Movement of Moisture in the Unsaturated Zone in a Loess-Mantled Area, Southwestern Kansas

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GEOLOGICAL SURVEY PROFESSIONAL PAPER 1021

Prepared in cooperation with the
Kansas Geological Survey

U.S. DEPARTMENT OF THE INTERIOR
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CONVERSION FACTORS

Multiply English units	*By*	*To obtain SI units*
	Length	
inches (in.)	2.54	centimeters (cm)
feet (ft)	.3048	meters (m)
miles (mi)	1.6093	kilometers (km)
	Flow	
feet per day (ft/d)	0.3048	meters per day (m/d)
feet per hour (ft/hr)	.3048	meters per hour (m/hr)
feet per minute (ft/min)	.3048	meters per minute (m/min)
	Area	
square feet (ft^2)	0.09290	square meters (m^2)
square feet per day (ft^2/d)	.09290	square meters per day (m^2/d)
	Volume	
cubic feet (ft^3)	0.02832	cubic meters (m^3)

GLOSSARY

Aquifer. A formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs.

Confined aquifer. A water-yielding zone in which ground water is confined under pressure by impervious or semipervious strata.

Confining bed. A body of impermeable material stratigraphically adjacent to one or more aquifers.

Dry unit weight. The ratio of the mass to the bulk or macroscopic volume of soil particles plus pore spaces in a sample.

Effective hydraulic conductivity. The rate of flow of water through a porous medium that contains more than one fluid, such as water and air, in the unsaturated zone.

Flux. The rate at which water of the prevailing kinematic velocity is transmitted through a cross section of unit area.

Hydraulic conductivity. The rate at which water of the prevailing kinematic velocity is transmitted through a cross section of unit area that is at right angles to the direction for flow, under a hydraulic gradient of unit change in head over unit length of flow path.

Hydraulic gradiant. The change in static head per unit of distance in a given direction.

Infiltration. The downward entry of water into the soil, expressed as a rate.

Moisture content. A ratio, expressed in percent, of the volume of water to the total volume of the porous material.

Perched ground water. Unconfined ground water separated from an underlying body of ground water by an unsaturated zone.

Perching bed. A bed that supports a body of perched ground water.

Percolation. Movement of water through soil.

Porosity. The property of containing intergranular space or voids. It is expressed as a ratio, in percent, of the total volume of intergranular space to total volume of the medium.

Potentiometric surface. A surface that represents the static head. As related to an aquifer, it is defined by the levels to which water will rise in tightly cased wells.

Pressure head. The height of a column of static water that can be supported by the static pressure at that point. The pressure head is positive when the height of water is above the point and is negative when the height of water is below the point.

Saturation percentage. A ratio, expressed in percent, of the volume of water to the total volume of intergranular space.

Saturated zone. A zone in which all spaces, large and small, are filled with water. The water table is the upper limit of this zone, and the water in it is under greater than atmospheric pressure.

Soil water. See term "Moisture content."

Static head. The height of a column of water above a standard datum that can be supported by the static pressure at a given point.

Storage coefficient. The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head.

Unconfined ground water. Water in an aquifer that has a water table.

Unsaturated zone. The zone between land surface and the water table.

Water table. That surface in an unconfined water body at which the pressure is atmospheric.

Wetting front. The leading edge of moisture buildup resulting from natural or artificial application of water at the land surface.

MOVEMENT OF MOISTURE IN THE UNSATURATED ZONE IN A LOESS-MANTLED AREA, SOUTHWESTERN KANSAS

By ROBERT C. PRILL

ABSTRACT

A study of moisture movement associated with four ponding tests in a loess-mantled area near Garden City, Kans., provides significant information on the potential of using the area for artificial recharge by water spreading.

Infiltration during the four ponding tests stabilized at rates ranging from 0.7 to 2.2 feet (0.2 to 0.7 meter) per day. The large differences in infiltration rates reflect changes in the hydraulic conductivity of the soil horizons developed in loess materials. The underlying loess has an appreciably greater hydraulic conductivity than the soil. Removing the soil zone should increase infiltration rates, provided that the underlying loess is not severely compacted during excavation or during subsequent recharge operations.

When the wetting front of infiltrated water is in the loess, the moisture-buildup pattern shows the characteristic wetting and transmission zones observed for infiltration in homogeneous materials. When the wetting front penetrates the underlying alluvium, the wetting front becomes indistinct.

The loess has the capacity to take large quantities of water into temporary storage. If adequate time is allowed between water applications for the loess to drain, the amount may be as much as 1 cubic foot (0.03 cubic meter) of water for each 6 cubic feet (0.17 cubic meter) of the material.

At the ponding site, several fine-grained strata are in the unsaturated alluvium underlying the loess. Because these strata have relatively high hydraulic conductivities, they did not act as effective perching beds during the ponding tests. Strata of this type probably would not cause sufficient mounding to impede infiltration significantly or cause water-logged conditions during water spreading.

The ground-water mound that developed after application of 21 feet (6 meters) of water has a maximum thickness of 2 feet (0.6 meter) at the edge of the pond. The boundary of the mound moved laterally a distance of 50 feet (15 meters) from the edge of the pond in 2 days. The mound, which dissipated very slowly because of additional drainage from the unsaturated zone, was discernible 3 months after ponding. Although the mound on the saturated zone spread rapidly as a result of pressure transmission, the recharged water actually spread slowly by lateral displacement.

Because accumulated salts are leached from the unsaturated zone, the specific conductance of water arriving at the water table is higher than that of the applied water. The amount of increase is dependent on the extent of leaching from previous applications of water and on dilution by infiltrated water.

A general appraisal of the ponding-test data indicates that the study area has an excellent potential for artificial recharge by water spreading. Infiltration rates in the loess-mantled area would be favorable for water spreading, and fine-grained strata in the unsaturated zone would not significantly impede downward percolation. Water that is put into underground storage by utilizing the dewatered part of the reservoir would help to sustain the productivity of the aquifer system.

INTRODUCTION

The extensive use of ground water for irrigation has caused appreciable declines in the water table in several loess-mantled areas in southwestern Kansas because the rate of withdrawal greatly exceeds the rate of replenishment. The life of the alluvial aquifer underlying the loess could be extended by more efficient irrigation practices and by artificial recharge to supplement natural replenishment.

Ponding tests in a loess-mantled area have yielded significant information on the potential of these deposits for artificial recharge by water spreading as well as information basic to the development of more efficient irrigation practices. This report describes infiltration rates under various test conditions, buildup of moisture during ponding and the subsequent redistribution after ponding, mounding on perching beds, and effects of ponding on the water table in terms of mounding and water-quality changes. Owing to the homogeneity of the loess materials, the data provide a classic field demonstration of water movement in the unsaturated zone according to theoretical projections. Green, Dabiri, Weinaug, and Prill (1970) have used a computer to simulate moisture changes with depth, as monitored by neutron moisture logs from this study. Excellent agreement between the calculated and the observed data was obtained.

Figure 1 shows the study area, 9 mi (14.5 km) northwest of Garden City in Finney County, southwestern Kansas, and the distribution of loess deposits that mantle about 60 percent of the 11-county area that forms southwestern Kansas. Much of the irrigation in southwestern Kansas takes place in the areas mantled by loess. Because soil surveys show the loess deposits of the 11 counties to be similar in physical and chemical properties, the results of this study have application throughout this area.

Details of the ponding site and pertinent facilities of the study area are shown in figure 2. The test pond is

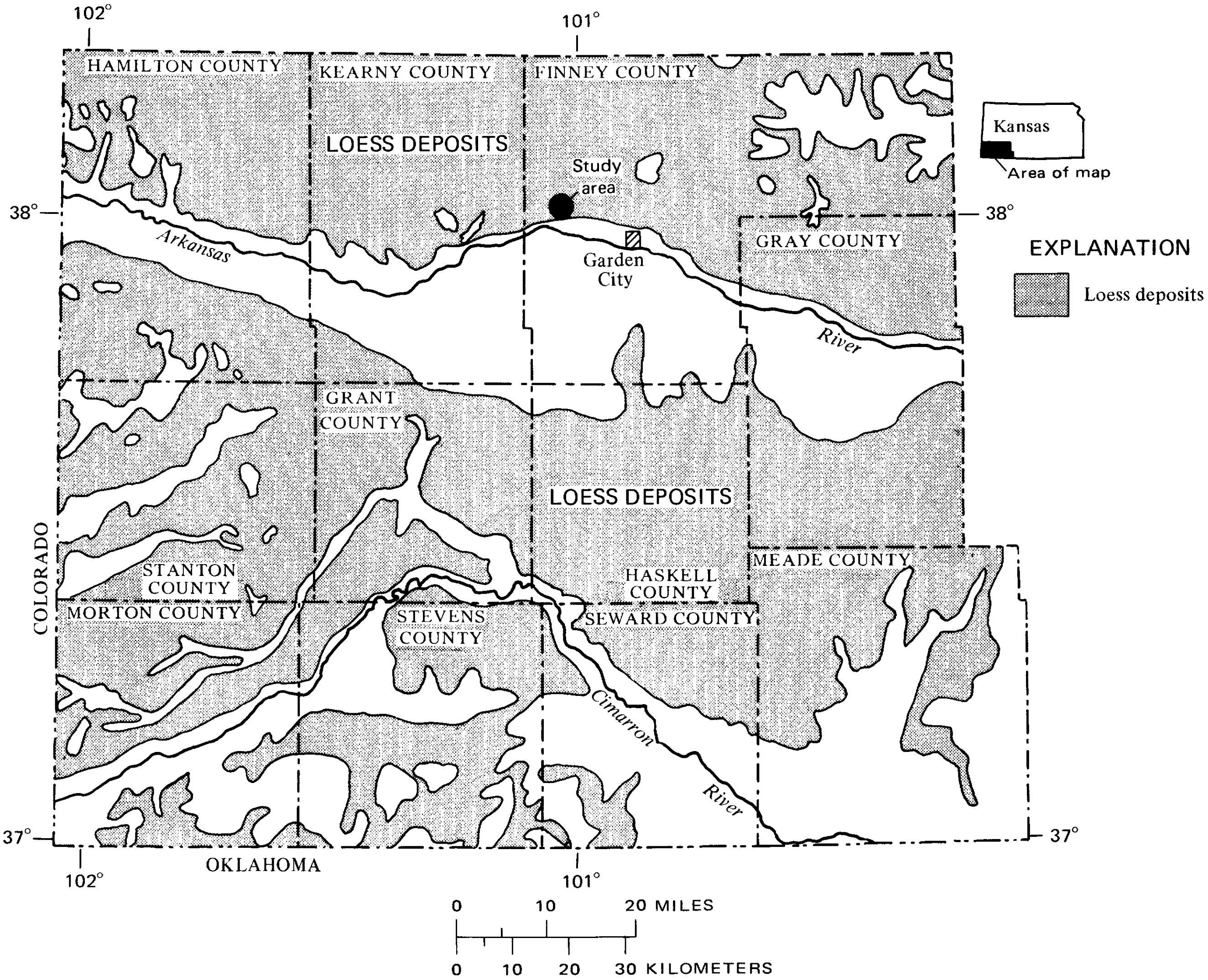

FIGURE 1.—Map of southwestern Kansas showing location of study area and distribution of loess deposits.

located on the Irrigation Rresearch Project Farm of the Garden City Branch, Kansas Agricultural Experiment Station. The land within the study area is irrigated mostly by ground water obtained from 11 wells (fig. 2). Some supplemental supplies are obtained from ditches that convey water diverted from the Arkansas River.

ACKNOWLEDGMENTS

The writer is indebted to A. B. Erhart, superintendent, and to Paul Penas, Jay Swensen, and Kenneth Snelling, staff members of the Experiment Station, for their cooperation and assistance in conducting these experiments.

Special recognition is extended to W. A. Long, U.S. Geological Survey, for assistance in the installation of test facilities and in the collection and interpretation of neutron-moisture data. Appreciation is expressed for the cooperation of personnel of the Kansas Geological Survey, the Division of Environment of the Kansas Department of Health and Environment, and the Division of Water Resources of the Kansas State Board of Agriculture.

GEOHYDROLOGY OF THE STUDY AREA[1]

Consolidated rock (defined as bedrock) underlying the study area is a calcareous shale within the Greenhorn Limestone of Late Cretaceous age (Meyer and others, 1970). The Greenhorn is relatively impervious and yields little or no water to wells.

Unconsolidated alluvial deposits of Pliocene and Pleistocene age, which overlie the bedrock, are the principal source of ground water in the study area. These deposits, consisting of interbedded clay, silt,

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[1] The classification and nomenclature of the rock units used in this report are those of the U.S. Geological Survey and differ somewhat from those used by the Kansas Geological Survey.

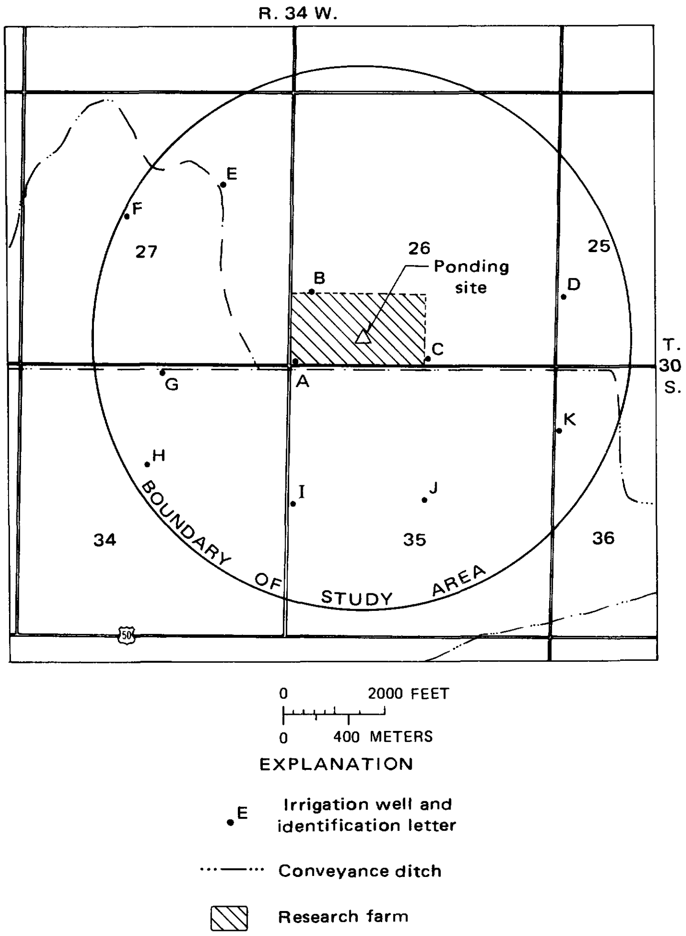

FIGURE 2.—Study area and facilities pertinent to ponding tests.

sand, and gravel, extend to a depth of about 340 ft (104 m). During the study, depth to water near the ponding site flucturated with seasonal pumping from 72 to 82 ft (22 to 25 m) below land surface.

