TEXAS DEPARTMENT OF WATER RESOURCES

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EVALUATING THE GROUND-WATER RESOURCES OF THE HIGH PLAINS OF TEXAS

Neutron-Probe Measurements of Deep Soil Moisture as an Indication of Aquifer Recharge Rates

By

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ABSTRACT

A network of recharge investigation sites in 20 Texas counties was constructed and intensively monitored to determine recharge to the High Plains aquifer. Each monitoring site was equipped with a recording rain gage and two aluminum logging-access tubes set approximately 30 feet into the ground. The neutron moisture logging method was employed in both dryland and irrigated land at each of these sites to evaluate the depth to which rainfall and irrigation water percolate through the soil mantle overlying the aquifer. Soils underlying dryland (cultivated and grassland) locations showed deep percolation of less than 3/16 inch of water per year. With a few exceptions, tested fields that had been irrigated 25 years or more showed evidence of deep percolation only to depths of 20 to 30 feet. For the Texas High Plains as a whole, the likelihood of appreciable recharge by downward percolation of precipitation and applied irrigation water appears remote. It is emphasized that the conclusions are tentative and based on only one year of data.

INTRODUCTION

Purpose and Scope

In 1978, the Texas Department of Water Resources initiated a regional ground-water study of the High Plains aquifer. The study is being conducted by Department, High Plains water districts, and Texas Tech University personnel and was partially funded by the U. S. Geological Survey. Results of the study are to be included in the Survey's eight-state study of the Ogallala aquifer. As part of the study, the Department, utilizing neutron moisture logging equipment, conducted an infiltration study to determine the amount of recharge that occurs from deep percolation of rainfall, snowfall, and applied irrigation water.

A quantitative study of actual deep percolation to the aquifer has not been available heretofore. It is hoped that this report will satisfy needs for such data, provide information concerning the mechanisms of recharge, and also provide data that can be used to evaluate the feasibility of increasing recharge to the High Plains aquifer.

Data were collected from 22 specially constructed test sites in 20 counties of the Texas High Plains (Figure 1). Installation of 44 neutron moisture logging access tubes and 22 recording rain gages was conducted from October 1978 through March 1979. Weekly neutron moisture logging was concluded in March 1980.

Acknowledgements

The author appreciates the cooperation of the many owners and operators of the farms and ranches on which the recharge test sites were located. Acknowledgement is also extended to the following persons for providing valuable information on the soils and vegetation within the study area and expertise on neutron moisture logging techniques and equipment: Edwin P. Weeks, U. S. Geological Survey; Dr. Arland D. Schneider, USDA Southwestern Great Plains Research Center at Bushland; Dr. Charles Wendt and H. P. Harbert III, Texas A&M University Agricultural Experiment Station at Lubbock; and Kelsey Martin, consultant to Gearhart-Owens.

A note of appreciation is also due the staff members of the Department, the High Plains Underground Water Conservation District No. 1, North Plains Ground Water Conservation District No. 2, and Panhandle Ground Water Conservation District No. 3 who participated in this study.

Thanks are also due to Ray Elder (formerly with the Department), who spent many days in the field preparing study sites and calibrating the neutron moisture logging equipment.

Personnel

The infiltration study was conducted by personnel of the High Plains Underground Water Conservation District No. 1, the North Plains Ground Water Conservation District No. 2, the Panhandle Ground Water Conservation District No. 3, and the Department's Data and Engineering Services Division. It was conducted under the general supervision of C. R. Baskin, P. E., Director, Data and Engineering Services Division, and Dr. Tommy R. Knowles, P. E., Chief, Data Collection and Evaluation Section, of the Texas Department of Water Resources.

Drilling and laboratory testing were conducted by the Department's Geotechnical Services Unit under the supervision of Marion Striegler, P. E.

The drilling crew was headed by Lewis Barnes.

Tabulation of results and preparation of illustrations were done by Doug Coker and Dan McElhany (both formerly with the Department). Writing of the report and direct supervision of the project was the responsibility of the author.

GEOGRAPHIC SETTING

Geology, Hydrology, and Soils

The Ogallala Formation of Pliocene age is the major water-bearing unit on the High Plains of Texas. Hydraulic continuity occurs between the Ogallala Formation and the underlying Cretaceous, Triassic, and Permian rocks in many areas of the High Plains. Therefore, for the purpose of this study, the High Plains aquifer will be considered to consist of the saturated sediments of the Ogallala Formation and those underlying, potable water-bearing units that are in hydraulic continuity with it.

Pleistocene soils form the major mantle overlying the Ogallala Formation. Caliche horizons, at depths ranging from 1 to 6 feet, underlie the top and subsoil zones over most of the Texas High Plains. These caliche zones are generally 1 foot to 2 feet thick and grade downward into the lower Pleistocene subsoils or into hard indurated calcium carbonate (Caprock). The Caprock in many cases separates the Pleistocene sediments from the Ogallala Formation. The topsoils consist of three major textural types: (a) fine sandy and silty loams; (b) clay and clay loams; and (c) fine sandy loams. The general distribution of the top soils and extent of the High Plains aquifer are illustrated on Figure 1. These delineations are very general in nature, and localized conditions may vary from those shown on the figure.

