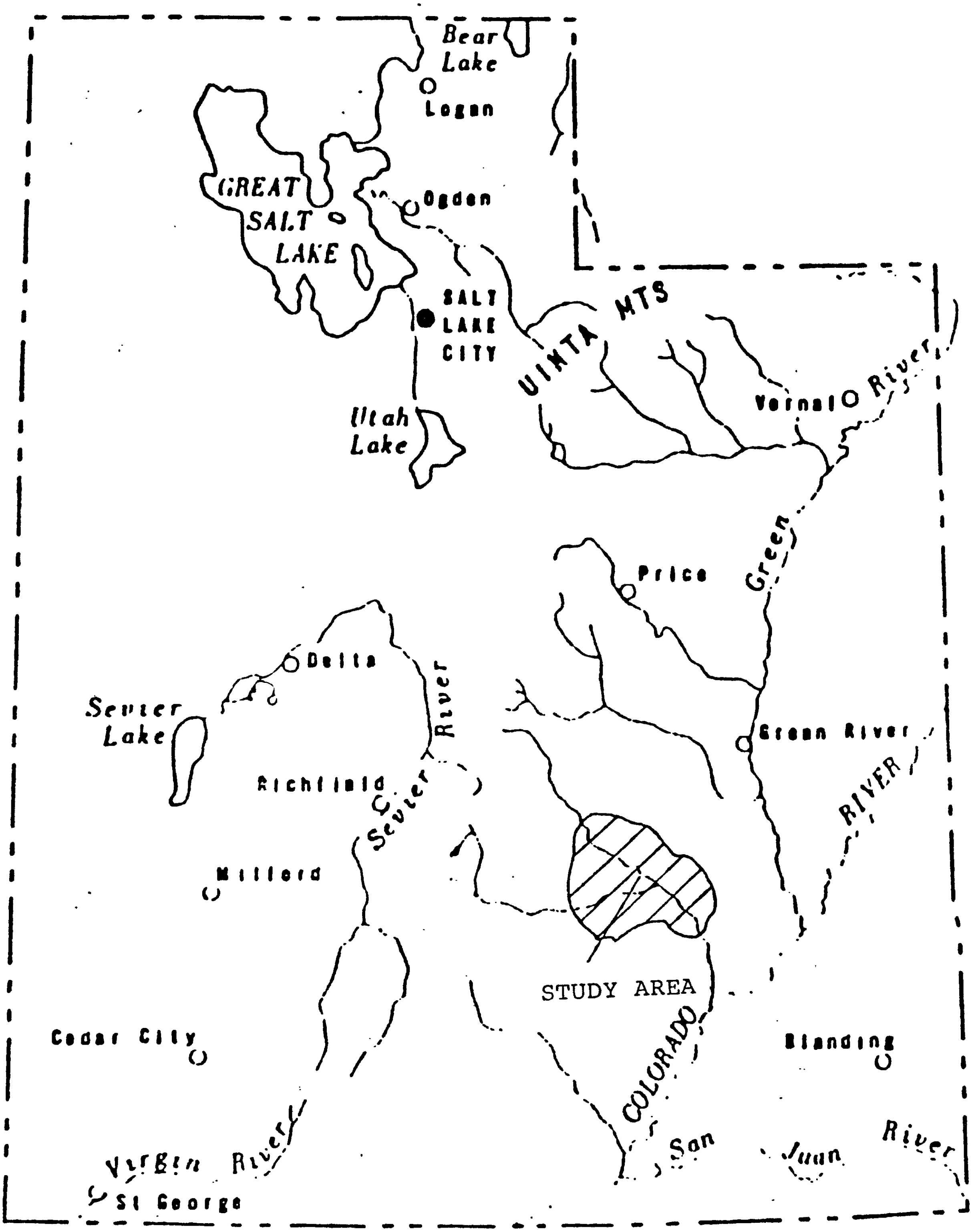

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Figure 1.--Location of the study area.

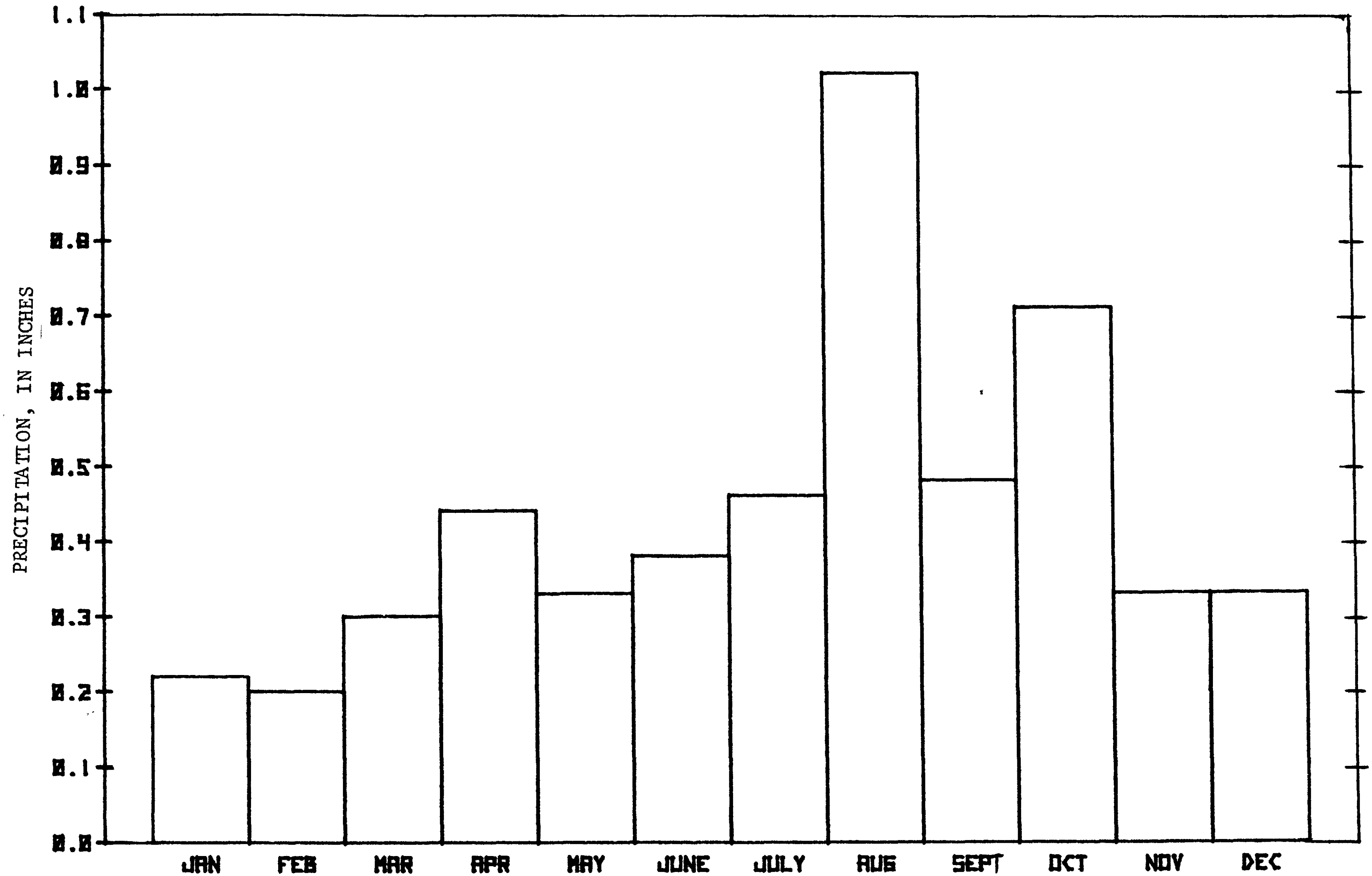

Figure 2.—Average monthly precipitation at Hanksville, 1941-70.

greatest potential for recharge are in the mountains, where annual rates of precipitation are large, and in areas where streams cross the outcrop.

The data-collection sites for this study are listed in table 1 and located on plate 1. Values in this report are given in the unit system (either inch-pound or metric) in which they were originally measured. Conversion from one system to another may be made using the table on page v.

INFILTRATION TO THE NAVAJO SANDSTONE

In unsaturated material above the capillary fringe, infiltration in fine-grained material may be occurring during those times for which it can be shown that moisture content decreases with depth and the moisture content at depth fluctuates with time. Increasing moisture with depth, unchanging moisture content at depth, or a lack of moisture gradient may indicate that little, if any, infiltration is taking place.

Monitoring Infiltration

Measurements of moisture content in soil or consolidated rock may be made with neutron emitting and receiving equipment, which are called neutron-moisture probes. A probe containing a small radioactive source (commonly radium beryllium or americium beryllium) is lowered into an access hole made in the material to be tested. "Fast" neutrons emitted by the source penetrate the material in all directions, colliding with other atomic nuclei. The loss of energy is greatest when a neutron collides with a particle of mass nearly equal to its own, such as a hydrogen nuceus. Thus, collision with the hydrogen atom in a water molecule attenuates the energy of the neutron more than when it passes through dry material. Some of the "slowed" neutrons return and are received by a slow-neutron detector in the probe assembly. A resulting pulse emitted by the detector is amplified and counted by electronic equipment at the land surface, which displays the slow-neutron flux in pulses per minute. The slow-neutron flux is proportional to the abundance of hydrogen atoms and therefore the water content of the material. The radius of influence of the probe varies according to the moisture content. deVries and King (1961, p. 257) state that the vertical radius of influence of a probe similar to the one used in the study at 5 percent moisture is 17 centimeters and at 34 percent moisture is 8 centimeters.

Portable equipment was used in the study area to drill the access holes for the neutron-moisture probes. Locations where information was desirable were inaccessible to larger drilling rigs. Holes were drilled to depths of 3 1/2 to 4 feet using compressed air for cooling and cuttings removal. Compressed air was used because the use of water to remove cuttings would have changed the natural moisture gradients more than compressed air. The maximum depth of the holes was limited by the size of the largest compressor that could be hand carried to the sites.

Thin-walled aluminum tubing 1.55 inches inside diameter and plugged on the bottom was placed in the hole and extended above the land surface. The tubing was sealed with a removable rubber stopper. In areas of possible vandalism and in streambeds, a thick-walled, 6-inch long, 2-inch inside diameter galvanized pipe with end cap was installed over the thin-walled pipe for protection (fig. 3).

Table 1.--Data-collection sites

Site Number	Site
1	Old Woman Wash
2	Jeffery well
3	U.S. Geological Survey test hole 2
4	Hanksville
5	Upper Sand Slide Spring
6	Angel Cove Spring
7	U.S. Geological Survey test hole 3
8	Crescent Creek headwaters
9	Bull Creek headwaters
10	McMillan Spring
11	Weaver well
12	Waterpocket Fold (near Oak Creek)
13	Oak Creek headwaters
14	Pleasant Creek headwaters
15	Capitol Reef National Park
16	Fremont River
17	Fremont River
18	Fremont River
19	Intermountain Power Project observation well 1A
20	Intermountain Power Project test well 1
21	Caine Springs
22	Last Chance well
23	Thousand Lake Mountain
24	Sidehill Spring
25	Pine Creek Spring

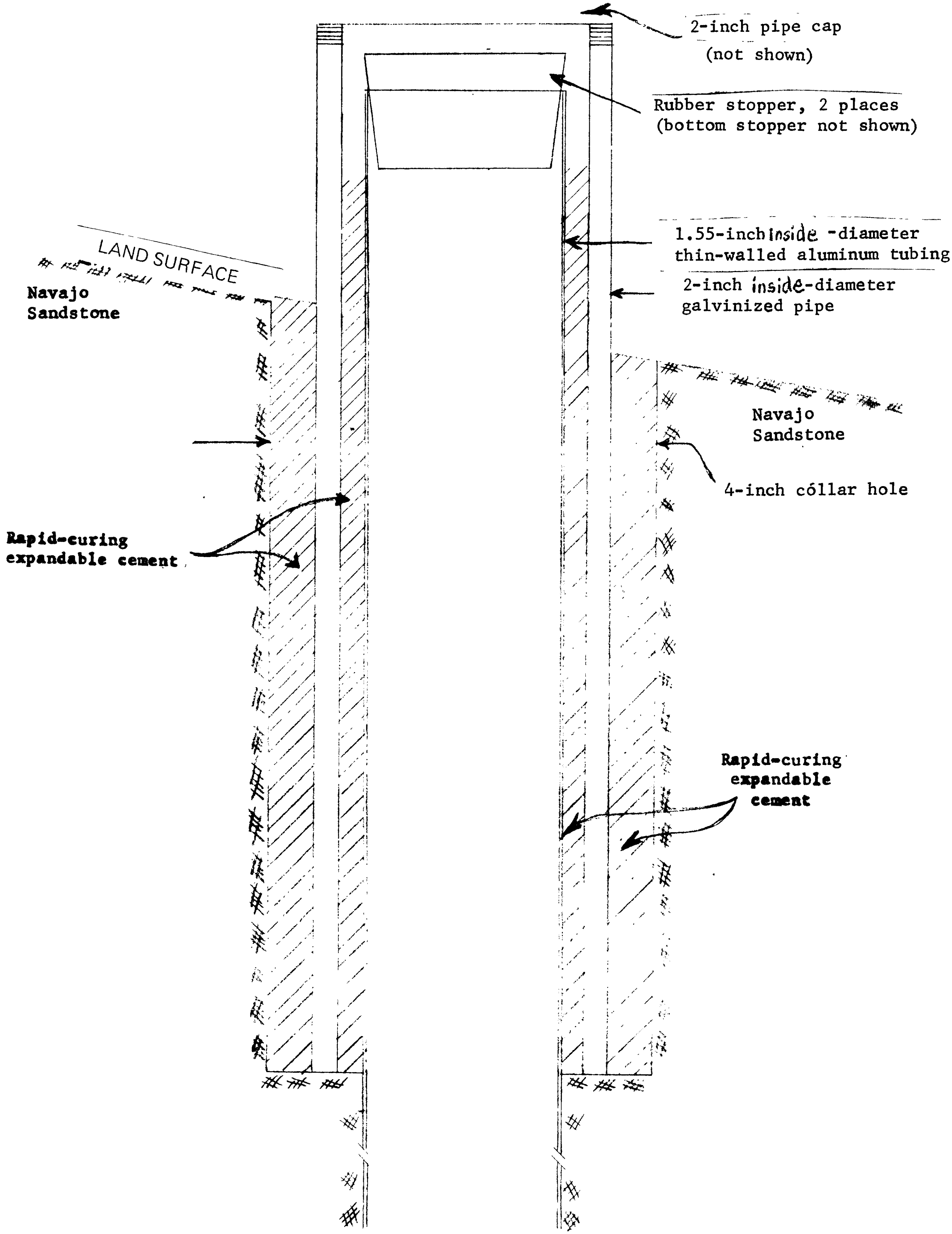

Figure 3.—Section of access hole for neutron-moisture probe.

Moisture-Monitoring Sites

Three moisture-monitoring sites in the study area were selected, taking into consideration the topographic and climatic factors that affect infiltration.

