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LABORATORY TESTS TO STUDY DRAINAGE FROM SLOPING LAND

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Engineering and Research Center
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16. ABSTRACT
An investigation was made to study drainage from sloping land. A tilting sand tank (flow tank) 2 ft wide, 2-1/2 ft deep, and 60 ft long was used. Drains to simulate agricultural tile were placed in the sand tank at 6-ft intervals 2 ft above the tank bottom. Water (recharge) was applied at a steady rate on the sand surface to simulate irrigation. Drain discharges and water table profiles were measured for 54 tests with different recharge rates, 6- and 12-ft drain spacings, and sand tank slopes from 0 to 10%. Four tests were made introducing dye into the tank and streak-lines obtained showing directions of water movement in the sand. Pressure measurements were made at points on the tank side to obtain the potential field between drains. An equilibrium area occurred in the middle length of the sloping sand tank where the drain discharges equaled the amount of water applied between two operating drains. This condition occurred during all tests, regardless of slope, recharge rate, or drain spacing. For a given recharge rate and in the equilibrium area, water table profiles measured perpendicular to the tank bottom were the same for slopes between 0 to 10%. The report includes tables of the drain discharges, plots of the water table profiles, photographs of the dye streak-lines, and diagrams showing the potential field occurring between drains. Effects of slope and recharge rate upon drain discharges, water table profiles, and water movement in the sand tank were analyzed.

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UNITED STATES DEPARTMENT OF THE INTERIOR ★ BUREAU OF RECLAMATION
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INTRODUCTION

The Bureau of Reclamation plans, designs, and constructs many irrigation projects in the Western United States. On most projects the addition of irrigation water raises the ground-water table, sometimes to damaging heights. Subsurface agricultural drains are usually required to control the ground water and also to prevent unfavorable salt balances from occurring within the plant root zone. In recent years there has been an increased use of sprinkling systems for irrigating. These sprinkling systems can irrigate land having steeper slopes than the older furrow-type method of irrigation. Thus, a more frequent use of drainage systems on sloping land is anticipated. The purpose of this investigation was to obtain basic knowledge about the flow in porous media for agricultural drains on sloping land. The emphasis of the investigation was directed toward determining what effect various slopes and recharge rates have upon the location of the water table, upon drain discharges, and path of water flow through the soil. Because of the basic nature of the study no attempt was made to determine design parameters for placement of drains.

THE TEST APPARATUS

General

A test facility was designed to simulate steady state flow conditions of agricultural (interceptor) drains operating on sloping land. The test facility was a very simplified representation of a hillside with agricultural tile drains. None of the complex or various aquifer formations that may exist on hillsides was simulated in the test facility. This facility consisted of a sand tank having drains spaced at regular intervals. Water was applied at a steady rate upon the sand surface. The water after dropping upon the sand surface flowed into the water table, through the sand into the drains, and finally flowed out of the drains.

Sand Tank

The photographs on page 2 show each side of the sand tank.

The sand tank rested on two large beams. The beams, which were longitudinal to the sand tank, were supported at two points. One support was a pivot point and the second support a lifting point. Two chain hoists were used to lift the sand tank. The slope of the sand tank could be varied between 0 and 12 percent. The sand tank was 60 feet (ft) (18.29 meters (m)) long, 2-1/2 ft (0.76 m) deep, and 2 ft (0.61 m) wide (inside dimensions). It was constructed from wood and the inside was lined with galvanized sheet metal. One side of the tank was constructed from transparent plastic panels.

Water was placed in the tank before filling the tank with sand. Sand was placed in the water and mixed with a shovel to prevent air bubbles being trapped in the voids between individual sand grains. The mean sand diameter was 0.2 millimeter (mm). The depth of sand in the tank was approximately 2 feet 5 inches (0.74 m).

Drain Construction and Location

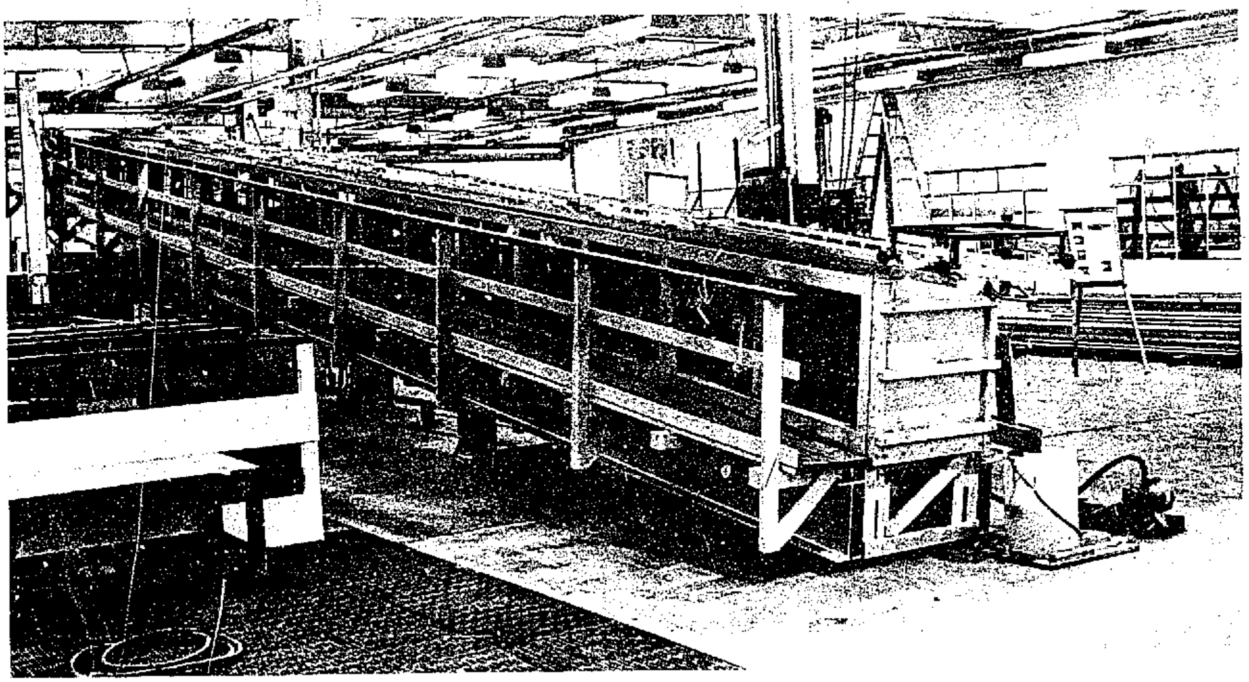
Eleven horizontal drains, to simulate agricultural pipe drains, were placed perpendicular to the sides of the sand tank. One end of the drain butted against the transparent side of the tank and the drain passed through the other side of the tank. The drain effluent dumped into a collection trough. Drains were spaced at 6-ft (1.83-m) intervals along the 60-ft (18.29-m) length of the tank. The centerline of the drains was 2 ft (0.61 m) above the tank bottom. Location and numbering of the drains are shown on Figure 1.

The drains were constructed from plastic tubing with an outside diameter of 5/8 inch (1.59 centimeters (cm)) and an inside diameter of 1/2 inch (1.27 cm). On one side of the tube 1/16-inch (0.16-cm) wide slots were cut perpendicularly in the tube and spaced at 1-inch (2.54-cm) intervals along the tube. The slots extended about halfway through the tube. On the other side of the tube the slots were offset 1/2 inch (1.27 cm) from the opposite slots. To prevent the fine sand base material from entering the drain, an envelope of No. 16 sand was placed around the drain. The envelope was 0.2 ft (6.1 cm) outside diameter. The photographs on page 3 show the sequence of placing a ground-water drain in the sand tank.

The drain at each end of the sand tank had the No. 16 sand envelope extending from the bottom of the tank to the top of the sand surface, Figure 1—Detail B. The end drain envelope was 0.5 ft (15 cm) thick. The purpose of these envelopes was to provide versatility for making tests. If needed, additional water could be added or withdrawn from the envelopes. Also, the water table elevation within the envelope could be controlled. This type envelope was helpful in making permeability tests.

Water Recirculating System

The water recirculating system consisted of a set of recharge units, the drains, a collection trough, and a



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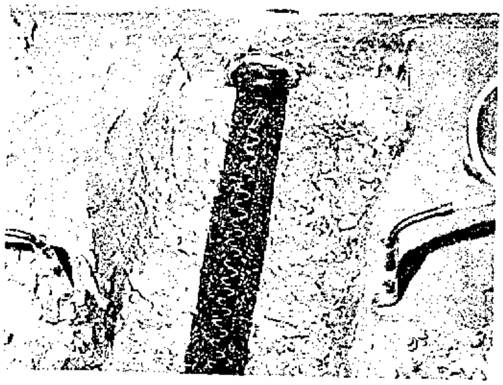

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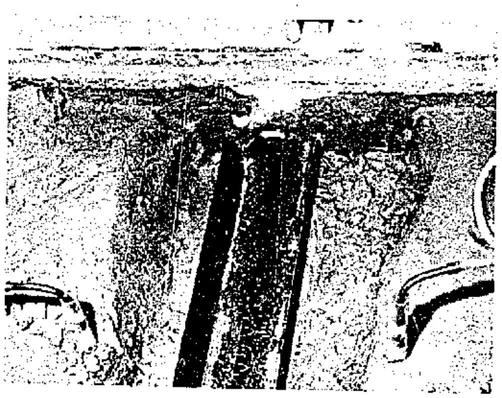

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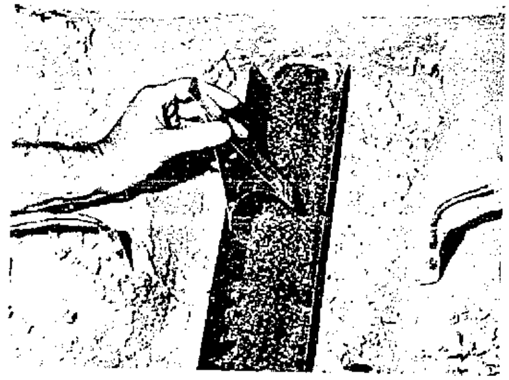

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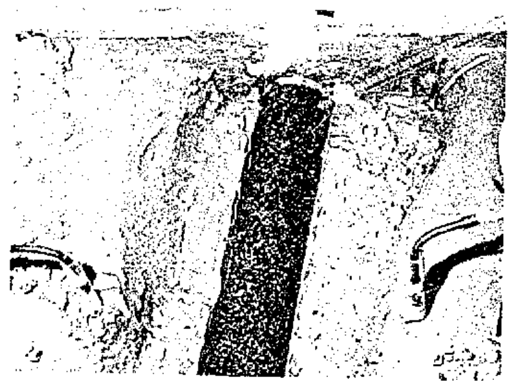

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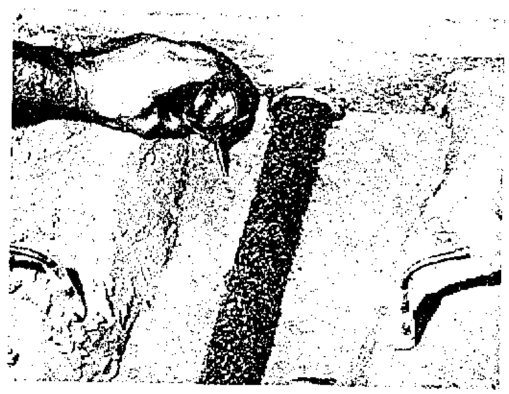


(f)

(a) Using a 0.2-foot outside-diameter tube a semicircle was formed in the fine sand. Photo PX-D-70727. (b) Envelope sand was placed into the semicircle and the 1/2-inch inside-diameter plastic drain tube was installed. Note the slots that were cut into the tube. Photo PX-D-70728 (c) To prevent the envelope sand from mixing with the fine sand, sheet metal guard strips were placed along the envelope. Then envelope sand was placed on top of the plastic drain tube. Photo PX-D-70729 (d) A semicircular metal strip was used to form the top of the drain envelope. Photo PX-D-70789 (e) The metal guard strips were removed. Photo PX-D-70790 (f) With the aid of water, fine sand was placed around the envelope. The plastic tubes on either side of the drain envelope are ground-water measuring wells. Photo PX-D-70791

Sequence of photographs showing the placement of a ground-water drain and envelope collection tank, Figure 2. The purpose of the water recirculating system, was to keep water flowing through the sand tank at room temperature. The dissolved air in the water would be at equilibrium with the temperature and pressure of air around the sand tank. This prevented the tendency for air to come out of solution and collect in voids between the sand grains, and thus change the permeability of sand in the tank. Previous experience showed that cold water from the high-pressure water supply system had an abundance of dissolved air.

There were 10 recharge units (Figure 2B) on top of the sand tank. Each recharge unit consisted of two plastic tubes that applied water to the sand surface, an orifice to measure the applied water, and a differential manometer. The plastic tubes were positioned between the drains. The plastic tubes of the recharge units were placed with the discharge holes (diameter 0.020 inch (0.51 mm)) pointing up to prevent clogging. With the aid of rubber bands small plastic caps were held over the holes. The caps caught the small jets squirting from the tubes and changed the jets into drops of water falling directly beneath the caps. The recharge tubes were maintained in a horizontal position for the various sand tank slopes so different vertical distances did not occur between discharge holes on the same tube. This procedure made the recharge application rate uniform over the entire area.

The discharge from each recharge unit (Figure 2C) was measured with a small orifice plate whose diameter was 0.078 inch (1.98 cm). Preliminary testing showed slight variations of the differential head occurring across the 10 orifices for 1 specific discharge. Therefore, each recharge unit measuring system was calibrated separately. A calibration curve or graph was obtained (Figure 3) for each recharge unit. The points on the graph were the differential head occurring across the orifice when making a discharge measurement. The discharge was measured volumetrically using a stop watch and graduated cylinder. Since the graduated cylinder was marked in milliliters, the discharge was also given in ml/sec.

Wells and Manometers for Measuring the Water Table Location

Plastic tubes (vertically positioned) were inserted in the top portion of the sand tank. The plastic tube provided a well in which the water could collect. The water surface elevation within the well corresponded to the ground-water table elevation of the sand surrounding the well. Well tubes, Figure 4, were placed at approximately 1-ft (0.30-m) intervals along the sand tank. The location of the well tubes in the sand tank is given in Table 1.

The wells were made of 7-1/2-inch (19.05-cm) lengths of plastic tubing. The outside diameter of the well was 5/8 inch (1.59 cm) and the inside diameter was 1/2 inch (1.27 cm). The well bottom was plugged with a plastic insert. Four slots were cut in the lower portion of the well tube to allow water from the sand tank to flow into the tube. A fine No. 200-mesh screen (Figure 4B) was placed in the well tube to prevent fine sand from entering the well tube. A copper tube and flexible tubing conveyed the pressure or water level within the well to the manometer (Figure 4A). Numbering of the manometers corresponded to numbering of the ground-water table measuring wells given in Table 1.

The accuracy of measuring the vertical location of the ground-water table was subject to the inherent measuring capabilities of glass-tubed manometers. The inside diameter of the glass tubes was approximately 6 mm. Capillary rise within the individual tubes varied depending upon variation of the inside tube diameter and also upon the glass surface condition within the tube. The capillary rise was probably less than 0.02 ft (0.61 mm). The manometer boards were marked in feet and hundredths. Manometer readings were made in thousandths of a foot by interpolation. The thousandth foot readings were useful in determining when the water table profile was at a stable location for the steady-state tests.