The saturated part of the alluvial deposits consists of a lower sand and gravel aquifer that is semiconfined (semiartesian), a semiconfining layer of silt and clay that retards the vertical movement of water, and an upper sand and gravel aquifer where the water is unconfined. Irrigation wells in the study area pump water from the lower aquifer at a depth of 190–280 ft (58–85 m)

The unsaturated part of the alluvial deposits, which extends from about 16 to 80 ft (5 to 24 m) below land surface, consists of sand and gravel layers interbedded with clay, silty clay, and loam layers.

The loess, which is generally correlated by Frye and Leonard (1952) with Peoria Loess of late Pleistocene age, underlies the land surface to depths ranging from 5 to 30 ft (1.5 to 9 m). In the study area, the loess is subdivided into an upper loess (0–12.5-ft or 0–3.8-m zone) and a lower loess (12.5–16.5-ft or 3.8–5.0-m zone). The association of molluscan fauna in the upper loess, which was identified by E. D. Gutentag (oral commun., 1969), is indicative of the lower molluscan zone of the Peoria Loess of early Wisconsin age (Leonard, 1952). The lower loess is considered to be equivalent to the basal zone of the Peoria Loess (Leonard, 1952). A reddish hue in the clay loam of the lower loess clearly distinguishes this stratum from the yellowish-brown silt loam of the upper loess in field sampling.

Surveys by the U.S. Department of Agriculture in cooperation with the Kansas Agricultural Experiment Station show that Richfield, Spearville, and Ulysses soils are the predominant loess-derived soils in southwestern Kansas. The ponding experiments were run in an area of Richfield soil. (A detailed description of the soil at the ponding site is given in the following paragraph.) Reports of the soil survey show that the texture of the A horizon of the Richfield ranges from silt loam to clay loam, and the texture of the B horizon ranges from silty clay loam to clay loam. These surveys show the profile characteristics of the Ulysses and Spearville soils to be very similar to those of the Richfield soils. The profiles differ primarily in the amount of clay in the B horizon. In the B horizon, the clay content of the Richfield soils is several percent greater than that of the Ulysses soils and is several percent less than that of the Spearville soils.

The following description of the Richfield soil was obtained from a pit dug in the pond area after completion of the tests. The description is according to soil survey nomenclature (Soil Survey Staff, 1951).

Ap —0–0.4 foot, very dark grayish brown (10YR 3.5/2); medium silty clay loam, weak, fine, subangular block structure, friable when moist, slightly calcareous.

B1 —0.4–0.9 foot, very dark grayish-brown (10YR 3.5/2); heavy silty clay loam, weak, fine to medium, subangular block structure, firm when moist, slightly calcareous.

B2 —0.2–1.2 feet, very dark grayish brown (10YR 3.5/2) with many dark-brown mottles (10YR 4/3); heavy silty clay loam, weak, fine to medium, subangular block structure, firm when moist, slightly calcareous.

B3 —1.2–1.7 feet, dark brown (10YR 4/3) with many dark grayish-brown mottles (10YR 3.5-2); medium silty clay loam, weak, fine, subangular block structure, friable to firm, slightly calcareous.

Cca—1.7–2.9 feet, brown (10YR 5.5/3) with many dark grayish-brown mottles (10YR 4/2); light silty clay loam, massive, friable to firm, very calcareous.

Cca—2.9–4.0 feet, brown (10YR 5/3) with many grayish-brown mottles (10YR 5/2); silt loam, massive, friable, very calcareous.

The materials in the upper part of the unsaturated zone (0–25-ft or 0–8-m-depth interval) are shown in figure 3. The classification of the materials is based on samples collected during the installation of neutron-probe access holes. Physical properties of the materials are presented in table 1.

The materials in the lower part of the unsaturated zone and the upper part of the saturated zone (25–90-ft or 8–28-m zone) are shown in figure 4. The classification is based on samples from rotary drill cuttings and natural gamma-ray logs of observation wells.

TEST PROCEDURES

Four ponding tests were made at the study site. The location of facilities installed for these tests is shown in figure 5. Information concerning the application of water and the types of data collected during the four tests are summarized in table 2.

A circular pond 50 ft (15 m) in diameter was formed by constructing a 1-ft (0.3-m)-high earthen berm with a 1:1 inside slope. The soil of the pond area, which had been used for growing sorghum the previous year, was not appreciably altered. During three of the tests, a black polyethylene sheet covered the pond to reduce the effects of evaporation and precipitation.

Water for the test was pumped from irrigation well A (fig. 2) at the southwest corner of the Research Farm. An underground pipeline from the well supplied water to a riser pipe equipped with an alfalfa-valve hydrant to control discharge. Water was conveyed from the hydrant to the pond by 120 ft (37 m) of 8-in. (20-cm) pipe. A flow meter was installed in the pipeline to measure the quantity of water applied. In all four tests, the temperature of the applied water was about 59°F (15°C). The temperature of the water in the pond differed only slightly from that of the applied water.

The depth of the water in the pond was maintained between 0.1 and 0.6 ft (0.03 and 0.2 m) in three of the tests and between 0.1 and 0.9 ft (0.03 and 0.3 m) in the last test. During test 1, water levels were measured with a steel tape. A continuous water-level recorder was used during subsequent tests. The manner in which the depth of water fluctuated during ponding is illustrated by the data for test 2, shown in figure 6. Infiltration rates were determined from the water-level records when the depth of water in the pond was 0.40 ft (0.12 m). The rate was based on the slope of the water-level decline curve at the 0.40-ft (0.12-m) depth.

Sixteen access holes were installed (fig. 5) for measurement of moisture content by a nuclear meter. Thin-wall aluminum tubing with welded joints was used for casing. Holes 1–15 were installed by driving tubing behind a percussion barrel. The depths of holes 1–9 are shown in figure 3; holes 10–15 are 8.0 ft (2.4 m) deep, and hole 16 was augered to a depth of 105 ft (32 m).

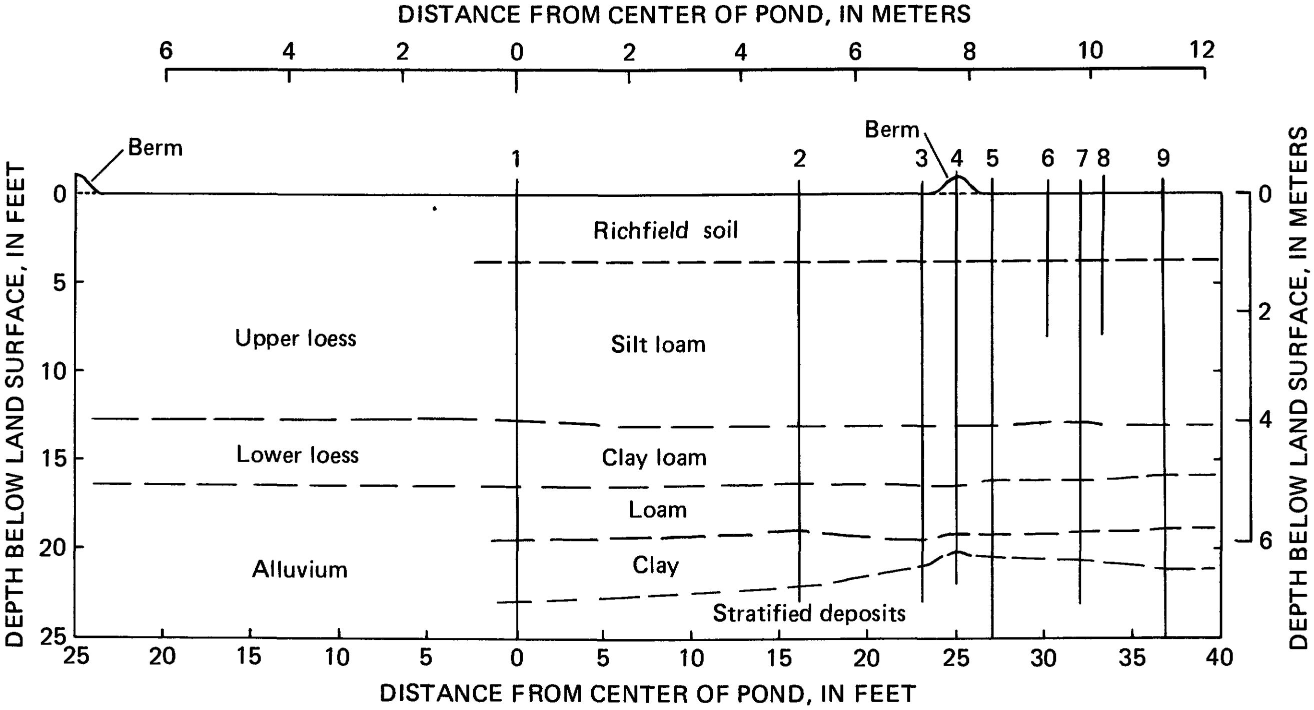

FIGURE 3.—Cross section of ponding site showing neutron-probe access holes and lithologic units of the 0–25-ft (0–7.5-m) zone.

TABLE 1.—*Physical properties of strata in the 0–20.5-ft (0–6.2 m) zone*

Depth interval (ft)	Distribution (percent) for indicated particle size (mm)[1]				Dry unit weight[2] (g/cm³)	Specific gravity[3] (g/cm³)	Porosity[2] (percent)	Type of clay[4]
	Clay (0.002)	Fine silt (0.002–0.02)	Coarse silt (0.02–0.05)	Sand (0.05)				
0.1– 0.4	38.7	16.7	24.2	20.4	1.27	------	52.3	
.5– .8	38.3	17.3	24.4	20.0	1.39	------	47.7	
.9– 1.2	34.6	16.5	28.7	20.2	1.42	------	46.6	
1.3– 1.4	34.2	19.4	28.5	17.9	1.40	------	47.4	
1.7– 1.9	----	----	----	----	1.44	------	45.9	Mixed layered clay: montmorillonite and illite.
2.0– 2.4	----	----	----	----	1.38	------	48.1	
2.5– 2.9	----	----	----	----	1.40	------	47.4	Mixed layered clay: montmorillonite and illite.
3.0– 3.4	----	----	----	----	1.41	------	47.0	
3.5– 3.9	----	----	----	----	1.38	------	48.1	
4.0– 4.4	----	----	----	----	1.32	------	50.4	
4.5– 4.9	----	----	----	----	1.30	------	51.1	
5.0– 5.4	----	----	----	----	1.28	------	51.9	
5.5– 5.9	----	----	----	----	1.22	------	54.1	Mixed layered clay: montmorillonite and illite.
6.0– 6.2	28.5	22.6	30.6	18.3	1.26	2.66	52.6	
6.5– 8.5	----	----	----	----	1.20	------	54.9	
8.6–10.5	25.4	24.1	28.4	22.1	1.24	------	53.4	
10.6–12.5	----	----	----	----	1.29	------	51.4	
14.0–15.0	31.4	18.1	22.1	28.4	------	------	------	
19.5–20.5	44.2	11.8	8.3	35.7	------	------	------	

[1] Analysis by Garden City Branch, Kansas Agricultural Experiment Station.
[2] Analysis by Garden City Subdistrict Office, U.S. Geological Survey.
[3] Analysis by Hydrologic Laboratory, U.S. Geological Survey, Denver, Colo.
[4] Analysis by Hydrologic Laboratory, U.S. Geological Survey, Denver Colo. Differential thermal analysis.

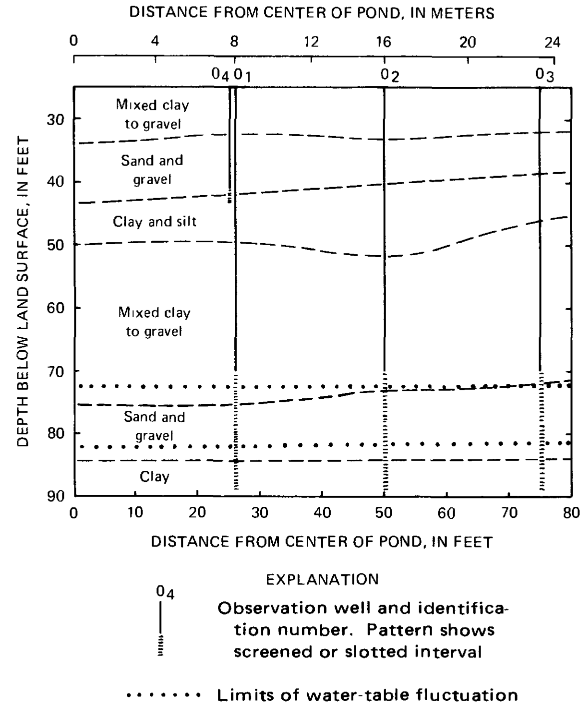

FIGURE 4.—Cross section of southeast radial of ponding site showing observation wells and lithologic units of the 25–90-ft (7.5–27-m) zone.