The first site (site 1) was located in and near Old Woman Wash on the San Rafael Reef at an altitude of about 5,000 feet. The precipitation at this site averages less than 8 inches per year. It was assumed that most of the recharge in this area takes place through the Navajo Sandstone on the channel bottoms of streams, all of which are ephemeral or intermittent. It was also assumed that recharge was most likely to occur in those reaches where there is sufficient alluvium to retain storm runoff and transmit it to the underlying bedrock. Four access holes were drilled near site 1: The "channel under sand hole" in Old Woman Wash beneath 12 to 16 inches of alluvial sand; the "exposed channel hole" in the same channel at a spot devoid of alluvium; the "channel depression hole" in a low area of another channel where water ponds after periods of precipitation; and the "sloping sandstone surface hole" on a sloping sandstone surface about 50 feet away from the latter channel.

The second site (site 12) was near Oak Creek on the Waterpocket Fold at an altitude of about 6,000 feet where the average annual precipitation exceeds 11 inches. This site consisted of two access holes: The "intermittent channel hole" in an intermittent channel tributary to Oak Creek and the "sloping sandstone surface hole" on the sloping sandstone surface adjacent to the channel.

The third site (site 23) was on the eastern slope of Thousand Lake Mountain at an altitude of about 8,500 feet where the average annual precipitation is about 30 inches. This site also consisted of two access holes: the "sandstone hole" on a bare outcrop of the Navajo Sandstone and the "colluvium hole" in colluvium that mantles the Navajo. The colluvium overlying the Navajo Sandstone on most of Thousand Lake Mountain consists largely of igneous material with an apparent maximum thickness of about 10 to 15 feet. This material appears to have the ability to absorb water quickly, permitting rapid infiltration to the underlying sandstone. Vegetation, however, is abundant, indicating that there is probably little percolation deeper than the root zone during the growing season.

The three monitoring installations, including a recording rain gage at each site, were completed in June 1976. The recording of moisture content was started the following month using a neutron probe calibrated to a wide range of moisture content.

The moisture content, duration and amount of precipitation at site 1, 12, and 23 are shown in figures 4, 5, and 6. Although measurements were taken at 0.75-foot-depth intervals, only the moisture content at the hole bottom is shown on the graphs.

Data Analyses

San Rafael Reef

Data collected from the four holes near Old Woman Wash showed some correlation between amounts and intensities of precipitation and changes in

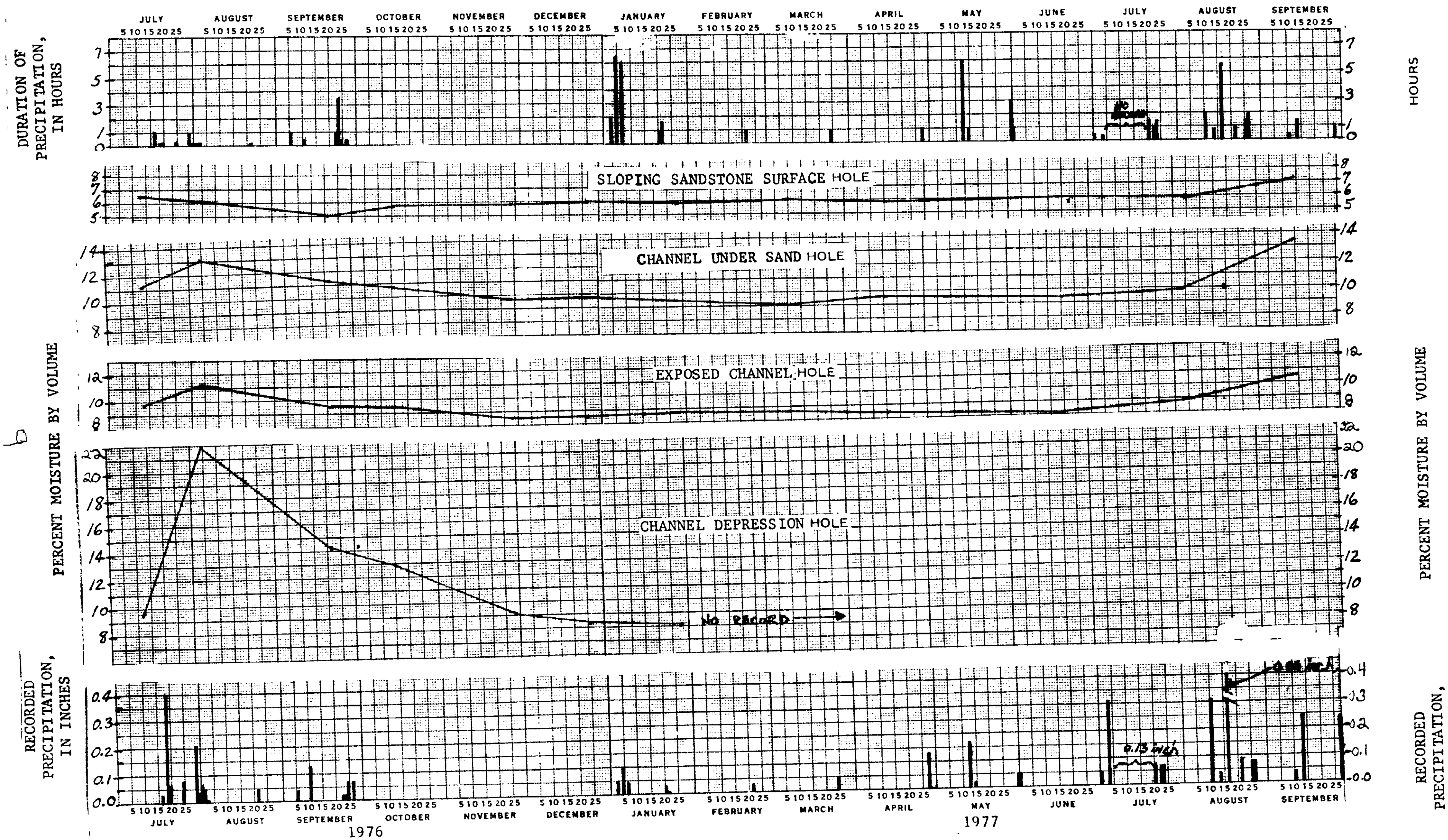

Figure 4.–Data collected in and near Old Woman Wash at the San Rafael Reef (site 1). Moisture measured 3.2 feet below land surface.

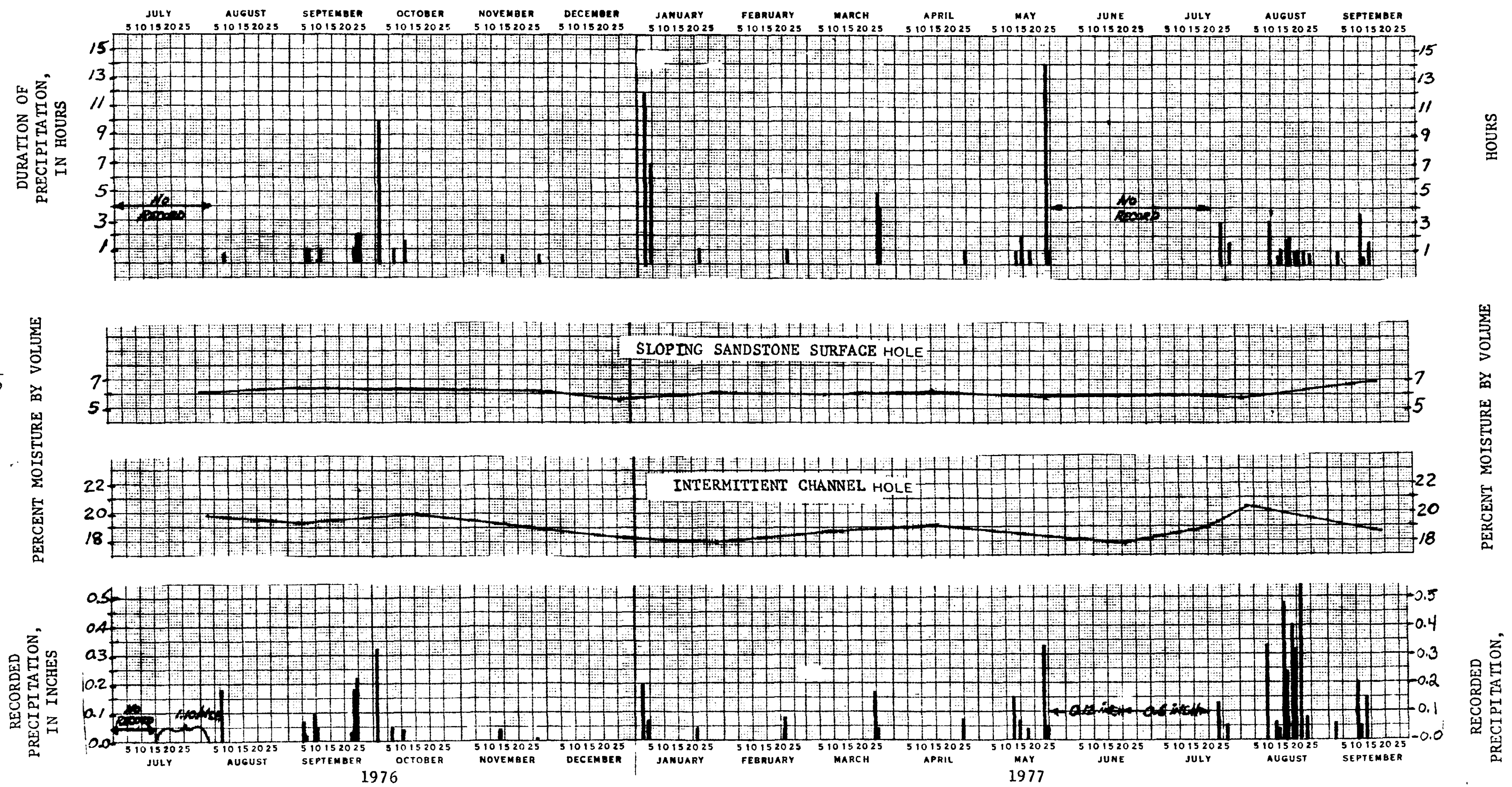

Figure 5.--Data collected on Waterpocket Fold near Oak Creek (site 12). Moisture measured 3.7 feet below land surface.

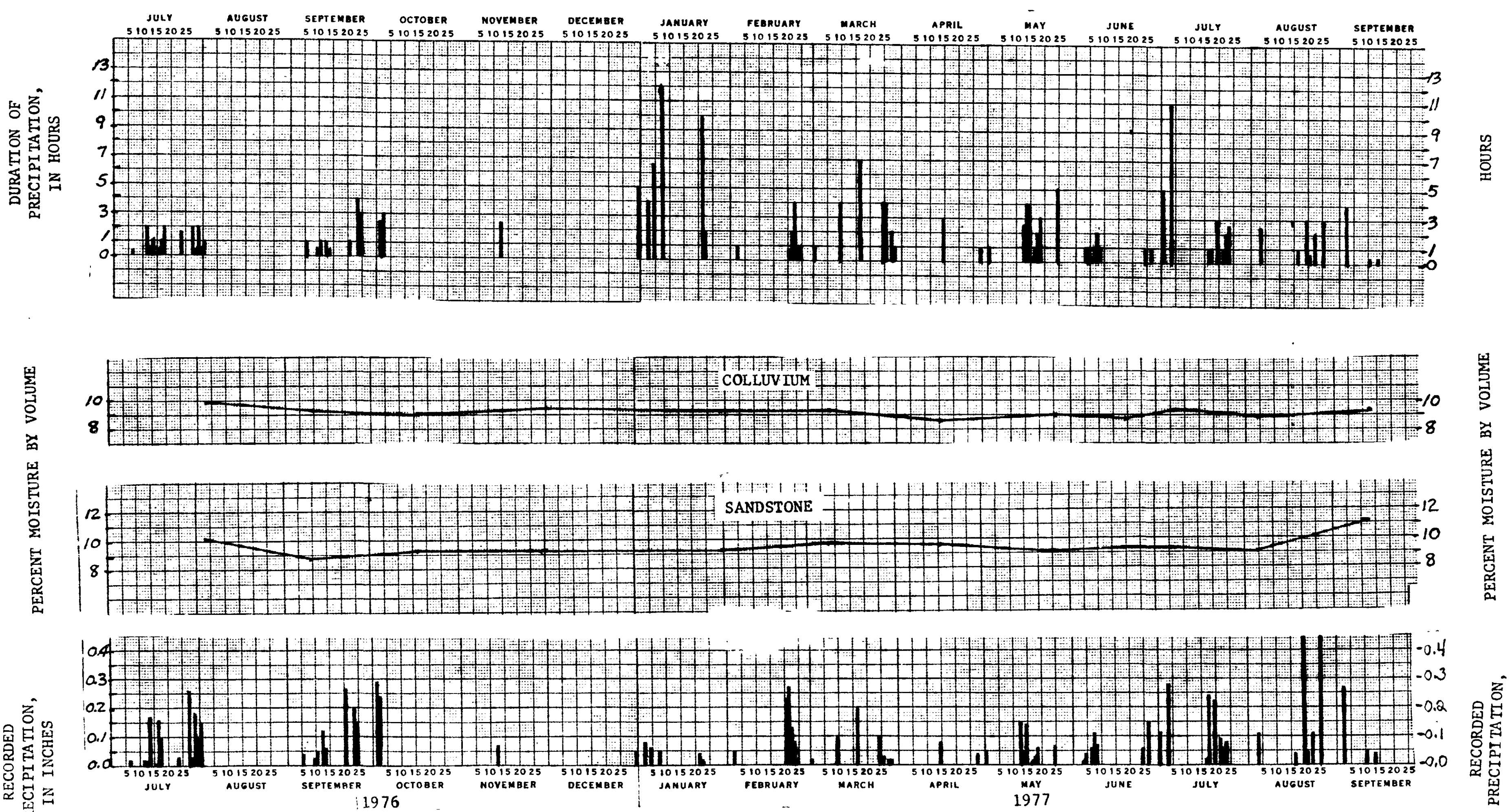

Figure 6.–Data collected at Thousand Lake Mountain (site 23). Moisture measured 3.7 feet below land surface.

moisture content of the rocks (fig. 4). Even though significant amounts of moisture fell during the summer of 1976, moisture content at the sloping sandstone surface hole continually decreased, indicating that little or no infiltration took place. This occurred because the rainfall was intense and ran off rapidly into the adjacent stream channels. Although measurements at the exposed channel hole indicated some infiltration, the retention of water by the alluvial sand for long periods allowed a greater amount to infiltrate at the channel under sand hole. The largest amount of infiltration was recorded at the channel depression hole where ponding apparently occurred. Rainfall of longer duration resulted in some infiltration at the sloping sandstone surface hole in late September 1976 although no increase in moisture content (fig. 4) was recorded at the other holes. Apparently, the ability of the sandstone at the sloping surface site to accept infiltration was greater than at the other sites in Old Woman Wash probably because of a steeper near-surface suction gradient.