THE TESTING PROGRAM AND TEST PROCEDURES

Types of Tests

The testing was done in four phases. In the first phase drain discharges were measured and the water table was determined between drains for various recharge rates and slopes. Tests investigating location of streamlines and path of water movement through the sand were made in the second phase. The third phase tests consisted of pressure measurements made through the transparent side of the sand tank, and in the fourth phase permeability tests of the aquifer sand were made in the sand tank.

Phase 1, Tests for Measuring Drain Discharge and Water Table Locations

Fifty-four different tests were made with various sand tank slopes, recharge rates, and drain spacings. The sand tank slope was varied from 0 to 10 percent, the recharge rates from 2-1/2 to 10 ml/sec. Tests were made with 6-ft (1.83-m) and 12-ft (3.66-m) drain spacings. A summary of the tests performed are listed in Table 2. The general procedure for making a given test was as follows. Water was applied on the sand surface at a constant rate using the 10 recharge units. Recharge rates were given in milliliters-per-second per-recharge unit. For example, a test designated with a 2-1/2-ml/sec recharge rate means 2-1/2 ml/sec of water flowed from one recharge unit. The recharge rate, as defined in the report, is the discharge rate from one recharge unit, and this discharge placed on a 12-sq ft (1.1-m^2) sand surface area per unit time. Actual infiltration rates for the designated recharge rates tested are listed in the following table.

Designated test recharge rate ml/sec	Infiltration rate $\frac{ft^3}{ft^2\text{-sec}} \times 10^{-5}$	$\frac{ft^3}{ft^2\text{-day}}$	$\frac{\text{liters}}{m^2\text{-day}}$
10	2.94	2.54	775
7-1/2	2.21	1.91	581
5	1.47	1.27	388
4	1.18	1.02	310
3	0.98	0.85	258
2-1/2	0.74	0.64	194

Observations were made to determine when the sand tank reached a steady state condition. It was found that a 4-hour time period was adequate to obtain steady state flow conditions. Drain discharges and water table data were taken only after the sand tank had reached a steady state condition. Drain discharges were measured with a graduated cylinder and stop watch. Each set of water table data consisted of 60 manometer readings.

For the 12-ft (3.66-m) drain spacing tests, odd numbered Drains No. 1 through 11 were plugged for the 0 percent slope tests. For the sloping tests, end Drain No. 11 was unplugged to prevent water from ponding at the downslope end and overflowing the top of the sand tank. The end drain envelope was believed to influence drainage conditions up slope from the envelope, but how far up slope this influence extended was unknown. Therefore, to determine the extent of this influence, two types of tests were made at each percent slope and recharge rate of the 12-ft (3.66-m) drain spacing tests.

(1) Free flow tests where discharge from Drain No. 11 was allowed to flow freely. Atmospheric pressure acted at the end drain.

(2) Controlled tests where a pressure was applied at the end of Drain No. 11.

For locating the controlled water table profiles between Drains No. 10 and 11 the standard used was the 0 percent slope water table profiles. The objective was to make the controlled water table profile the same as the 0 percent profile for a given recharge rate. Both water table profiles (controlled and 0 percent slope) would be at the same relative perpendicular location above the sand tank bottom. Computed values for manometer readings between Drains No. 10 and 11 were obtained by using the 0 percent slope profile data. These computed values were obtained for each slope and recharge rate.

Figure 26B helps show how height of the water table was controlled. A flexible tube connected the end of Drain No. 11 to a small box with an overflow weir. By raising or lowering the overflow weir, the water table profile near the sand tank end could be raised or lowered. Elevation of the weir box was adjusted until manometer readings between Drains No. 10 and 11 were approximately within 0.01 ft (3 mm) of the precomputed values.

Phase 2, Streak-Line Tests Investigating Direction of Water Movement Through the Sand

Colored blue water was injected into the sand along the transparent side of the sand tank. "Patent Blue" dye in a powder form was used to color the water. The properties of the colored water were very good, in that; (1) the colored water was stable in nature and the blue color did not disperse too rapidly, (2) when injected into the sand tank the colored water did not appear to have undesirable density effects, and (3) a large proportion of the colored water could be flushed from the tank without excessively staining the sand. The colored water was inserted into the sand tank at desired points through small glass tubes pushed into the sand. Care was taken to insure that the tube ends were against the transparent sides of the sand tank. Colored water was introduced into the tubes at a rate of approximately 1 to 5 drops every 5 minutes. A blue dye streak-line was formed from the tube end as the flowing water moved the dye away. (The term "streak-line" instead of "streamline" is used for describing the dye tests because it is more accurate and is more descriptive of the dye tests than the term streamline.) Photographs of the streak-lines gave a vivid picture of the ground-water movement, Figure 8. The grid on the transparent sand tank side was 3 by 3 inches (7.6 x 7.6 cm). Four dye streak-line tests were made with a sand tank slope of 2-1/2 percent. The drain spacing was 6 ft (1.83 m) and the recharge rates were 2-1/2, 5, 7-1/2, and 10 ml/sec.

Phase 3, Pressure Measurement Tests

The purpose of the pressure measurement tests was to measure or define the potential field occurring between drains. Pressure measurements were made through the transparent side of the tank.

Approximately 200 small holes were drilled through the transparent side of the sand tank. The holes were small enough to prevent sand from passing through. Plastic piezometer taps were fastened to the sides and flexible tubes conveyed the fluid pressure to the measuring equipment. The location of the piezometer taps is shown in Figures 13A and 13B. A differential pressure transducer, amplifer, and digital readout instrument were used in making the pressure measurements. The differential pressure measurements were made in feet of water and the digital readout showed the measurement in feet and thousandths. The pressure measurement was the pressure difference between an established datum and the given piezometer tap, Figure 13C. The datum of reference was the centerline elevation of Drain No. 6. With the two manifolds, a series of 60 pressure measurements could be made before changing the flexible tubes to another set of 60 piezometer taps.

Twelve pressure measurement tests were made. The tests were for 0 percent slope at the 5- and 10-ml/sec recharge rates, 2-1/ -percent slope at the 2-1/2-, 5-, 7-1/2-, and 10-ml/sec recharge rates, and for 5, 7-1/2, and 10 percent slopes at 2-1/2- and 10-ml/sec recharge rates.

Phase 4, Sand Tank Permeability Tests

For ground-water studies it is important to know the permeability of the porous material. Therefore, permeability tests were made with the sand tank at a 10 percent slope. The permeability measurement represents the average horizontal permeability of the sand within the tank. The method for making the inplace permeability measurement was as follows:

> The depth of water flowing within the sand tank is controlled at the upper and lower ends of the tank. Then the discharge and area of water flow through the sand tank is measured. The coefficient of permeability is computed using the following formulas:

$$Q = iKA \qquad A = yw \qquad (1)$$

or

$$k = \frac{Q}{iyw}$$

where,

- Q = discharge flowing through the sand tank, ft^3/sec
- i = slope or hydraulic gradient, ft/ft
- k = coefficient of permeability, ft/sec
- A = area of flow for the given Q, ft^2
- y = depth of flow, ft
- w = 2-foot width of sand tank, ft

A small box with an overflow weir was connected to each end drain of the sand tank. Flexible tubes were used to connect the boxes to the end drains. All other drains (No. 2 through 10) were plugged. Water was supplied to the up slope box. The water flowed with a uniform depth down the slope through the sand tank and came out the downslope box and through the overflow weir. By adjusting elevations of the weirs, the water flow depth within the sand tank was established at approximately 2.3 ft (0.7 m), as measured perpendicular to the tank bottom. Water flow in the fine sand was also parallel to the tank bottom near the tank ends because of the end drain envelope construction. An excessive amount of water was supplied to the up slope box so water flowed through the overflow weir. The quantity of water supplied to the up slope box and the quantity of water flowing through both overflow weirs were measured. Water depth flow through the sand tank was obtained at each of the 59 ground-water table measuring wells that were in the fine sand. The average depth was used to get the area of flow.

Results of the permeability tests were:

February 12, 1968	k = 0.000589 ft/sec, 50.1 ft/day, (0.000177 m/sec)
December 19, 1968	k = 0.000552 ft/sec, 47.7 ft/day, (0.000168 m/sec)
Average	k = 0.000566 ft/sec, 48.9 ft/day, (0.000172 m/sec)

RESULTS OF THE TEST PROGRAM

Drain Discharge and Water Table Tests

The measured drain discharges for the tests are listed in Table 3. Also listed in Table 3 are the drain discharges (Percent Recharge) expressed as a percent of the recharge rate. These "drain discharge percents" were helpful in following trends of drain discharge for the various tests.

Water-table elevations were determined from the manometer readings. The manometer readings were corrected for the sand tank slope and the physical location properties of the individual ground-water measuring wells. An illustration of the location property and slope corrections made to the manometer readings is shown in Figures 5A and 5B. A digital computer was used to make the numerous computations.

Some of the water-table profiles shown in this report were made with an X-Y plotter. Figure 6 was a graph of the water-table profiles for the 0 percent slope tests. The water-table profiles were a series of straight lines drawn from point to point. These points were the elevations of the water table as determined at the ground-water table measuring wells. The water table profile curves are discontinuous. Breaks in the curves are made near the drains. Encircled numbers designate drain numbers as shown in Figure 1. Drain discharges and drain discharge percents are also shown on Figure 6. The drain discharge percent is the drain discharge expressed as a percent of the discharge rate from one recharge unit.

One graph giving water-table profiles in sloping form and for the complete tank length is shown on Figure 7. It gives a plot of the water-table profiles for the 6-ft (1.83-m) drain spacing and 7-1/2 percent slope tests. The water-table profiles are divided into two sets of curves. The upper set shows the first 30 ft (9.1 m) and the lower set the last 30 ft (9.1 m). In the upper set the abscissa scale is at the top of the figure and ordinate scale at the upper right side. For the lower set the abscissa scale is shown at the bottom and the ordinate scale is at the lower left edge. Datum planes for hoozizontal and vertical distances are shown in Figure 5B. Near Drains No. 1, 2, and 3 part of the water-table profiles is missing because the water table in the sand tank was below the ground-water table measuring wells.

Streak-Line Tests Investigating Direction of Water Movement Through the Sand

In Figure 8 a series of photographs show the first streak-line tests. Bottoms of the photographs are parallel with the sand tank bottom. The recharge rate is 10 ml/sec. This sequence of photographs shows progressive movement of the dye traces. Streamlines of water flow are shown by the dye traces. The streak-lines show the path of water movement of the recharge, after it enters the water table, and flows toward the drains. The last photograph was taken after completion of the test. Lines were drawn with a grease pencil on the sand tank sides.

After completing the drain discharge and water-table profile tests, it was suspected that there were two different types of flow systems present in the sand tank—one flow system where recharge enters the water table and flows into the drains and the second flow system where water moves downslope and passes beneath the drains. Therefore, one objective of the streak-line tests was to visually distinguish and show the two different flow systems. Streak-line tests showing the first flow system were done between Drains No. 6 and 7, Figure 9. The photographs were of the grease penciled lines made at the completion of the tests. Streak-line tests showing the second flow system were shown between Drains No. 8 and 9 and partially between Drains No. 7 and 8, Figure 10.

Figures 11 and 12 were photographs of streak-lines that illustrate topics in the discussion and analysis part of the report.

Pressure Measurement Tests

Equipotential lines, resulting from the pressure tests, are shown on Figures 14, 15, 16, and 17. The sand tank slope and recharge rate are labeled beneath each diagram. For the various tests, contour lines of equal pressure or equipotential lines were drawn through the pressure measurement data points. These lines were drawn by inspection and were labeled in thousandths of a foot of water. Also shown on the figures are the visualized paths of water movement through the sand.

The water-table profiles for the 0 percent slope tests are shown as solid lines. These profiles were determined from pressure measurements made at the piezometric taps (row 1 of the form shown in Figure 13A) which were 2 ft above the sand tank bottom. Water-table profiles for all the other tests are shown as dashed lines. These profiles were not determined from the pressure measurement data but from the water-table profile data shown in Figure 6. The water-table profiles between Drains No. 4, 5, and 6 were plotted with respect to the sand tank bottom.

DISCUSSION AND ANALYSIS OF TEST RESULTS

Zero Percent Slope Tests

Interior drain discharges.—Water-table profiles and drain discharges are shown on Figure 6 for the 0 percent slope tests. The upper set of curves were for a 12-ft (3.66-m) drain spacing and the lower set for a 6-ft (1.83-m) drain spacing. At 0 percent slope the drain discharges should be equal to the amount of water applied between two operating drains. For the 12-ft (3.66-m) drain spacing tests the drain discharges were approximately twice the recharge rate since there are two recharge units per drain. Therefore, drain discharge percents are nearly 200 percent. For the 6-ft (1.83-m) drain spacing tests, discharges from the interior drains, No. 3 to 8, were approximately equal to the recharge rates. Discharge from the drains was approximately equal to the quantity of water applied between the operating drains. The maximum deviation of the drain effluent from the recharge rate was 8 percent. The deviations were attributed to the inherent error present in the sand tank system.

Water-table profiles.—The water-table elevation midway between the drains increased linearly with the recharge rate for both the 6- and 12-ft (1.83- and 3.66-m) drain spacing tests (Figure 18). For the 6-ft (1.83-m) drain spacing the midpoint water-table profile elevations between Drains No. 3 to 9 were averaged and for the 12-ft (3.66-m) drain spacing the midpoint water-table profile elevations between Drains No. 2 to 10 were average.

Also shown on Figure 18 were midpoint water-table elevations computed using the Dupuit-Forchheimer assumptions[1]. These assumptions are:

(1) The point velocity along the water-table interface is proportional to the slope of the water table.

(2) The flow is everywhere horizontal.

(3) The velocity is uniform below the water table.

Using these assumptions, an equation of the form

$$S^2 = \frac{4kH}{v}(2d + H) \qquad (2)$$

can be derived. This equation was solved for H, where

S = horizontal distance between operating drains, feet
k = coefficient of permeability, ft/sec
v = infiltration rate, recharge rate divided by 12-foot area the recharge water acted upon, ft/sec
d = vertical distance from the drain centerline to the impermeable barrier, ft
H = distance of the water-table profile above the drain centerline midway between two operating drains, ft

The computed midpoint water-table elevations were considerably lower than the measured midpoint water-table elevations obtained from the tests.

Comparisons of some computed and measured water-table profiles are shown in Figure 19. The Dupuit-Forchheimer assumptions were used for the computed profiles. The equation used for making the computations was similar to equation (2), but in a slightly different form. The equation was:

$$y^2 + 2dy = \frac{vx}{k}(S - x) \qquad (3)$$

where the symbols were the same as previously defined, except for x and y,

y = vertical distance of a given point on the water-table profile above the drain centerline, ft
x = horizontal distance of a given point on the water-table profile from the drain centerline, ft

The solid lines with data points were the measured profiles and the dashed lines were the computed profiles. Figures 19A and 19B were for the respective 12- and 6-ft (3.66- and 1.83-m) drain spacing tests. In all cases and for a given test condition the computed profiles were lower than the measured profiles. The Dupit-Forchheimer assumptions do not accurately define water-table elevations for the sand tank tests where there was a convergent pattern of water flowing into the drain envelope.

For flow convergence into a drain a correction or adjustment can be made to the Dupit-Forchheimer assumptions. The adjusted d value in equation (3) provides a more accurate water-table elevation[2].

Equilibrium in the Sand Tank

The idea or concept of equilibrium as discussed in this report means the discharge from a given drain is equal to the amount of water applied between two operating drains. In a sense the drain discharge was at equilibrium with the recharge. For illustration, the drain discharges and water-table profiles shown on Figure 7 will be discussed using drain discharges and percents for the 2-1/2-ml/sec recharge rate test. At the upper end of the sand tank the water table was below Drains No. 1 and 2, therefore, there was no flow from these drains. The recharge between Drains No. 1 and 2 was flowing down slope, through the sand tank, and passing beneath Drain No. 2. The recharge between Drains No. 2 and 3 had raised the water table and the water table was just barely up to Drain No. 3.