Moisture was measured with a continuous-logging nuclear meter (Prill and Meyer, 1968) at a logging speed of 2.5 ft/min (0.8 m/min). Because it is difficult to relate nuclear-meter readings to moisture content near land surface, moisture contents from the land surface to a depth of 0.5 ft (0.15 m) were estimated.

Five observation wells were drilled (fig. 5). Wells

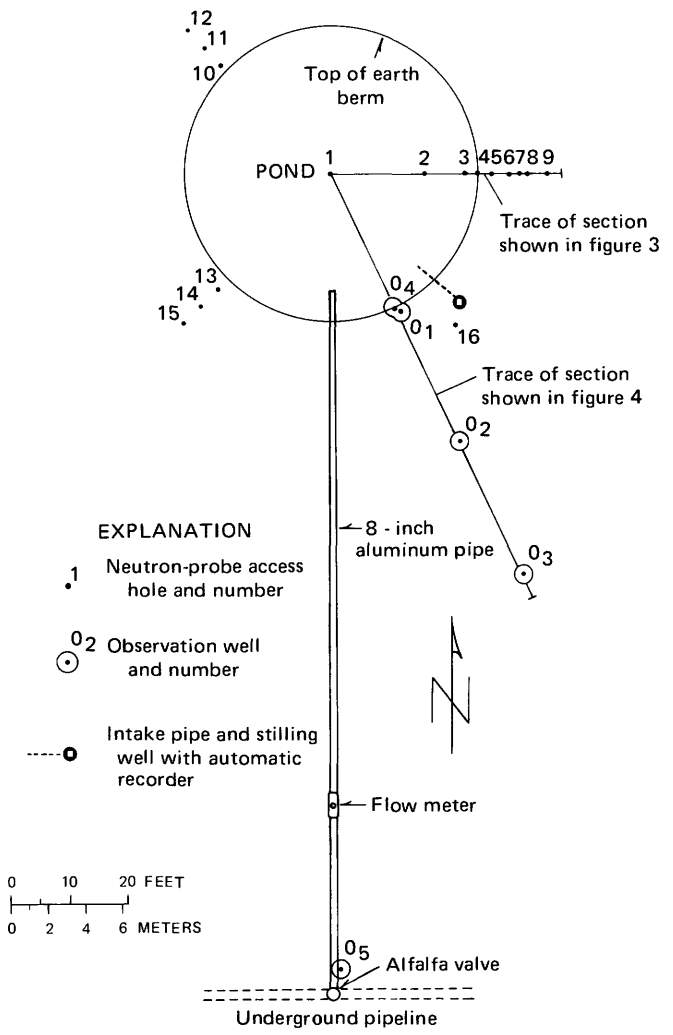

FIGURE 5.—Location of facilities installed at ponding site.

TABLE 2.—*Information concerning application of water and collection of data for ponding tests*

	Test 1	Test 2	Test 3	Test 4
Covering on pond	polyethylene sheet	polyethylene sheet	polyethylene sheet	none
Date tests were started	4–26–66	10–20–66	4–4–67	11–6–67
Time from start to end of ponding, in days	5.3	2.5	0.2	11.7
Quantity of water applied, in feet	3.25	7.00	1.00	21.50
Depth of water in pond, in feet	0.1–0.6	0.1–0.6	0.1–0.6	0.1–0.9
Neutron-probe access holes monitored for moisture movement	1, 5, 6, 8–15	1–16	1–9	none
Wells monitored for water levels	none	none	none	O_1–O_5
Wells sampled for measurements of predominant chemical constituents and specific conductance	none	none	none	O_1–O_4

O_1–O_3 were screened in the sand and gravel stratum in which the water table fluctuated (the 72–84-ft or 22–26-m zone). Well O_4 was screened just above a clay and silt stratum that occurs at the 42–49-ft (13–15-m) zone. Well O_5 was screened in the confined aquifer, which is at the 190–280-ft (58–85-m) zone. Water samples from these wells were analyzed for specific conductance and predominant chemical constituents.

TEST RESULTS

Test results are discussed in the order of water movement: infiltration into the soil, percolation through the unsaturated zone, and addition to the saturated zone.

INFILTRATION

Marked variations in infiltration rates were observed during the four tests, as shown in figure 7. The initial rate was high in all tests but decreased at a decreasing rate during the first day of testing. After about 1 day, the rate stabilized. The infiltration rate in test 1 stabilized at 0.7 ft/d (0.2 m/d), whereas the rate in test 2 stabilized at 2.2 ft/d (0.7 m/d). Test 3 was not run long enough for the rate to become stable, and in test 4 the infiltration rate stabilized after the first day at 1.2 ft/d (0.4 m/d). As ponding continued, however, the rate in the fourth test gradually increased until the end of 7 days. Thereafter, the infiltration rate remained at 2.1 ft/d (0.6 m/d) until the end of ponding (about 12 days).

In general, the variations in infiltration rates after the first day of ponding can be related to changes in the hydraulic conductivity of the soil horizons. Although an analysis of the causes of these changes is beyond the scope of this study, some possible reasons for the changes in infiltration rates are listed. (1) The protection afforded by the polyethylene covering on the pond probably increased biological activity in the soil zone. This increased biological activity could have created a soil structure more favorable for conducting water and caused part of the large increase in infiltration rates from test 1 to test 2. (2) The effect of compaction would have been greatest during test 1 because the land was tilled during the previous season but not prior to the subsequent tests. Compaction by the tillage implements could reduce hydraulic conductivity and cause the infiltration rates to be lowest during test 1. (3) Because of the abnormally large applications of water, the accumulated soluble salts would be leached from the soil horizons. A change in chemical composition of the soil owing to the loss of salts would likely modify the soil structure and increase its water-transmitting capability.

The decrease in infiltration rates during the first day of ponding in all tests is related to a number of factors. The most significant of these probably are a change in hydraulic gradient in the soil zone as the wetting front moves to greater depth and swelling of montmorillonite and illite clays in the soil zone. Both factors probably have a significant effect on the infiltration rate during the first few hours of ponding.

After several hours, the hydraulic gradient becomes stable; thereafter, the principal cause for reduction in the infiltration rate is the swelling of clay colloids. This suggestion is supported by the data from ponding test 1. The application of water during this test was temporarily discontinued after 12 hours because of wind damage to the polyethylene cover. The cover was repaired, and the application of water was resumed 42 hours after the start of the test. During the first 12 hours, as shown in figure 7, the infiltration rate followed the characteristic pattern of decreasing at a decreasing rate with time. At the end of the initial application, the rate was 1.3 ft/d (0.4 m/d). When

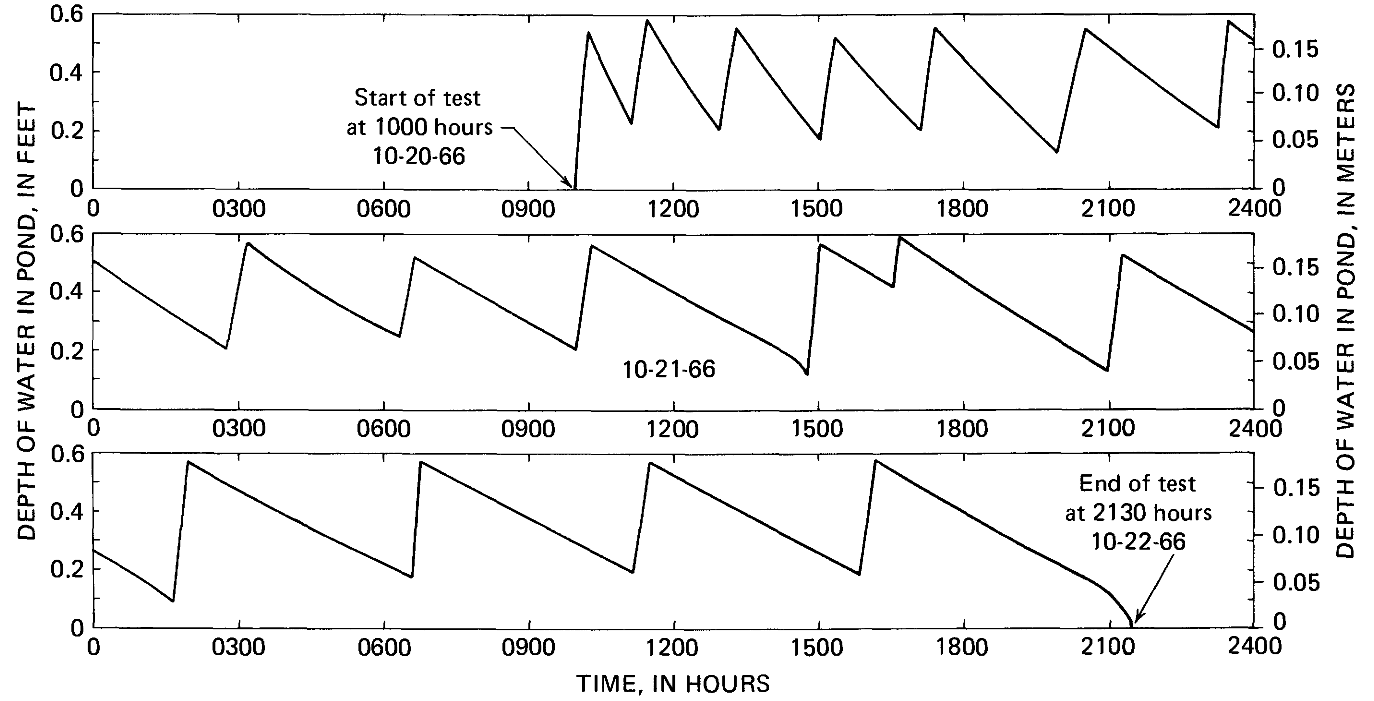

FIGURE 6.—Recorded depth of water in pond during test 2.

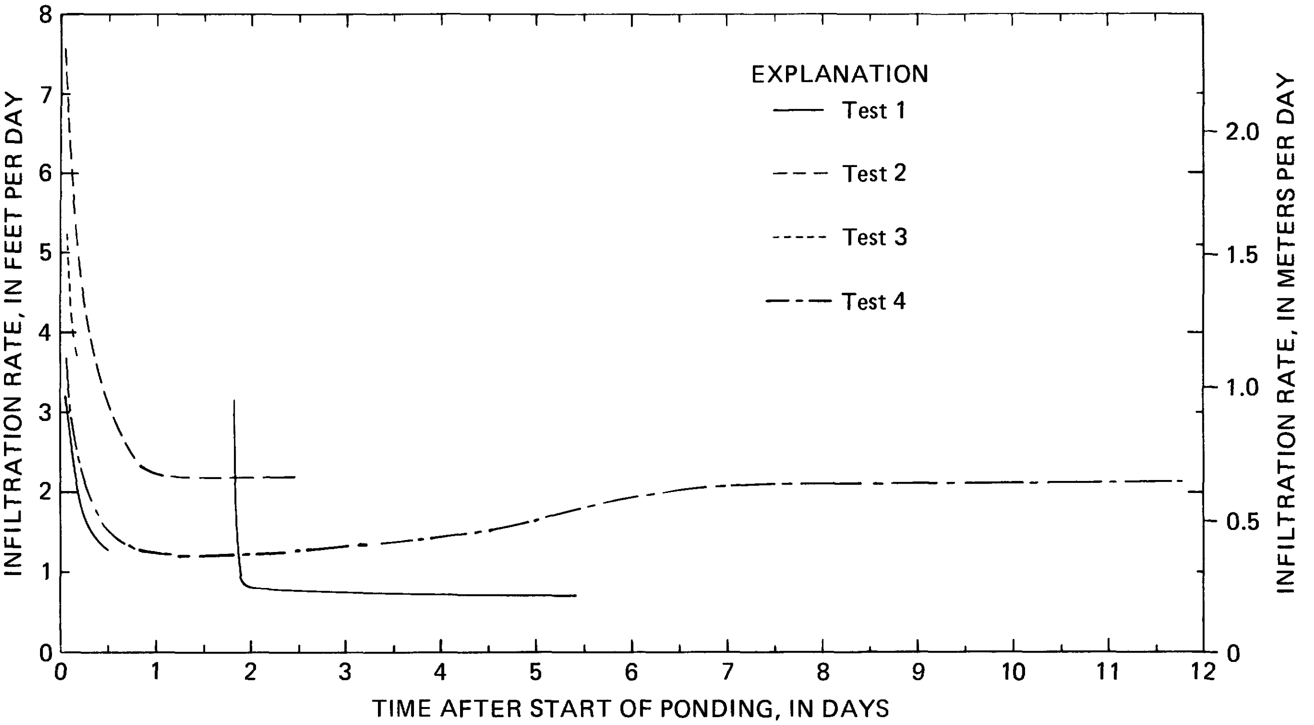

FIGURE 7.—Relation between time and infiltration rate during ponding tests.

application of water was resumed at 41 hours, the infiltration rate was again high but decreased rapidly, and within 2 hours it had essentially stabilized at 0.8 ft/d (0.2 m/d), which is 0.5 ft/d (0.2 m/d) less than the rate at 12 hours. During the nonapplication period, the hydraulic conductivity apparently continued to decrease as though the water application had been continuous. The decrease was probably caused by the swelling clay colloids. The resumption of a high infiltration rate at 42 hours probably reflected a moisture buildup and a high hydraulic gradient in the soil horizon. The effects of these factors apparently were short lived, however, for the infiltration rate stabilized after 2 hours.

MOVEMENT OF MOISTURE DURING PONDING

The movement of moisture below the ponding area was analyzed by comparing logs of moisture content run during ponding with logs run before the start of ponding. The most complete record of moisture movement was obtained from ponding test 2; therefore, the data reported in this section pertain to that test. Although emphasis is placed on moisture movement in the loess, data that describe moisture movement in the upper part of the underlying alluvial deposits also are given.

MOISTURE BUILDUP NEAR THE CENTER OF THE POND

The nature of moisture movement at the center of the pond is illustrated by the logs for access hole 1 in figure 8, which shows the moisture content in the 0.5–22.0-ft (0.15–6.7-m) zone at selected times after the start of ponding.