Topography and Drainage

The Texas High Plains is essentially a flat plateau. A remarkable characteristic of the region is the great number of shallow depressions, or playas, which dot its surface. During periods of rainfall the playas accumulate drainage from local watershed areas ranging in size from less than one square mile

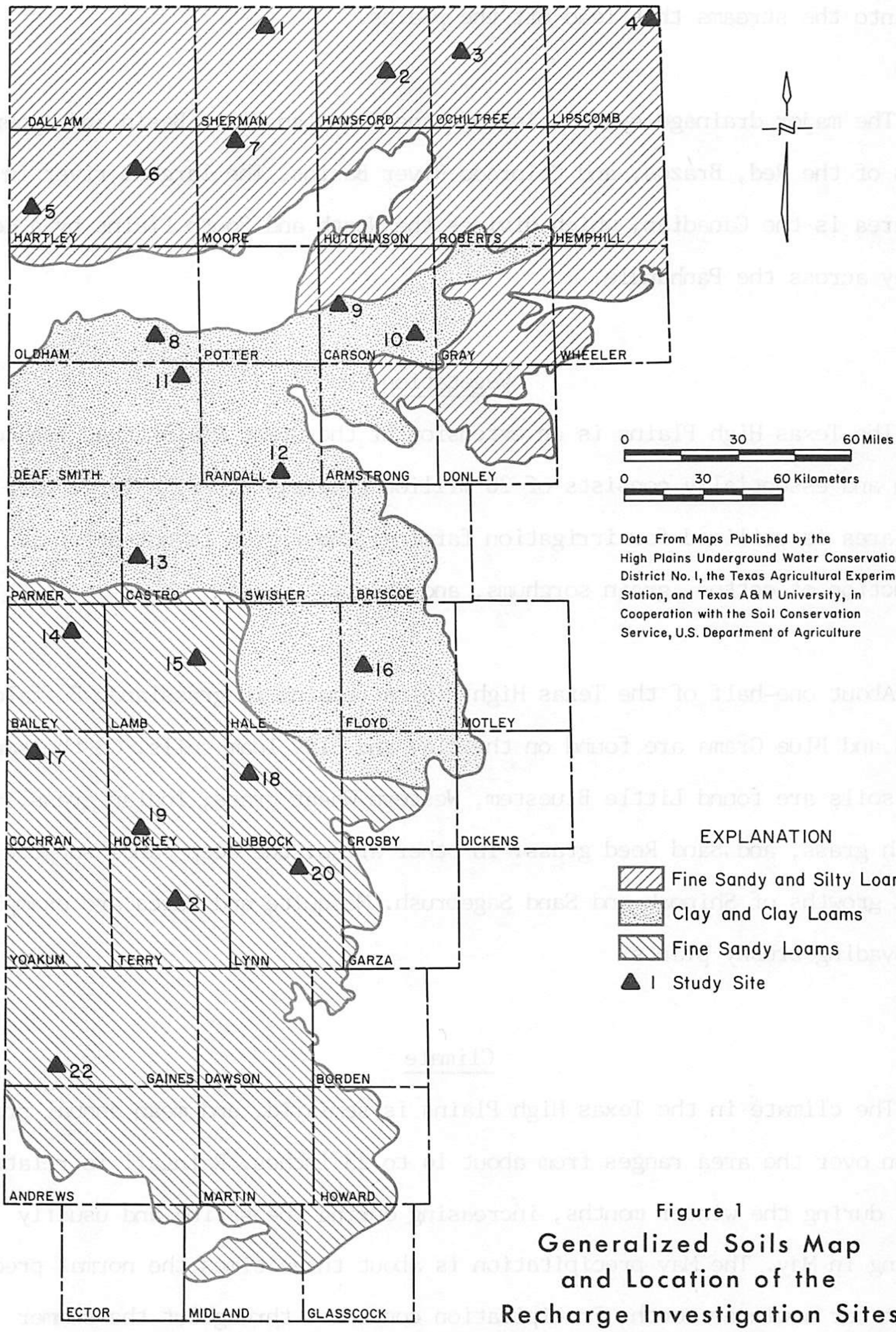

Figure 1
Generalized Soils Map and Location of the Recharge Investigation Sites

to several square miles. Only a very small portion of the rainfall finds its way into the streams that lead off the plains.

The major drainage systems include the Canadian River Basin and upper parts of the Red, Brazos, and Colorado River Basins. The largest river in the area is the Canadian, which divides the North and South Plains by a deep valley across the Panhandle.

Vegetation

The Texas High Plains is an extension of the Great Plains that lie to the north and essentially consists of 20 million treeless acres. A large part of this area is utilized for irrigation farming; the region is noted for its production of cotton, grain sorghums, and wheat.

About one-half of the Texas High Plains remains in grassland. Buffalo grass and Blue Grama are found on the clay and clay loam soils. On the sandy loam soils are found Little Bluestem, Western Wheat grass, Indian grass, Switch grass, and Sand Reed grass. In other areas, the deep sands support thick growths of Shinoak and Sand Sagebrush. Mesquite and Yucca are examples of invading brushy plants.

Climate

The climate in the Texas High Plains is semiarid, and mean annual precipitation over the area ranges from about 14 to 23 inches. Rainfall is relatively light during the winter months, increasing during the spring and usually peaking in May. The May precipitation is about three times the normal precipitation for a winter month. Precipitation continues throughout the summer months and then reaches a second peak in September, with slightly less precipitation than the May peak. Snowfall is an important source of moisture in the winter months.

Evaporation is greatest during the summer months. In Lubbock County, the average annual evaporation potential for an open-water surface is about 3½ times the average annual precipitation.

The mean annual temperature for the High Plains is about 59 degrees Fahrenheit. The average difference between summer and winter temperatures is on the order of 40 degrees. The length of the growing season (frost-free period) varies from year to year but on the average is about 200 days.

DESCRIPTION OF STUDY SITES

Study sites on the Texas High Plains were selected based on soil type, land use, water management history, and subsurface conditions. A recording rain gage to monitor precipitation and two 30-foot long neutron moisture logging access tubes were installed at each site. One access tube was installed in an irrigated area, and the second was placed in non-irrigated soil. Some of the non-irrigated sites were covered by grasses and others were in areas under cultivation. Appendix A contains data on landowners, soils, precipitation, water management, and land use at these locations.

The depth of wetting resulting from irrigation at 18 sites is given in Table 3. At three of the 22 sites, the wetting front due to irrigation was below the bottom of the access tube (30 feet), and at one site the position of the wetting front could not be postulated. The soils and moisture profile data illustrated in Appendix B were used to establish the position of the wetting front.