[1] Luthin, James N., Drainage Engineering, John Wiley & Sons, Inc., p 153, 1966.

[2] Carlson, E. J., Drainage From Level and Sloping Land, REC-ERC-71-44, U.S. Bureau of Reclamation, December 1971.

The percent (18.0 percent) of discharge was very small. The recharge between Drains No. 3 and 4 made a further increase in drain discharge. The discharge percent was 96.8 percent. From Drains No. 4 through 9 the drain discharge was approximately at equilibrium with the recharge.

The same trends are observed in the drain discharges and percents for the 5-, 7-1/2-, and 10-ml/sec recharge rates shown on Figure 7. Drain discharge increases as one progresses from Drain No. 1 to Drain No. 4. Along the midslope of the sand tank (Drains No. 4 to 9) the drain discharge was at equilibrium with recharge between drains. The drain discharges listed in Table 3 also exhibit equilibrium for the various tests.

Effect of Slope and Recharge Rate Upon the Water Table Profile

Change of the water table profiles for a constant recharge rate and different slopes.—Figure 20 shows the water table profiles between Drains No. 6 and 8 for a recharge rate of 5 ml/sec and a 12-ft (3.66-m) drain spacing. Drains No. 6 and 8 were selected because the drains were located within the midslope or the equilibrium portion of the sand tank. Also the drains were far enough up slope from end Drain No. 11 for the water table profiles to be negligibly affected by Drain No. 11. The datum of reference for Figure 20 is the centerline of Drain No. 8. The origin is located at the lower right corner of the figure. Water table profiles and the location of Drain No. 6 are plotted with respect to Drain No. 8. These plots were made for the five different test slopes. A "V" or pointer on each water-table profile designates zero slope of the water-table profile. Therefore, it is the dividing point for waterflow into Drains No. 6 and 8. Recharge entering the water table left of the pointer flows into the up slope Drain No. 6 and recharge entering the water table right of the pointer flows into the downslope Drain No. 8. For the 0 percent slope water-table profile the "V" or dividing point is approximately midway between Drains No. 6 and 8. Progressively increasing the sand tank slope moved the dividing point to the left. This trend was observed with other recharge rates and also for the 6-ft (1.83-m) drain spacing tests.

Change of the water-table profiles for a constant slope and different recharge rates.—Figure 21 shows the water-table profiles between Drains No. 6 and 8 for a slope of 2-1/2 percent and 12-ft (3.66-m) drain spacing. The datum of reference for Figure 21 is the centerline of Drain No. 8. Progressively increasing the recharge rate moved the location of the dividing point to the right. This observation is valid for the other slopes and also for the 6-ft (1.83-m) drain spacing tests.

Change of the water-table profiles with respect to the sand tank bottom.—Another way of comparing differences between horizontal and the various sloped water-table profiles was to plot the water-table profiles normal to the sand tank bottom, Figures 22 to 25. The ordinate scale is the distance of the water table measured perpendicular above the bottom of the sand tank. The abscissa scale is the station location in feet along the sand tank where the water-table measurement was made. Water-table profiles are shown for different slope tests but for the same recharge rate. The water-table profile represented by the line is for the 0 percent slope tests and symbols designate the 2-1/2, 5, 7-1/2, and 10 percent slope profiles. Drain discharges and drain discharge percents are also shown on the figures.

In considering the water-table profiles for the 2-1/2-ml/sec recharge rate shown in Figure 22, two observations were noted:

(1) For the up slope portion of the sand tank, increasing the percent slope caused the water surface profile to be displaced farther down the slope with respect to the 0 percent slope water-table profile.

(2) For the equilibrium portion of the sand tank, water-table profiles were approximately the same for the 0, 2-1/2, 5, 7-1/2, and 10 percent slope tests. There were deviations of the water-table profiles about the 0 percent slope water-table profile, but the deviations were such that no distinguishable trend was found for water-table profiles of one particular test.

For larger recharge rates, Figures 22 and 23, it was also noted that;

(3) For the up slope portion of the sand tank, increasing the recharge rate caused the water-table profiles to be displaced further up the slope with respect to the 0 percent water-table profile.

Similar observations were noted for the 12-ft (3.66-m) drain spacing tests, Figures 24 and 25.

Effect of Slope and Recharge Rate Upon Drain Discharge

General.—In the equilibrium portion of the sand tank, the slope or recharge rate had no effect upon the drain discharge. The drain discharge was approximately equal to the water applied between operating drains. Only near the sand tank ends were the drain discharges affected by the slope and recharge rate.

Change of drain discharge for a constant recharge rate and different slopes.—For a given recharge rate, increasing the sand tank slope increased the discharge from the lower end drain (No. 11) while the discharge from drains near the upper end decreased. For example, with the 2-1/2-ml/sec recharge rate tests and 6-ft (1.83-m) drain spacing, Figure 22, the discharges from Drain No. 3 decreased as the slope increased. The 10 percent slope affected discharges from drains as far downslope as the No. 4 drain. Whereas, at the downslope Drain No. 11, increasing the slope increases the drain discharge from 74.4 to 364.0 percent.

The effect of slope upon drain discharges is not as great with higher recharge rates. At the 10-ml/sec recharge rate (6-ft (1.83-m) drain spacing, Figure 23) discharges from Drains No. 3 and 4 were not significantly affected by the 10 percent slope. Similarly, the difference between discharges from Drain No. 11 were less at the 10-ml/sec recharge rate. The drain discharge increased from 67.6 to only 145.4 percent.

Change of drain discharge for a constant slope and different recharge rates.—For a given sand tank slope, increasing the recharge rate increases the disch ge from both the lower and upper end drains, Figure 7. However, there was a contradiction between drain discharges and drain discharge percents for end Drain No. 11. As the recharge rate increased the drain discharge increased, but the drain discharge percent decreased.

Streak-Lines and Direction of Water Movement Through the Sand Tank

Figure 8 shows the results of the first streak-line test. These photographs are of the flow system where recharge water enters the ground-water table and then flows into the drains. Some properties shown in this test are typical of the other three streak-line tests. Dye forming the streak-lines was introduced at the 2-ft (0.61-m) level in the sand tank (centerline elevation of the drains). The streak-lines originating near the drains flow nearly parallel with the sand tank bottom and into the drains. Streak-lines that originate farther from the drains penetrate deeper into the sand tank.

In many instances, the streak-line thickness indicated velocity of water flowing through the sand. At high velocities the streak-lines are thinner. For example water velocities are higher near the drains because of convergent flow. At low velocities the streak-lines are thick. There was more time for the dyed water to diffuse. The dividing point streak-line at the middle part of the left plexiglass panel had a very slow velocity. This streak-line originates 5-1/2 grid spaces to the left of the center post below the clock. Note the grid distance travel between the 5- and 17-hour photographs. Recharge left of the dividing point streak-line flows upslope into Drain No. 7. This dividing point streak-line emerged from the zero slope point of the water-table profile.

Streak-line tests were made with four recharge rates with a 2-1/2 percent slope, Figure 9. Photographs were taken after completion of the tests. Paths of the streak-lines were grease penciled upon the sand tank sides. For a constant slope, the effect of the recharge rate upon the flow system was observed. With decreasing recharge rates the dividing streamline moves up slope, to the left and closer to Drain No. 6 in the photographs. Also when the recharge rate was decreased the recharge flow area decreased.

A similar series of tests were made to define the area in which water passed beneath the drains, Figure 10. Some streak-lines of water passing beneath the drains may be seen between Drains No. 7 and 8. Between Drains No. 8 and 9 an effort was made to completely dye the area blue where water was flowing downslope beneath the drain. Again it can be observed that with decreasing recharge rates the flow area of the water passing beneath the drains increases.

In the sand tank tests equilibrium did not exactly occur. There were slight differences among the drain discharges along the midslope portion of the sand tank. In reality some recharge between drains would escape into the flow system of water passing beneath the drains. For other drains water was drawn from the flow system of water passing beneath the drains. Figure 11 shows one of the streak-line tests where recharge water escaped into the flow system of water passing beneath the drains.

The effect of the end drain envelope upon streak-lines of flow entering Drain No. 11 was also observed, Figure 12. The streak-lines, while in the fine aquifer sand, flow parallel along the sand tank bottom and then into the end drain envelope. The streak-lines do not converge toward Drain No. 11 until after entering the end drain envelope. This figure also illustrates a case where streak-lines of recharge entering between drains escape into the flow system passing beneath the drains. The dark strip along the sand tank bottom is the dyed water from beneath Drain No. 8.

Pressure Measurement Tests

Zero percent slope tests.—Results of the 0 percent slope pressure measurement tests are shown on Figure 14. Theoretically the equipotential lines should be symmetrically located with respect to a vertical line midway between the drains. However, results of the pressure measurement data are not exactly symmetrical. For example, the shape of the 100-thousandth-foot equipotential line is unsymmetrical between Drains No. 4 and 5. Two explanations for deviation of the measured potential field with respect to the theoretical potential field are; (1) the recharge water applied to the sand surface was not exactly uniform, and (2) the sand or porous medium was not exactly homogeneous.

Permeability variations were noted within the sand tank. For example, streak-line below Drain No. 7 (Figure 11) shows one such variation. Therefore, streamline patterns were not superimposed on the equipotential lines because of the recharge and permeability deviations. Instead of drawing an exact flow net, arrows are drawn perpendicular to the equipotential lines. There arrows show the visualized path of water movement through the sand.

2-1/2 percent slope tests.—Results of the four 2-1/2 percent slope pressure measurement tests are shown on Figures 14 and 15. The heavy lines, with arrows, separate the two different flow systems. Results of the corresponding streak-line tests were used as an aid for locating the heavy lines. Below the heavy line the flow system of water moved downslope and passed beneath the drains. Above the line the flow system consisted of recharge water which flowed into the drains. The upper flow system is divded into two parts, recharge flowing into the downslope drain and recharge flowing into the up slope drain. The point where the flow systems intersected is shown by dashed lines, since this intersection point is not readily defined. The change in stream potential occurring at the intersection point is small. This can be seen from the wide spacing of the equipotential lines near the intersection point. Another factor contributing to the indeterminate nature of the intersection point is the absence of pressure data immediately downslope from the drains, Figure 13A.

5, 7-1/2, and 10 percent slope tests.—Results of pressure measurement tests made at the minimum and maximum recharge rates for the 5, 7-1/2, and 10 percent slopes are shown on Figures 16 and 17. The effect of varying slope and recharge rate upon the potential field may be observed. Increasing the slope for a given recharge rate produced a larger number of equipotential lines for the same contour interval. Higher downslope velocities occurred in the sand tank because of the increased slope. For pressure measurements made in the sand tank a small slope increase (from 0 percent slope) greatly influenced the potential field between drains. For instance, at the 0 percent slope a large area between drains contained equipotential lines with a horizontal-type inclination, but at a 2-1/2 percent slope the area between drains mostly contained equipotential lines with a vertical-type inclination. There is a further increase of the vertical inclination for the equipotential lines at the 5 percent slope. The slope changes to 7-1/2 and 10 percent did not affect the potential field (with respect to horizontal-type equipotential lines) nearly as much as the 0 to 5 percent slope changes.

Increasing the recharge rate for a given slope altered the potential field near the drains. With the 2-1/2-ml/sec recharge rate the equipotential lines were somewhat evenly spaced, Figure 17. However, at the 10-ml/sec recharge rate the equipotential lines are unequally spaced. Here, the lines are closer together up slope from Drain No. 5 and farther apart downslope.

With the exception of the 5 percent slope and a 10-ml/sec recharge rate test the potential field was not well enough defined to determine the intersection point and to show the two flow systems.

Influence of the End Drain Envelopes

Comparison of flow into an interior and an end drain.—The envelopes for the two end drains (No. 1 and 11) were different than envelopes for the interior drains. For the interior drains there was a circular envelope around the drains, Figure 1. This created a converging pattern of streamlines entering the envelope, Figure 26A. For the most part the pattern of converging streamlines occurred in the fine sand. Thus, the closer the particle of water was to the drain the higher the velocity and the higher the friction or headloss.

For the two end drains, the envelopes extended 0.5 ft (15.0 cm) from the ends of the sand tank and from the bottom of the sand tank to the top surface. The pattern of streamlines entering an end drain envelope consisted of a somewhat parallel or horizontal pattern. Then the streamlines traveled vertically upward in the envelope and into the end drain, Figures 12 and 26A. Waterflow into an end drain envelope more closely resembled the Dupuit-Forschheimer assumptions than the converging-type flow entering and interior drain envelope. Furthermore, the permeability of the medium-size sand was greater than permeability of the fine sand. Thus, from Equation 1, one can infer that there was less headloss occurring for a given flow entering an end drain than for the same flow entering an interior drain. Therefore, an end drain envelope is more efficient for drainage.

Zero-percent slope tests.—If flow conditions for the end drains were similar to the interior drains, then the end drain discharge should be about 50 percent of the recharge rate. However, the tests showed that the end drain discharges were always greater than 50 percent, Figure 6. In addition, the water-table profiles were lower than the corresponding interior drain profiles. These differences were probably due to the greater efficiency of the end drains. The flow rates from the two ends of the tank were not equal. Probably the unequal distances between Drains No. 1 and 2, and Drains No. 10 and 11 accounted for the differences of profiles and discharges of the two end drains.

The water-table profiles were measured and computed between Drains No. 10 and 11, Figure 19C. Equation 3 of the Dupuit-Forchheimer assumptions was used to obtain the computed water-table profiles. The drain spacing distance (S) used was 8 ft (2.44 m) instead of 6 ft (1.83 m) since Drain No. 11 acted upon a greater distance than one-half the 6-ft (1.83-m) drain spacing test distance. The effect of Drain No. 11 can be seen by examining the measured water-table profiles which show the point of 0 percent slope to be approximately 4 feet (1.22 m) left of the drain. Agreement between the computed and measured profiles for Figure 19C was considerably better than for the interior drains of Figures 19A and 19B.

Twelve-foot drain spacing tests.—The purpose of the controlled tests was to isolate or eliminate the effect of the end drain envelope upon drainage up slope from end Drain No. 11. At end Drain No. 11 the water-table profile was raised, Figure 26B. The controlled water-table profiles between Drains No. 10 and 11 were above the water-table profiles that occurred for the corresponding free flow tests. With the added pressure at end Drain No. 11 the efficiency of the end drain envelope was somewhat reduced.

The controlled and free flow tests provide information about how far up slope influence of the end drain envelope effect extends, Figure 27. As one progresses up slope the difference between the controlled and free flow profiles becomes less. For the 2-1/2 percent slope, the controlled and free flow profiles were approximately the same at Drain No. 8. Results of the water-table profiles for 5, 7-1/2, and 10 percent slope tests were similar to the 2-1/2 percent slope tests. In addition to similarities in water surface profiles, at Drain No. 8 the controlled and free flow discharges were practically the same. Therefore, it was concluded that for free flow tests influence of the end drain envelope did not extend up slope past Drain No. 8.

Six-foot drain spacing tests.—No controls were imposed upon Drain No. 11 for the 6-ft (1.83-m) drain spacing tests. However, conclusions could be reached about the distance up slope which was affected by the end drain. For Drain No. 9 all the discharges were approximately equal to the equilibrium discharge, Table 3 and Figures 22 and 23. For Drain No. 10 the discharges were less than the equilibrium discharges. Thus, it was concluded that the influence of the end drain envelope affected discharge from Drain No. 10, but had an insignificant effect on Drain No. 9. Thus, the influence of the end drain envelope upon the water-table profiles was assumed not to extend up slope beyond Drain No. 9.