The logs are assumed to reflect the pattern of flow below the center of the pond. As shown in table 3, the values for moisture buildup at 6.8, 9.3, and 15.3 hours after ponding are markedly similar to values for cumulative infiltration for the same periods of time. Because flow in the center of the pond is essentially vertical (see section "Wetting-Front Patterns"), the similarity of values indicates that the infiltration rate near access hole 1 is about the same as the average infiltration rate for the pond. Green, Dabiri, Weinaug, and Prill (1970), using a mathematical model based on the theory of unsaturated flow, have successfully reproduced the moisture curve for 9.3 hours. Their work has demonstrated the effectiveness of modeling techniques for predicting water movement in unsaturated materials.

When all the moisture buildup is contained in the upper loess, as it was 6.8 hours after the start of

TABLE 3.—*Comparison of moisture buildup in the 0–22-ft (9–6.6-m) zone at access hole 1 and cumulative infiltration (test 2)*

Hours after start of ponding	Moisture buildup at access hole 1 (ft)	Cumulative infiltration (ft)
6.8	1.5	1.7
9.3	2.0	2.1
15.3	2.8	2.8

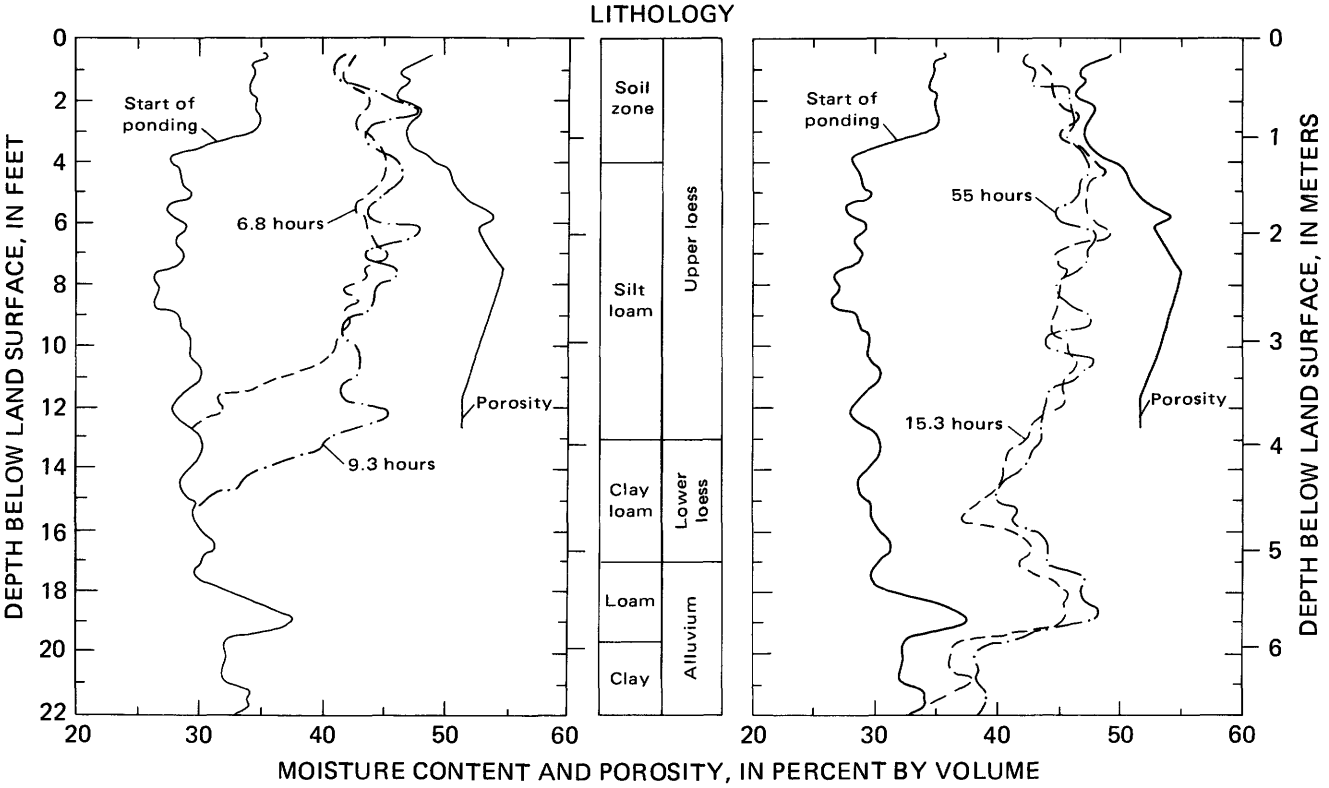

FIGURE 8.—Logs at access hole 1 showing moisture content before ponding and at selected times during ponding in test 2 compared with porosity of upper loess.

ponding, the moisture-distribution curve shows the characteristic wetting and transmission zones observed for infiltration in homogeneous materials (Bodman and Coleman, 1944). The wetting zone, which extends from a depth of 10.5–12.5 ft (3.2–3.8 m), is a zone of rapid change in moisture content. The transmission zone, which extends from the base of the soil zone (4.0 ft or 1.2 m) to the wetting zone (10.5 ft or 3.2 m), is characterized by an essentially constant moisture content. The transmission zone increases in length as infiltration proceeds. When the wetting front penetrates the alluvium, as shown on the log at 15.3 hours after the start of ponding (fig. 8), wide variations in moisture content occur in the wetting and transmission zones because of large differences in the hydraulic properties of individual strata. Thus, the wetting and transmission zones tend to lose their identity.

The amount of entrapped air is apparently reduced as infiltration proceeds. This reduction is indicated by a general increase in moisture content of about 2 percent in the upper loess during the 6.8–15.3-hour period of ponding. It is significant that the infiltration rate during this period decreased from 4.1 to 2.6 ft/d or 1.2 to 0.8 m/d (fig. 7). Thus, the moisture content was increasing as the rate of water moving through the upper loess was decreasing. This inverse relationship probably reflects a changing hydraulic conductivity of the loess materials caused by swelling of clay colloids, as discussed in the section "Infiltration."

An appreciable quantity of water will be taken in temporary storage in the loess during ponding regardless of the restriction that the underlying deposits have on the downward movement of water. During test 2, when the underlying alluvial deposits did not affect flow through the loess, moisture buildup in the silt loam loess was about 15 percent. If adequate time intervals were provided between water applications to allow the loess to drain to antecedent conditions, as was done before the start of test 2, then as much as 1 ft^3 (0.03m^3) of water could be put into temporary storage for each 6 ft^3 (0.16 m^3) of the material.

MOISTURE BUILDUP OUTSIDE THE POND

The nature of moisture buildup associated with lateral movement outside the ponded area is illustrated in figure 9 by logs for access hole 5, which is 2.5 ft (0.8 m) outside the center of the berm.

At 16 hours after the start of ponding, the lateral movement of moisture extended only slightly beyond access hole 5. A moisture increase occurred only in the materials above a depth of about 6 ft (1.8 m). This increase represents a moisture buildup of only a few percent, which suggests that the wetting front is nearby.

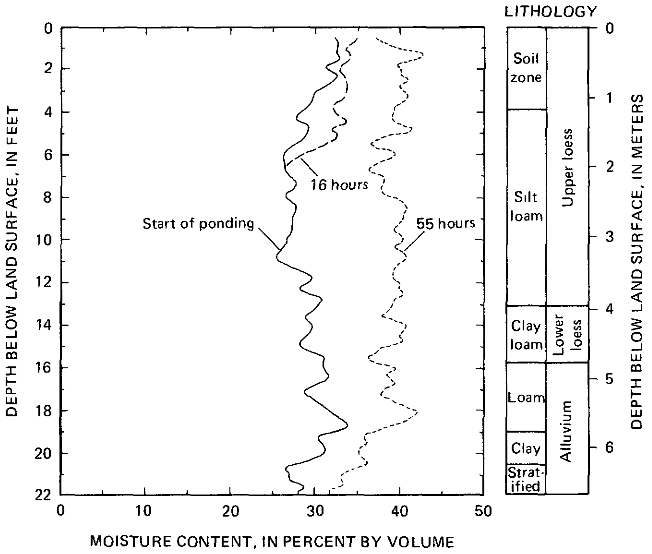

FIGURE 9.—Logs at access hole 5 showing buildup of moisture content with time during test 2.

At 55 hours after the start of ponding, the buildup of moisture content extended throughout the 0.5–22-ft (0.15–6.7-m) zone. However, the values of moisture content are noticeably less than values for comparable materials below the center of the pond (fig. 8). The apparent lower saturation percentages for the materials at access hole 5 are evidence that none of the materials at this location were acting as perching beds. It is significant that the clay stratum at the 19.0–20.5-ft (5.8–6.2-m) zone did not appear to be acting as a perching bed even though the infiltration rate at 55 hours was 2.2 ft/h (0.7 m/h). Apparently, this fine-grained stratum either has a high hydraulic conductivity or is discontinuous.

WETTING-FRONT PATTERNS

The wetting-front patterns shown in figure 10, which are based on moisture-content measurements for the access holes on the east radial during test 2, illustrate how applied water moved vertically and laterally below the ponded area. Moisture measurements at the access holes on the northwest, southwest, and east radials (fig. 5) all showed similar patterns of lateral movement, which indicates that flow below the ponded area had radial symmetry. Therefore, measurements along the east radial shown in figure 10 should provide a representative projection of the wetting-front pattern associated with ponding.

The wetting-front patterns indicate that the major part of the water applied during ponding test 2 (estimated to be about 90 percent) moved downward below the pond. Lateral movement was very slow and

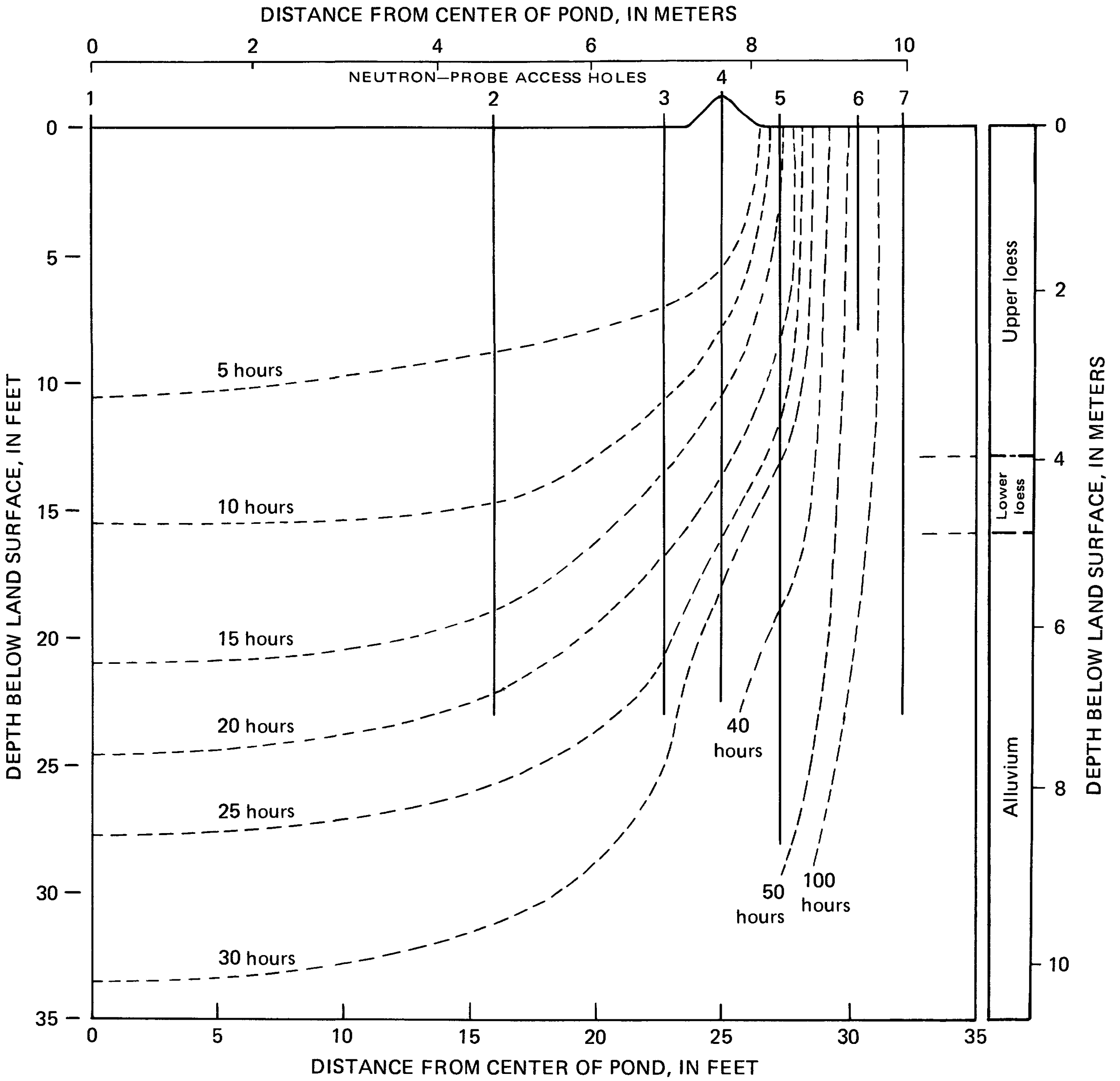

FIGURE 10.—Location of wetting front with time after start of ponding during test 2.

was restricted to a short distance. By the end of the ponding period (59 hours), the wetting front in the loess was not evident at access hole 6, located about 5 ft (1.5 m) outside the center of the berm. Although moisture content was measured several months after ponding had ceased, no moisture buildup was discernible at access hole 7, located 7 ft (2 m) from the center of the berm. Lateral movement of the wetting front after ponding apparently was restricted to a few feet.