METHODS OF INVESTIGATION

Theoretical Considerations and Assumptions

Many researchers have shown that the downward movement of soil moisture is layered. A single rainfall or irrigation event will form a layer of moisture which moves downward between older moisture below and younger moisture above. The average downward velocity (infiltration rate) is determined by many factors in the soil such as: (a) chemical or capillary forces; (b) order of the grain size; and (c) the associated lateral and vertical diffusion of the percolating moisture. The percentage of water moving downward from a single rainfall or irrigation event depends to a large extent on these factors plus the effects of evapotranspiration and the rainfall characteristics at the particular location and time. Therefore, any investigation to determine the amounts of natural recharge and irrigation returns should take into consideration the soils, rainfall patterns, vegetative conditions, and farming practices within the study area.

With a neutron moisture logger, moisture can be rapidly and accurately measured. Thus, the general way that moisture moves through a soil profile can be observed. The neutron method is based on the principle that fast neutrons lose energy in elastic collisions with nuclei of low atomic weight, particularly hydrogen. The neutrons with the reduced energy (thermal neutrons) continue their travel, but are subject to scatter and reflection upon additional collisions. Therefore, a logging system (surface instrumentation and borehole logging tool) containing a source capable of constant, fast emissions of neutrons and a detector sensitive to thermal neutrons can be operated in a subsurface environment through an access tube and used to indicate the relative moisture content in soils, since hydrogen nuclei, found largely in water, constitute nearly all of the very low atomic weight nuclei in the subsurface.

Estimates of annual deep percolation resulting from precipitation and irrigation water movement using the neutron moisture logging method are made using the following relationship:

Water (ft) = Moisture Change (%) x Infiltration Rate (ft/yr) x 0.01

The moisture change within a particular depth interval below the land surface can be determined by comparing the areas under the moisture curves for logs obtained at different times at the same site. The difference in area is then converted into a percent moisture change for the time interval. Moisture change and the infiltration rate can also be determined by knowing the depth of the wetting front, history of land use, and increase in moisture content in the section from the land surface to the wetting front.

Soil water and salinity data (Aronovici and Schneider, 1972) from borings in Pullman clay loam soils indicate infiltration rates of approximately 0.25 and 1 foot per year for the non-irrigated and irrigated condition, respectively. It is the author's opinion that the infiltration rate of a sandy, permeable soil is approximately twice that of a clay loam given the same moisture conditions. Sandy soils have a field moisture capacity (water content at which internal drainage ceases) which is approximately half that of clay soils. For that reason soil water in a sandy soil will percolate downward about twice as far as would soil water in a clay loam, given equal moisture conditions. Estimates of infiltration rates for the non-irrigated and irrigated condition at the sites studied in this investigation are given in Tables 2 and 3, respectively.

The annual deep percolation as computed above considers the water as passing through a horizontal plane (recharge threshold). The depth to the recharge threshold is considered to be greater than 10 feet below the land surface and is based on the depth of feeder roots of vegetation growing at the moisture logging sites when considered collectively.

Access Tubes

The following conditions should be met in placing access tubes: (a) no voids between soil and tube (skintight); (b) no mixing of soil horizons during placement; (c) no vertical flow of water should occur along the tube from the surface or a perched water table; and (d) bottom of tube must be plugged to exclude water. Goldberg and others (1955) have indicated that installation of thin-wall aluminum tubes of a diameter approximately the same as that of the probe, in a hole with tight contact between the tube and soil, yielded the most favorable results. However, Teasdale and Johnson (1970) showed that a reasonable degree of accuracy in measurements could be obtained by the neutron method with less complicated and more economical installations, such as with gravel-packed access tubes, provided that the neutron moisture log values are corrected by correlation with laboratory moisture content determined from volumetric sampling at the site (Figure 3). The above authors also indicate that aluminum tubing is the most efficient material for access tubes because it has less dampening effect.

Figure 2 shows two moisture-content logs obtained by the High Plains Water District No. 2 logging instrument inside 2-inch diameter aluminum access tubes. The installation with the skintight fit between access tube and soil (installa-