Flow of Water Downslope Passing Beneath the Drains

A study was made to determine what affect changes in percent slope, recharge rate, and drain spacing had upon the flow of water downslope passing beneath drains. For this study an inventory was made using the drain discharge data in which the amount of water flowing downslope and passing beneath the drain was computed for each drain, Figure 28. The flow values were averaged for each test and they represent an equilibrium condition of drain discharge, Table 4 and Figure 29. Drains that were considered not to be in equilibrium were excluded in the averaging. For example flow values for Drains No. 1, 2, 3, 4, and 10 were not used. Similarly, with the 12-ft (3.66-m) drain spacing tests the flow values for Drains No. 2, 4, and 10 were not used. The effect of the slope and recharge rate upon the downslope flow was readily determined, Figures 29A and 29B. With a constant recharge rate, increasing the sand tank slope increased the flow of water downslope that was passing beneath the drains, Figure 29A. On the other hand, for a constant slope an increase in the recharge rate decreased the downslope flow passing beneath the drains, Figure 29B. However, the percent slope variable appeared to have the strongest influence on the downslope flow. As the slope varied there was a six-fold change in the downslope flow. Whereas, the recharge rate variations were 3/10 or less, depending upon the percent slope, Figure 29B. Two (S/d) ratios were used in the tank tests,

(1) S/d = 6 for 12-foot drain spacings
(2) S/d = 3 for 6-foot drain spacings.

For a given recharge rate and percent slope, there is less downslope flow passing beneath the drains when S/d = 6, Figure 29A. Evidently different (S/d) ratios cause variations in the flow patterns below the drains.

Development of Water Movement Beneath Drains

General.—The streak-line tests (Figures 9, 10, and 11) and the pressure measurement tests (Figures 14, 15, 16, and 17) show a complex pattern of water movement beneath the drains. An understanding of how the recharge rate and slope affect the flow beneath a drain may be helpful for interpreting the sand tank test results and for analyzing drainage conditions other than those tested in the sand tank. The description of the flow conditions occurring beneath the drains is of a hypothetical character. In the following description the (S/d) ratio is held constant.

Constant recharge rate and effect of slope changes.—Water movement toward a drain will be considered first for a 0 percent slope, Figure 30A. The velocity change that occurs along a given vertical and horizontal plane will be examined. The vertical plane is from the Stagnation Point C to the drain. The horizontal plane is on the sand tank bottom between the Stagnation Points C and P. A particle of water has a relatively low velocity near the stagnation points. Due to convergence of flow into the drain, the velocity along the vertical plane beneath the drain continually increases from Point C to the drain. Along the horizontal plane the direction of water movement is to the left and the maximum velocity occurs somewhere between Stagnation Points C and P. Also if the recharge rate is increased there will be a proportionate increase in the velocities along the vertical and horizontal planes.

As the slope of the ground is increased (or the sand tank is tilted) the entire streamline pattern is altered, Figure 30B. Because of the tilt there is a downslope or downhill force acting upon the system. Even though the two planes are no longer vertical or horizontal the planes will still be referred to as the vertical and horizontal planes. There are now two velocity components along the vertical plane. One velocity component is still parallel with the vertical plane. The second velocity component acts downslope and is perpendicular to the vertical plane. Along the horizontal plane the downslope velocity component is parallel with the plane and acts in a downslope direction. Therefore upslope velocities acting along the horizontal plane will decrease. The part of the horizontal plane influenced the most by the downslope velocities are the areas near the Stagnation Points C and P. As the slope increases, the Stagnation Point C is located farther downslope at C′. The Stagnation Point P has moved upslope to P′.

As a series of slope increases are made the downslope velocities increase along the horizontal plane and the distance between the two Stagnation Points C′ and P′ become less. At some critical slope the two stagnation points meet. At this slope the downslope velocities have become large enough to overcome the existing upslope velocities along the horizontal plane. With further increases in slope some water will flow downslope and pass beneath the drains, Figure 30C. This creates two flow systems; one consisting of recharge flowing into the drains, and the second consisting of water flowing downslope and passing beneath the drain. The two previous Stagnation Points C′ and P′ are now a common Stagnation Point "I" located on the boundary between the two flow systems, an analysis of the dye traces in conjunction with the pressure measurements clearly show the existance of the Stagnation Point "I", Figure 14, and 15.

A further increase in slope results in an increase in the downslope velocities. The proportionate area of the downslope flow system also expands, Figure 30D. With a constant recharge rate increasing the slope increases the flow passing beneath the drains, Figure 29A.

Constant slope and effect of recharge rate changes.—Uniform flow parallel with the sand tank bottom, with no recharge, is considered first, Figure 31A. The water-table profile almost touches the drain. If a small recharge is added the water-table profile will rise and there will be a discharge from the drains. Once again there is a Stagnation Point

"I" and two flow systems are established, Figure 31B. The boundary line between the two flow systems can be thought of as an envelope curve enclosing the flow system to the drains.

If the recharge rate is increased the upward velocity component along the vertical plane (Point C—Drain) is increased. Also, the downslope velocity component acting along the envelope is affected by an increase in the recharge rate. An increase in the recharge rate forces the envelope closer to the bottom of the sand tank, Figure 31C. This results in a decreased flow area for the flow system of water passing beneath the drains. The Stagnation Point "I" is farther downslope and closer to the sand tank bottom.

In general for a constant slope, increasing the recharge rate decreases the flow passing beneath the drains, Figure 29B.

Location of the First Upslope Drain

General.—One problem arising in the installation of agricultural drainage systems on sloping land is location of the first up slope drain. For instance, if a drain is located too far up slope it will never function. Actually the sand tank tests were not oriented toward this type of an investigation, but an approximate method was found to locate the first up slope drain. General results or observations of the sand tank tests were used in developing the approximate method. In reality the location of the first up slope drain, obtained by the approximate method, is too far down the slope. Factors, such as (1) the existing up slope waterflow conditions and (2) the varying quantity of downslope flow passing beneath a drain, can cause the first drain location to be further up the slope. Therefore, the approximate method provides only the lower-most downslope location to be considered in placing the first up slope drain. Engineering judgment must be used to obtain a more accurate location for the first up slope drain.

Empirical development of the approximate method.—For the sand tank tests a consistant trend in the drain discharges was noted at the upper end of the sand tank. The discharge of each succeeding downslope drain increased until the equilibrium area of the sand tank was reached. In the equilibrium area of the sand tank all the drain discharges were approximately the same. Therefore, the objective was to position the first up slope drain at a location where discharge from the drain would be approximately equal to the equilibrium discharge. An example that illustrates the interpretation of a sand tank test for locating the first up slope drain can be found with the 2-1/2-ml/sec recharge rate, 7-1/2 percent slope, and 6-ft (1.83-m) drain spacing test, Figure 7. Drains No. 1 and 2 were not operating. Drain No. 3 was operating only at a partially optimum discharge, 0.45-ml/sec. An optimum discharge was assumed to be equal to the equilibrium discharge, or for this specific test 2-1/2 ml/sec. Therefore, Drain No. 3 was not used at full capacity. Drain No. 4 had a 2.42-ml/sec discharge. For this specific test the most probable location for a hypothetical first up slope drain in the sand tank would be between Drains No. 3 and 4 with the location closer to Drain No. 4 than to Drain No. 3. By visual inspection a good location for the first up slope drain appears to be approximately 16 ft (4.88 m) from the upper end of the sand tank.

Another rational method for placing the first up slope drain would be to locate it one drain spacing downslope from the point where the water table crosses the depth at which the drains are placed. For example, use the same 2-1/2-ml/sec recharge rate, 7-1/2 percent slope. and 6-ft (1.83-m) drain spacing test, Figure 22. At a position 10.5 ft (3.2 m) from the upper end of the sand tank the water table crosses the 2-ft (0.61-m) depth. If the first up slope drain was located one drain spacing distance of 6 ft downslope from the 10.5-ft position, the downslope distance for the first up slope drain would be 16.5 ft (5.03 m). This compares favorably with the 16-ft (4.88-m) distance made by the visual inspection. The location where the water table reached a 2-ft elevation (centerline elevation for the drains) was considered a very helpful and significant aid for indicating the location of the first up slope drain.

Description of the approximate method.—An approximate computational procedure was developed to locate the first up slope drain. The computational procedure considers slope, permeability, recharge rate, and the depth of the aquifer, which is assumed equal to the perpendicular distance from the impermeable barrier to the drain centerline. The computational procedure is based on the distance needed to accumulate a recharge which is equal to the downslope flow. Very idealized and simplified conditions of water movement were assumed when making the downslope flow computations. The following conditions (similar to Dupuit-Forchheimer assumptions) were assumed; (1) the downslope flow is parallel with the sand tank bottom, and (2) slope of the water-table profile producing this water movement is equal to the sand tank slope. These assumptions are contrary to the actual flow conditions which occurred in the sand tank. The downslope flow was not parallel with the sand tank bottom. In addition, the assumed water-table profile slope was probably too large. Therefore, the approximate method gives the location of the first up slope drain too far downslope.

The quantity of downslope flow is computed using Equation (1). The following example computation was made using a 2-ft (0.61-m) depth, 7-1/2 percent slope, and 2-1/2-ml/sec recharge rate:

Downslope Flow

$$Q = VA = ikA = 0.075 \times (5.66)10^{-4} \times (2 \times 2)$$

$$Q = (1.698)10^{-4}\ \mathrm{ft^3/sec}\ (4.81\ \mathrm{ml/sec})$$

Recharge rate changed to $\mathrm{ft^3/sec}$

$$\frac{2.5\ \mathrm{ml/sec}}{(2.8317)10^{-4}\ \mathrm{ml/ft^3}} = (0.8829)10^{-4}\ \mathrm{ft^3/sec}$$

Recharge rate per linear foot of sand tank

$$\frac{(0.8829)10^{-4}\ \mathrm{ft^3/sec}}{6\ \mathrm{ft}} =$$

$$(0.1472)10^{-4} \frac{\mathrm{ft^3}}{\mathrm{ft\text{-}sec}}$$

Length needed for accumulated recharge to equal downslope flow

$$L = \frac{(1.698)10^{-4}\ \mathrm{ft^3/sec}}{(0.1472)10^{-4}\ \frac{\mathrm{ft^3}}{\mathrm{ft\text{-}sec}}} = 11.54\ \mathrm{ft}\ (3.52\ \mathrm{m})$$

Add 6 ft (1.83 m) (drain spacing distance) to the 11.54 ft (3.52 m) and then by the approximate method location of the first up slope drain is 17.54 ft (5.35 m) from the upper end of the sand tank.

Comparison of the approximate method for locating the first up slope drain with results of the sand tank tests.—Location of the 2-ft (0.61-m) water-table elevation (drain centerline elevation) was the criterion for making the comparison. The distance of the 2-ft elevation determined by the computational procedure was compared with the location of the 2-ft elevation in the sand tank. Using the computational procedure, distances were computed for recharge rates of 2-1/2-, 3-, 4-, 5-, 7-1/2-, and 10-ml/sec recharge rates at each percent slope, Figure 32. For the various sand tank tests, distances of the 2-ft water-table elevation were determined from Figures 22 to 25. The data were plotted on Figure 32.

In general, the sand tank tests confirmed that the computational curves of the approximate method located the first up slope drain too far down the slope. The one exception was the 6-ft (1.83-m) drain spacing test with the 10 percent slope and 2-1/2-ml/sec recharge rate. The largest difference between the 6-ft drain spacing test curves and the computational curves was 2-1/2 ft, or approximately two-fifths the drain spacing distance. For the 12-ft (3.66-m) drain spacing tests, the largest difference was 2-1/2 ft (0.76 m) or approximately one-third of the drain spacing distance. The maximum difference for both drain spacings occurred with the 2-1/2 percent slope tests.

In the approximate method the entire aquifer below the drain was assumed to transport flow down the slope and past the drain. However, in the actual sand tank tests two flow systems existed, Figures 9 and 10. The flow system of water passing beneath the drains was affected by changes of the sand tank slope, the recharge rate, and the (S/d) ratio. Tests with a given percent slope and recharge rate indicate that the actual location of the first drain is farther up slope with a larger (S/d) ratio than with a smaller (S/d) ratio. The probable reason is the change in the flow field with the different drain spacings. For instance with the larger (S/d = 6) ratio of the 12-ft (3.66-m) drain spacing there is less downslope flow passing beneath the drains than with the smaller (S/d = 3) ratio of the 6-ft drain spacing, Figure 29A. The downslope flow passing beneath the drains for both 6- and 12-ft drain spacings in the sand tank is less than the computed downslope flow used in the approximate method.

CONCLUSIONS

The following conclusions are based on results of steady state tests made in the sand tank:

1. Drain discharges varied in the upper length of the sand tank depending upon slope and recharge rate. However, all the tests had the same tendency of varying drain discharge. Each drain discharge was greater than the discharge from the preceding up slope drain. The drain discharge increased downslope until the equilibrium area of the sand tank was reached. For all the sand tank tests an equilibrium condition occurred in the middle length

of the sand tank. This equilibrium condition was defined such that discharge from a drain was approximately equal to water applied between two operating drains.

2. Within the limits of experimental error, the water-table profiles measured perpendicular to the sand tank bottom for a given recharge rate were almost identical for slopes between 0 and 10 percent. This occurred in the equilibrium area of the sand tank.

3. There were two distinct ground-water flow systems within the equilibrium area of the sand tank. The recharge flow system consisted of recharge water entering the water table moving partially downward into the sand tank, and then flowing into the drains. The downslope flow system consisted of water which moved downslope below the recharge flow system.

4. The predominant area of the two flow systems were affected by slope and recharge. Holding the recharge constant and increasing the slope decreased the area of the recharge flow system. Holding the slope constant and increasing the recharge rate increased the area of the recharge flow system.

5. Drainage characteristics for the end drains were different from the interior drains of the sand tank due to design differences of the envelopes. The end drain envelope extended down to the sand tank bottom. The Dupuit-Forchheimer assumptions better simulated water flowing toward the end drains than it simulated the convergent pattern of water flowing toward the interior drains.

APPLICATIONS

The investigation was for steady state flow and of a general nature. No conditions for a specific geographical location, such as permeability, dimensions of drains or envelopes, distance between drains, distance from the drain to the impermeable barrier, and recharge rates were simulated in the sand tank tests. For specific applications to a given locality, additional studies would be required. However, results from this research study will help drainage engineers obtain a better understanding about flow conditions in the porous media for agricultural drains on sloping land. In addition, approximate methods for determining the location of the first up slope drain on sloping land are included.

Results of the investigation indicate that sloping drainage has aspects similar to drainage for 0 percent slopes. Therefore, studies later were made to investigate how well the theory and equations for the 0 percent slope conditions would apply to sloping sand tank tests.[2]

NOTATION

The following symbols were used in this report:

- d = vertical distance from the drain centerline to the impermeable barrier, ft;
- i = slope or hydraulic gradient, ft/ft;
- k = coefficient of permeability, ft/sec;
- v = infiltration rate, ft/sec;
- w = 2-foot width of sand tank, ft;
- x = horizontal distance of a given point on the water-table profile from the drain centerline, ft;
- y = (Equation 1) depth of flow, ft;
- y = (Equation 3) vertical distance of a given point on the water-table profile above the drain centerline, ft;
- A = area of flow, ft^2;
- H = distance of the water-table profile above the drain centerline midway between two operating drains, ft;
- L = length needed for accumulated recharge to equal downslope flow, ft;
- Q = discharge flowing through the sand, ft^3/sec;
- S = horizontal distance between operating drains, ft.