Throughout most of the winter, a stabilization or gradual decrease in moisture content took place. The moisture content at that time may have represented "field capacity"[1], which was about 6 percent beneath the sloping surfaces and 2 to 3 percent greater beneath the ephemeral channels. Infiltration during this period may have been prevented by frost near the sandstone surface.

Waterpocket Fold

Moisture content in the intermittent channel hole (fig. 5) at site 12 was generally between 18 and 20 percent during the study period. These unusually high measurements indicate that saturation of the Navajo Sandstone probably exists in this area and a close agreement between moisture content and the porosity (23 percent) of core samples tends to support this conclusion. Carbon-14 analyses (appendix) indicate this is probably a recharge area for the aquifer. Changes in moisture content (fig. 5) may have indicated fluctuations of the water table or the presence of additional moisture in the overlying material. The homogeneity of the Navajo Sandstone indicates that this saturated zone was not perched but was part of the main water body.

Although significantly more moisture falls at this site than at site 1 on the San Rafael Reef, little, if any, additional (or less) moisture appears to infiltrate the sloping bedrock surface. The moisture content here, as on the San Rafael Reef, tended to be in equilibrium at about 6 percent.

Thousand Lake Mountain

Fluctuations in moisture content (fig. 6) between holes at site 23 were inconsisitent. Moisture content increased by about one-half percent at the sandstone hole, but no increase was recorded at the colluvium hole during a winter storm in late February 1977. Bright sunshine reflected from the almost-white sandstone surface may have increased temperatures enough to melt snow and permit infiltration in the sandstone while on the colluvium, moisture may have been lost by sublimation.

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[1]Although the term "field capacity" is highly subjective, Veihmeyer and Hendrickson (1949, p. 75) state that field capacity is ". . . the amount of water held in soil after excess water has drained away and the rate of downward movement has materially decreased."

Although moisture content at the sandstone hole increased considerably after thunderstorms of August-September 1977, a lesser increase was recorded at the colluvium hole. Water probably passed through the colluvium quickly without substantially increasing the moisiture content.

Precipitation at the Thousand Lake Mountain site during the study period was approximately 10 percent greater than at the Waterpocket Fold site and 75 percent greater than at the San Rafael Reef site.

RECHARGE TO THE NAVAJO SANDSTONE

Moisture monitoring using neutron probes has shown that some infiltration (and perhaps some ground-water recharge) occurs in most parts of the study area where the Navajo Sandstone is at or near the land surface. This monitoring alone. however. does not provide the information necessary to determine the rate or amount of recharge. A method was devised, therefore, to measure suction heads at several depths of the near-surface profile using tensiometers. Data collected from periodic monitoring of those suction heads, in conjunction with knowledge of the rock's hydraulic conductivity within the full range of moisture contents, permitted computation of recharge from precipitation.

Recharge contributed by perennial streams was estimated from discharge measurements made where the stream crossed the outcrop.

Monitoring Recharge From Precipitation

Tensiometers were installed in the Navajo outcrop in areas considered to have maximum and minimum infiltration potential. Two holes were drilled in the outcrop: one at Thousand Lake Mountain (site 23) and the other at the Waterpocket Fold (site 12). The holes, drilled with the same equipment used to drill the neutron-probe access holes, were 2 1/4 inches in diameter with a 4-inch diameter collar. An assembly of five 1 1/4-inch diameter ceramic ring tensiometers spaced at 4-inch intervals and separated by hollow, rigid plastic pipe was placed in each hole. Details of the installation are shown in figure 7. The shallowest ceramic ring tensiometer was placed about 8 inches below land surface. Each ceramic ring was hydraulically connected to an above-ground mercury manometer by water-filled flexible plastic tubing (not shown) within the hollow pipe.

Measurements were made at the Thousand Lake Mountain and Waterpocket Fold sites during July-October 1977. Suction-head values (p) recorded at the different levels at each site are listed in table 2. Readings are absolute; they do not include the affect of the difference in altitude (elevation head) between the ceramic rings. The bottom ceramic ring at a depth of 60 centimeters below land surface at the Waterpocket Fold site was broken on installation and not used.

Data Analyses

A technique suggested by Rose and Stern (1965) was used to compute the downward drainage component of infiltration in the Navajo Sandstone. Assuming steady-state conditions, the drainage flux (ν), in centimeters per second, can be computed by the equation:

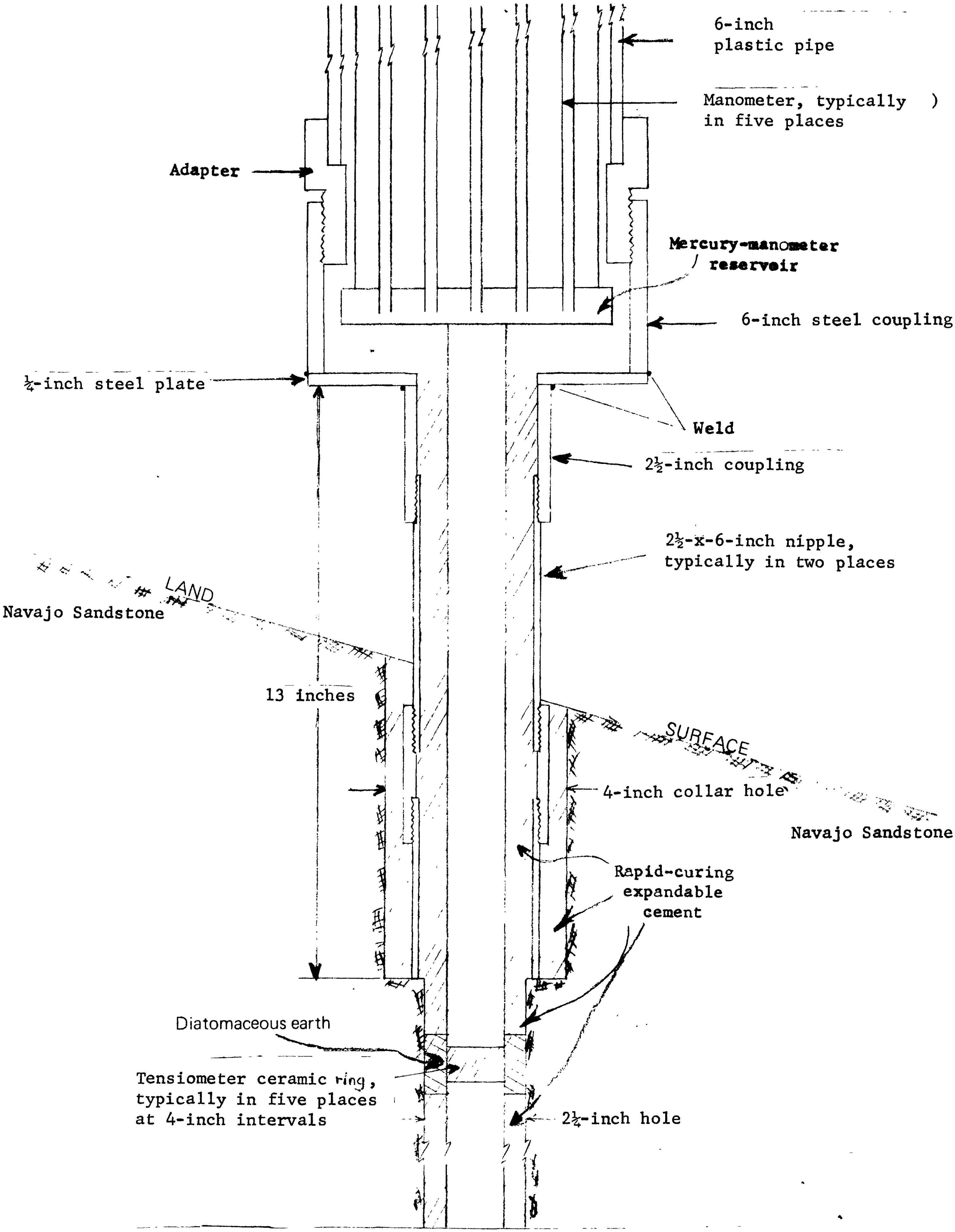

Figure 7.—Tensiometer installation in Navajo Sandstone.

Table 2.--Suction head (p), in centimeters of water, in the Navajo Sandstone

Date	Depth below land surface, in centimeters								
	20	30	40	50	60	20	30	40	50
	Thousand Lake Mountain					Waterpocket Fold			
1977									
July 13	154	141	148	158	167	-	-	-	-
19	126	136	156	164	173	-	-	-	-
21	96	97	116	161	174	156	147	124	116
22	104	98	112	149	173	-	-	-	-
26	114	110	111	128	159	180	174	145	130
27	118	112	113	126	156	188	179	146	131
28	121	116	115	125	154	-	-	-	-
Aug. 3	-	-	-	-	-	230	229	160	145
4	-	-	-	-	-	235	225	163	147
5	147	132	131	135	151	290	230	164	148
8	146	136	133	132	147	232	221	154	145
9	149	138	132	132	147	244	235	158	148
10	152	140	136	133	149	249	240	162	152
11	-	-	-	-	-	252	242	166	158
12	158	144	139	138	150	255	247	170	160
15	-	-	-	-	-	210	202	154	145
16	165	151	143	149	158	-	-	-	-
17	168	153	145	149	158	-	-	-	-
18	171	155	145	150	158	-	-	-	-
19	174	157	147	151	157	-	-	-	-
22	116	130	143	155	164	-	-	-	-
23	118	128	140	155	165	124	120	160	154
24	124	128	135	153	165	107	100	151	149
25	126	129	134	152	165	-	-	-	-
30	120	123	125	143	162	116	109	139	134
31	-	-	-	-	-	116	108	137	134
Sept. 1	119	121	125	140	161	116	108	138	133
2	118	120	124	138	158	115	107	136	133
6	106	111	118	132	154	143	135	138	134
7	110	112	116	128	150	147	140	140	135
8	119	115	118	127	148	-	-	-	-
12	133	129	125	134	149	-	-	-	-
13	135	130	127	134	149	160	162	150	144
14	139	132	129	135	150	165	163	153	146
15	143	135	131	136	151	168	166	155	149
16	147	136	132	138	151	169	168	157	152
Oct. 13	138	142	144	159	170	189	182	160	152

$$\nu = k\,\partial p/\partial z + k \qquad (1)$$

where k, in centimeters per second. is the hydraulic conductivity in the vertical (z) direction (positive downward) and p is the soil-water suction, in centimeters of water[1]. The total amount of water (q). in centimeters, passing a given depth in the profile over a given period of time (t) may then be expressed as

$$q = \int_{o}^{t} \nu dt \qquad (2)$$

If short periods of time are involved, equation 2 may be solved using finite differences and expressed as

$$q = \sum_{o}^{t} \nu\Delta t \qquad (3)$$

and substituting equation 1

$$q = \sum_{o}^{t} k(\Delta p/\Delta z + 1)\Delta t \qquad (4)$$

Soil moisture, especially shortly after rainfall, is in a dynamic state as the soil profile approaches a new quasi-state of moisture equilibrium. Nevertheless, during short periods of time, suction heads change little and steady-state conditions probably can be assumed.

Computations of infiltration were made for the Thousand Lake Mountain and Waterpocket Fold sites. The computational depth (location at which the drainage flux is computed) was generally the depth of the second ceramic ring from the bottom of the tensiometer assembly; the rock at this point was assumed to be imbibing if suction values were decreasing and draining if suction values were increasing. Suction head was assumed to vary linearly from this depth to the ceramic ring above and below. The difference in suction (Δp) between rings (a distance, Δz, of 20 centimeters) wasdetermined andthe gradient $\Delta p/\Delta z$ computed. It was also assumed that each suction-head value was unchanged, that is, steady-state conditions existed for a period, Δt,equal to one-half the time difference to the prior observation plus one-half the time difference to the subsequent observation. Appropriate values of hydraulic conductivity associated with the suction head at the computational depth werecomputed from equations shown in figures 17 and 18 (P=p) in the appendix[2].

Thousand Lake Mountain

Infiltration as a percentage of rainfall appears to vary from storm period to storm periodat site 23 on Thousand Lake Mountain. A plotof cumulative infiltration and precipitation is shown in figure 8. During the

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[1]Methods used in the computation of hydraulic conductivity, including the development of moisture-retention curves, are given in the appendix.

[2]Hydraulic conductivity values computed for the "channel under sand" hole on the San Rafael Reef were adjusted and used in the computations of infiltration for the Thousand Lake Mountain site. Pore-size distribution curves developed from core samples from both sites are similar. Adjustments were needed to account for a porosity difference of 8 percent.

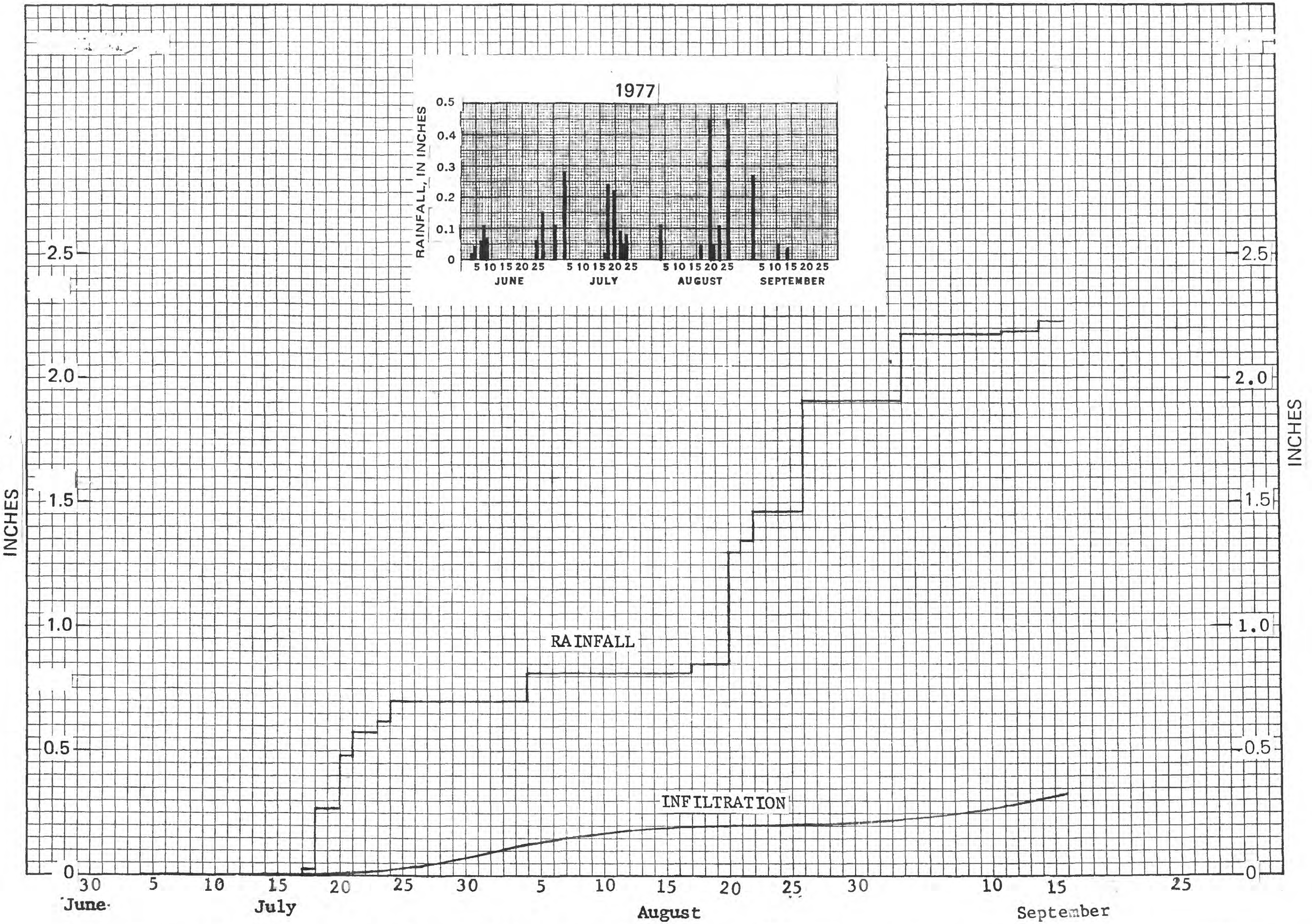

Figure 8.—Cumulative rainfall and infiltration at the Thousand Lake Mountain tensiometer site. Inset shows rainfall histogram.

period July 15 to August 5, infiltration was computed to be about 0.2 inch or about 25 percent of the total 0.81 inch of accumulated rainfall. However, during the period August 16 to September 4, infiltration amounted to only 0.13 inch or about 12 percent of the total 1.1 inches of rainfall. One reason for these relatively large differences was that the intensity of the storms during the latter period was greater than at any other time of the study. Consequently, considerably more water ran off so it was not available for infiltration. Another reason was that more evaporation probably occurred. Rather than a period of nearly continuous rainfall activity such as that between July 15 and August 5, the later period was interrupted by hot. sunny days between rainfall events.