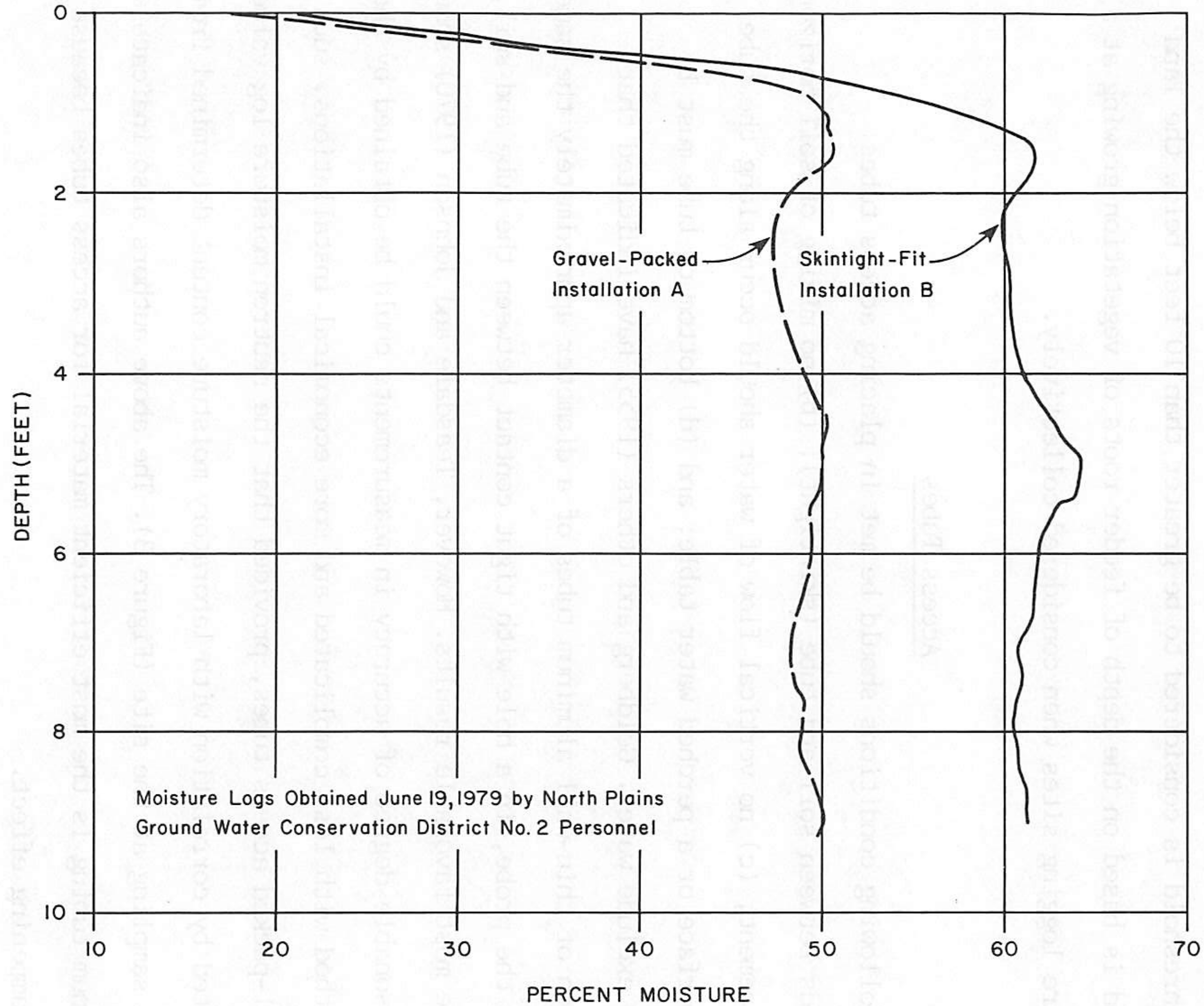

Figure 2

Comparison of Water District No. 2's Neutron Moisture Logs Using Two Access Tube Installation Techniques

tion B) shows a much higher apparent moisture content than the gravel-packed tube (installation A); however, the two logs are very similar in character. This evaluation was performed on the grounds of Texas A&M University's North Plains Experiment Farm at Etter, Texas.

The Department's modified Failing 1500 drilling rig was used to install the 44 access tubes at the 22 sites shown in Figure 1. The installation procedure was as follows: (a) a 4-inch diameter hole was drilled to an approximate depth of 30 feet; (b) 2-inch O. D. aluminum tubing was installed to total depth and back-filled with a commercially available fine gravel; and (c) a concrete collar (4½-inch O. D.) was placed around the tubing approximately 2 feet below land surface to prevent water from traveling freely down the outside surface of the tube.

Undisturbed cores were collected at each access tube location in 1-foot increments using push tubes and dry barrel sampling methods. Written descriptions of the soil samples were prepared, and then the samples were placed in plastic bags to prevent moisture loss, transported to the Department's hydrologic laboratory, and analyzed for moisture content. The boring log and soil moisture distribution versus depth for each site are illustrated in Appendix B.

At those locations where farming practices required the top of the tube to be below plow or disk level at certain times of the year, the tubes were fitted with a short extension which could be removed, thus allowing the tubes to be buried. Continuous moisture logs at these sites were obtained by logging through the access tube extensions from the land surface, or, after removal of the overburden, from the top of the access tube below ground level.

The bottoms of the access tubes were plugged to exclude water and, at the surface, expandable rubber plugs were used to seal the tubes against moisture. Silica gel was also suspended within the tubes to prevent the buildup of moisture.

Equipment

The instrumentation required in measuring moisture content of soil materials consists of three parts: (a) a source of fast neutrons; (b) a detector for thermal neutrons; and (c) an instrument to determine the count rate from the detector. Suitable comparison standards are also required in order to calibrate and verify the performance of the equipment.

Both the High Plains Water District No. 1 and North Plains Water District No. 2 utilized the multifunction Well Reconnaissance, Inc., Geo-Logger (Model 10406) equipped with 500 feet of single-conductor (1/10-inch) logging cable, 2-pen chart recorder (10 inch), 1½-inch-diameter neutron moisture tool, and surface module (gamma). The detecting assembly utilized in the Geo-Logger is a photomultiplier coupled to an enriched lithium iodide crystal. Suitably spaced and shielded from the detector is a 250-millicurie, Americium-beryllium neutron source, double-encapsulated in stainless steel. Three cylindrical polyethylene calibrators (10%, 25%, and 35% moisture) are used to standardize the instruments. The logging unit is normally truck-mounted.

The Department's Well Reconnaissance, Inc., neutron moisture logging instrument (Model 10611) is similar to the Geo-Logger except that the surface electronics, hand-operated winch, and chart recorder (5 inch) are compactly arranged in an aluminum suitcase-style container. The unit uses pressure-sensitive chart paper and is portable.

Calibration of Neutron Moisture Probes

Calibration of the moisture logging instruments used by the Department and Water Districts was based on log moisture readings (percent by volume) and laboratory volumetric moistures of samples taken from known depths at Site 18 (dryland). Standardization of logging tool response was made possible through the use of the previously described polyethylene calibrators. Calibration of the logging instruments is illustrated by Figure 3.

According to Figure 3, moisture log values obtained at Site 18 with the High Plains Water District No. 2's logger correlate better with the Department's laboratory sample moistures than do the values obtained with the Department's instrument. Consequently, in order to standardize the three moisture logging instruments, the reading from the Department's logging instrument was correlated to the response of Water District No. 2's instrument for the purpose of developing the adjusted trend line for Department equipment shown on Figure 4. The calculation of percent moisture for the Department's logging instrument as described in the following sections is based on the adjusted values.