The progressive downward movement of the wetting front (fig. 10) indicates that none of the strata between the soil zone and the 25-ft (8-m) zone acted as perching beds; also, the wetting-front patterns are not distorted enough to suggest appreciable lateral movement above any particular stratum.

The relatively slow rate at which the water moved the short distance outside the pond indicates that the size of the pond could be increased appreciably without markedly reducing the soil's ability to accept water.

REDISTRIBUTION OF MOISTURE AFTER PONDING

The redistribution of moisture after the cessation of ponding was analyzed by comparing the soil-moisture contents at various depths at selected times. Observed data from access hole 1 (center of the pond) during tests 2 and 3 were used to illustrate the subsequent movement of moisture within the 0–22-ft (0–7-m) zone.

PONDING TEST 2

Logs of moisture content at selected times after the cessation of ponding in test 2 were compared to show the reduction of moisture content with time. Because the redistribution period was from late fall to early spring (October 22, 1966, to April 3, 1967) and the pond was covered with a polyethylene sheet, little water evaporated. Most of the moisture reduction was by gravity drainage or by deep percolation.

A typical pattern of moisture reduction with time after water application is a very rapid initial rate that decreases with time (Van Bavel and others, 1968). The series of logs in figure 11 shows how moisture content decreased with time after ponding in the 0.5–22-ft (0.15–6.7-m) zone; figure 12 shows the total moisture content calculated for the 0.5–12.0-ft (0.15–2.6-m) zone (upper loess) versus the number of days after cessation of ponding. The curve in figure 12 shows that total moisture content in the 0.5–12.0-ft (0.15–3.6-m) zone had decreased 22 percent at 10 days, 29 percent at 30 days, and 35 percent at 100 days. Although the amount of reduction after the 100-day period is very small, the nature of the curve indicates that reduction would continue at an ever-decreasing rate for several months.

Because the infiltrated water applied during test 2 reached the water table just prior to the cessation of ponding, there was a buildup of moisture content throughout the unsaturated zone at the end of the test. Addition of infiltrated water to the water table would be expected to continue at a decreasing rate for several months after the cessation of ponding. The decrease in moisture content at a selected time after cessation of ponding depends on the depth of material below the ponded area. The general relationship is this: the greater the depth of material below the ponded area, the smaller the decrease in moisture content. Although data concerning moisture reduction with time after ponding were not available for the entire unsaturated zone (approximately the 0–75-ft or 0–23-m zone), it is probable that the reduction of moisture content in this zone after ponding would be much more gradual than the reduction in the 0.5–12.0-ft (0.15–3.6-m) zone. Thus, appreciable additions to the saturated zone would be anticipated for an extended period after ponding—probably several months.

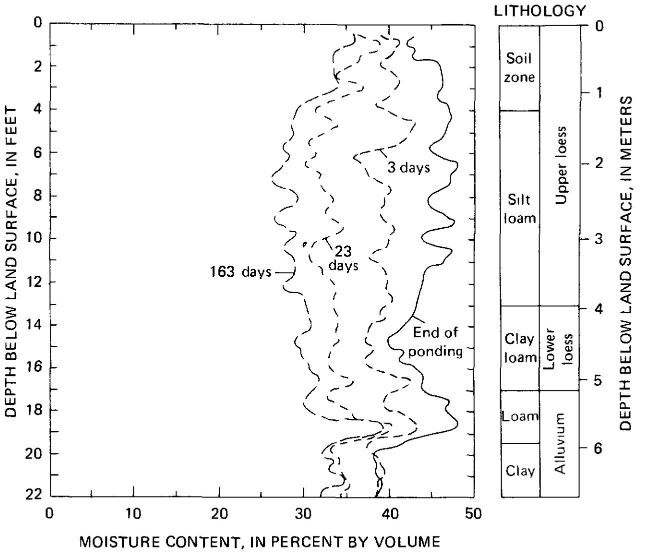

FIGURE 11.—Logs at access hole 1 showing moisture content at end of ponding and at selected times after end of ponding in test 2.

PONDING TEST 3

One ft (0.3 m) of water was applied to the pond in a 4-hour period during test 3. Logs at access hole 1, as shown in figure 13, illustrate moisture content before ponding, at the end of ponding, and about 6 days after the end of ponding. At the end of the ponding period, the depth of the wetting front was 9 ft (2.7 m), and the buildup in moisture content was calculated to be 1.0 ft (0.3 m). Six days after the end of ponding, the depth of the wetting front was 17 ft (5.2 m), and the buildup of moisture content was calculated to be 1.1 ft (0.33 m). The similarity of moisture-content buildup at the two measurement times indicates that moisture movement after ponding was essentially downward.

Because the zone of evapotranspiration extends to a depth of about 6 ft (2 m) for predominant row crops of southwestern Kansas, such as sorghum (Musick and Grimes, 1961) and sugar beets (Herron and others, 1964), most of the buildup in moisture content below

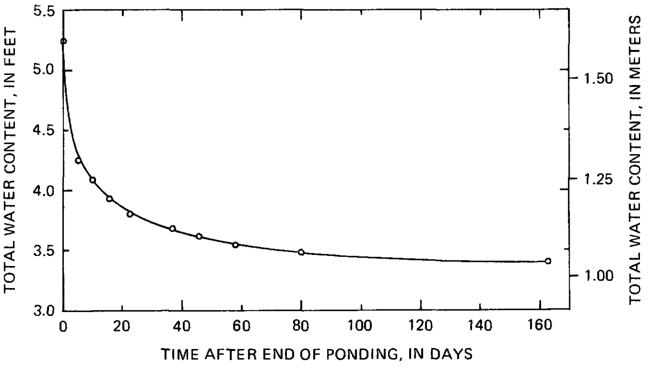

FIGURE 12.—Reduction in total moisture content in the 0.5–12.0-ft (0.15–3.6-m) zone with time after end of ponding in test 2.

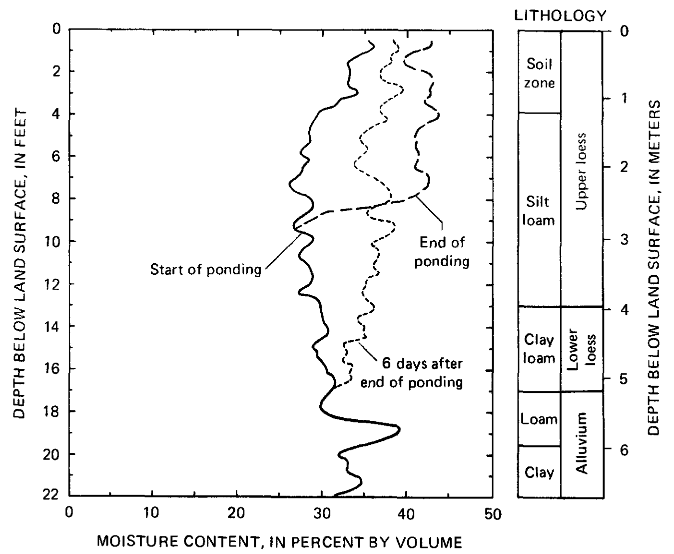

FIGURE 13.—Logs at access hole 1 showing moisture content before ponding, at end of ponding, and 6 days after end of ponding in test 3.

this zone will move as deep percolation. The decrease in calculated moisture content in the 0.5–6-ft (0.15–1.8-m) zone in relation to time after cessation of ponding in test 3 is plotted in figure 14 to illustrate how deep percolation may occur if irrigation water is applied when soil-moisture content is high and evapotranspiration losses from the soil zone are low. The total moisture content in the 0.5–6-ft (0.15–1.8-m) zone was reduced about 0.2 ft or 0.06 m (8 percent) within 2 days after the end of ponding; reduction after 13 days was about 0.4 ft (0.12 m). The test results indicate that a measurable reduction will continue for several weeks, but at an ever-decreasing rate.

The manner in which soil moisture is reduced by vertical percolation after infiltration is an important factor in determining appropriate water-management practices. Deep percolation can be very rapid when water is applied prior to or at the time of planting. The moisture in the loess will be especially high when the moisture content has not been diminished appreciably by evapotranspiration by the previous crop. During the long period required for seed germination and establishment of a crop's root system, a large part of the water applied may move below the root zone. For maximum irrigation efficiency, water should be applied at the proper time and in the proper quantity to meet plant requirements and to allow sufficient deep percolation to maintain an appropriate salt balance in the soil by leaching.

PERCHING BEDS

During the ponding tests, mound development was observed on two perching beds—the soil zone and a clay and silt stratum 42–49 ft (13–15 m) below land surface.

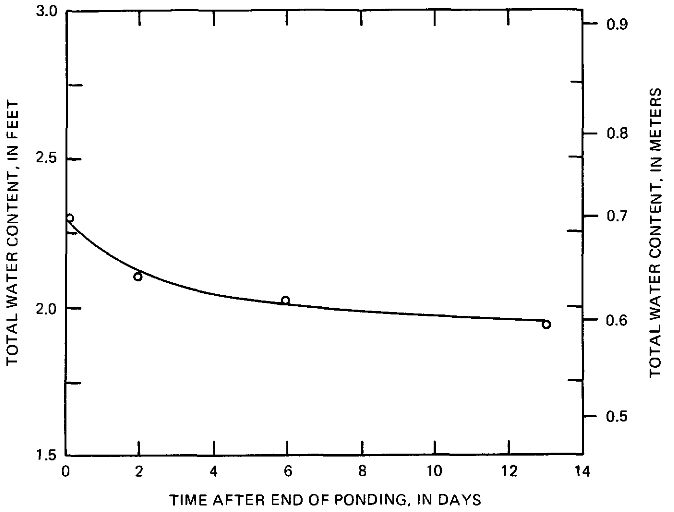

FIGURE 14.—Reduction in total moisture content in the 0.5–6-ft (0.15–1.8 m) zone with time after end of ponding, test 3.

SOIL ZONE

Ground water held by a perching bed is unconfined and is separated by an unsaturated zone from an underlying body of ground water. During ponding, the water level in the pond represents a perched water table. The underlying perching bed may not be completely saturated because of entrapped air, but most of the intergranular space will be filled with water.

The nearly saturated zone immediately below the pond and the underlying unsaturated zone are depicted in figure 15 by saturation percentages for the upper loess during ponding test 2. Percentages are plotted for access holes 1, 2, and 3, which are all within the ponding area (fig. 5). The percentages for the B and C_{ca} horizons (0.5–4-ft or 0.15–1.2-m zone) are almost all greater than 90 percent, which indicates a nearly saturated condition. The saturation percentages in the C horizon are mostly between 80 and 87 percent, which indicates an unsaturated condition. The perching bed controlling infiltration rates during test 2 evidently extended to about the 4-ft (1.2-m) depth, which includes the entire soil zone (the A, B, and C_{ca} horizons).

The pattern of saturation percentages in figure 15 suggests that infiltration rates would be increased if the soil zone were removed. The saturation percentages of the soil zone exceeded 90, while the percentages of the C horizon averaged about 84. Because the effective hydraulic conductivity of a material increases as the saturation percentage decreases, the hydraulic conductivity of the nearly saturated C horizon must be

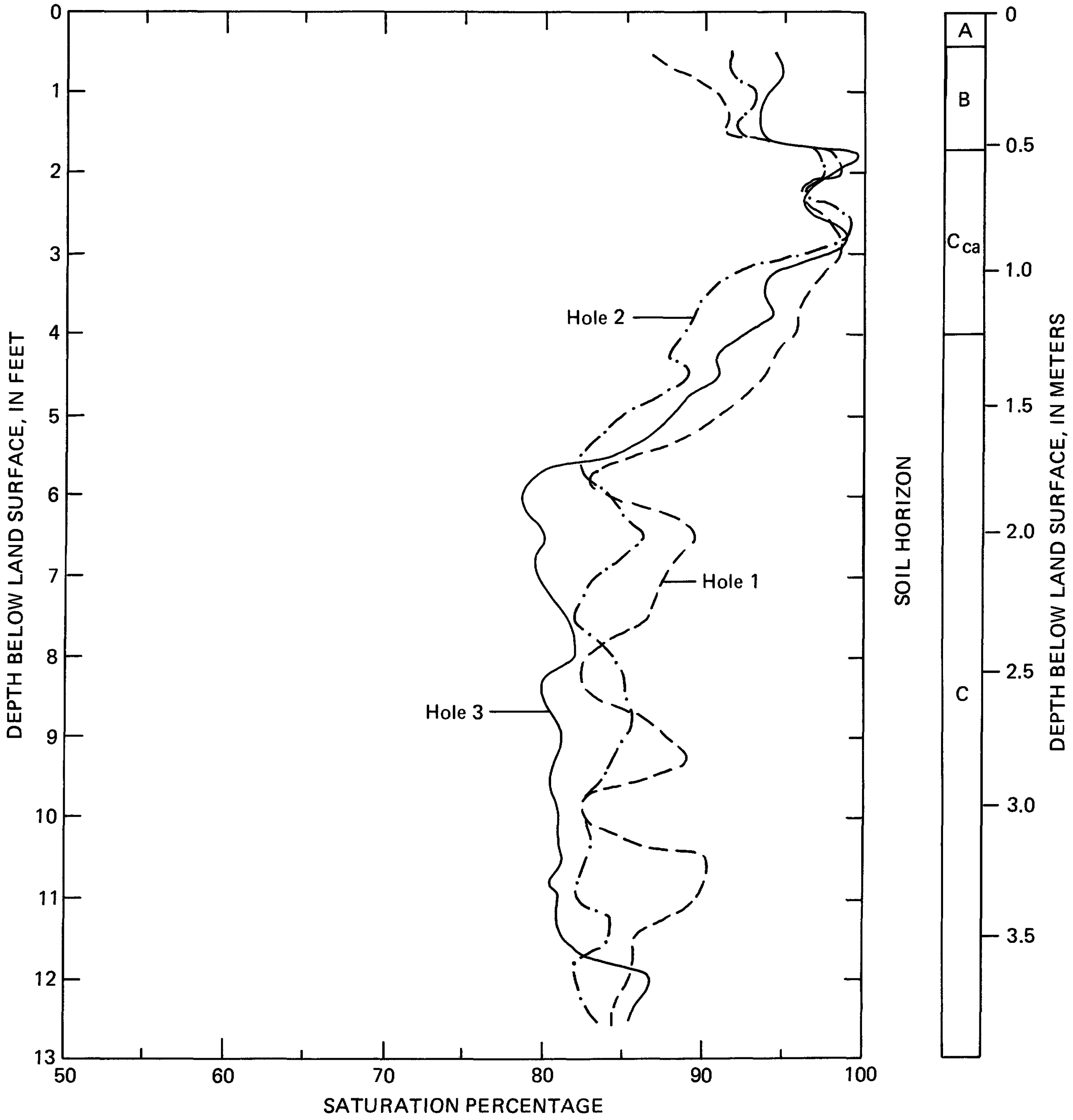

FIGURE 15.—Comparison of saturation percentages in the upper loess at access holes 1, 2, and 3 after 2 days of ponding in test 2.

appreciably higher than that of the soil zone. The excavation of tail water and recharge pits in southwestern Kansas indicates, however, that the friable silt loam of the C horizon is easily compacted. Thus, caution would be required in excavating the soil zone to prevent compaction of the underlying material.