Infiltration at the Thousand Lake Mountain site during the total monitoring period July 13 to September 16 was computed to be 0.32 inch, or about 14 percent of the total precipitation (2.23 inches) for the period. Infiltration at the computational depth. however, lags precipitation by several days or weeks, and therefore the total infiltration corresponding to rainfall for the period is somewhat greater. Lower suction values at all levels on September 16 as compared to values on July 13 (table 2) indicate more water in storage that has not yet reached the computational depth. Since the drainage flux across the computational depth was always downward, evaporation from this depth was considered to be negligible during the study period and the computed infiltration can be considered recharge.

Characteristics of moisture movement through the Navajo on Thousand Lake Mountain may be observed in figure 9. Suction-head values at the 20-centimeter level can be seen to decrease (indicating increased moisture) between July 19 to July 21; then increase (indicating decreased moisture) after July 21. During the period, moisture was infiltrating to deeper levels. By observing the profiles, it may be seen that moisture at the computational depth increased continuously from July 19 to at least July 28 (no observations July 29 to August 4), and decreased in moisture (increased suction) after this time. These observations indicate that with respect to the storm period July 17 to 24 (see rainfall inset), no rainfall infiltrated past the 20-centimeter depth after July 21 and also that all moisture from the storm passed the computational depth by at least August 4 (more reasonably about July 29, see table 2). Therefore, the approximate velocity of the moisture was 30 centimeters in about 8 days or a little less than 4 centimeters per day and travel time from the surface to computational depth approaches about 13 days for this particular storm period. Travel times for other storms would probably vary due generally to different antecedent moisture conditions.

<u>Waterpocket Fold</u>

Moisture-content profiles (fig. 10) at the Waterpocket Fold site indicate that, unlike Thousand Lake Mountain, the Navajo Sandstone at this location received little recharge. Equation 1, simplified to

indicates that infiltration takes place when the suction gradient is positive or has a negative value less than one and evaporation or upward flux takes place whenever the gradient has a negative value greater than one. Relating this to figure 10, infiltration took place whenever the slope of the suction profile was negative or less than +2. Thus, infiltration at the second ceramic ring from the bottom (40-centimeter depth) took place on each date except August 15. At that time, evaporation apparently was occurring above

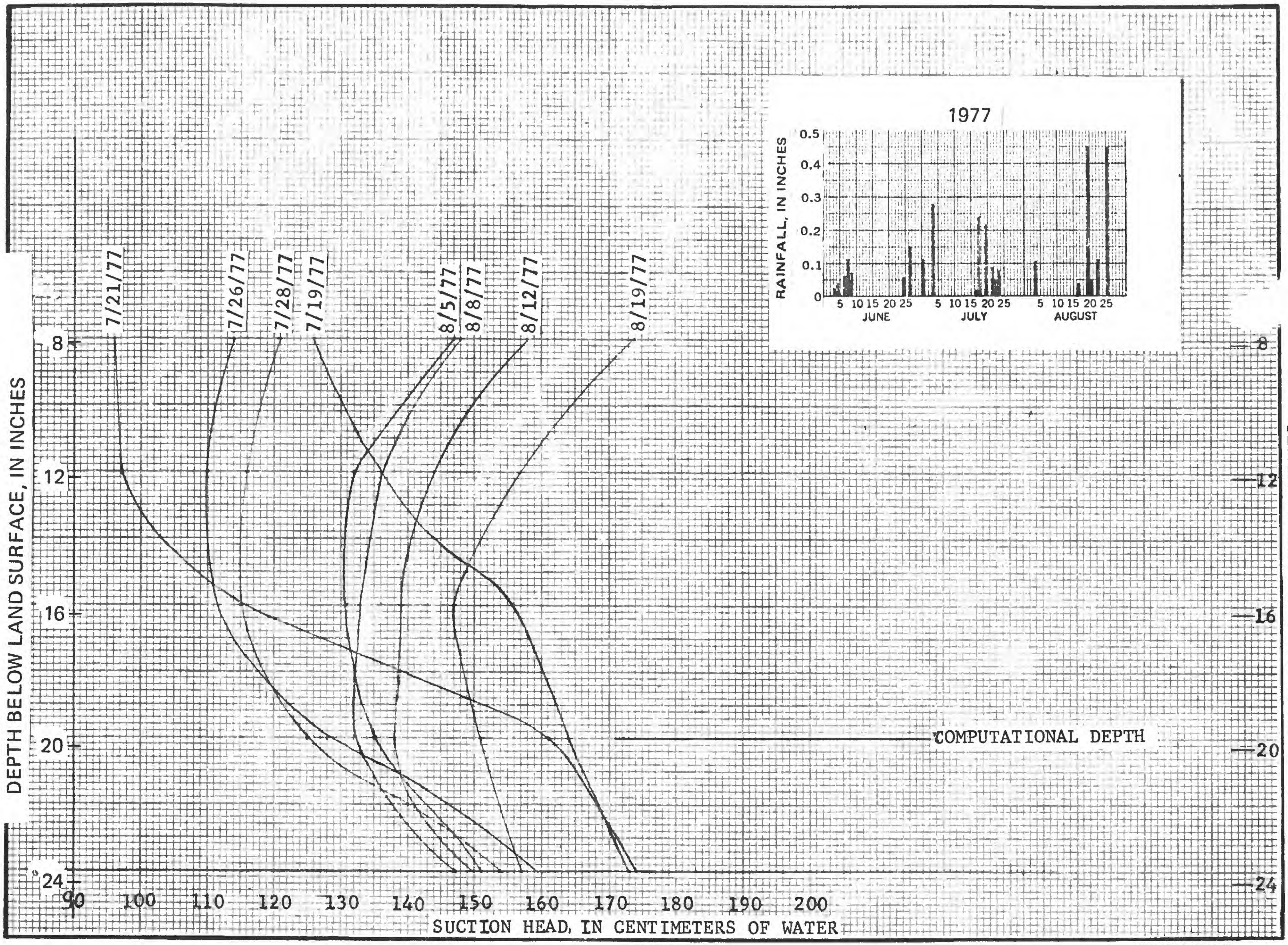

Figure 9. – **Relative moisture-content profiles for the Thousand Lake Mountain tensiometer site. Larger suction-head values connote drier soil conditions. Inset shows rainfall histogram.**

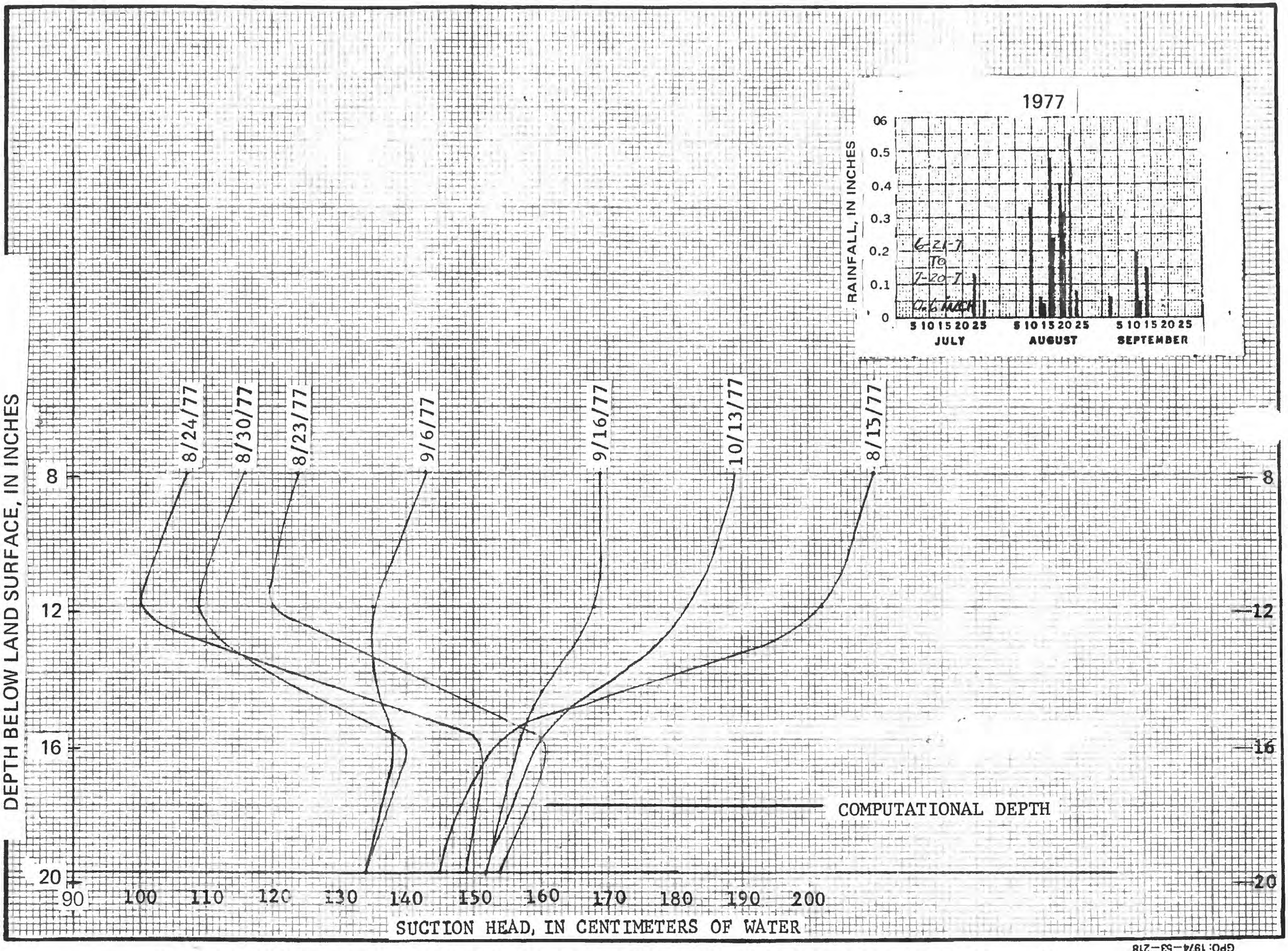

Figure 10.—Relative moisture-content profiles for the Waterpocket Fold tensiometer site. Larger suction-head values connote drier soil conditions. Slope of profile curve may be used as indicator of the occurrence of evaporation or infiltration. Inset shows rainfall histogram.

this depth and infiltration below. In order to avoid these segments of the profile when computing suction-head gradient, the computational depth was moved to a point equi-distant between the bottom two ceramic rings. A linear relationship was assumed between the suction heads at each ring. Net infiltration was computed to be 0.03 inch as compared to a total rainfall from July 13 to September 16 of 2.34 inches. This indicated that there was little or no infiltration at the site from summer thunderstorms.

Effects of Storage

Improper use of data obtained from tensiometers may indicate significant apparent infiltration when there is little or none at all. For example, consider a tensiometer at 20 centimeters below the land surface and another at 60 centimeters. After rainfall. suction at the upper tensiometer may decline sharply as the wetting front reaches this level. At this time, and before the wetting front arrives at the 60-centimeter depth, a relatively steep gradient may be assumed if only the two tensiometers are considered (and assuming the rock to be relatively dry at the 60-centimeter level). Calculation of infiltration for the period may indicate a large addition of water to the subsurface reservoir if it is assumed that the moisture is penetrating past the computational depth. The moisture, in fact, may be adding to the storage between the two tensiometers.

Until the suction gradient ($\Delta p/\Delta z$) has a negative value greater than one (equation 1). it may be assumed that moisture is still penetrating below the computational depth, although the wetting front may not have even arrived at this level. Subsequently. evaporation may gradually remove much or all the water that moved past the top tensiometer. If it is assumed that the moisiture content at the 60-centimeter tensiometer did not change in value, no infiltration actually took place past this level, although a considerable amount may have been computed. Placing the tensiometers as close together as practical (Δz as small as possible) and below the evaporation zone will alleviate most of the potential problems. Evaporation from the Navajo may be considered negligible below about 40 centimeters as indicated by a continuously positive suction gradient (fig. 10) below that depth.

Comments on Methods

More accurate figures for moisture flux through the Navajo Sandstone could have been computed had a greater number of suction-head measurements been available. Design of a continuous-recording pressure gage adaptable to the manometer system should not be difficult. Freezing, however, would prevent data collection during the winter months.

The use of empirical formulas for the determination of unsaturated hydraulic conductivities (see appendix) in media such as the Navajo Sandstone probably cannot be eliminated by laboratory methods. Addition or collection of fluid to or from the samples creates complex problems in the laboratory. For example, suppose a large sample 6 inches in diameter has a hydraulic conductivity of 10^{-8} cm/s (0.00086 cm/d) and 6 days is required to inject 1 mL of fluid once equilibrium is reached. Protection from evaporation and the use of proper injection techniques are critical, and extrapolation of hydraulic conductivity versus moisture-content curves to lower moisture-content values may introduce significant errors.

Hysteresis involved in the wetting and drying cycles possibly introduces error in computations of infiltration. It was assumed that the material was imbibing if the suction trend was toward smaller values and draining was assumed if the trend was toward larger values. When changing from one trend to another, values of hydraulic conductivity occur somewhere between those obtained from either the imbibition or drainage curves. The transition from imbibition to drainage is complex and not fully understood.