Verification of the above relationships (Figure 3) was performed by comparing the response of the Districts' and Department's instruments with that of the A&M neutron moisture instrument which was run in the access tube located at the Lubbock Experimental Station. The A&M instrument was assumed to be calibrated for the Lubbock location.

In the foregoing discussion, it has been assumed that the presence of hydrogen in the investigated soils results solely from moisture. Actually,

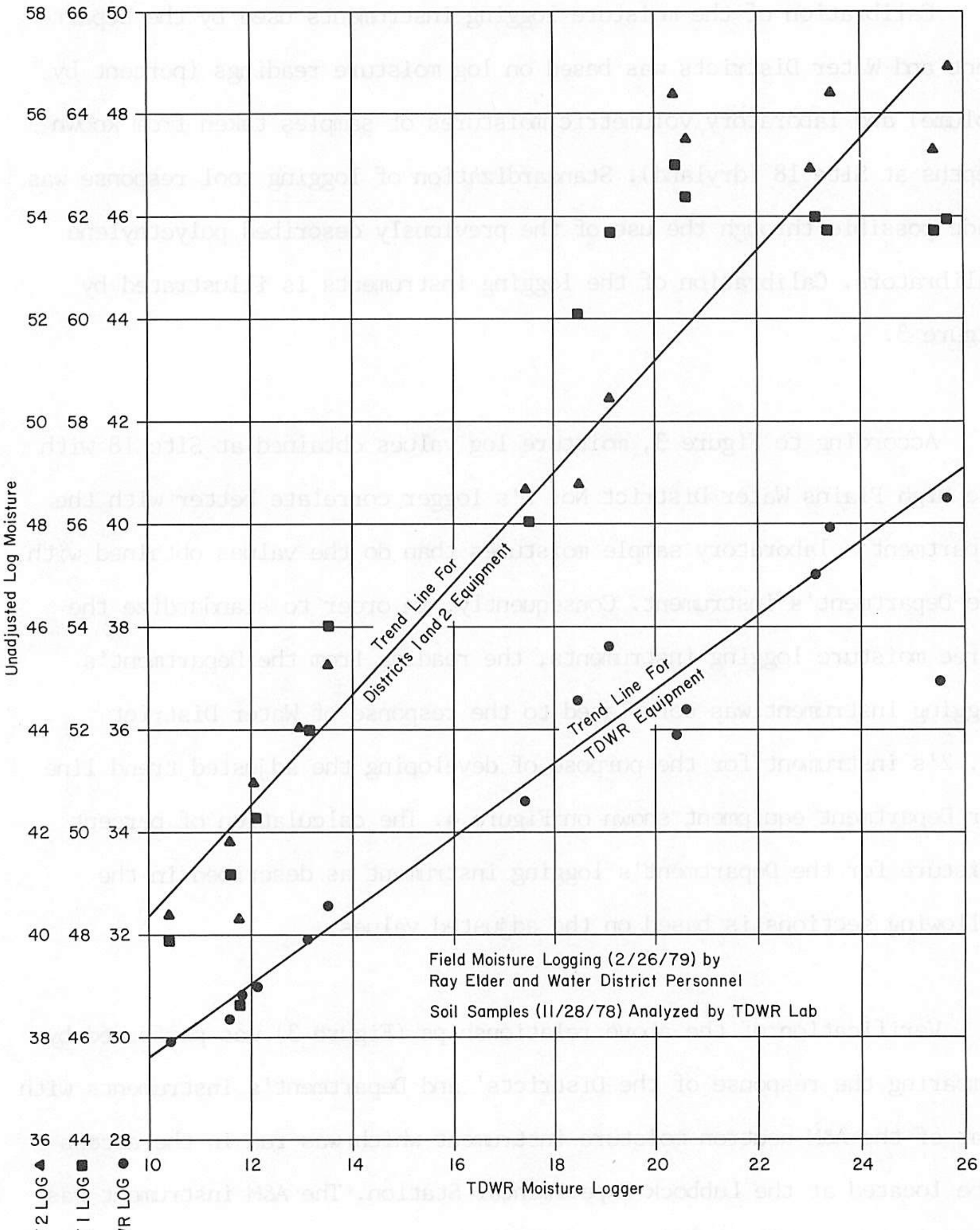

Figure 3

Neutron Probe Field Calibration at Site 18 (Dryland) Using the Water Districts' and Texas Department of Water Resources Equipment