One objective in many water-spreading operations is to apply the available water over the smallest possible area in order to reduce land requirements. Thus, it is important to know how changes in the height of water in the spreading area will affect the infiltration rate. The following discussion shows how the data for ponding-test 2 can be used to define the relationship between the height of water in a pond and infiltration rates.

When water moves through a perching bed, flow resulting from head gradients across the bed should follow Darcy's law. At the center of the pond, where flow is essentially vertical, this relationship can be stated as

$$q = K\left(\frac{\Delta h}{\Delta l} + 1\right)$$

where

q = flux or infiltration rate,

K = hydraulic conductivity,

Δh = change in pressure head across the perching bed, and

Δl = thickness of the perching bed.

By the use of data from ponding test 2, the hydraulic conductivity of the perching bed can then be determined. The perching bed is the 0–4-ft (0–1.2-m) zone. The infiltration rate is 2.2 ft (0.7 m) per day (fig. 7). The pressure head at the upper boundary is 0.4 ft or 0.12 m (the average height of water in the pond), and the pressure head at the lower boundary of the perching bed is considered to be −2.5 ft or −0.76 m (based on tensiometer readings made during subsequent tests when infiltration rates were near 2.2 ft/d or 0.7 m/d). The hydraulic conductivity is determined to be

$$K = \frac{q}{\frac{\Delta h}{\Delta l} + 1} = \frac{2.2 \text{ ft/day}}{\frac{2.9 \text{ ft}}{4.0 \text{ ft}} + 1} = 1.28 \text{ ft/day (0.39 m/d).}$$

By using 1.28 ft/d (0.39 m/d) as the hydraulic conductivity and assuming the pressure head at the lower boundary of the perching bed to be −2.5 ft (−0.76 m), we can compute the infiltration rates when the water levels in the pond are at 0.1 and 0.6 ft (0.03 and 0.18 m) above the land surface as follows:

When h_l is 0.1 ft (0.03 m),

$$q = 1.28 \text{ ft/day} \left[\frac{0.1 \text{ ft} - (-2.5 \text{ ft})}{4.0 \text{ ft}} + 1\right] = 2.11 \text{ ft/day (0.64 m/d);}$$

when h_l is 0.6 ft (0.18 m),

$$q = 1.28 \text{ ft/day} \left[\frac{0.6 \text{ ft} - (-2.5 \text{ ft})}{4.0 \text{ ft}} + 1\right] = 2.27 \text{ ft/day (0.69 m/d).}$$

These computations show only a 7-percent decrease in the infiltration rate with a change in depth of water in the pond from 0.6 to 0.1 ft (0.18 to 0.03 m). Although the pressure head at the lower boundary of the perching bed in these examples is shown as a constant, a change in flux would cause a slight change in pressure head at the lower boundary. Because this change is directly related to flux, an increase in depth of water in the pond would result in an increase in the pressure head at the lower boundary of the perching bed. Consequently, the range in the infiltration rates would be slightly less than the 7 percent shown here.

That infiltration rate is not greatly affected by the depth of water in the pond is also indicated by the nature of the curves showing water-level decline for test 2. In general, the slope of the curve decreased gradually as the height of the water in the pond decreased. For instance, the height of water in the pond between 1200 and 1500 hours on November 22, 1966, decreased from 0.52 to 0.25 ft (0.15 to 0.07 m), whereas the slope of the decline curve decreased from 2.22 to 2.15 ft/d (0.67 to 0.65 m/d). This change represents only a 3-percent decrease in the infiltration rate.

CLAY AND SILT STRATUM AT 42–49 FT (13–15 M)

A thin mound of water was observed during test 4 above a clay and silt stratum at a depth of 42–49 ft (13–15 m), which showed that this stratum was acting as a perching bed. During test 4, a total of 21 ft (6.4 m) of water was applied to the pond over a period of 12 days. The water-level hydrograph for observation well O_4, shown in figure 16, shows that mounding occurred in the overlying sand and gravel after 7 days of ponding. The mound, which obtained a maximum height of 1 ft (0.3 m), dissipated rapidly after the cessation of ponding and disappeared in 1 day.

The nature of the growth and decline of the perched ground-water mound indicates that the clay and silt stratum acts as a perching bed only when infiltration rates are high. The first evidence of a water-table mound in the saturated zone was noted after 7 days of ponding (see section "Water-Table Mound"), which is the same time that mounding was first observed above the perching bed. Because the water table of the saturated zone is about 40 ft (12 m) below the perching bed, water probably had been moving through the perching bed for several days before mounding commenced. The apparent delay in the development of mounding may be related to the gradual increase in the infiltration rate from the 2d to 7th day. As shown in figure 7, the infiltration rate for test 4 initially stabilized at 1.2 ft/d (0.4 m/d), then gradually increased until it stabilized again at 2.1 ft/d (0.6 m/d) after 7 days. Because the clay and silt stratum apparently functions as a perching bed only at the higher infiltration rates, the hydraulic conductivity of this fine-grained stratum must be quite high.

ADDITIONS TO THE SATURATED ZONE

Additions to the saturated zone from water applied at land surface are difficult to measure. Observed water levels during the test period also reflect the fluctuations associated with ground-water pumping

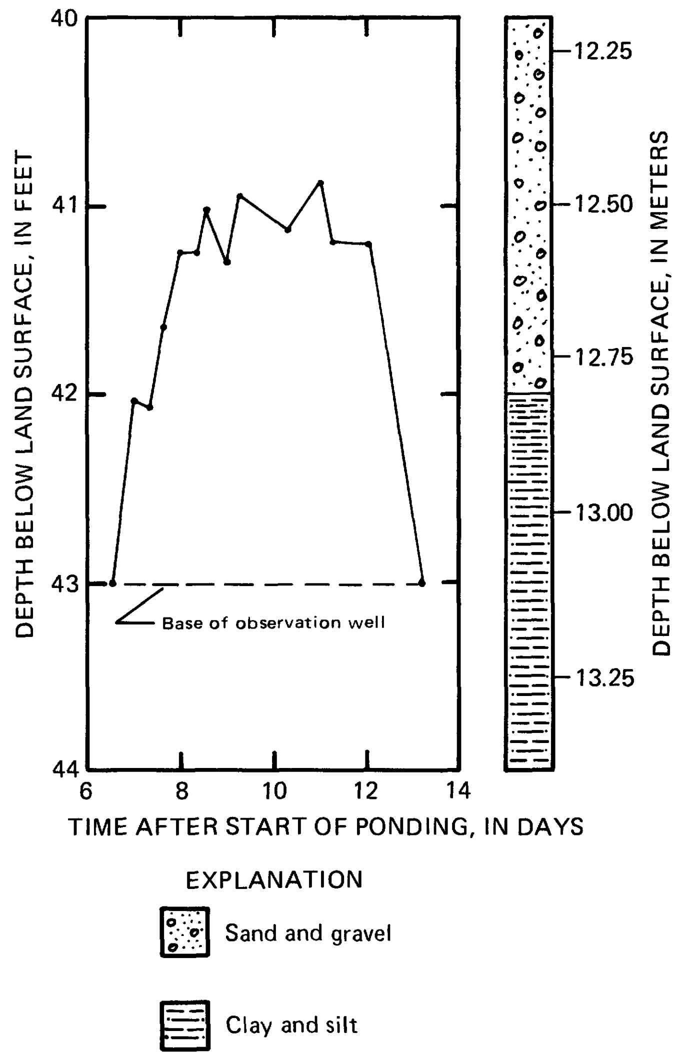

FIGURE 16.—Hydrograph for observation well O_4 showing mounding above a perching bed during test 4.

from a confined aquifer and return flow from applied irrigation water. Although a sharp rise in the water table measured in an observation well at the edge of the pond indicates that initial mounding was easily detected, the configuration of the mound became less evident with time and distance from the pond. In the following section, data describing water-level changes in the study area are used to show fluctuations in water levels that result from pumping for irrigation. Data from ponding test 4 are used to estimate the relative thickness and radial extent of mounding caused by ponding alone. Both water-level measurements and changes in chemical quality of water are analyzed to evaluate lateral spreading.

WATER-LEVEL FLUCTUATIONS

Water levels in the study area fluctuate during the year as a result of ground-water pumping for irrigation. The observed magnitude of the fluctuations depends on the zone in which the observation well is screened. Because these seasonal changes mask the water-table mounding that occurs during the ponding tests, the following information is basic to the evaluation of mounding directly associated with ponding.

The saturated zone at the study site contains an unconfined aquifer from 72 to 84 ft (22 to 26 m), a confining bed from 84 to 190 ft (26 to 58 m), and a semiconfined aquifer from 190 to 280 ft (58 to 85 m) below land surface. Aquifer-test data from the study area show that the transmissivity of the semiconfined aquifer is 1.0×10^4 ft^2/d (9.3×10^2 m/d) and the hydraulic conductivity of the confining bed is 3.2×10^{-2} ft/d (9.7×10^{-3} m/d).

The water-level hydrographs in figure 17 show the fluctuations of the water table of the unconfined aquifer (observation well O_2) and fluctuations of the potentiometric surface of the semiconfined aquifer (observation well O_5) in 1968. The water level in well O_2 fluctuated between 73 and 82 ft (22 and 25 m) below land surface in this period. A change in water level in this well reflects a corresponding change in the volume of water in storage. The water level in well O_5 fluctuated between 73 and 95 ft (22 and 29 m) below land surface in the observed period. A change in the potentiometric surface measured in this well reflects a response to changes in pressure.

During the irrigation season, the change in the water table of the unconfined aquifer was markedly different from the change in the potentiometric surface of the semiconfined aquifer, as shown by the hydrographs from March through October 1968. The water level declined gradually during the season; the maximum rate of decline was 0.07 ft/d (0.02 m/d), and the maximum decline was 9 ft (2.7 m). In the same period, the potentiometric surface fluctuated erratically in response to pumping for irrigation. The maximum decline during the season measured in well O_5 was about 18 ft (5 m).

The water levels in both observation wells declined during the irrigation season and rose during the nonirrigation season. The potentiometric surface was much lower than the water table in the pumping season but rose 1–2 ft (0.3–0.6 m) above the water table in the nonpumping season. Because very little ground water pumped for irrigation is withdrawn directly from the unconfined aquifer, it is evident that some water leaks through the confining zone in response to a pressure gradient. In general, the lag is about 3 weeks between pressure changes in the semi-confined aquifer and water-table changes in the unconfined aquifer.

The resaturation of materials resulting from a rise in

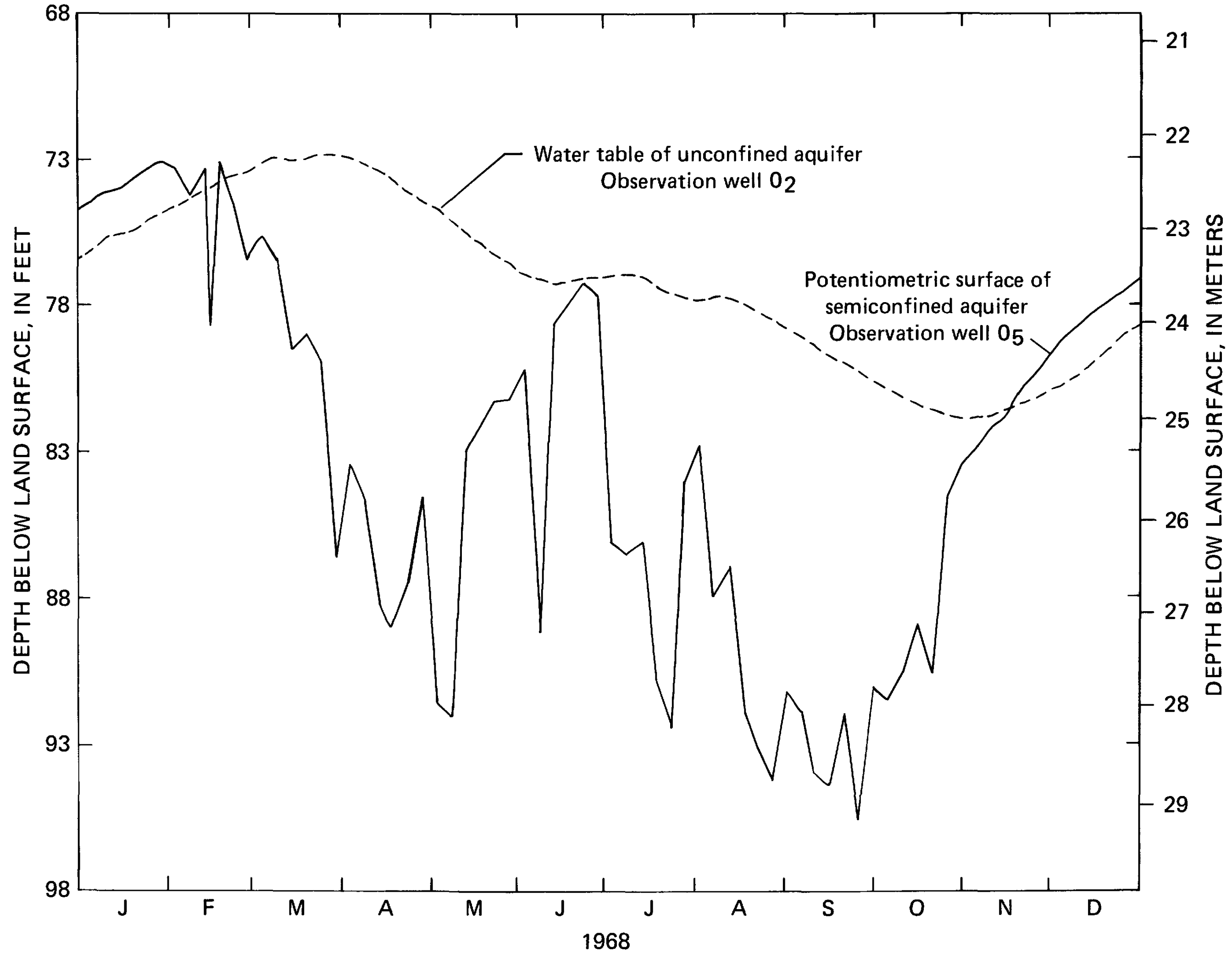

FIGURE 17.—Hydrographs showing water table in the unconfined aquifer and potentiometric surface of the semiconfined aquifer in 1968.