[2] Carlson, E. J., Drainage From Level and Sloping Land, REC-ERC-71-44, U.S. Bureau of Reclamation, December 1971.

Table 1

LOCATIONS OF THE GROUND-WATER TABLE MEASURING WELLS

Manometer number	Station in feet	Slope distance	Manometer number	Station in feet	Slope distance
1	0.40	−6.43	31	30.18	4.60
2	1.16	−5.73	32	31.18	5.54
3	2.21	−4.75	33	32.16	6.46
4	3.20	−3.82	34	33.18	7.42
5	4.16	−2.92	35	34.18	8.35
6	5.16	−2.04	36	35.19	9.24
7	6.17	−1.10	37	36.17	10.15
8	7.16	−0.17	38	37.21	11.13
9	8.16	0.77	39	38.19	12.05
10	9.15	1.70	40	39.19	12.99
11	10.15	2.57	41	40.19	−8.63
12	11.15	3.51	42	41.22	−7.66
13	12.16	4.45	43	42.23	−6.72
14	13.16	5.40	44	43.24	−5.77
15	14.17	6.34	45	44.21	−4.86
16	15.18	7.23	46	45.22	−3.98
17	16.17	8.15	47	46.23	−3.03
18	17.19	9.11	48	47.25	−2.07
19	18.19	10.05	49	48.24	−1.14
20	19.18	10.98	50	49.26	−0.19
21	20.18	−4.65	51	50.09	0.52
22	21.18	−3.71	52	51.24	1.61
23	22.19	−2.76	53	52.27	2.57
24	23.20	−1.82	54	53.28	3.52
25	24.20	−0.88	55	54.32	4.50
26	25.20	0.01	56	55.32	5.38
27	26.20	0.93	57	56.30	6.29
28	27.20	1.87	58	57.34	7.27
29	28.17	2.78	59	58.32	8.18
30	29.20	3.74	60	59.17	8.97

Manometer Number—Identification number of the ground-water table measuring wells and manometers.
Station in feet—The station location where the ground-water table measuring wells were placed along the sand tank. The left end of the sand tank (up slope) was Station 0 and the right end (downslope) was Station 60.
Slope distance—The distance between the well and manometer. Negative distance shows that the well was up slope from the manometer. Used in computations shown in Figure 5A.

Table 2

SUMMARY OF TESTS PERFORMED

6-foot drain spacing			12-foot drain spacing free flow tests			12-foot drain spacing controlled flow tests		
Percent slope	Recharge rate	Date performed	Percent slope	Recharge rate	Date performed	Percent slope	Recharge rate	Date performed
0	2-1/2	2-28-68	2-1/2	2-1/2	3-19-68	2-1/2	2-1/2	3-25-68
0	5	2-28-68	2-1/2	3	3-20-68	2-1/2	3	3-22-68
0	7-1/2	2-27-68	2-1/2	4	3-20-68	2-1/2	4	3-22-68
0	10	2-27-68	2-1/2	5	3-21-68	2-1/2	5	3-21-68
2-1/2	2-1/2	3-18-68	5	2-1/2	3-29-68	5	2-1/2	3-26-68
2-1/2	5	3-15-68	5	3	3-29-68	5	3	3-26-68
2-1/2	7-1/2	3-14-68	5	4	3-28-68	5	4	3-27-68
2-1/2	10	3-13-68	5	5	3-28-68	5	5	3-27-68
5	2-1/2	4- 3-68	7-1/2	2-1/2	4- 9-68	7-1/2	2-1/2	4-11-68
5	5	4- 2-68	7-1/2	3	4- 9-68	7-1/2	3	4-11-68
5	7-1/2	4- 2-68	7-1/2	4	4- 8-68	7-1/2	4	4-10-68
5	10	4- 1-68	7-1/2	5	4- 8-68	7-1/2	5	4-10-68
7-1/2	2-1/2	4-15-68	10	3	4-23-68	10	3	4-24-68
7-1/2	5	4-15-68	10	4	4-23-68	10	4	4-24-68
7-1/2	7-1/2	4-12-68	10	5	4-22-68	10	5	4-25-68
7-1/2	10	4-12-68						
10	2-1/2	4-19-68						
10	5	4-19-68						
10	7-1/2	4-18-68						
10	10	4-18-68						

12-foot drain spacing		
Percent slope	Recharge rate	Date performed
0	2-1/2	2-29-68
0	3	2-29-68
0	4	3- 1-68
0	5	3- 1-68

Table 3

DRAIN DISCHARGES

6-foot Drain Spacing

Percent slope	Recharge rate ml/sec	Drain No. 1 Discharge	Drain No. 1 Percent recharge	Drain No. 2 Discharge	Drain No. 2 Percent recharge	Drain No. 3 Discharge	Drain No. 3 Percent recharge	Drain No. 4 Discharge	Drain No. 4 Percent recharge	Drain No. 5 Discharge	Drain No. 5 Percent recharge
0	2-1/2	1.64	65.6	2.30	92.0	2.30	92.0	2.46	98.4	2.48	99.2
	5	3.16	63.2	4.38	87.6	4.76	95.2	4.98	99.6	4.94	98.8
	7-1/2	4.62	61.6	6.46	86.1	7.32	97.6	7.56	100.8	7.55	100.7
	10	6.20	62.2	8.63	86.3	9.90	99.0	10.20	102.0	10.05	100.5
2-1/2	2-1/2	0.00	0.0	1.76	70.4	2.20	88.0	2.56	102.4	2.32	92.8
	5	1.02	20.4	4.42	88.4	4.55	91.0	5.14	102.8	4.82	96.4
	7-1/2	2.52	33.6	6.56	87.5	6.92	92.3	7.68	92.3	7.33	97.7
	10	4.00	40.0	8.80	88.0	9.38	93.8	10.60	106.0	9.95	99.5
5	2-1/2	0.00	0.0	0.05	2.0	1.91	76.4	2.34	93.6	2.16	86.4
	5	0.00	0.0	3.30	66.0	4.50	90.0	4.87	97.4	4.40	88.0
	7-1/2	0.45	6.0	6.35	84.7	6.97	92.9	7.40	98.7	6.67	88.9
	10	1.91	19.1	8.60	86.0	9.45	94.5	10.30	103.0	9.20	92.0
7-1/2	2-1/2	0.00	0.0	0.00	0.0	0.45	18.0	2.42	96.8	2.24	89.6
	5	0.00	0.0	1.68	33.6	4.56	91.2	5.28	105.6	4.66	93.2
	7-1/2	0.00	0.0	4.70	62.7	7.12	94.9	8.00	106.7	7.04	93.9
	10	0.00	0.0	8.22	82.2	9.66	96.6	10.80	108.0	9.50	95.0
10	2-1/2	0.00	0.0	0.00	0.0	0.00	0.0	1.06	42.4	2.04	81.6
	5	0.00	0.0	0.00	0.0	3.90	78.0	5.16	103.2	4.70	94.0
	7-1/2	0.00	0.0	3.08	41.1	6.40	85.3	7.70	102.7	6.90	92.0
	10	0.00	0.0	6.42	64.2	9.10	91.0	10.40	104.0	9.26	92.6

(1) Drain discharges are given in ml/sec.
(2) Percent recharge is the drain discharge expressed as a percent of the discharge rate from one recharge unit.

Drain No. 6 Discharge	Drain No. 6 Percent recharge	Drain No. 7 Discharge	Drain No. 7 Percent recharge	Drain No. 8 Discharge	Drain No. 8 Percent recharge	Drain No. 9 Discharge	Drain No. 9 Percent recharge	Drain No. 10 Discharge	Drain No. 10 Percent recharge	Drain No. 11 Discharge	Drain No. 11 Percent recharge	Total drain discharges
2.48	99.2	2.52	100.8	2.60	104.0	2.56	102.4	2.08	83.2	1.86	74.4	25.28
4.93	98.6	4.77	95.4	4.96	99.2	5.00	100.0	4.26	85.2	3.50	70.0	49.64
7.40	98.7	7.36	98.1	7.30	97.3	7.48	99.7	6.48	86.4	5.12	68.3	74.65
9.82	98.2	9.80	98.0	9.84	98.4	9.92	99.2	8.67	86.7	6.76	67.6	99.79
2.64	105.6	2.34	93.6	2.52	100.8	2.48	99.2	2.10	84.0	3.80	152.0	24.72
5.02	100.4	4.75	95.0	4.85	92.0	4.85	97.0	4.27	85.4	5.56	111.2	49.23
7.58	101.1	7.20	96.0	7.25	96.7	7.23	96.4	6.40	85.3	7.23	96.4	73.99
9.90	99.0	9.70	97.0	9.60	96.0	9.75	97.5	8.75	87.5	9.20	92.0	99.63
2.56	102.4	2.37	94.8	2.49	99.6	2.47	98.8	1.90	76.0	5.60	224.0	23.85
4.85	97.0	4.64	93.0	4.65	93.0	4.75	95.0	4.08	81.6	7.45	149.0	47.50
7.25	96.7	7.00	93.3	6.80	90.7	7.00	93.3	6.20	82.7	9.26	123.5	71.35
9.70	97.0	9.40	94.0	9.16	91.6	9.64	96.4	8.55	85.5	11.00	110.0	96.91
2.66	106.4	2.38	95.2	2.60	104.0	2.58	103.2	2.02	80.8	7.45	298.0	24.80
5.14	102.8	4.88	97.6	4.94	98.8	5.02	100.4	4.14	82.8	9.18	183.6	49.48
7.56	100.8	7.20	96.0	7.24	96.5	7.42	98.9	6.36	84.8	11.20	149.3	73.84
9.90	99.0	9.65	96.5	9.77	97.7	9.86	98.6	8.76	87.6	12.86	128.6	98.98
2.62	104.8	2.38	95.2	2.56	102.4	2.52	100.8	1.86	74.4	9.10	364.0	24.14
5.06	101.2	4.82	96.4	4.78	95.6	4.98	99.6	4.04	82.4	10.88	217.6	48.32
7.32	97.6	7.10	94.7	7.00	93.3	7.40	98.1	6.18	82.4	12.64	168.5	71.72
9.60	96.0	9.60	96.0	9.40	94.0	9.92	99.2	8.40	84.0	14.54	145.4	96.64

Table 3—Continued

DRAIN DISCHARGES

12-foot Drain Spacing

Percent slope	Condition Drain No. 11	Recharge rate	Drain No. 2		Drain No. 4		Drain No. 6		Drain No. 8		Drain No. 10		Drain No. 11		Total drain discharges
			Discharge	Percent recharge	Discharge	Percent recharge	Discharge	Percent recharge	Discharge	Percent recharge	Discharge	Percent recharge	Discharge	Percent recharge	
0	Free flow	2-1/2	5.05	200.2	4.80	192.0	4.80	192.0	4.97	198.8	5.13	205.2	–	–	24.75
		3	6.02	200.7	5.75	191.7	5.78	192.7	5.94	198.0	6.05	201.7	–	–	29.54
		4	7.96	200.4	7.62	190.7	7.78	194.5	8.00	200.0	8.15	203.8	–	–	39.51
		5	10.02	200.4	9.87	197.4	9.80	196.0	9.80	196.0	10.10	202.0	–	–	49.59
2-1/2	Free flow	2-1/2	2.80	112.0	4.56	182.4	4.80	192.0	4.68	187.2	3.15	126.0	3.96	158.4	23.95
		3	3.83	127.7	5.60	186.7	5.60	186.7	5.50	183.3	3.72	124.0	4.30	143.3	28.55
		4	5.76	144.0	7.60	190.0	7.50	187.5	7.30	182.5	5.00	125.0	5.10	127.5	38.26
		5	7.80	156.0	9.47	189.4	9.45	189.0	9.35	187.0	6.40	128.0	5.83	116.6	48.30
2-1/2	Controlled flow	2-1/2	2.87	114.8	4.47	178.8	4.62	188.0	4.66	186.4	4.76	190.4	2.04	81.6	23.42
		3	3.88	129.3	5.60	186.7	5.70	190.0	5.70	190.0	5.90	196.7	1.99	66.3	28.77
		4	5.80	145.0	7.50	187.5	7.52	188.0	7.68	192.0	7.95	198.8	2.07	51.8	38.52
		5	7.82	156.4	9.48	189.6	9.42	188.0	9.50	190.0	9.86	197.2	2.18	43.6	48.26
5	Free flow	2-1/2	0.96	38.4	4.40	176.0	4.82	192.8	4.70	188.0	3.00	120.0	5.90	236.0	23.78
		3	1.90	63.3	5.40	180.0	5.74	191.3	5.62	187.3	3.10	103.3	6.30	210.0	28.06
		4	3.76	94.0	7.40	185.0	7.50	187.5	7.43	185.8	4.85	121.2	7.09	177.0	38.02
		5	5.89	117.8	9.40	188.0	9.40	188.0	9.25	185.0	6.20	124.0	7.78	155.6	47.92
5	Controlled flow	2-1/2	0.85	34.0	4.37	174.8	4.73	189.2	4.76	190.4	4.85	194.0	3.88	155.2	23.44
		3	1.80	60.0	5.28	176.0	5.63	187.7	5.70	190.0	5.72	190.7	3.98	132.7	28.11
		4	3.78	94.5	7.32	183.0	7.45	186.2	7.42	185.5	7.87	196.8	3.76	94.0	37.60
		5	5.80	116.0	9.25	185.0	9.30	186.0	9.10	182.0	9.90	198.0	3.82	76.4	47.17
7-1/2	Free flow	2-1/2	0.00	0.0	4.35	174.0	5.12	204.8	5.27	210.8	3.28	131.2	7.65	306.0	25.67
		3	0.48	16.0	5.86	195.3	6.12	204.0	6.20	206.7	3.89	129.7	8.02	267.3	30.57
		4	2.37	59.2	8.02	200.5	8.08	202.0	8.22	205.5	5.18	129.5	8.82	220.5	40.69
		5	4.14	82.8	10.00	200.0	9.97	199.4	10.25	205.0	6.78	135.6	9.50	190.0	50.64
7-1/2	Controlled flow	2-1/2	0.00	0.0	3.92	156.8	4.90	196.0	5.22	208.8	4.90	196.0	5.98	239.2	24.92
		3	0.14	4.7	5.75	191.7	5.98	199.3	6.25	208.3	5.90	196.7	5.90	196.7	29.92
		4	2.23	55.8	7.82	195.5	8.00	200.0	8.25	206.2	8.00	200.0	5.78	144.5	40.08
		5	4.30	86.0	9.86	197.2	9.90	198.0	10.25	205.0	10.10	202.0	5.95	119.0	50.36
10	Free flow	3	0.00	0.0	3.86	128.7	5.50	183.3	5.70	190.0	3.63	121.0	9.70	323.3	28.39
		4	0.18	4.5	7.10	177.5	7.50	187.5	7.60	190.0	4.80	120.0	10.50	262.5	37.68
		5	2.06	41.2	9.10	182.0	9.20	184.0	9.50	190.0	6.20	124.0	11.30	226.0	47.36
10	Controlled flow	3	0.00	0.0	3.86	128.7	5.57	185.7	5.86	195.3	5.60	186.7	7.52	250.7	28.41
		4	0.18	4.5	7.00	175.0	7.60	190.0	7.80	195.0	7.70	192.5	7.50	187.5	37.68
		5	2.30	46.0	8.94	178.8	9.38	187.6	9.70	194.0	9.80	196.0	7.60	152.0	47.72

(1) Drain discharges are given in ml/sec.
(2) Percent recharge is the drain discharge expressed as a percent of the discharge rate from one recharge unit.