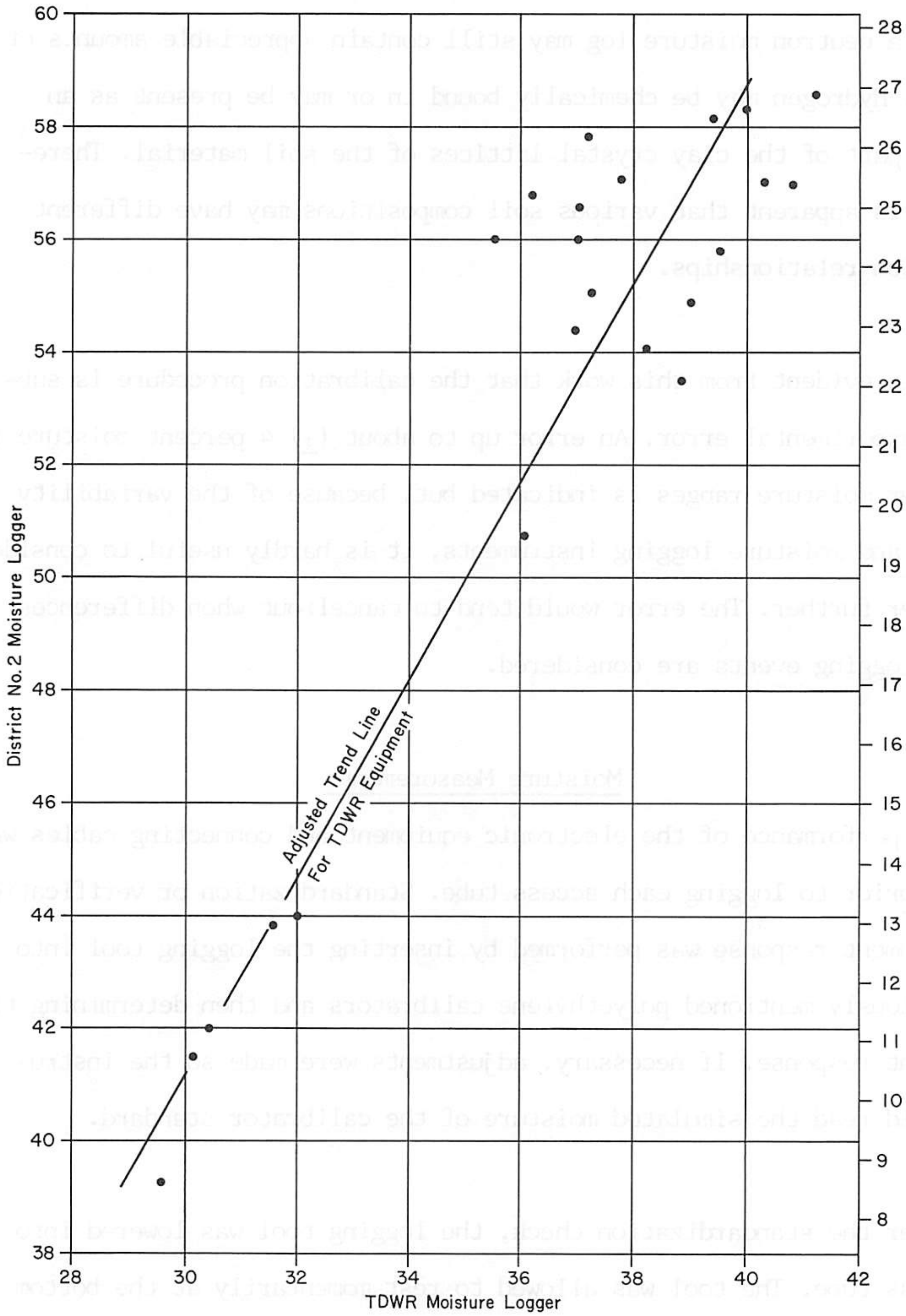

Figure 4

Correlation of Water District No.2 and Texas Department of Water Resources Neutron Log Moistures at Site 18 (Dryland)

this may not be true. A soil sample that has been oven dried and correlated to a neutron moisture log may still contain appreciable amounts of hydrogen. Hydrogen may be chemically bound in or may be present as an integral part of the clay crystal lattices of the soil material. Therefore, it is apparent that various soil compositions may have different calibration relationships.

It is evident from this work that the calibration procedure is subject to experimental error. An error up to about ($\pm$) 4 percent moisture in the higher moisture ranges is indicated but, because of the variability of soils and moisture logging instruments, it is hardly useful to consider the matter further. The error would tend to cancel out when differences between logging events are considered.

Moisture Measurements

The performance of the electronic equipment and connecting cables was checked prior to logging each access tube. Standardization or verification of instrument response was performed by inserting the logging tool into the previously mentioned polyethylene calibrators and then determining the instrument response. If necessary, adjustments were made so the instrument would read the simulated moisture of the calibrator standard.

After the standardization check, the logging tool was lowered into the access tube. The tool was allowed to rest momentarily at the bottom and then was slowly retrieved from the access tube. A continuous record of the relative percentage of moisture in the soil versus depth was recorded on the chart paper.

Sites 1 through 7 were monitored by staff of the North Plains Ground Water Conservation District No. 2. The Department's staff monitored sites 8 through 12. The remaining 10 sites were monitored by staff of the High Plains Underground Water Conservation District No. 1.

Computations of Moisture Movement

The neutron moisture logs used in this study were obtained between March 1979 and March 1980 and on as nearly a weekly basis as possible. Soil moisture gains and losses were established for the 10- to 29-foot interval spanned by the moisture access tube by comparing the area of the first log obtained to the area of the second. The area of the second log was compared to the area of the third. This routine was continued for all logs. The difference in area between any two moisture logs was obtained by the following steps: (a) the area of each log was determined by mechanically integrating the area horizontally from the 5 percent moisture line to the log trace and vertically from 10 to 29 feet; (b) the current log was superposed on the preceding log, matching the log traces at the 25- to 29-foot interval and keeping the horizontal and vertical axes of the two logs parallel; (c) in the matched position, an adjustment in the current log's area was made in order to compensate for the shift in the log trace; and (d) one log area was subtracted from the other to obtain the difference. The above match procedure was required in order to establish a common base line for any two logs and eliminate instrument shift.

The differences in area between the Water Districts' logs was converted directly into weekly percent moisture gain or loss depending on the situation.

Differences in the areas on Department logs were multiplied by 3.93 to obtain the true difference in moisture. This factor represents the average ratio of Department log moistures to true moistures in the 10- to 29-foot interval at the calibration site. The adjusted trend line for Department equipment as shown on Figure 4 was used in determining the factor.

The annual moisture gain and loss for a given access tube at a particular site was calculated by separately summing the weekly gains and losses as derived from the year's accumulation of neutron moisture logs. The difference in the annual moisture gain and loss was then compared to the moisture change between the first and last log. Adjustments were made to the annual gain and loss in order that the two differences would be equal. Results of the above computational procedure are given in Table 1.

Finally, 3 percent of the moisture loss was subtracted from each of the adjusted annual losses given in column 7 of Table 1. The resultant is shown in column 3 of Table 2 and represents the true percent moisture change for the 10- to 29-foot interval. This was done in order to compensate for calculated moisture changes at Sites 4, 6, 7, and 16 where, in the author's opinion, downward percolation of soil water was not taking place. The 3 percent value subtracted was the average of adjusted moisture losses shown in column 7 of Table 1 for the above four sites.