Recharge From Perennial Streams

Seepage from perennial streams is another potential source of recharge to the Navajo Sandstone. In order to estimate this value, current-meter measurements were made in all areas where streams crossed the outcrop.

Fremont River

Measurements were made on the Fremont River at its crossings near the bottom, center, and top of the Navajo Sandstone (sites 17, 18, and 19). A summary of gains (+) or losses (-) expressed as a percentage of total flow for nine seepage runs during 1975-77 is shown in table 3. The mean change in discharge across the total reach of the Navajo outcrop for the nine seepage runs was 0.4, expressed as a percentage of the total discharge. At an average discharge of 67 ft^3/s, this would indicate a loss of 0.26 ft^3/s.

Confidence limits may be applied to the data in table 3, using the "student's" t distribution and appropriate statistical computations. Necessary assumptions for this analysis are:

1. The ratio of the difference in measured discharge between sections to the total discharge results in values that are normally distributed around some mean value.

2. The sign of the mean value gives an indication of a gaining or losing stream.

3. All measurements have the same degree of accuracy.

Results of this analysis for the total reach indicates that at 90-percent confidence, the loss-gain ratio will range between -2.8 and +2.0 percent. At 60-percent confidence, the range will be between -0.84 and +0.04 percent. At an average flow of 67 ft^3/s, these ranges expressed as discharge would be -1.84 to +1.30 ft^3/s (90 percent) and -0.56 to +0.027 ft^3/s (60 percent).

Other Streams

Discharge measurements were made on Oak and Pleasant Creeks during August-October 1975. Two sets of measurements on Pleasant Creek, both about 6 ft^3/s. and one set of measurements on Oak Creek, about 3 ft^3/s, indicate losses of about 20 percent to the Navajo Sandstone.

One set of measurements across the Navajo Sandstone on Muddy Creek (San Rafael Swell) in October 1975 indicated no significant gains or losses through the northern outcrop and perhaps a slight gain across the southern outcrop at a discharge of about 0.3 ft^3/s.

Table 3.--Discharge of the Fremont River. [Length of reach between sections 1-2 is 1.55 miles, between sections 2-3 is 2.75 miles, and between sections 1-3 is 4.30 miles]

	Measured discharge, in cubic feet per second			Change in discharge ÷ total discharge (in percent)		
Date	Section 1	Section 2	Section 3	Section 1-2 (upstream)	Section 2-3 (downstream)	Section 1-3 (total)
8-22-75	40.7	--	42.0	--	--	+3.2
9- 3-75	26.3	--	28.1	--	--	+6.8
10-30-75	81.6	78.1	85.7	-4.3	+9.7	+5.0
12-30-75	106.2	102.1	103.9	-3.9	+1.8	-2.2
3-25-76	88.3	--	87.4	--	--	-1.0
5-11-76	53.4	50.4	50.6	-5.6	+0.4	-5.2
10- 6-76	49.4	52.3	49.4	+5.9	-5.5	0
5- 4-76	29.5	32.1	29.3	+8.8	-8.7	-0.7
5- 5-77	30.6	29.6	27.7	-3.3	-6.4	-9.5

No gains or losses were confirmed by two sets of measurements across the outcrop in Dirty Devil Canyon during September 1976 and October 1977. Discharges were about 17 ft^3/s during September and 60 ft^3/s during October.

Annual Recharge

The total annual recharge to the Navajo Sandstone was estimated to consist of losses from perennial streams as they cross the outcrop of the Navajo and recharge from precipitation in most other areas where the Navajo is at or near the land surface. Although it was shown that infiltration may occur through the beds of intermittent and ephemeral streams, these areas are not considered significant sources of recharge. As compared to the total outcrop, the potential surface area for infiltrations in these channels is extremely small.

Infiltration from perennial streams may contribute large quantities of recharge to the Navajo. It has been shown statistically that losses in the Fremont River may be as much as 2 percent of the total flow. Losses from Pleasant and Oak Creeks were determined to be about 20 percent of ther total flows. Assuming the measured discharges of 6 ft^3/s from Pleasant Creek and 3 ft^3/s from Oak Creek to be a conservative estimate of their average flow and the average flow of the Fremont River to be 67 ft^3/s, total losses by perennial streams to the Navajo Sandstone may be as large as 3 ft^3/s or 2,000 acre-feet per year.

The potential area for recharge where the Navajo Sandstone is at or near the land surface is about 110 square miles. The area includes outcrops on the east and west borders of the San Rafael Swell, along the Waterpocket Fold, and on Thousand Lake Mountain, where it is mantled by colluvium and glacial deposits. The Navajo outcrop in Dirty Devil Canyon is known to be an area of ground-water discharge and little is known about subsurface conditions in the Henry Mountains. Therefore, these areas were not considered as recharge areas.

Recharge to the Navajo Sandstone where it is at or near the land surface was estimated by using data obtained during a 3-month period at Thousand Lake Mountain as a factor to be applied to an average precipitation value for the entire area. An assumption for this method was that most ground water is derived from precipitation that occurs from September through May. This assumption was based on deuterium and oxygen-18 data (see appendix) which indicate that a large part of the recharge may be attributed to precipitation that occured during the fall. winter[1]. and spring and tensiometer data which indicate that no recharge occurs during the thunderstorm season on the sloping surfaces. Due to uplifting of the formation and also its natural cliff- and dome-forming characteristics, almost all the outcrop may be considered a sloping surface.

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[1]This assumption may appear to contradict the neutron-probe data which indicated that no infiltration occurred during the winter months due to freezing in the upper layers of the outcrop area. However, snow that occurs during this period may, at the higher altitudes, remain on the ground until spring before infiltrating into the rock.

From a map prepared by Covington and Williams (1972), it was estimated that the average annual precipitation on most of the outcrop area is about 8 inches. Long-term precipitation records from Hanksville, Green River, Loa, and Fruita show that about 64 percent of the annual precipitation occurs during September through May. Thus, precipitation of about 5.1 inches was used to compute recharge to the Navajo Sandstone.

Tensiometer data from Thousand Lake Mountain during July 13 to September 16, 1977, indicated that the recharge was about 14 percent of the recorded precipitation. Extrapolating this information throughout the 110 square mile area of outcrop results in a total recharge of about 4,200 acre-feet. This is an absolute maximum value because recharge conditions on Thousand Lake Mountain are more favorable than elsewhere in the outcrop area. Recharge of 14 percent may, however, be realistic in some areas where accumulations of snow melt at a very slow rate resulting in a much longer period for infiltration.

The total annual recharge to the Navajo Sandstone in the study area (including stream channel infiltration) is estimated to be no more than about 6,000 acre-feet.

SUMMARY

Moisture content was measured using a neutron probe in three areas with dissimilar infiltration potential to the Navajo Sandstone; areas of potential ponding, alluvial cover, and sloping surfaces. Although magnitudes of infiltration were not computed, it was shown that some infiltration occurs in all areas investigated. Substantially more quantities of water per unit area infiltrate to the subsurface in areas of potential ponding than in other outcrop areas. Alluvium in ephemeral stream channels retains water for long periods, permitting more infiltration than from channels devoid of alluvium. Sloping surfaces, of which most of the outcrop of the Navajo is composed, showed evidience of small amounts of infiltration. Spring and fall appeared to be the time of year that most precipitation occurred. Correlation of deuterium concentrations in samples of ground water and precipitation (appendix) supports this observation. Saturation of the Navajo was detected below an ephemeral streambed on Waterpocket Fold. Carbon-14 analyses of ground water samples (appendix) indicate that this area is probably an intake for recharge to the aquifer.

Soil-suction measurements were made at several levels of the Navajo Sandstone profile to a depth of 50 to 60 centimeters throughout the thunderstorm season (July-September 1977). Computation of moisture flux indicates that virtually no recharge occurred on the sloping surface of the outcrop at Waterpocket Fold. On Thousand Lake Mountain, relatively large amounts of infiltration to the exposed outcrop occurred throughout the summer months; approximately 14 percent of the moisture that occurred from July 13 to September 16, 1977, infiltrated to the subsurface and may be considered recharge.

Although it could not be determined whether the Fremont River is losing or gaining across the Navajo Sandstone, it was established, using statistical methods, that with 90-percent confidence, the gain or loss value is within 1.5 ft^3/s. Oak and Pleasant Creeks may contribute more water to the Navajo

Sandstone than the Fremont River. A small number of discharge measurements on these creeks indicated losses of about 20 percent across the formation.

Total recharge to the Navajo Sandstone outcrop in the study area is estimated to be no more than 4,000 acre-feet per year from precipitation and no more than 2,000 acre-feet per year from streams.

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APPENDIX

Other Techniques of Estimating Where and When Recharge Occurred

Tensiometer data have indicated that little recharge takes place from summer thunderstorms except at the higher altitudes such as Thousand Lake Mountain. Neutron-probe data showed that deep infiltration took place in the outcrop mainly during fall and spring. It also indicated that the Navajo was saturated at one site on Waterpocket Fold. In order to gain further support for these interpretations and to gain additional insight into the recharge phenomena, special studies were conducted using isotopes of hydrogen and carbon.

Deuterium

Deuterium is a stable isotope of hydrogen that has a relative abundance in water of 0.016 percent with respect to other isotopes. The concentration of this isotope in precipitation that arrives at the Earth's surface is unique in many instances with respect to location, altitude, and season. This identifying concentration may remain unchanged as the precipitation enters and moves through the soil to the ground-water reservoir. Therefore, this phenomena has been used in hydrologic studies to determine when and where ground water originated. Such studies have been conducted by Harpez and others (1963), Thatcher (1965), and Simpson, Thorud, and Friedman (1970). The next few paragraphs address some of the reasons for these "identifying" concentrations. Interpretation of the collected data will follow.

Standard mean ocean water (SMOW) is the ratio of the concentration of deuterium (D) and the normal hydrogen (protium) ion (H) in ocean water. This ratio is constant in the ocean but varies substanially in the water vapor that evaporates, moves across the land mass, and eventually falls as precipitation. The deviation[1] of this ratio from SMOW generally is due to the effect of vapor pressure differences between the deuterium (HDO^{16}) and water (H_2O^{16}) molecules. Water vapor becomes more concentrated or "heavier" in deuterium during evaporation because the vapor pressure of H_2O^{16} is greater than that of HDO^{16} and consequently water molecules are lost preferentially; during condensation, water vapor becomes "lighter" in deuterium.

Storm tracts affect the deuterium concentration (D) in precipitation. As storms generated over the ocean move inland and precipitate some of their moisture, the "heavier" deuterium is precipitated preferentially. As the storm system moves farther inland and additional precipitation occurs, D of the remaining vapor becomes less and less.

Temperature affects the concentration of deuterium (D) in precipitation. The ratio of the vapor pressures of H_2O^{16} and HDO^{16} increases or decreases with the temperature of the environment. Consequently, precipitation at higher altitudes will have smaller D (more negative δD) than at lower altitiudes in the same area.

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[1] It is common practice to compute the deviation (δD) from SMOW (standard mean ocean water) as a per mille deviation as follows:

$$\delta D = \frac{D/H\ (\text{sample}) - D/H\ (\text{SMOW})}{D/H\ (\text{SMOW})} \times 1{,}000$$

The "amount effect" causes variations in D in precipitation. As precipitated moisture moves through the atmosphere, the vapor pressure of water droplets tends toward a state of equilibrium with the moisture already present in the air. In arid and semi-arid climates, evaporation from the droplets, as they progress downward, causes the remaining water in the droplet to become concentrated (more positve δD) with respect to D. In more humid climates, where the air is less dry, D at the Earth's surface consequently is less. This principle can be applied to variations in rainfall intensity. Intense rainfall may quickly saturate the atmosphere, even in arid climates, permitting the next increment of precipitation to progress downward with unchanged deuterium concentration. Less intense rainfall is affected more severly, and in some instances, δD may become positive if sufficient evaporation takes place.

The origin of storms entering southern Utah varies throughout the year. In summer, most of the moisture originates in the Gulf of Mexico. These storms are generally intense and of short duration. A few isolated storms of longer duration may also occur but they originate off the coast of Baja, California. Winter precipitation generally originates in the Pacific Ocean. Storms occurring during this period are usually less intense and of relatively long duration. These variabilities in storm tracks, intensities, and durations result in precipitation with concentrations of deuterium equally as variable.

A plot of the deviations of deuterium and oxygen-18 concentration from those of a Vienna (V) SMOW standard (Gonfiantini, 1978) for individual and integrated precipitation samples and for water from wells completed in the Navajo Sandstone is shown in figure 11[1] (actual values in table 4).

Craig's (1961) Meteoric Water Line represents a linear correlation of D and O^{18} in surface water and precipitation throughout the world that have not undergone excessive evaporation. Craig (1961) notes that the line has a slope of 8 and fits the equation $\delta D = 8\delta O^{18} + 10$. When free evaporation at ordinary temperatures takes place, laboratory analyses and on-site investigations have indicated that the slope is reduced to 5.

Several conclusions may be obtained from figure 11: (1) Although δD values related to individual storm precipitation encompass an extremely large range (14 to 168), only those corresponding to spring and fall precipitation are similar to those in samples from wells; (2) there is a pronounced seasonal

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[1] $$\delta O^{18} = \frac{O^{18}/O^{16}\ (\text{sample}) - O^{18}/O^{16}\ (\text{SMOW})}{O^{18}/O^{16}\ (\text{SMOW})} \times 1000$$

where O^{18} and O^{16} are concentrations of the isotopes of oxygen. Water samples analyzed for deuterium are generally also analyzed for these isotopes of oxygen so that a check of the sample stability and analyzation accuracy can be made. If, for example, the plot of δD and δO^{18} shows a value too far from the Meteoric Water Line, problems with evaporation or in analyzation of the sample may have occurred.