Table 4

FLOW IN ML/SEC DOWNSLOPE PASSING BENEATH THE DRAINS

6-foot Drain Spacing

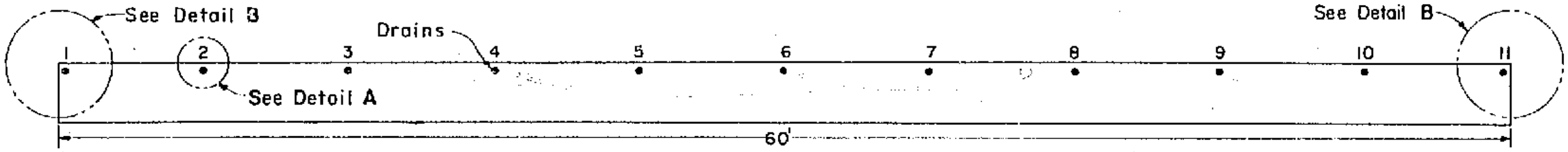
Test slope	2-1/2 percent				5 percent				7-1/2 percent				10 percent			
Test recharge	2-1/2	5	7-1/2	10	2-1/2	5	7-1/2	10	2-1/2	5	7-1/2	10	2-1/2	5	7-1/2	10
Average recharge	2.472	4.925	7.399	9.963	2.385	4.750	7.135	9.691	2.480	4.948	7.384	9.898	2.414	4.832	7.172	9.664
Drain No. 2	0.71	0.96	0.91	0.98	2.33	1.45	1.89	1.76	2.48	3.27	3.54	3.66	2.41	4.83	4.09	3.25
3	1.31	1.08	1.27	1.56	2.80	2.25	1.94	1.84	4.51	3.66	3.92	4.06	4.83	5.76	4.86	5.11
4	1.30	1.11	1.36	1.25	2.84	2.21	2.15	1.72	4.57	3.33	3.30	3.30	6.18	5.43	4.33	4.53
5	1.44	1.29	1.43	1.09	3.06	2.64	2.38	2.05	4.81	3.62	3.77	3.56	6.55	5.57	4.60	4.94
6	1.29	1.03	0.88	0.99	2.88	2.46	2.16	1.87	4.63	3.43	3.46	3.23	6.35	5.34	4.46	4.85
7	1.38	1.19	1.08	1.08	2.89	2.64	2.41	2.32	4.73	3.50	3.89	3.81	6.38	5.35	4.53	4.91
8	1.25	1.27	1.23	1.44	2.78	2.51	2.52	2.53	4.61	3.51	3.78	3.61	6.24	5.40	4.70	4.86
9	1.28	1.25	1.15	1.82	2.69	2.74	3.01	2.74	4.51	3.44	3.87	3.98	6.13	5.25	4.47	5.09
10	1.31	1.41	1.90	2.20	3.17	2.70	3.24	3.24	4.97	4.25	3.78	4.46	6.69	6.05	5.46	4.90
*Average flow beneath drains	1.32	1.19	1.19	1.28	2.86	2.53	2.44	2.20	4.64	3.47	3.68	3.58	6.30	5.39	4.52	4.86

*Average obtained from flow beneath Drains No. 4, 5, 6, 7, 8, and 9.

12-foot Drain Spacing

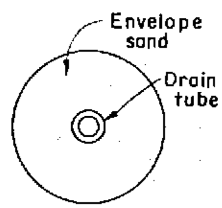
Test slope	2-1/2				5 percent				7-1/2 percent				10 percent		
Test recharge	2-1/2	3	4	5	2-1/2	3	4	5	2-1/2	3	4	5	3	4	5
Average recharge	2.342	2.877	3.852	4.826	2.344	2.811	3.760	4.717	2.492	2.992	4.008	5.036	2.841	3.778	4.772
Drain No. 2	0.37	0.39	0.30	0.47	1.49	1.34	0.86	0.57	2.49	2.85	1.78	1.58	2.84	3.60	2.47
4	0.58	0.59	0.37	0.24	2.12	1.91	1.31	0.75	3.55	3.08	2.78	2.21	4.66	4.16	3.08
6	0.61	0.49	0.55	0.39	2.04	1.86	1.31	0.96	3.64	3.09	2.79	2.30	4.77	4.12	3.88
8	0.67	0.49	0.71	1.02	2.01	1.83	1.40	1.30	3.40	2.83	2.56	2.20	4.59	3.88	3.73
10	1.13	0.92	0.52	0.57	1.85	1.78	1.25	1.22	3.48	2.91	2.57	2.17	4.67	3.73	3.48
**Average flow beneath drains	0.64	0.49	0.63	0.70	2.02	1.84	1.36	1.13	3.52	2.96	2.68	2.25	4.68	4.00	3.80

**Average obtained from Drains No. 6 and 8.



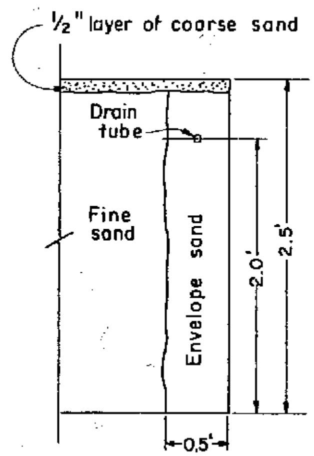
Drains are numbered consecutively beginning at the left end of the sand tank. The drains were spaced at approximately 6-foot intervals along the sand tank. Horizontal location of the drains is given by station. Station 0 is at the left edge of the sand tank.

DRAIN NUMBER	STATION IN FEET
1	0.34
2	5.72
3	11.72
4	17.71
5	23.72
6	29.69
7	35.68
8	41.66
9	47.68
10	53.69
11	59.70

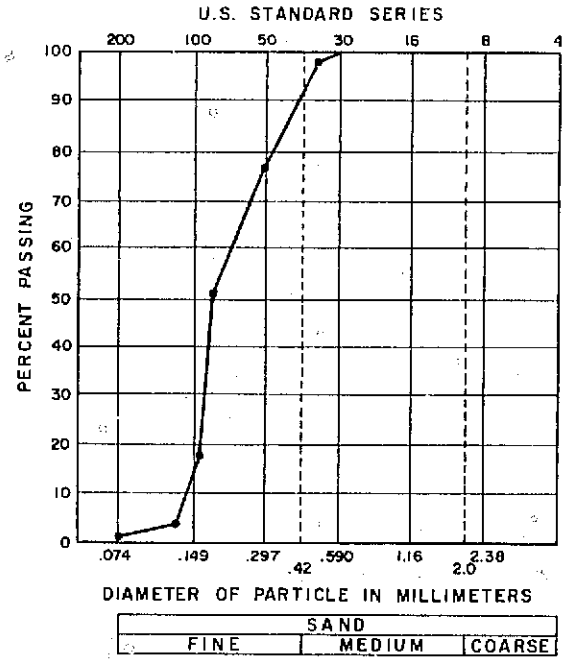


Dia. of envelope 0.2'. Size of sand used for the envelope was sand passing the #8 sieve and retained on the #16 sieve. The plastic drain tube had an O.D.= 5/8" and I.D.= 1/2".

DETAIL A



DETAIL B



SAND SIEVE ANALYSIS

Figure 1. Ground-water drain details.

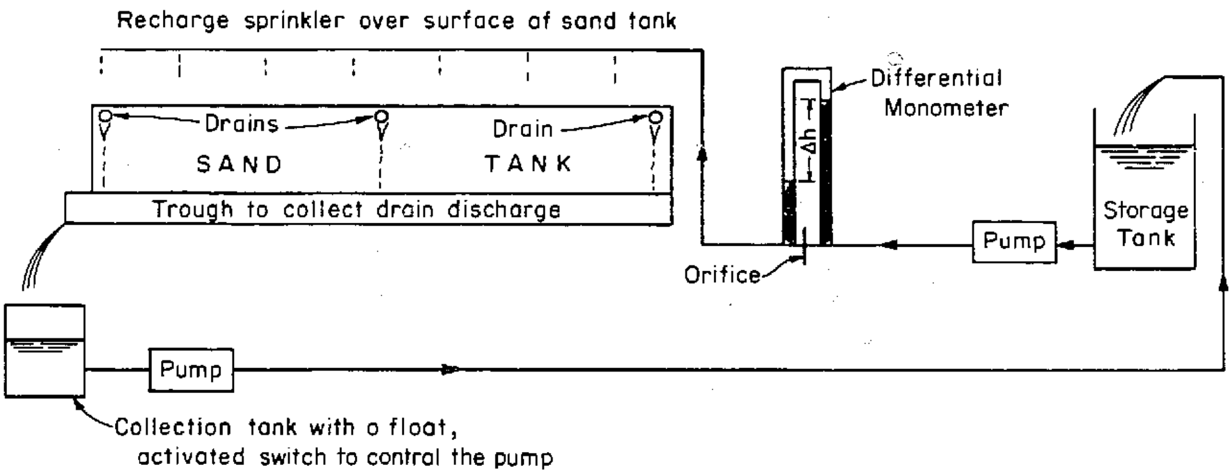


Figure 2A.

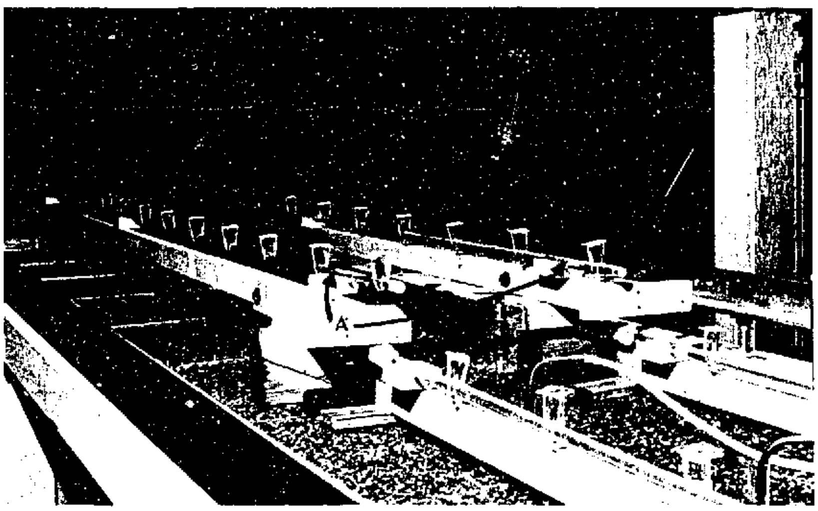


Figure 2B. Recharge unit—Upper photograph. (A) Longitudinal tubes that applied water upon the sand surface. Photo PX-D-70131

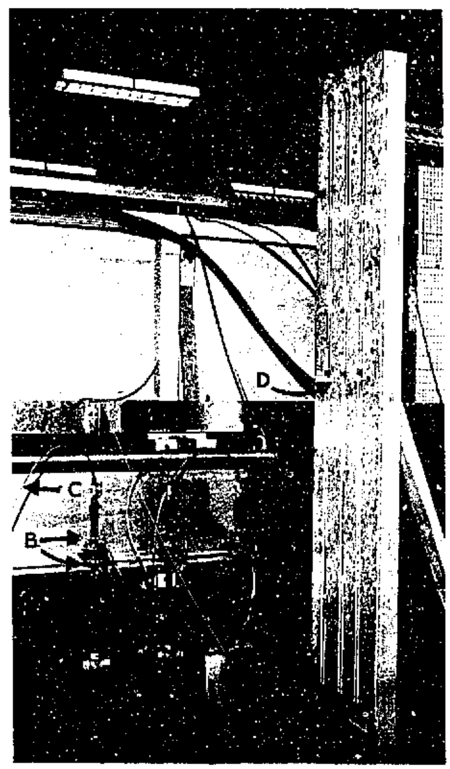


Figure 2C. Recharge unit measuring system—Photograph at the right. (A) Orifice plate. (B) Pressure taps across the orifice plate. (C) Line to a recharge unit. (D) Manometers to measure the differential head occurring across the orifice. Photo PX-D-70129

Figure 2. Water recirculating system for the sand tank.

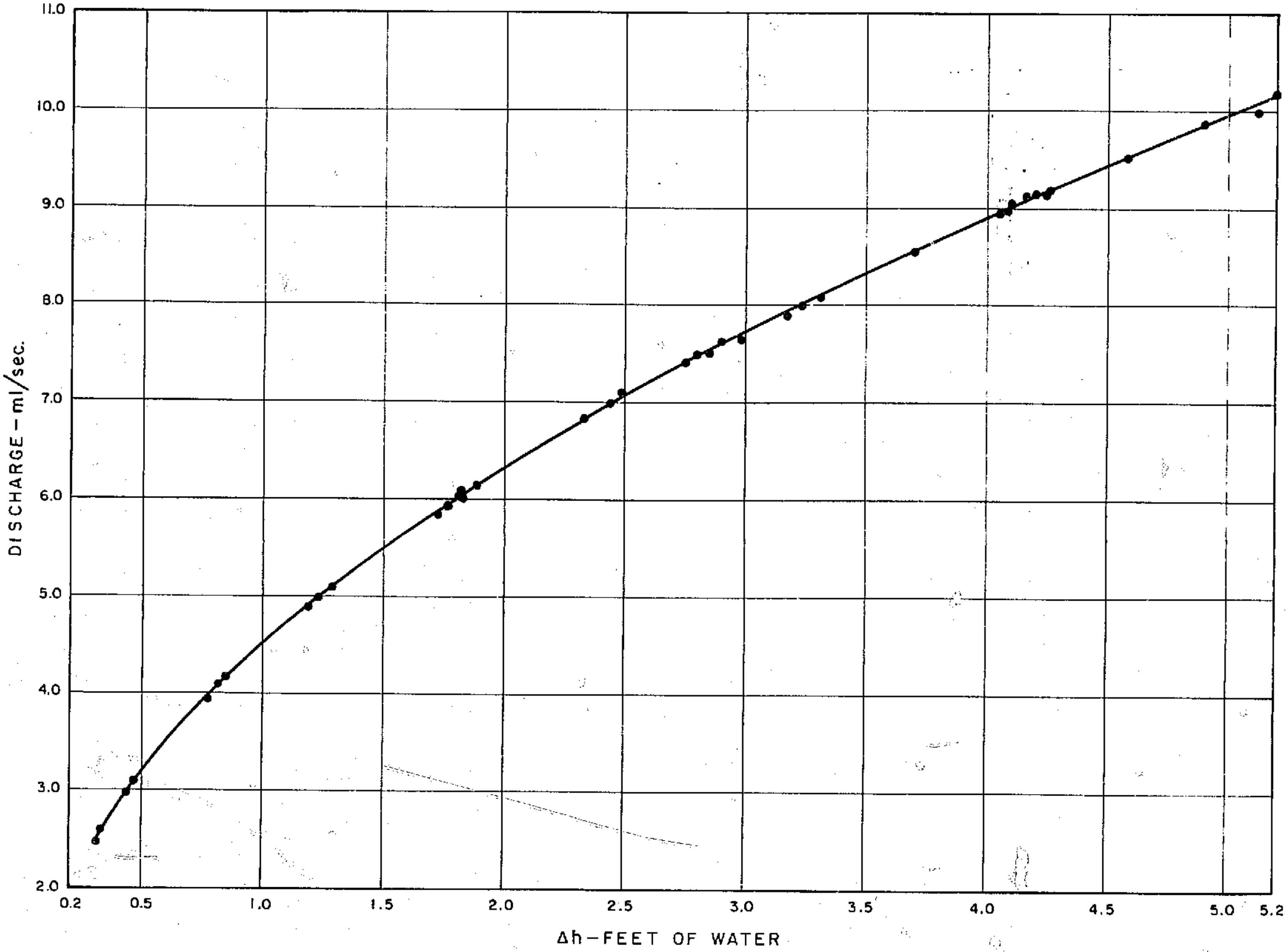


Figure 3. Calibration curve recharge Unit No. 10.