the water table is illustrated by the moisture-content logs on figure 18. During the period from October 23, 1966, to April 5, 1967, a 7.7-ft (2.3-m) rise in the water table was measured in access hole 16. On the basis of moisture-content values in the formation from figure 18, the total moisture buildup was determined to be 1.7 ft (0.5 m). This represents a ratio of a 1-ft (0.3-m) rise in the water table for each 0.22 ft (0.07 m) of water added to the upper aquifer.

WATER-TABLE MOUND

The water-table mound associated with ponding test 4 is shown in figure 19 by hydrographs of observation wells 25 ft or 8 m (O_1), 50 ft or 15 m (O_2), and 75 ft or 23 m (O_3) from the center of the pond. The period of observation began November 6, 1967 (date of initial application of water for test 4), and ended February 10, 1968. The water table was rising during this period in response to the general cessation of irrigation pumping. Thus, the water-level hydrographs in figure 19 reflect both the seasonal rise and the addition of water from ponding.

A projected water-table rise due to recovery when the wells are shut off, without additions from ponding, was drawn to estimate the thickness of the groundwater mound. The rate of the projected rise was based on the measured rise prior to mounding and on the effect of pumpage from nearby irrigation wells during the following year. The rate of rise measured in the observation wells for a 7-day period prior to mounding was 0.04 ft/d (0.012 m/d). Because several irrigation wells were pumped for short intervals throughout the 0–40-day period, the rate of 0.04 ft/d (0.012 m/d) is considered to be applicable for the rise projected to 40 days after the start of ponding. During the 40–100-day period, the regional rate of rise probably increased

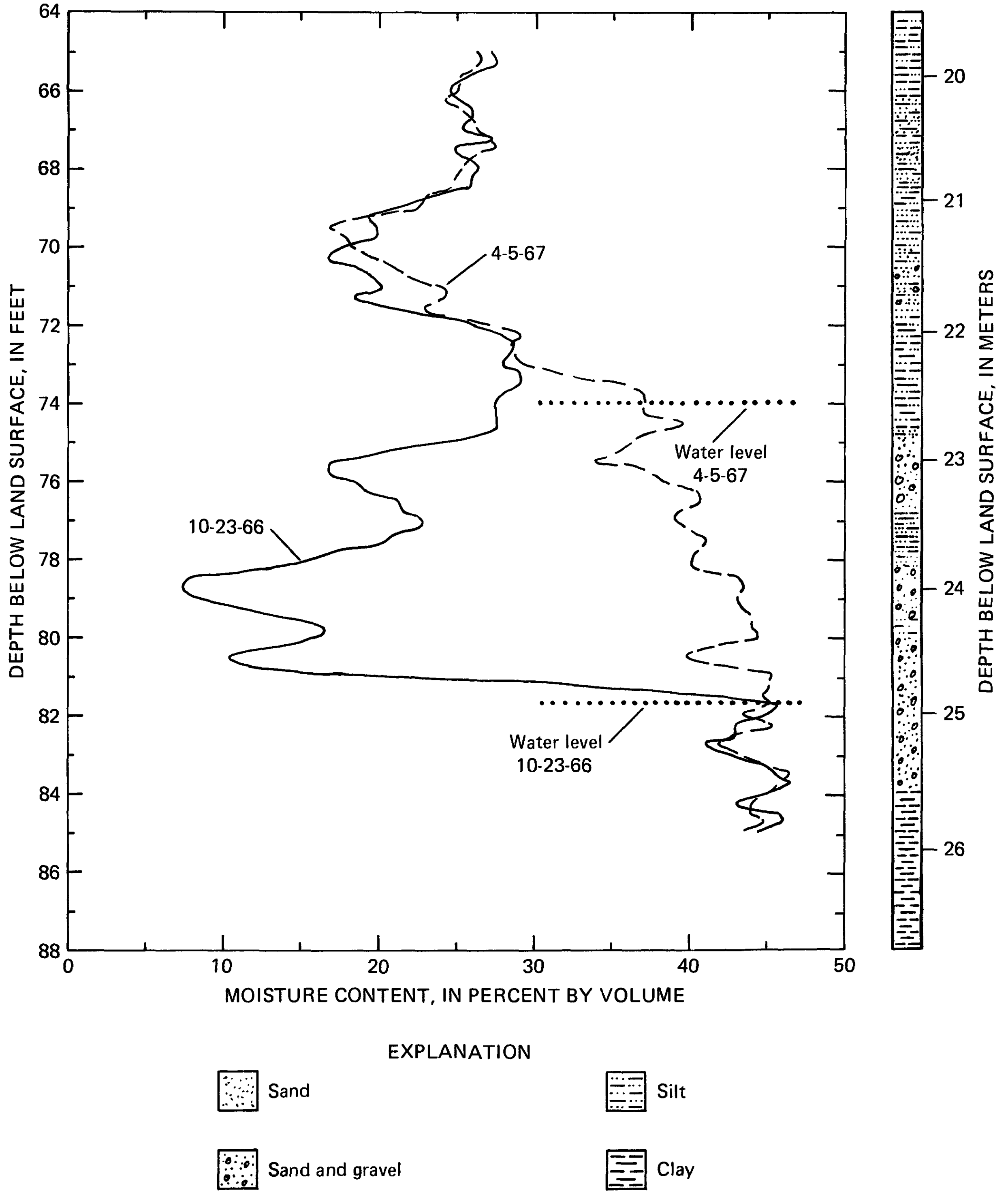

FIGURE 18.—Moisture-content logs at access hole 16 showing the resaturation of materials associated with a rising water table.

slightly because all irrigation pumping had ceased. The rise at observation well O2 for a comparable period in the winter of 1968-69 indicates a rate of 0.06 ft/d (0.018 m/d). The rate for the latter period, which reflects no additions of water from ponding and no irrigation-well pumping, is considered applicable for the rise projected from 40 to 100 days after the start of ponding.

Only a small part of the water-table rise, as shown by the hydrographs on figure 19, appears to be related

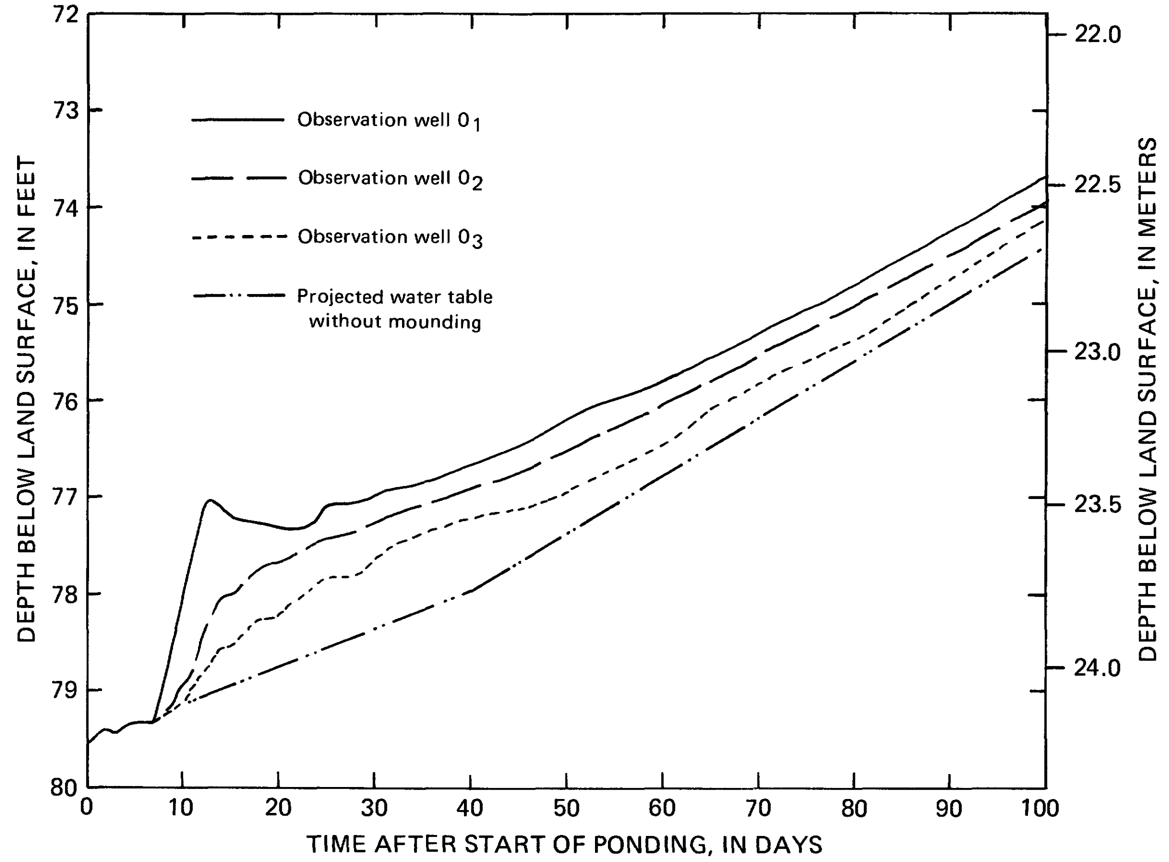

FIGURE 19.—Hydrographs showing effects of ground-water mounding at southeast radial of pond during test 4.

to mounding during ponding test 4. Most of the rise is in response to the recovery of the water table in a well field during the nonirrigation season.

Because the water-table changes result from a complex hydrologic interaction, only a few general features of the mound are discernible from the test data. The significant features of the observed mounding are the initial rate of spreading during development, the relative thickness, and the manner of dissipation after the ponding ceases.

The mound spread rapidly during its early development (fig. 19). The first occurrence of mounding, which was indicated by a sharp increase in the rate of water-table rise, was observed after 7.5 days at well O_1 and 10.5 days at well O_3; thus, the mound spread laterally from well O_1 to well O_3—a distance of 50 ft (15 m) from the edge of the pond—in only 3 days. This spreading represented a severalfold increase in the areal extent of the mound.

When the hydrographs are compared with the projected rate of seasonal rise, the ground-water mound resulting from ponding appears to be very thin. The estimated maximum thickness of mounding during ponding test 4 was 2.0 ft (0.6 m) at well O_1, 1.2 ft (0.4 m) at well O_2 and 0.8 ft (0.2 m) at well O_3. The mound attained maximum thickness at each observation well in a relatively short time; for example, it reached maximum thickness at well O_1 in 12.5 days, or 5 days the first indication of mounding. Thereafter, the thickness gradually diminished to about 0.7 ft (0.2 m) at 100 days.

The ground-water mound is shown to dissipate very slowly with time. At 100 days after the start of ponding, there is still distinct evidence of a mound. The persistence of the mound is related to the slow drainage of the unsaturated zone. As discussed in the section "Ponding Test 2," appreciable additions to the saturated zone from drainage can be anticipated for several months after ponding.