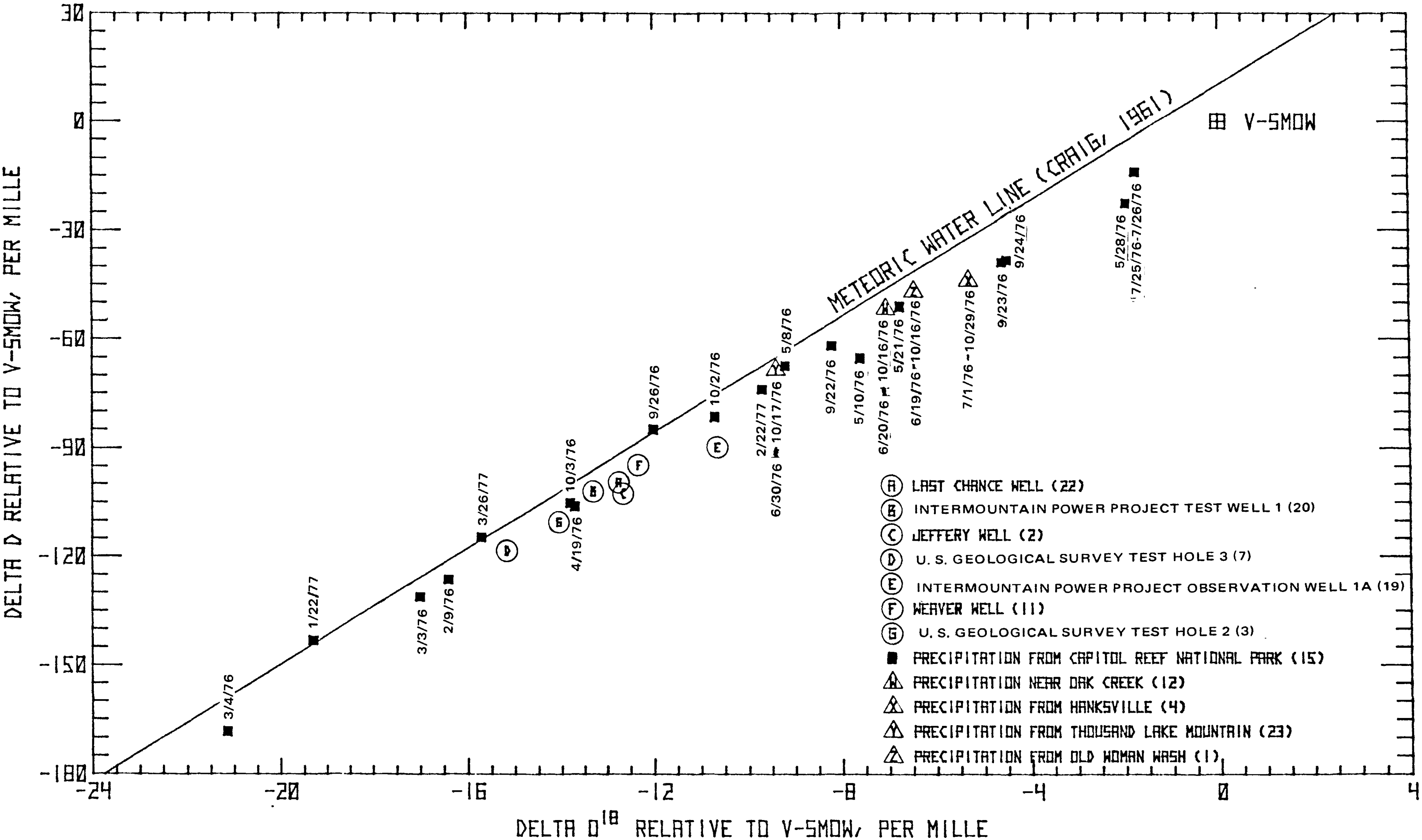

Figure 11.—Deuterium and oxygen-18 isotope data for precipitation and water from wells. Solid blocks represent individual precipitation samples, triangles represent a combined sample of all summer and fall rainfall, and circles represent samples from wells completed in the Navajo Sandstone. Numbers in parentheses refer to site designations on figure 2.

Table 4.--Isotope analyses and apparent age of water from precipitation, springs, creeks, and wells

[Deviation of deuterium (δD) and oxygen-18 (δO^{18}) relative to Vienna - Standard mean ocean water]

Source	Site No.	Date	δD	δO^{18}	Apparent age (years)
Old Woman Wash (precipitation)	1	6- 9-76 to 10-16-76	- 47.0	- 6.45	--
Hanksville (precipitation)	4	7- 1-76 to 10-29-76	- 44.1	- 5.30	--
Thousand Lake Mountain (precipitation)	23	6-30-76 to 10-17-76	- 68.6	- 9.40	--
Near Oak Creek (precipitation)	12	6-20-76 to 10-16-76	- 51.5	- 7.05	--
Upper Sand Slide Spring	5	9-20-76	-118.8	-15.00	--
Angel Cove Spring	6	9-21-76	- 98.4	-11.45	--
McMillan Spring	10	4-19-77	-106.00	-14.70	--
Caine Springs	21	11-30-76	-114.3	-15.0	--
Sidehill Springs	24	8- 4-76	-118.0	-15.5	--
Pine Creek Spring	25	10-29-76	-114.4	-15.2	--
Oak Creek headwaters	13	5- 3-77	-103.4	-14.75	--

Table 4.--Isotope analyses and apparent age of water from precipitation, springs, creeks, and wells--Continued

[Deviation of deuterium (δD) and oxygen-18 (δO^{18}) relative to Vienna - Standard mean ocean water]

Source	Site No.	Date	δD	δO^{18}	Apparent age (years)
Pleasant Creek headwaters	14	5- 3-77	-106.25	-14.75	--
Crescent Creek headwaters	8	4-19-77	-103.60	-14.75	--
Bull Creek headwaters	9	4-19-77	-105.10	-14.95	--
Last Chance Well	22	9-27-76	- 99.6	-12.75	31,200-32,800
Jeffery Well	2	9-25-76	-102.6	-12.65	30,800-34,200
U.S. Geological Survey test hole 3	7	8- 9-76	-118.4	-15.15	19,700-20,300
U.S. Geological Survey test hole 2	3	8- 6-76	-110.5	-14.05	24,300-25,300
Intermountain Power Project test well 1	20	9-26-76	-102.1	-13.30	23,300-24,400
Intermountain Power Project observation well 1A	19	10- 5-76	- 89.9	-10.65	22,600-23,400
Weaver well	11	9-26-76	- 94.7	-12.30	7,000- 7,300

effect with respect to the individual storm samples, the summer (June-September) rainfall being much "heavier" in D than is the winter precipitation; (3) all combined samples from the summer rainfall are significnatly "heavier" in D than are the well waters; and (4) there is a correlation (linear if plotted) between altitude (temperature) of the collection site and δD from the combined rainfall samples.

Water samples representative of snowmelt were collected in May 1977 from Oak and Pleasant Creeks at the Waterpocket Fold, from Crescent and Bull Creeks and McMillian Spring on Henry Mountain, from Sidehill Spring on Thousand Lake Mountain, and from Pine Creek Spring near Bicknell. Although Pine Creek Spring is at a relatively low elevation, the source of its discharge is undoubtedly snowmelt from high on Boulder Mountain and the Awapa Plateau 10 to 15 miles west of the study area.

Water samples of discharge from the Navajo were collected at Caine Springs, Upper Sand Slide Spring, and Angel Cove Spring. Caine Springs discharges from the Carmel Formation of middle Jurassic age overlying the Navajo. The top of the Navajo is about 500 feet below land surface at Caine Springs but is probably the source of water which moves upward through fractures. Upper Sand Slide and Angel Cove Spring discharge directly from the Navajo in the Dirty Devil Canyon.

A plot of the isotopic deviations from SMOW in the snowmelt, well, and spring samples is shown in figure 12 (values in table 4). All δD values from ground water in the Navajo lie within the relatively narrow range of about -90 to -119 and average about -105. The range of δD values representing winter and early spring precipitation is also small; the average is about -108. This may indicate that a large portion of the recharge to the Navajo is derived from precipitation that occurs (but not necessarily infiltrates) in the winter and early spring.

It is interesting to note (fig. 12) that δD in water from Angel Cove Spring is significantly different from that in U.S. Geological Survey Test Hole 3 even though the orifice of the spring is down-gradient from the water level in the test hole. The sample from Upper Sand Slide Spring (also down-gradient) has an almost identical δD to that of the test hole as expected. Angel Cove Spring was sampled in September 1976 under less than ideal conditions. The air temperature was at least 32°C and discharge was so small that a syringe was required to secure a sample of less than 1 liter. It is possible, therefore, that evaporation could have increased D of the sample. As previously explained, the unaltered concentration may be determined by moving the symbol (A) along a line with slope 5 toward the Craig Meteoric-Water Line. Interception with the symbols for the Upper Sand Slide Spring and U.S. Geological Survey Test Hole 3 indicates that the waters are probably of the same origin.

Carbon-14

The unadjusted age of water samples collected from seven wells completed in the Navajo was determined using carbon-14 to carbon-12 ratios. Large volumes (25 gallons) of water were collected from each well and the carbon precipitated in the field. Laboratory results on the concentrated samples are listed in table 4. Although waters as old as 40,000 years may be dated by

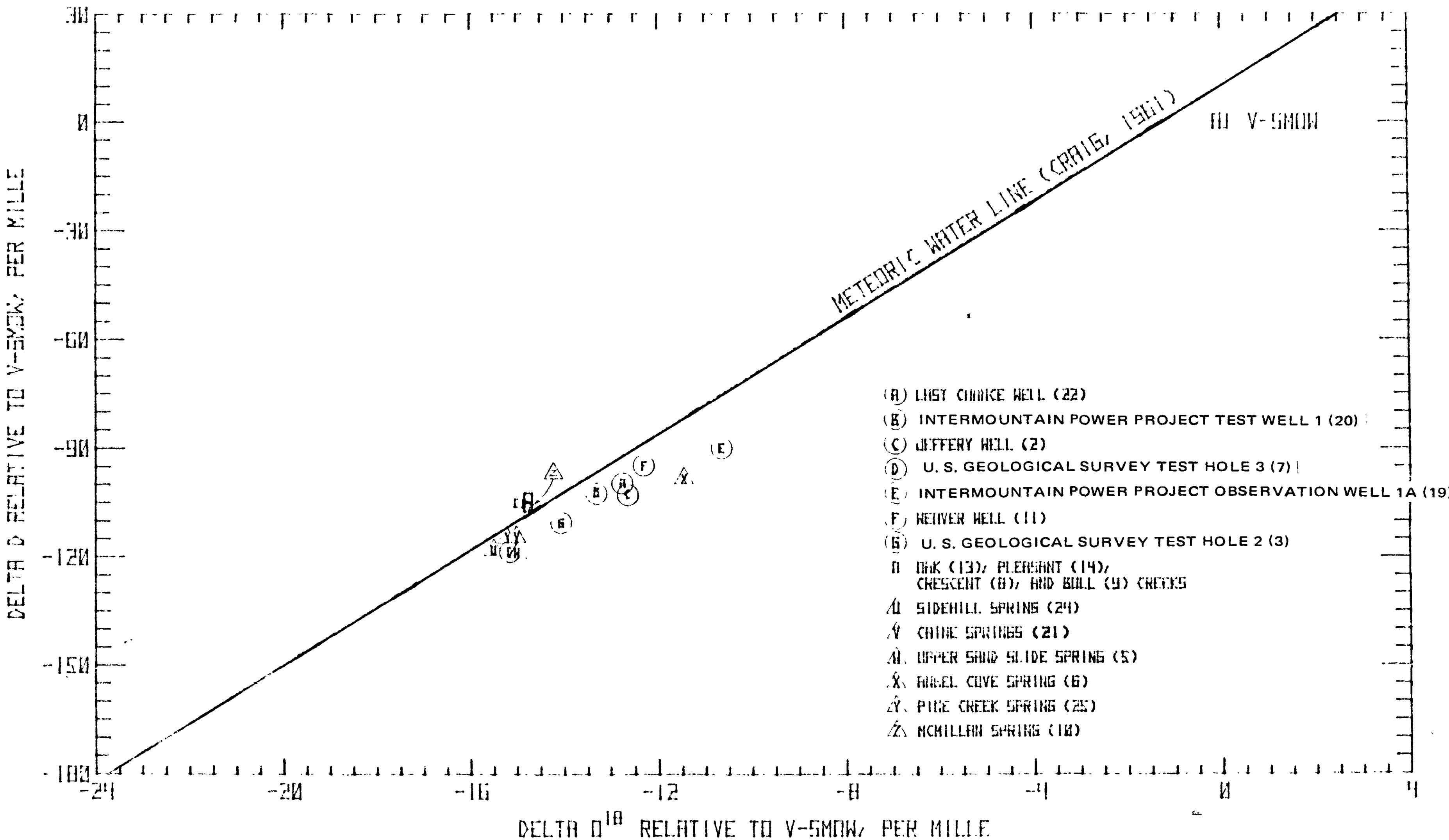

Figure 12.—Deuterium and oxygen-18 isotope data for water from wells, creeks, and springs. Squares represent high-altitude surface-water samples and represent relative concentrations in snowpack, triangles represent spring waters, and circles represent samples from wells completed in the Navajo Sandstone. Numbers in parentheses refer to site designations in figure 2.

this method, interferences due to the solution of old carbon limit the accuracy of the method. Therefore, although the relative ages are reasonably accurate, the unadjusted ages are probably much older than the true ages.

The unadjusted ages (table 4) indicate that the Navajo is probably being recharged at Waterpocket Fold, but they also indicate that movement through the Formation is very slow. As compared to the age of water from the other sites, the relatively young age (7,000 years) of water from the Weaver well (site 11) indicates the well is near a source of recharge to the aquifer. The age difference of samples collected at sites 19 and 20 indicate that ground water is moving to the east at about 6 feet per year.

Computation of Hydraulic Conductivity

Unsaturated hydraulic conductivity was computed for several cores of Navajo Sandstone using empirical equations. These equations, however, required data concerning the pore pressure of the rock at various moisture contents (moisture-retention curves) as necessary input. These data were determined by Professor R. H. Brooks of Oregon State University using a method developed in 1976 (Su and Brooks, 1976, p. 55). In the next few paragraphs, we will briefly explain the procedures used to develop the moisture-retention curves. Procedures used in the computation of hydraulic conductivity will follow.

Moisture-Retention Curves

Pore pressure (suction) values in unsaturated porous media are not commonly unique to one specific value of moisture content. Rather, the values are dependent on antecedent moisture conditions; that is, whether the material has previously been in a wetter (material now draining) or drier (material now imbibing) state. Therefore, a plot of these data (moisture-retention curves) commonly split into two branches as moisture content increases. A schematic of the apparatus used by Brooks to determine suction values corresponding to moisture content in cores from the Navajo is shown in figure 13.

To determine experimental data points in the drainage branch, the retention cell (including sample) was vacuum saturated, and the lower part of the system (below zero datum) was filled with water, with the regulator set at zero pressure. The pressure was reduced until a specified volume of water was removed from the sample. At that time, the burette valve was closed and the system permitted to equilibriate. At equilibrium, the volume of water removed was determined; the ratio of this volume to the total pore volume of the core indicated a percentage of saturation corresponding to the pressure (suction) indicated on the manometer. The process of removing incremental amounts of water was repeated until relatively large pressure differences corresponding to relatively small water removal was encountered. This ended the drainage test; the sample was now ready for the imbibition test.

To determine experimental data points in the imbibition branch, a measured quantity of water was added to the sample and the pressure was increased to prevent sample drainage. The amount of water removed at the end of the drainage cycle minus the amount of water added indicated the new percentage of saturation corresponding to the new adjusted manometer pressure. This procedure was repeated until saturation (zero pressure) was achieved.