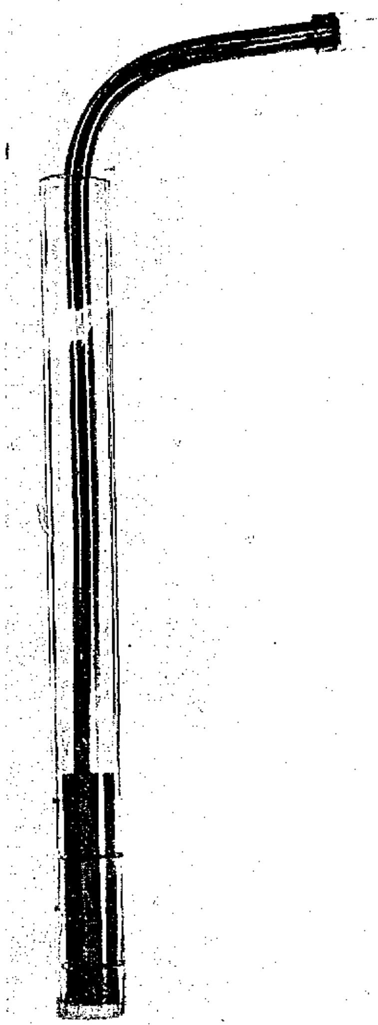


Figure 4A. Ground-water table measuring well. About 1 inch of the plastic tube protruded above the sand surface in the sand tank and the well bottom was approximately 1 inch below the centerline elevation of the drains.

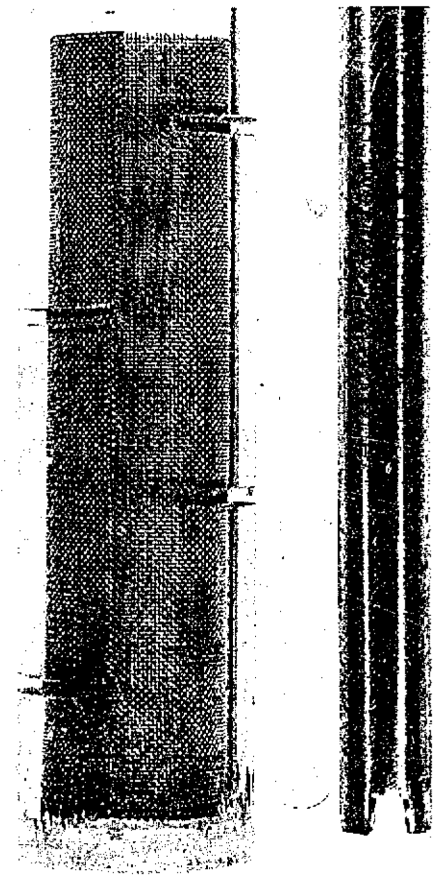


Figure 4B. Lower portion of ground-water measuring well. At the right is the copper tube that was placed in the well. The slot in the bottom of the copper tube allowed water to flow freely in and out of the copper tube. Photo PX-D-70792

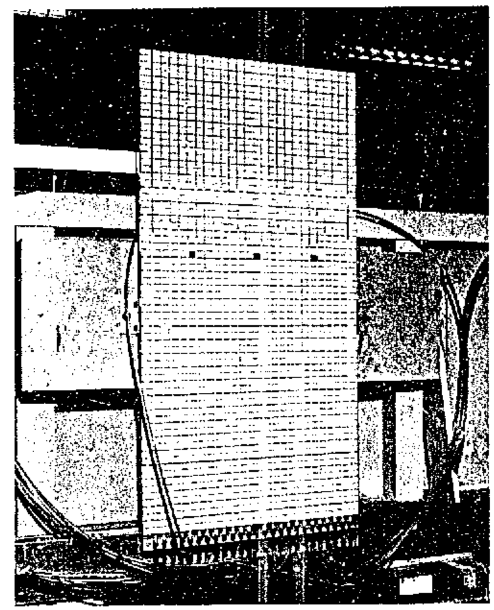


Figure 4C. Manometer board. Each manometer board had 20 ground-water measuring wells connected to it. Photo PX-D-70128

Figure 4. Ground-water table measuring wells.

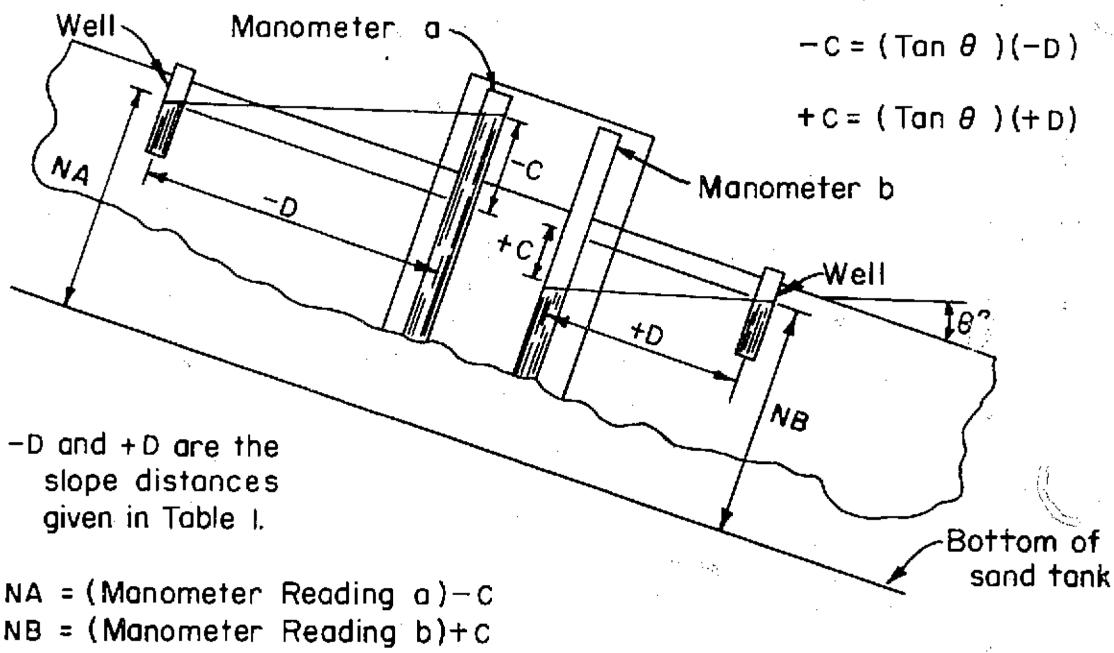


Figure 5A. Water table profiles normal to the bottom of the sand tank.

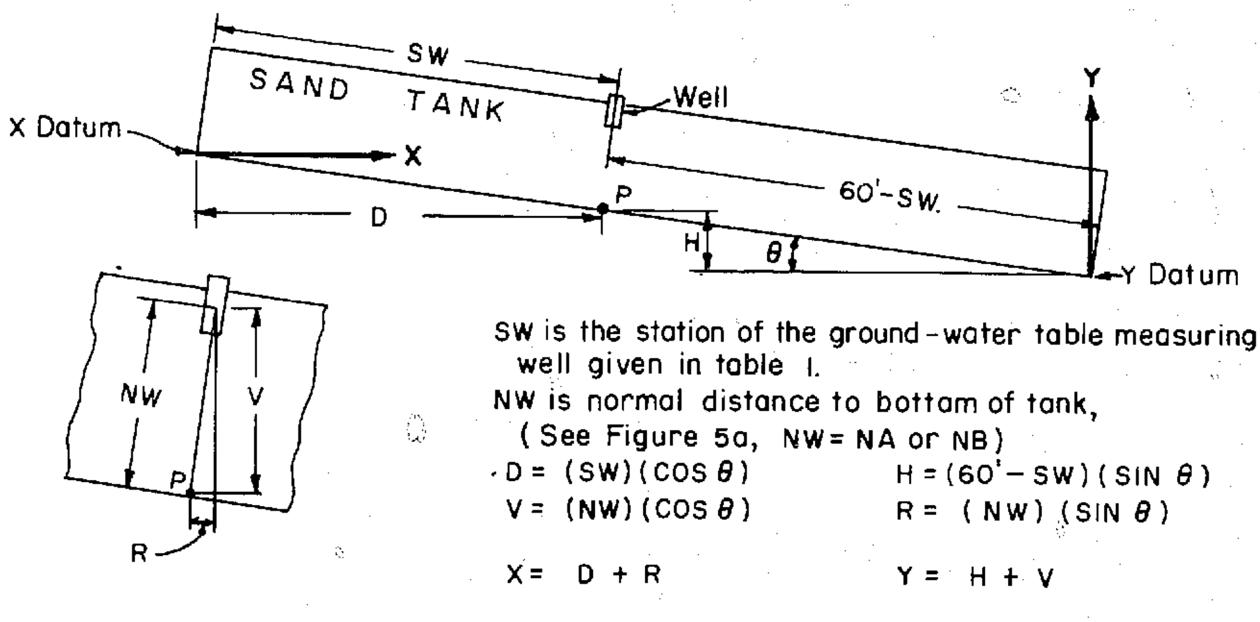


Figure 5B. Trigonometric computations made to correct monometer readings.

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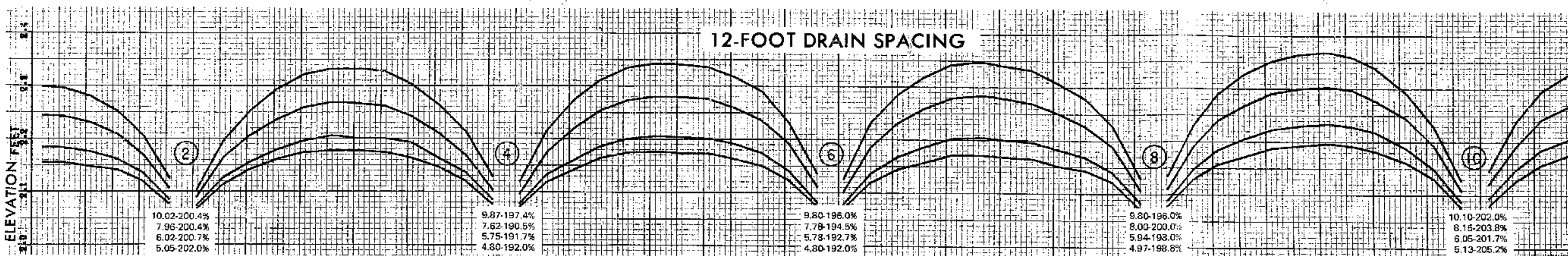


Note for the 12-foot drain spacing tests. The drain discharges are listed in order of the 5, 4, 3, and 2-1/2 ml/sec recharge rate tests. Also listed is the drain discharge expressed as a percent of the discharge rate from one recharge unit. Water table profiles are shown in descending order of recharge rates. The upper profile is for the 5 ml/sec recharge rate and the lower profile for the 2-1/2 ml/sec recharge rate.

Note for the 6-foot drain spacing tests. The drain discharges are listed in order of 10, 7-1/2, 5, and 2-1/2 ml/sec recharge rate tests. Also listed is the drain discharge expressed as a percent of the discharge rate from one recharge unit. Water table profiles are shown in descending order of recharge rates. The upper profile is for the 10 ml/sec recharge rate and the lower profile for the 2-1/2 ml/sec recharge rate.

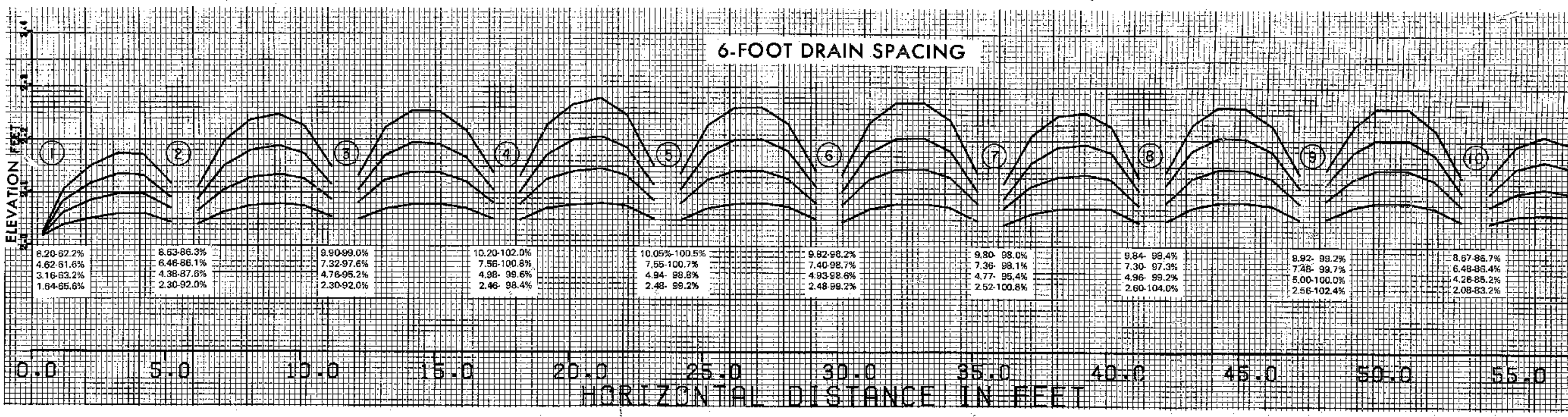
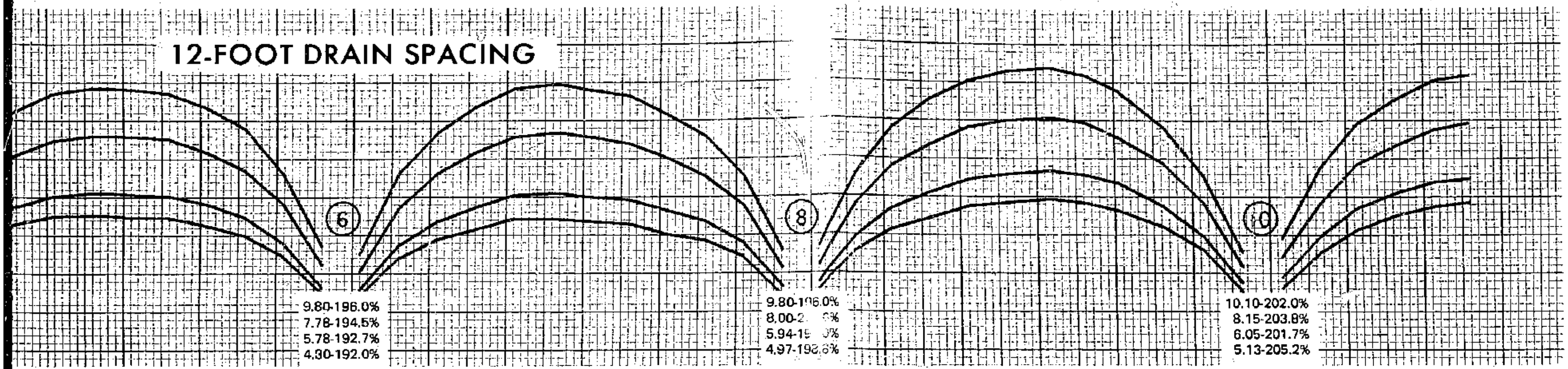


Figure 6. Water table profiles—0 percent slope.