Annual deep percolation as recharge (Col. 4, Table 2) for the dryland (cultivated and grassland sites) was calculated by multiplying the adjusted annual losses (Col. 3, Table 2) by the estimated infiltration rate (Col. 2, Table 2). This method was also used to estimate the annual amount of perco-

TABLE 1

RESULTS OF WEEKLY LOG ANALYSIS

(10-29 Feet)

Site Number	Logging Site	ANNUAL MOISTURE CHANGE Loss (%)	Gain (%)	Difference	DIFFERENCE IN MOISTURE (%) FIRST AND LAST LOG	ADJUSTED ANNUAL MOISTURE CHANGE Loss (%)	Gain (%)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
1	Grassland	7.39	5.73	-1.66	-0.26	6.69	6.43
	Irrigated	9.64	6.96	-2.68	-0.19	8.39	8.20
2	Grassland	5.55	5.44	-0.11	+0.80	5.09	5.89
	Irrigated	7.89	7.58	-0.31	+0.20	7.64	7.84
3	Grassland	7.18	8.19	+1.01	-0.46	7.91	7.45
	Irrigated	7.61	4.61	-3.00	-0.01	6.11	6.10
4	Grassland	3.28	2.59	-0.69	-0.20	3.03	2.83
	Irrigated	8.16	11.70	+3.54	-0.50	10.18	9.68
5	Grassland	5.65	5.22	-0.43	-0.42	5.64	5.22
	Irrigated	7.35	7.85	+0.50	-0.24	7.72	7.48
6	Grassland	2.49	3.00	+0.51	-0.18	2.84	2.66
	Irrigated	3.25	2.76	-0.49	-0.57	3.29	2.72
7	Dryland	2.41	3.39	+0.98	-0.01	2.90	2.89
	Irrigated	4.75	7.89	+3.14	+0.66	5.99	6.65
8	Grassland	7.86	9.82	+1.96	-0.08	8.88	8.80
	Irrigated	7.90	12.30	+4.40	+1.69	9.26	10.95
9	Grassland	6.01	7.03	+1.02	-0.16	6.20	6.64
	Irrigated	13.13	13.79	+0.66	+0.31	13.30	13.61
10	Grassland	10.73	7.68	-3.05	0.00	9.20	9.20
	Irrigated	6.84	9.08	+2.24	-0.16	8.04	7.88

Site Number (1)	Logging Site (2)	ANNUAL MOISTURE CHANGE Loss (%) (3)	Gain (%) (4)	Difference (5)	DIFFERENCE IN MOISTURE (%) FIRST AND LAST LOG (6)	ADJUSTED ANNUAL MOISTURE CHANGE Loss (%) (7)	Gain (%) (8)
11	Grassland	9.39	7.07	-2.32	-0.51	8.49	7.98
	Irrigated	13.05	10.77	-2.28	-0.35	12.09	11.74
12	Dryland	9.08	9.51	+0.46	+0.12	9.25	9.37
	Irrigated	14.66	9.63	-5.03	+0.04	12.13	12.17
13	Dryland	4.80	5.85	+1.05	+0.09	5.28	5.37
	Irrigated	7.60	5.66	-1.94	-1.15	7.20	6.05
14	Grassland	5.81	6.71	+0.90	+0.72	5.90	6.62
	Irrigated	5.39	6.03	+0.64	-0.73	6.07	5.34
15	Grassland	6.91	6.51	-0.40	+0.02	6.70	6.72
	Irrigated	6.09	10.97	+4.88	+1.65	7.71	9.36
16	Grassland	3.35	2.75	-0.60	+0.20	2.95	3.15
	Irrigated	5.94	6.48	+0.54	-0.19	6.30	6.11
17	Dryland	4.43	5.32	+0.89	-0.49	5.12	4.63
	Irrigated	4.59	5.44	+0.85	-0.20	5.10	4.90
18	Dryland	6.39	6.46	+0.07	-0.04	6.44	6.40
	Irrigated	8.27	6.79	-1.48	+0.33	7.69	8.02
19	Dryland	5.45	4.14	-1.31	-0.54	5.06	4.52
	Irrigated	5.64	7.80	+2.16	-0.19	6.81	6.62
20	Dryland	6.85	5.90	-0.95	+0.22	6.26	6.48
	Irrigated	7.41	6.59	-0.82	-0.61	7.30	6.69
21	Grassland	3.71	5.13	+1.42	-0.67	4.76	4.09
	Irrigated	6.98	5.48	-1.50	-0.31	6.38	6.07
22	Dryland	5.28	7.05	+1.77	-0.35	6.34	5.99
	Irrigated	6.72	10.81	+4.09	-0.47	9.00	8.53

TABLE 2

RESULTS OF NEUTRON MOISTURE LOG ANALYSIS AT DRYLAND (CULTIVATED OR GRASSLAND) SITES

Site Number	Estimated Infiltration Rate (Ft/yr)	Percent Moisture Change (10-29 Ft)	Estimated Total Recharge inches	Recharge as Percent of Normal Annual Rainfall
(1)	(2)	(3)	(4)	(5)
1	0.50	3.7	0.2	1.0
2	0.25	2.1	0.1	0.5
3	0.25	4.9	0.2	1.0
4	0.50	0.0	---	---
5	0.50	2.6	0.2	1.2
6	0.25	0.0	---	---
7	0.50	0.0	---	---
8	0.50	5.9	0.3	1.6
9	0.25	3.6	0.1	0.5
10	0.25	6.2	0.2	1.0
11	0.25	5.5	0.2	1.0
12	0.25	6.3	0.2	1.0
13	0.25	2.3	0.1	0.6
14	0.50	2.9	0.2	1.1
15	0.50	3.7	0.2	1.0
16	0.25	0.0	---	---
17	0.50	2.1	0.1	0.6
18	0.50	3.4	0.2	1.0
19	0.50	2.1	0.1	0.6
20	0.50	3.3	0.2	1.1
21	0.50	1.8	0.1	0.6
22	0.50	3.3	0.2	1.4

lated water from irrigation at Sites 9, 20, and 21 where the depth of wetting was greater than 30 feet below land surface (Col. 5, Table 3).