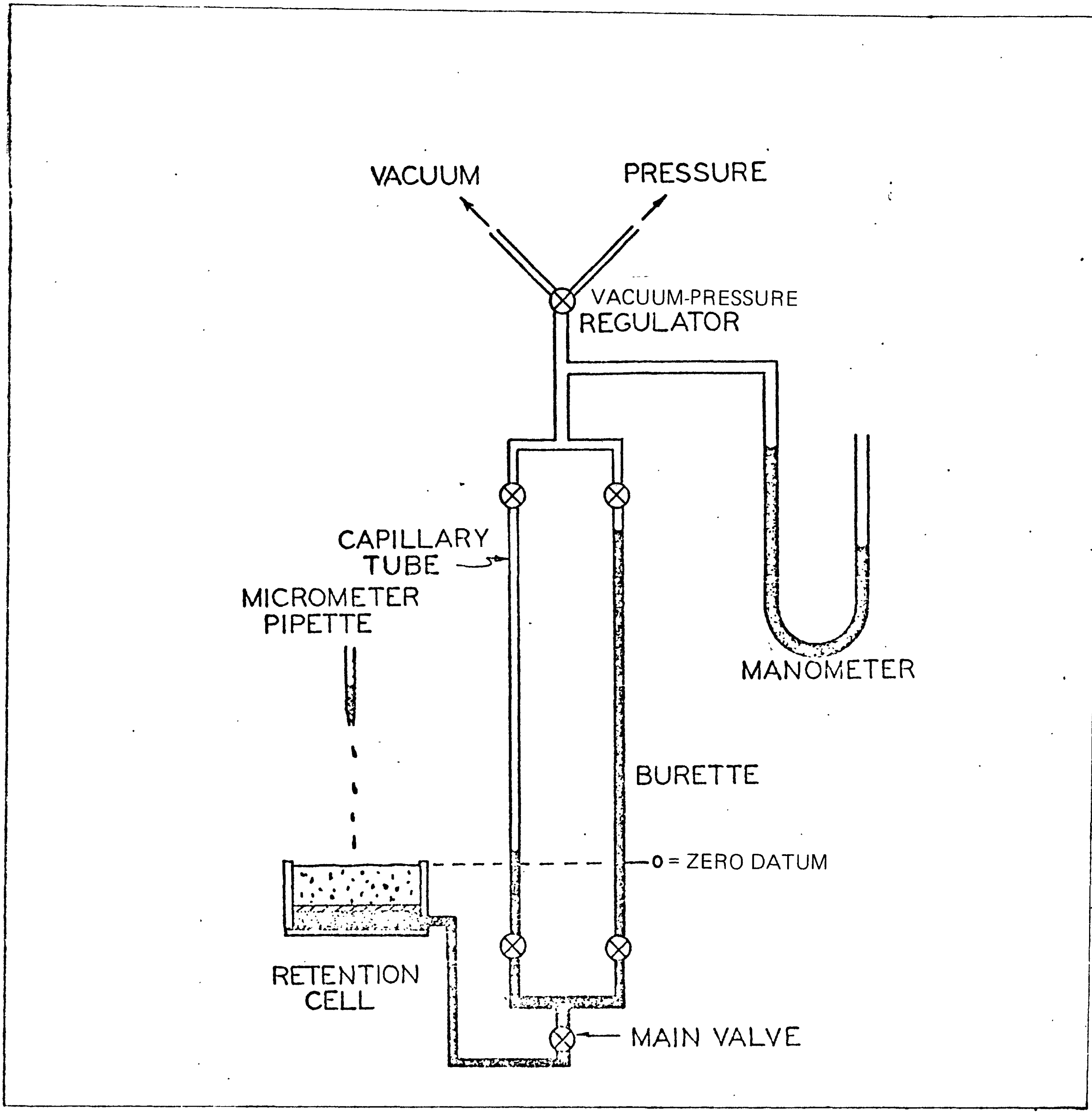

Figure 13.--Schematic diagram of the apparatus for obtaining moisture-retention data. (From Su and Brooks, 1976, p. 57.)

Su and Brooks (1976, p. 62-69) also devised a technique to mathematically describe the moisture retention function by fitting the experimental data points to fit a smooth curve. The procedure begins by manually fitting a curve through the data and subjectively selecting four of the experimental points that appear to best describe the function. These data points, along with first guesses of residual saturation (corresponding to the steep part of the curve) and maximum saturation, are used as input to a computer program incorporating the Pearson Type VIII distribution-function theory to generate the arguments necessary to mathematically describe the curve. It is assumed in the procedure that the sample pore-size distribution is of the same type on either side of a fictitious inflection point at which the curve reverses its concavity. Several simulations using a different set of experimental points may be required before a satisfactory solution is obtained.

The moisture-retention curves derived using the technique of Su and Brooks (1976, p. 62-69) for the core samples obtained from neutron-probe access holes at the San Rafael Reef and Waterpocket Fold sites are shown in figures 14-16. In the figures, P is the capillary pressure in centimemters of water; PF is the capillary pressure at the fictitious inflection point in centimeters; S is the saturation in perecent; M is a shape factor dependent on the pore-size distribution; A and B are the domains of saturation separated by the fictitious inflection point; SR is the residual saturation in percent (equal to 1-A-B); and SM is the maximum saturation in percent (equal to SR+A+B).

Results

Values of unsaturated hydraulic conductivity were determined for the Navajo cores by the following equation, proposed by Childs and Collis-George (1950) and modified by Marshall (1958) and Millington and Quirk (1959, 1960, 1961),

$$k = 2.75 \times 10^2 \varepsilon^p N^t [h_1^{-2} + 3h_2^{-2} + 5h_3^{-2} + \ldots\ldots + (2N-1)h_n^{-2}] \qquad (1)$$

The equation was used to calculate the hydraulic conductivity (k), in centimeters per second from the moisture-retention curves of figures 14, 15, and 16, using average suction values (h), in centimeters of water corresponding to equal volumes of moisture within the sample (h in equation 1 corresponds to P in figures 14-16). In the equation, H_1 corresponds to the average suction head of the volume with the largest pore opening and is the minimum head value used in the computation. If values for saturated hydraulic conductivity are desired, the entire moisture-retention curve is divided into equal divisions. Where values of hydraulic conductivity under conditions of partial saturation are desired, divisions start at that saturation valueof interest. N is the number of equal divisions, and ε is the volume of water per unit volume of sample and is equal to the porosity where saturated hydraulic conductivity is desired. Hydraulic conductivities were computed using the Millington and Quirk version of equation 1 ($p=4/3$, $t=-2$) and a coefficient suggested by Jackson, Reginato, and Van Bavel (1965). Graphs of hydraulic conductivities versus suction head are shown in figures 17 and 18.

Pore-size distribution curves may also be used to compute hydraulic conductivities as indicated by Marshall (1958, p. 4). Pore-size distribution

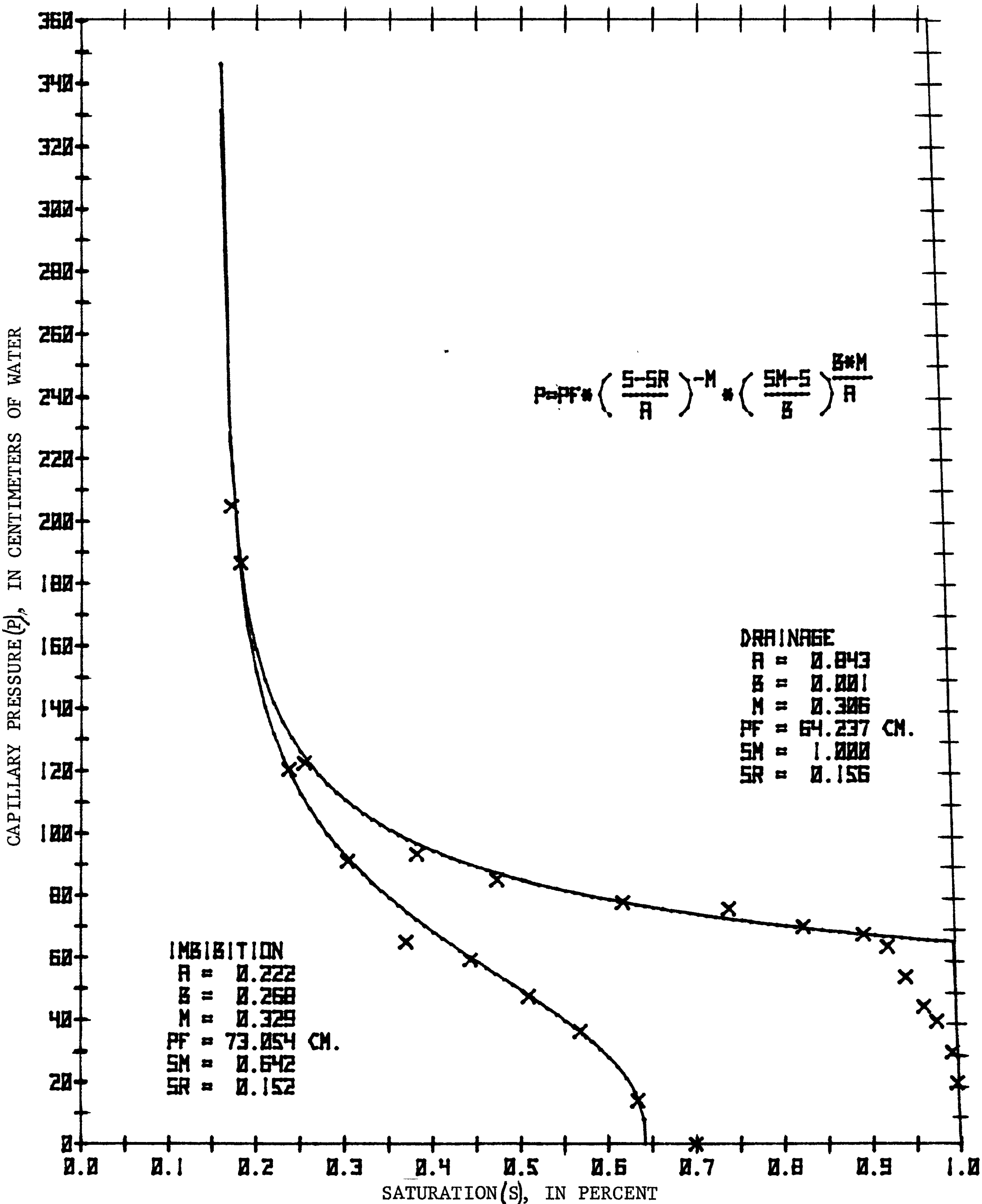

Figure 14.—Moisture-retention curves for core from the Navajo Sandstone, channel under sand hole in Old Woman Wash at the San Rafael Reef.

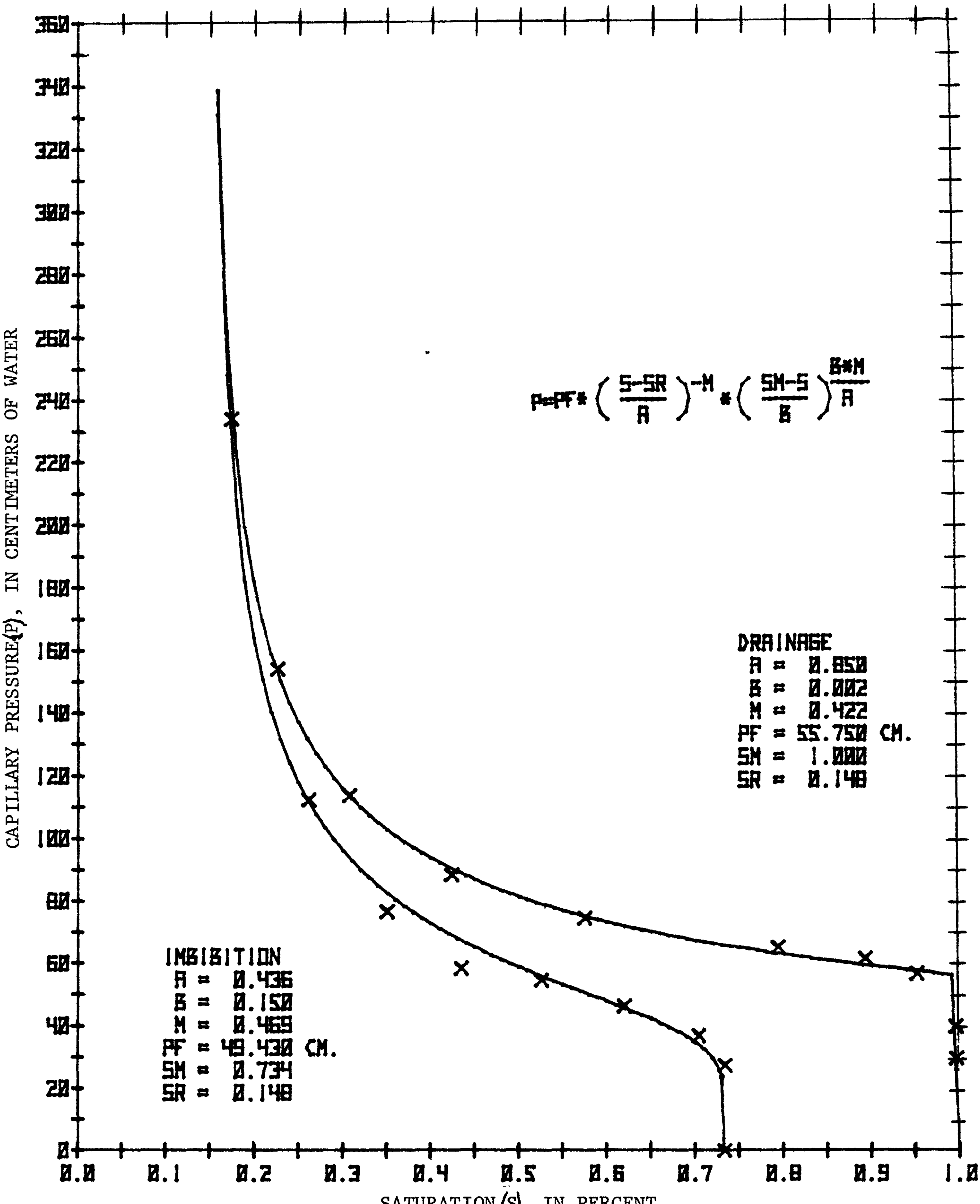

Figure 15.—Moisture-retention curves for core from the Navajo Sandstone, sloping sandstone surface hole at the San Rafael Reef near Old Woman Wash.