CHANGES IN WATER QUALITY

As water moves through the unsaturated zone, an increase in the concentration of dissolved solids and a corresponding increase in specific conductance are caused by the leaching of soluble salts from the soil. The increases caused by percolation during test 4 are reflected by changes in ground-water quality below the ponding site. Figure 20 shows the fluctuations in specific conductance of water samples collected at the

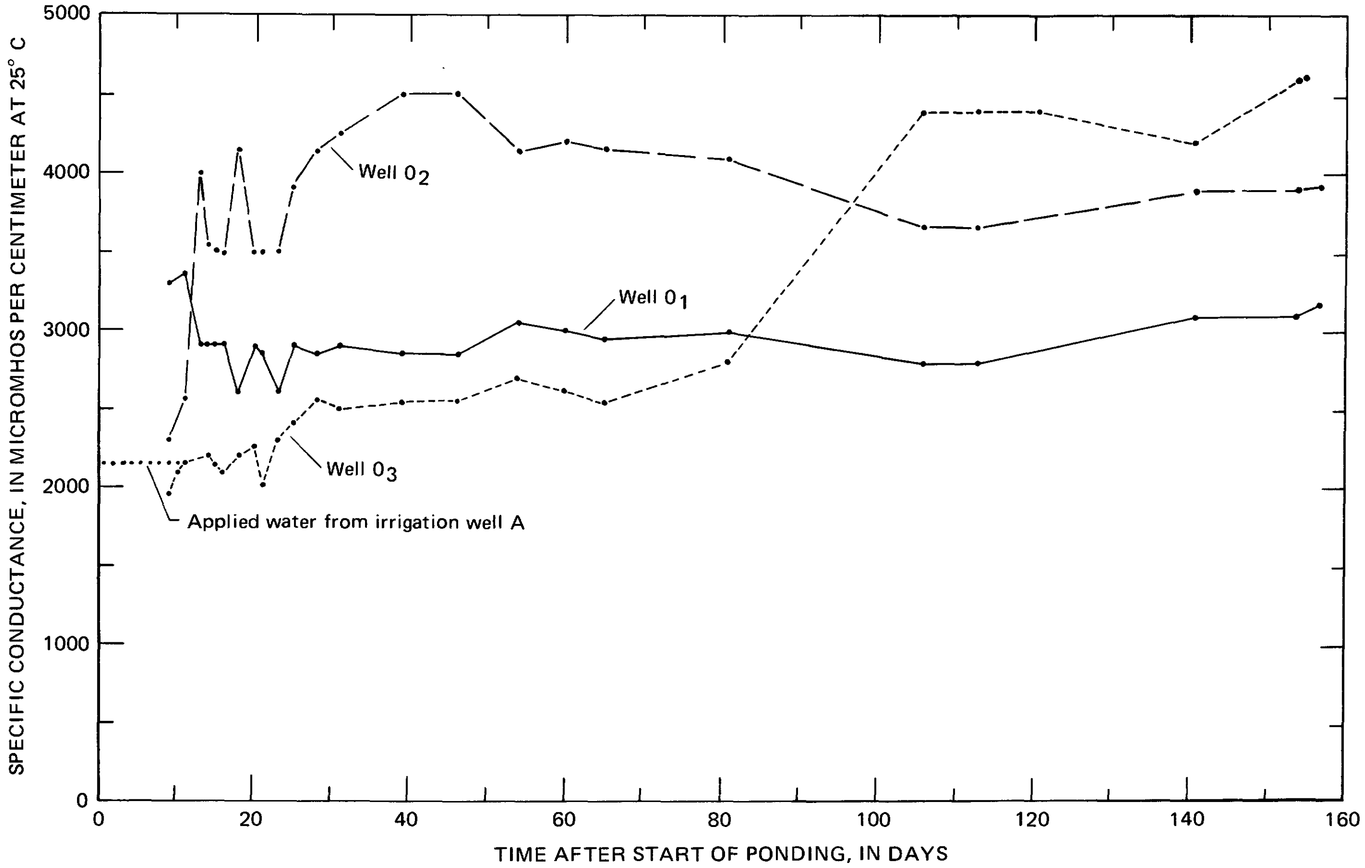

FIGURE 20.—Changes in specific conductance of water samples at selected observation wells on southeast radial of pond during test 4.

water table from three wells on the southeast radial of the pond. These wells are 25 ft or 8 m (O_1), 50 ft or 15 m (O_2), and 75 ft or 23 m (O_3) from the center of the pond. The measurements shown for a 157-day period represent the conditions during ponding as well as during subsequent drainage. The relationship of specific conductance to dissolved constituents for selected water samples is shown by the chemical analyses in table 4.

Appreciably higher specific conductances at the water table than that of the applied water apparently reflect additions of leachate to the water table. The initial occurrence of mounding was at 7.5 days at well O_1, 9 days at well O_2, and 10.5 days at well O_3 (fig. 19), whereas the initial specific conductance readings for the three wells were from samples collected at 9 days. The specific conductance values at well O_1, which is at the edge of the pond, averaged about 3,000 micromhos at 25°C, which is assumed to be representative of the average dissolved-solids content of water moving directly below the pond. The specific conductance of samples collected at wells O_2 and O_3 after 9 days were similar to that of the applied water, but appreciably higher values were recorded after 12 days at well O_2 and after 106 days at well O_3. These values, which range from 3,500 to 4,600 micromhos at 25°C, probably

TABLE 4.—*Chemical analyses of water samples*

[Analyses by Kansas Department of Health and Environment. Dissolved constitutents given in milligrams per liter]

Well No.	Depth (ft)	Date of collection	Dissolved solids	Specific conductance (micromhos per centimeter at 25°C)	pH	Silica (SiO_2)	Calcium (Ca^{++})	Magnesium (Mg^{++})	Sodium (Na^+)	Potassium (K^+)	Carbonate (CO_3^{--})	Bicarbonate (HCO_3^-)	Sulfate (SO_4^{--})	Chloride (Cl^-)	Nitrate (NO_3^-)	Fluoride (F^-)
Irrigation well A	309	11-20-67	1,643	2,130	7.8	20	250	94	123	11	0	181	932	113	10	0.9
Observation well O_1	89	11-20-67	2,230	2,910	8.0	24	152	141	345	17	0	278	1,260	129	28	1.2
Observation well O_1	89	04-11-68	2,490	3,170	7.3	14	251	169	305	16	0	459	1,360	125	18	1.1
Observation well O_2	89	11-20-67	3,010	3,540	7.7	14	368	232	228	17	0	273	1,810	176	30	1.1
Observation well O_2	89	04-11-68	3,430	3,930	7.4	16	432	256	260	18	0	410	2,060	165	24	1.1
Observation well O_3	89	11-20-67	1,660	2,200	7.5	7.9	222	107	146	12	0	154	920	167	.9	1.2
Observation well O_3	89	04-09-68	3,960	4,630	8.0	22	482	348	240	20	0	185	2,320	417	24	1.1

reflect the dissolved-solids content of both the water moving directly below the pond and the water moving laterally outside the pond. Water moving directly below the pond would tend to have a lower dissolved-solids content than water moving laterally beyond the edge of the pond before percolating downward because the leaching of salts by 11 ft (3.6 m) of water applied during the earlier ponding tests would be more intense in the materials immediately below the pond, and thus smaller quantities of salt would be present during subsequent percolation through those materials. Also, movement of water outward from the pond edge generally will occur at a lower saturation percentage than that moving downward below the pond, and water moving through a material at a low saturation percentage is more effective in leaching salts than at a high saturation percentage (Biggar and Nielsen, 1967).

Although the ground-water mound associated with additions of leachate to the saturated zone during ponding test 4 spread rapidly, the rate of lateral spreading of the leachate is apparently very slow. The first indication of mounding at well O_3 was at 10.5 days after the start of ponding, whereas a high specific conductance was first measured at 106 days. A gradual increase in specific conductance from 2,100 to 2,800 micromhos at 25°C that occurred from 10 to 80 days after the start of ponding may have been caused by factors unassociated with pond recharge, whereas the high specific conductances after 106 days probably were related to the lateral movement of pond leachate in the aquifer. Part of the leachate added to the saturated zone would be taken into storage as the water table rose, and part would move by displacing water in the saturated zone. Because the water generally moved upward through the confining bed during most of the period of observation (fig. 19), the displacement of water would mostly have occured in the unconfined aquifer (the saturated sand and gravel above 84 ft or 26 m).

A comparison of the volume of saturated materials in the upper aquifer within a radius of 75 ft (23 m) from the center of the pond with the volume of water applied during test 4 indicates that a long time lapse between mounding and the arrival of leachate at well O_3 is possible. The bulk volume of saturated materials was computed to be 17.7×10^4 ft^3 (5.0×10^3 m^3), whereas the quantity of water applied during test 4 was 4.3×10^4 ft^3 (1.2×10^3 m^3). Assuming that the quantity of water displaced per unit volume of saturated sand and gravel is 0.22, then the volume of displaceable water is 3.9×10^4 ft^3 (1.1×10^3 m^3), which is almost the volume of water applied.

SUMMARY

The study area, which is in a loess-mantled area underlain by thick unconsolidated alluvial deposits, has excellent potential for artificial recharge by water spreading. Infiltration rates observed during a series of ponding tests would be favorable for most water-spreading operations. Fine-grained strata in the unsaturated alluvium, which have high hydraulic conductivities, are not likely to cause sufficient mounding of water to impede infiltration. Water could be put into underground storage by using the volume of material that has been dewatered by pumping. The added water could sustain the productivity of the existing well field.

A primary factor in water-spreading operations in loess would be the development and maintenance of high hydraulic conductivities in the soil horizons. Infiltration rates, which ranged from 0.7 to 2.2 ft/d (0.2 to 0.7 m/d) during the ponding tests, indicate high hydraulic conductivities for the soil horizons at the study site. The lowest measured infiltration rate of 0.7 ft/d (0.2 m/d) probably would be considered favorable for many recharge operations. That the rate increased appreciably in subsequent tests illustrates that much can be done by appropriate management practices to increase the hydraulic conductivity of the soil horizons. If extensive water-spreading operations are considered, additional data should be obtained on the effects of different management practices and on the chemical compatability of water from other sources.

The silt loam loess underlying the soil zone has an appreciably higher conductivity than the soil zone. Thus, stripping the soil zone could be a procedure for obtaining higher recharge rates. As the silt loam loess is very susceptible to compaction, caution would be required to prevent compaction during the stripping operation and subsequent recharge operations.

The silt loam loess deposits have the capacity to take large quantities of water into temporary storage. If adequate time is allowed between water applications, the amount of water that can be taken into storage is about 1 ft^3 (0.03 m^3) of water for each 6 ft^3 (0.17 m^3) of material. In areas where the loess deposits are thick, considerable quantities of water can be applied by surface spreading regardless of the hydrologic characteristics of the underlying alluvium.

Several fine-grained strata are in the unsaturated alluvium underlying the loess at the study area. Owing to their relatively high hydraulic conductivities, they did not act as effective perching beds during the ponding tests. Strata of this type probably would not cause sufficient mounding to impede infiltratio significantly during water-spreading operations.

Most of the water applied during ponding moved directly downward below the pond. Lateral spreading in the loess was restricted to only a few feet. This small lateral movement indicates that the size of the pond could be increased appreicably without markedly reducing its effectiveness.

Moisture content of the loess decreased at a gradually decreasing rate for a 5-month period after the cessation of ponding. This pattern of moisture reduction shows that deep percolation from irrigation could be large when water is applied during periods when moisture content is high and evapotranspiration losses from the soil zone are low.

As the applied water moves from land surface through the unsaturated zone, an increase in the concentration of dissolved solids can be anticipated. The increase in dissolved-solids content, which is caused by the leaching of soluble salts, depends on the quality of the water applied, the extent of previous leaching, and the saturation percentage of the materials through which the water is moving. The amount of dissolved solids leached from the unsaturated zone can be expected to decrease with continued application by water spreading.

The manner in which water is redistributed in the unsaturated materials after ponding shows that, although drainage of the materials in the unsaturated zone continues for many months after the application of water, most of the applied water can be expected to reach the saturated zone in a few months. Once the water reaches the water table, it becomes part of the ground-water supply available for irrigation. In the study area, water-table levels fluctuated markedly during the year as a result of ground-water pumping for irrigation. During the 1968 irrigation season, the maximum decline of the water table was 9.0 ft (2.7 m). On the basis of moisture-content values, the water-table rise of 7.7 ft (2.3 m) during the following nonirrigation season represented a total moisture buildup of 1.7 ft (0.05 m). Thus, a 1-ft (0.3-m) rise in the water table represents an addition of 0.22 ft (0.07 m) of water to the upper aquifer. The nature of these water-table fluctuations suggests that there is considerable flow between the upper aquifer, where the depletion and accretion in storage occurs, and the lower aquifer, from which most of the ground water is withdrawn. Thus, for areas of similar lithologic and hydrologic conditions, additions from water spreading would become an integral part of the whole aquifer system contributing to the available ground-water supply. The actual applied water may not be immediately available for irrigation, but the resulting addition to pressure heads in the saturated zone would aid in maintaining the production of wells.

REFERENCES CITED

Biggar, J. W., and Nielsen, P. R., 1967, Miscible displacement and leaching phenomenon, *in* Hagen and others, eds., Irrigation of agricultural lands: Advances in Agronomy, no. 11, p. 254–274.

Bodman, G. B., and Coleman, E. A., 1944, Moisture and energy conditions during downward entry of water into soils: Soil Sci. Soc. America Proc.,v. 8, p. 116–122.

Frye, J. C., and Leonard, A. B., 1952, Pleistocene geology of Kansas: Kansas Geol. Survey Bull. 99, 230 p.

Green, D. W., Dabiri, Hassan, Weinaug, C. F., and Prill, R. C., 1970, Numerical modeling of unsaturated groundwater flow and comparison of the model to a field experiment: Water Resources Research, v. 6, no. 2, p. 862–874.

Herron, G. M., Grimes, D. W., and Finker, R. E., 1964, Effect of plant spacing and fertilizer on yield, purity, chemical constituents and evapotranspiration of sugar beets in Kansas: Am. Soc. Sugar Beet Technol, Jour., v. 12, p. 686–698.

Leonard, A. B., 1952, Illinoisan and Wisconsinan molluscan faunas in Kansas: Kansas Univ. Paleont. Contr., Mollusca, art. 4, 38 p.

Meyer, W. R., Gutentag, E. D., and Lobmeyer, D. H., 1970, Geohydrology of Finney County, Kansas: U.S. Geol. Survey Water-Supply Paper 1891, 117 p.

Musick, J. T., and Grimes, D. W., 1961, Water management and consumptive use by irrigated grain sorghum in western Kansas: Kansas Agr. Exp. Sta. Tech. Bull. 133, 20 p.

Prill, R. C., and Meyer, W. R., 1968, Neutron moisture measurements by continuous- and point-logging procedures, *in* Geological Survey research 1968: U.S. Geol. Survey Prof. Paper 600–B, p. B226–B230.

Soil Survey Staff, 1951, Soil survey manual: U.S. Dept. Agriculture Handb. 18, 501 p.

Van Bavel, C. H., Brust, K. J., and Stirk, G. B., 1968, Hydraulic properties of a clay loam soil and the field management of water uptake by roots: Soil Sci. Soc. America Proc., v. 32, p. 317–321.

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