The method for calculating the annual soil water percolation due to irrigation is similar to that used to estimate recharge at the dryland cultivated and grassland sites. The infiltrate rate of the percolating soil water was determined from the depth of wetting (Col. 2, Table 3) and the number of years the site was irrigated (Appendix A). The average moisture gain at a specific site due to irrigation was determined by comparing the moisture log of the dryland cultivated or grassland location with the log of the irrigated location (Appendix B). Estimates of annual soil water percolation due to irrigation (Col. 5, Table 3) were calculated by multiplying the "Wetting Front Infiltration Rate" (Col. 3, Table 3) by the "Moisture Gain" (Col. 4, Table 3).

The exact nature and location of the wetting fronts are best determined from the moisture data illustrated in Appendix B. For example, when the volumetric moisture curves for Site 15 (Lamb County) are superposed, the successive buildup and downward movement of accumulated moisture at the irrigated location is postulated at the first intersection of the curves (8.7 feet); the irrigated moisture curve indicates increasing moisture down to the wetting front. The neutron moisture logs can also be used in this manner. The above analysis was performed successfully at 18 sites and suggests that the demarcation of a wetting front from recent deep percolation is relatively sharp.

Limitations and Sources of Error

The neutron moisture logging technique for determining soil moisture has the following limitations: (a) the logging instrument is probably not accurate enough to reflect small moisture changes of less than 1 percent;

TABLE 3
RESULTS OF NEUTRON MOISTURE LOG ANALYSIS AT IRRIGATED SITES

Site Number (1)	Depth of Wetting (Ft below LSD) (2)	Wetting Front Infiltration Rate (Ft/yr) (3)	Moisture Gain or Loss* Above the Wetting Front (%) (4)	Estimated Percolation (inches/yr) (5)	Percolation as a Percent of Irrigation Water Applied (%) (6)
1	5.0	2.5	7.8	2.3	38.3
2	23.2	1.0	8.5	1.0	10.0
3	10.2	0.6	7.7	0.6	5.0
4	30.0	2.3	12.4	3.4	28.3
5	17.5	3.5	8.0	3.3	41.3
6	--	--	--	--	--
7	29.0	2.1	7.7	1.9	10.5
8	21.9	2.2	3.8	1.0	12.5
9	>30.0	2.0*	10.3**	2.5	41.7
10	14.8	0.7	4.8	0.4	20.0
11	28.5	1.2	9.0	1.3	8.1
12	4.8	1.6	1.8	0.3	1.5
13	27.6	0.8	5.3	0.5	3.1
14	9.6	2.4	5.2	1.5	12.5
15	8.7	8.7	10.5	11.0	39.3
16	22.4	1.9	9.6	2.2	7.9
17	22.6	0.9	3.8	0.4	13.3
18	11.8	1.3	3.4	0.5	6.3
19	29.3	1.2	2.4	0.3	2.5
20	>30.0	2.0*	4.3**	1.0	25.0
21	>30.0	2.2*	3.4**	0.9	7.5
22	27.9	1.7	2.6	0.5	8.3

*Estimated wetting front infiltration rate

**Moisture loss determined from weekly logs for the 10- to 29-foot interval

(b) sharp differences (boundaries) in moisture content cannot be adequately indicated due to the large sphere of influence of the neutron technique; (c) some soils contain appreciable quantities of non-water hydrogen; however, non-water hydrogen is generally absent in coarse-textured soils but may be present in appreciable quantities in organic soils and clays; (d) the moisture log can be affected by variations in the wall thickness of the access tube or eccentric positioning of the probe while logging; and (e) based on the calibration studies, the possibility of error appears to be greater as the moisture content increases.

For the most part, the above sources of error or limitations would tend to cancel out when differences in neutron moisture log content are considered. Also, the neutron method in this type of investigation will tend to be subject to less error than repeated volumetric sampling and subsequent laboratory analysis because the same soil mass is sampled each time by the non-destructive neutron method. However, although it is generally possible to obtain a better measure of soil moisture with a neutron log than a series of volumetric soil samples, there are circumstances where the neutron technique has serious limitations. Such is the case when successive moisture logs are used to determine the moisture gain or loss of a particular soil column below the recharge threshold; the amount of recharge cannot be determined with precision, and it is the author's opinion that cumulative errors are also introduced (see page 17).

CONCLUSIONS

Perhaps the most unknown and difficult to measure component in soil hydrology is deep percolation. Neutron moisture measurements from both irrigated and non-irrigated lands at each of 22 sites were used to estimate recharge to the High Plains aquifer through Pleistocene soils on the Texas High Plains. Soils underlying dryland (cultivated and grassland) sites transmit less than 3/16 inch of water per year as natural recharge to the aquifer. Most of the recharge probably occurs in areas of porous soils, although the data obtained by the Department did not confirm this.

The likelihood that the High Plains aquifer is being appreciably recharged on a regional basis as a result of deep percolation due to irrigation is remote. Fields that had been irrigated 25 years or more showed evidence of deep percolation only to depths ranging from 20 to 30 feet. Sites 9, 20, and 21, located in Carson, Terry, and Gaines Counties respectively, and where wetting fronts have advanced to depths greater than 30 feet, do provide an exception however. At these locations, the wetting front may have penetrated all of the sediments above the aquifer, and under these special conditions additional recharge may be taking place. However, the Department's data indicate that irrigation must continue over decades before the slow deep percolation associated therewith would offer some potential for increased recharge on a regional basis.

With only one year of data available for use in this study, the conclusions derived regarding deep percolation certainly cannot be considered as final. Accordingly, the discussions and results presented herein should be thought of as preliminary.

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