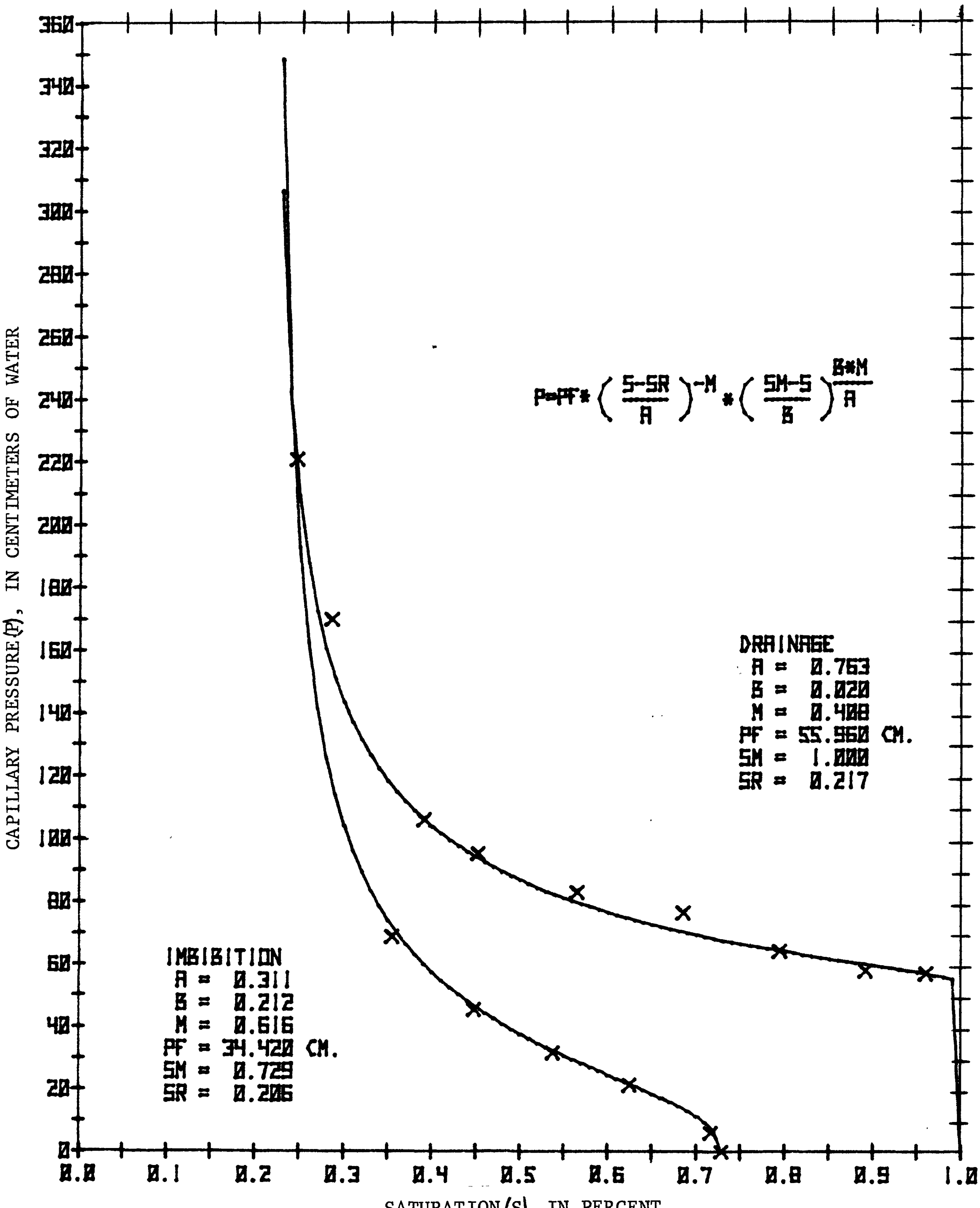

Figure 16.—Moisture-retention curves for core from the Navajo Sandstone, intermittent channel hole on Waterpocket Fold near Oak Creek.

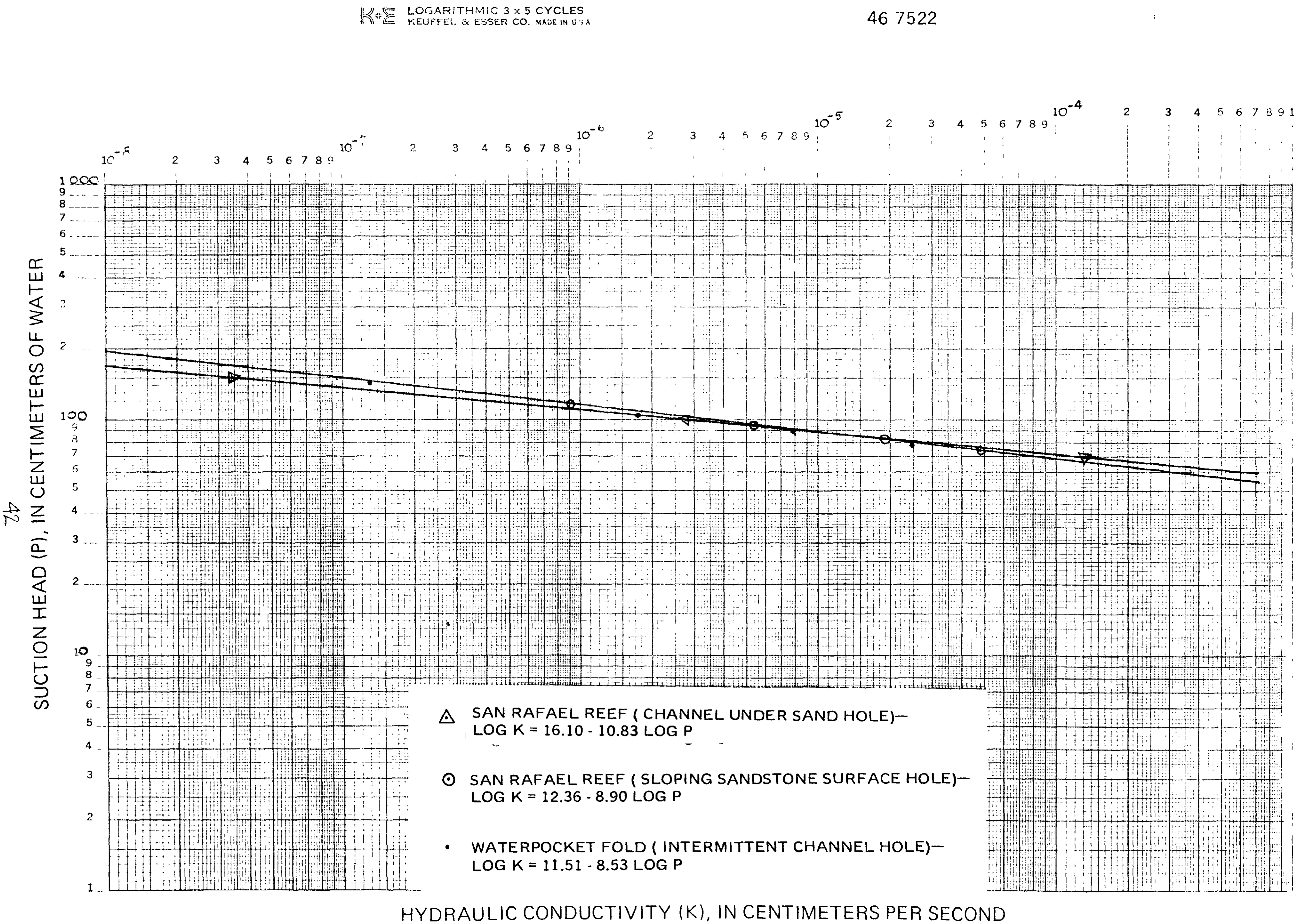

Figure 17.—**Curves for unsaturated hydraulic conductivity versus suction head (drainage branch) for three cores from the Navajo Sandstone.**

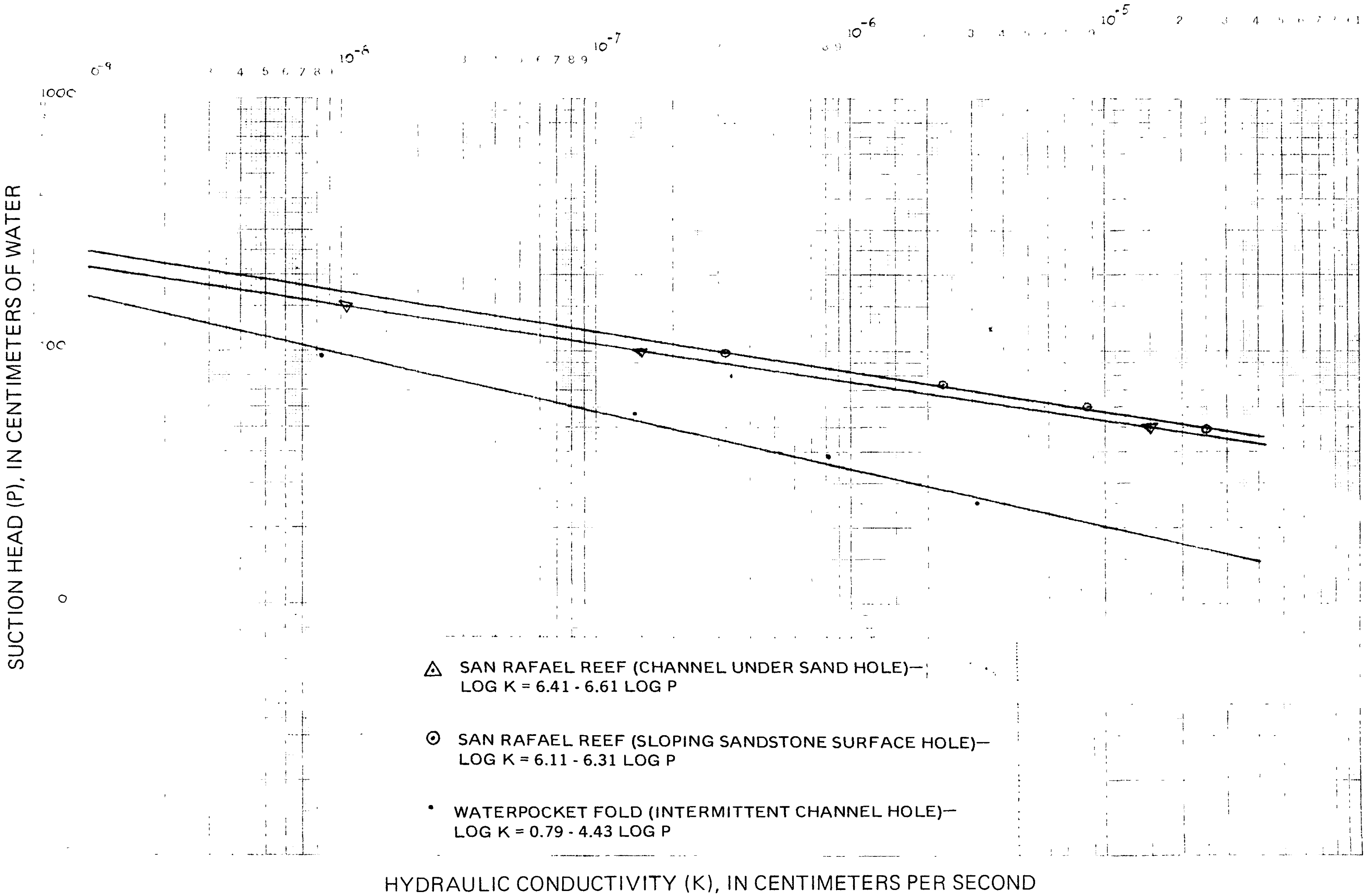

Figure 18.—**Curves for unsaturated hydraulic conductivity versus suction head (imbibition branch) for three cores from the Navajo Sandstone.**

curves determined by a mercury-injection technique on six cores removed from neutron-probe access holes are shown in figure 19. Differences in computed hydraulic conductivity using this method and the method discussed previously do not exceed about 17 percent at the moisture contents encountered during this study. This method, however, results in only one curve to be used for both drainage and imbibition.

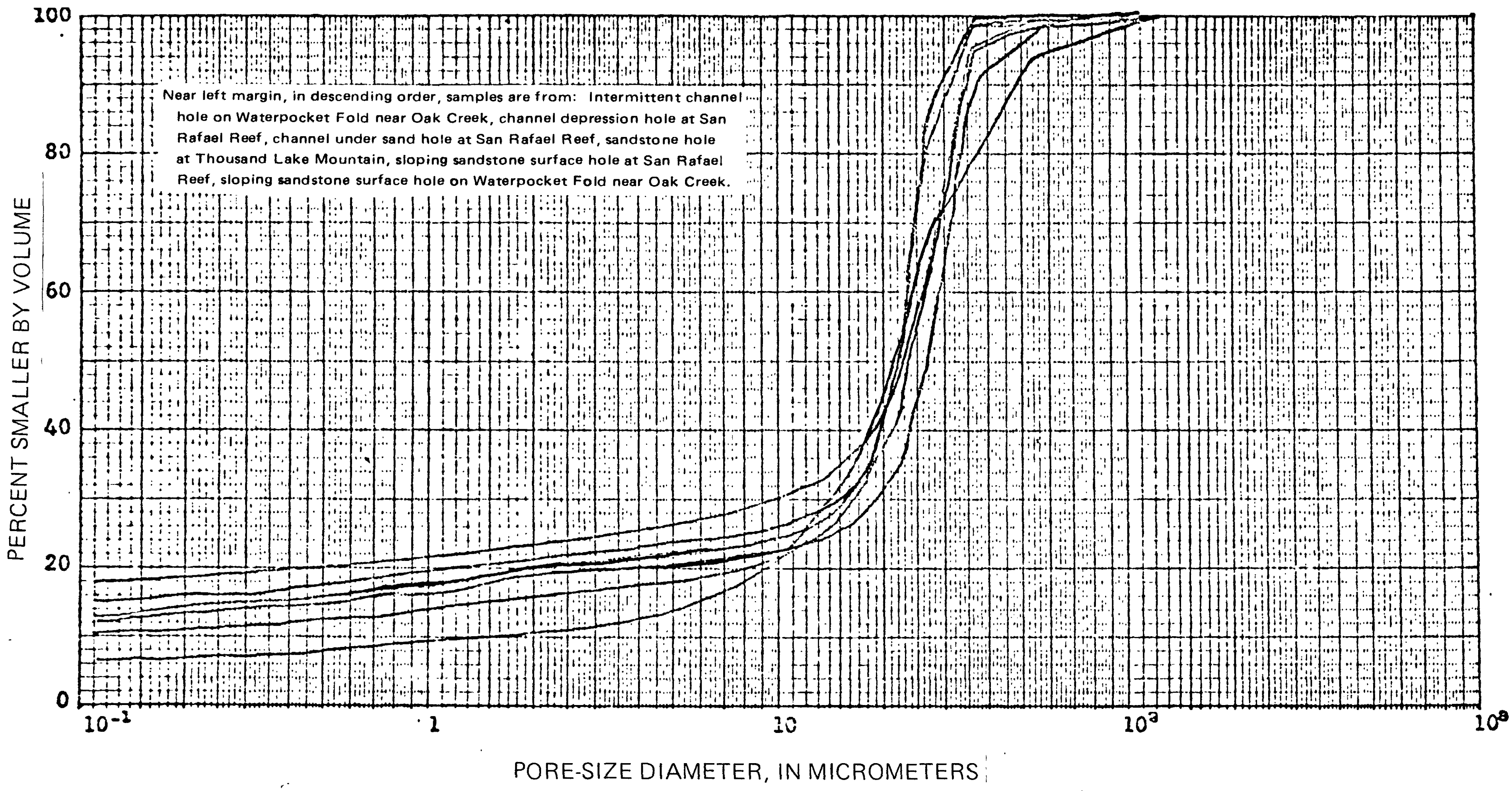

Figure 19.—Pore-size distribution curves for six samples from outcrop of Navajo Sandstone.