Note for the 6-foot drain spacing tests. The drain discharges are listed in order of 10, 7-1/2, 5, and 2-1/2 ml/sec recharge rate tests. Also listed is the drain discharge expressed as a percent of the discharge rate from one recharge unit. Water table profiles are shown in descending order of recharge rates. The upper profile is for the 10 ml/sec recharge rate and the lower profile for the 2-1/2 ml/sec recharge rate.

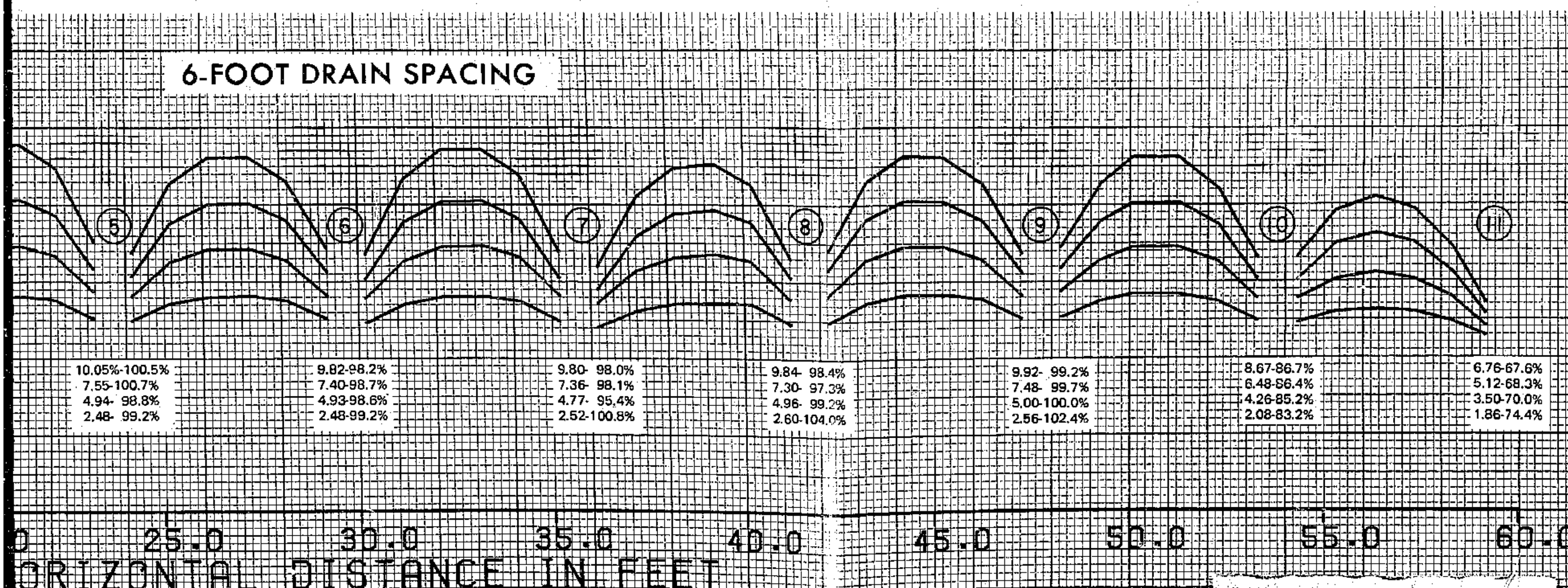


Figure 6. Water table profiles—0 percent slope.

FRAME 2

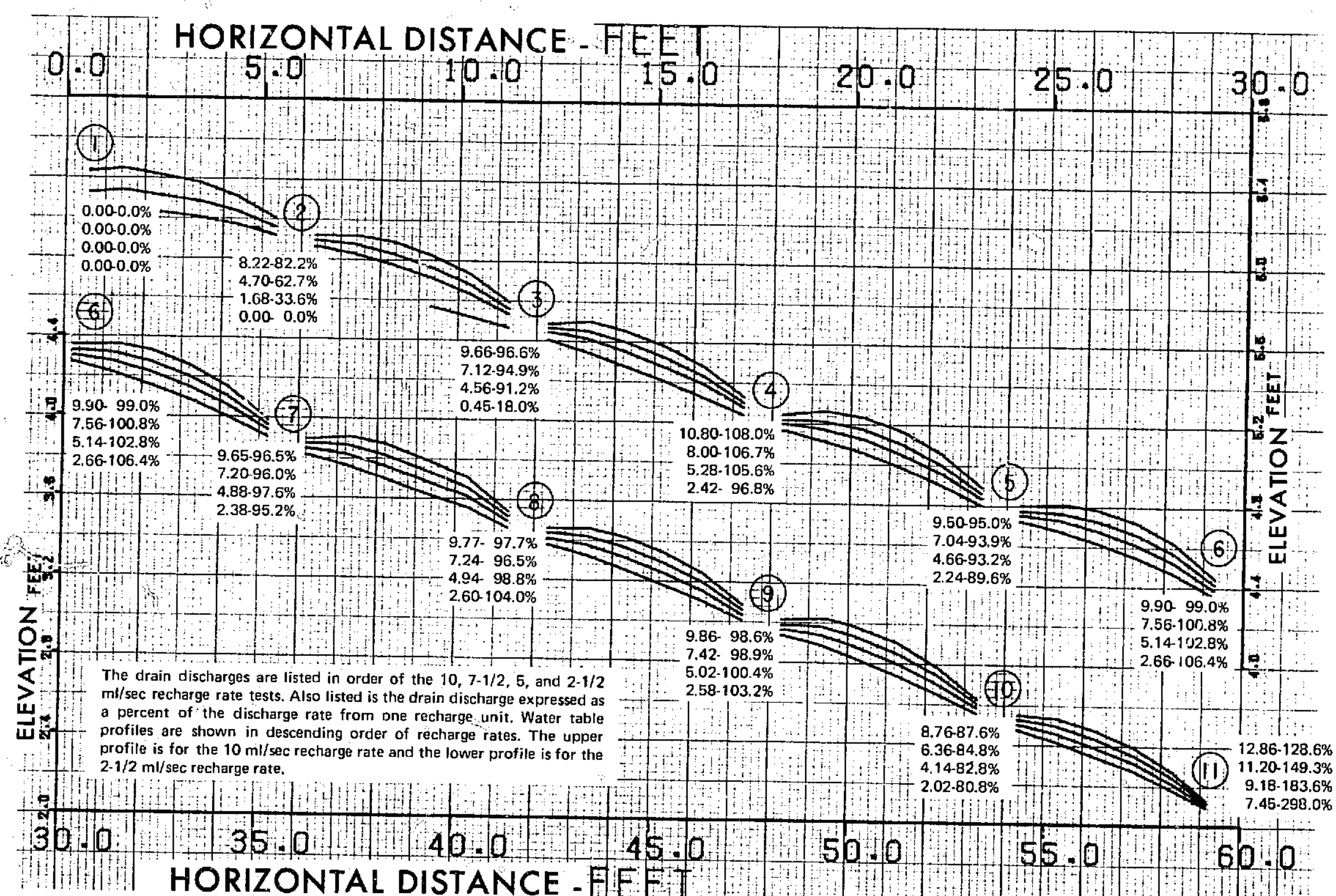
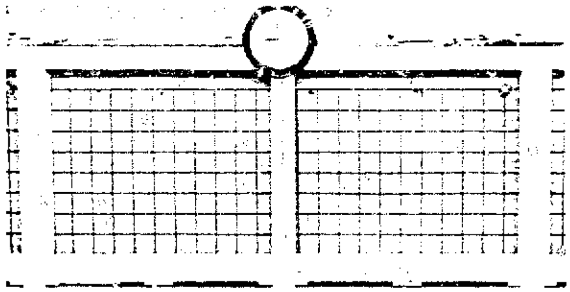
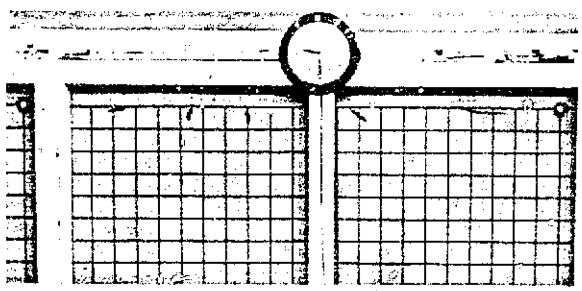


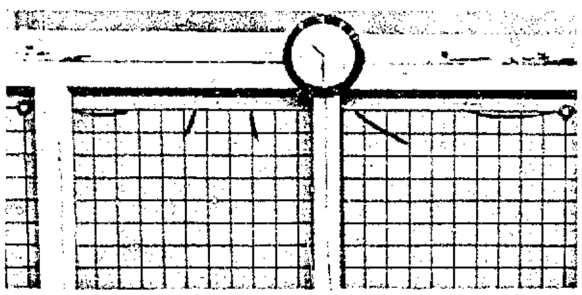
Figure 7. Water table profiles—7-1/2 percent slope—6-foot drain spacing.



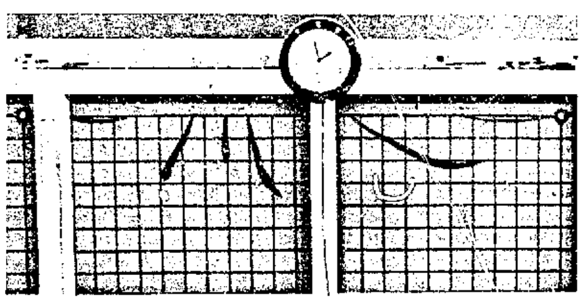
Start of test. Photo PX-D-70794



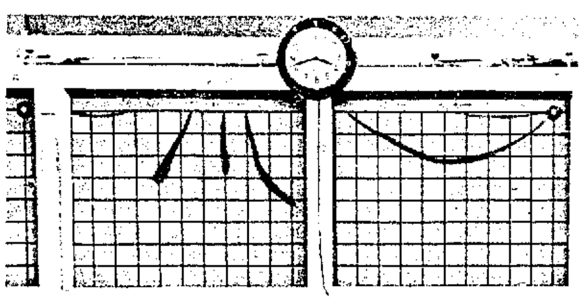
1/2 hour. Photo PX-D-70795



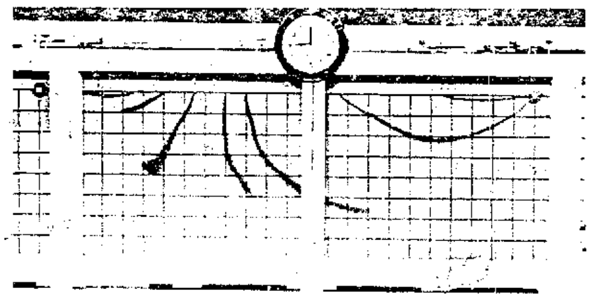
1-1/2 hours. Photo PX-D-70796



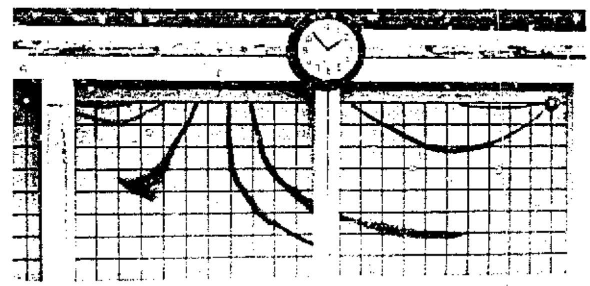
5 hours. Photo PX-D-70797



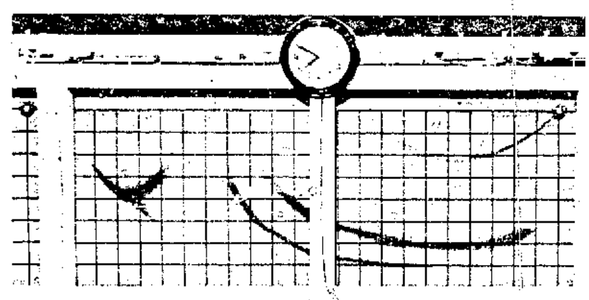
6-3/4 hours. Photo PX-D-70798



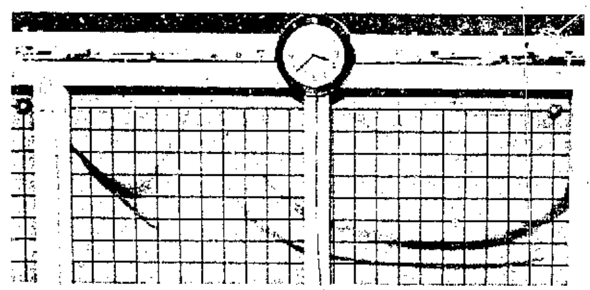
12 hours. Photo PX-D-70813



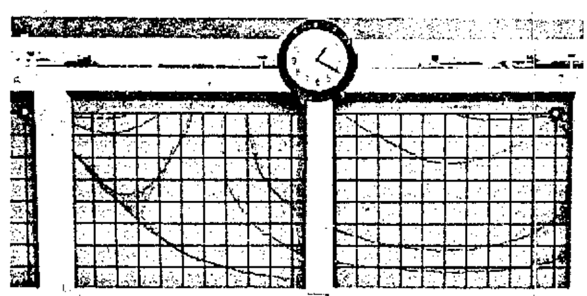
17 hours. Photo PX-D-70814



22-3/4 hours. Photo PX-D-70815

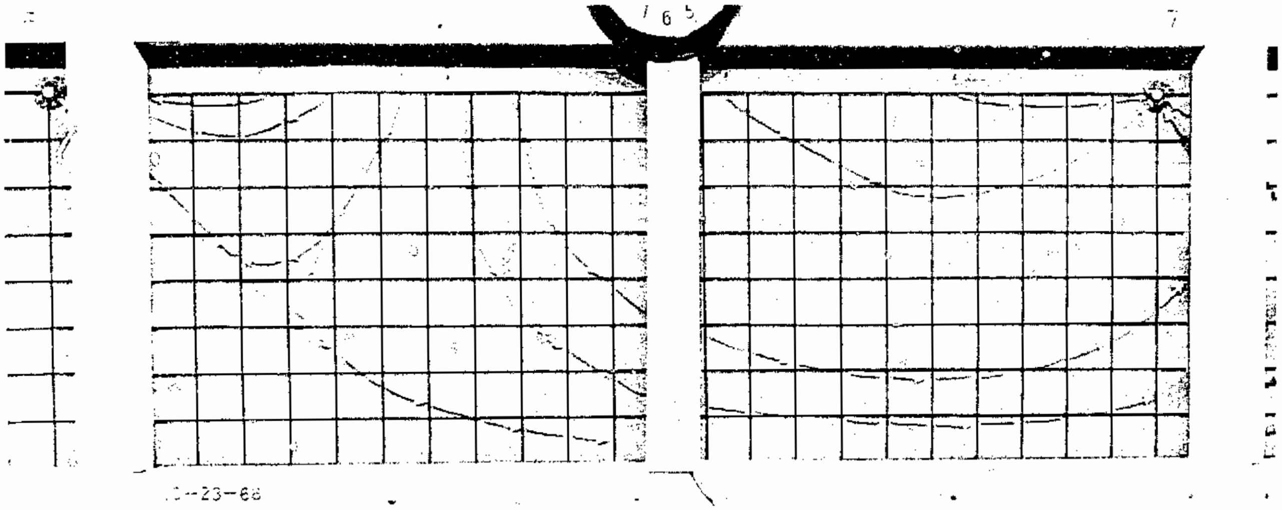


33-1/2 hours. Photo PX-D-70816

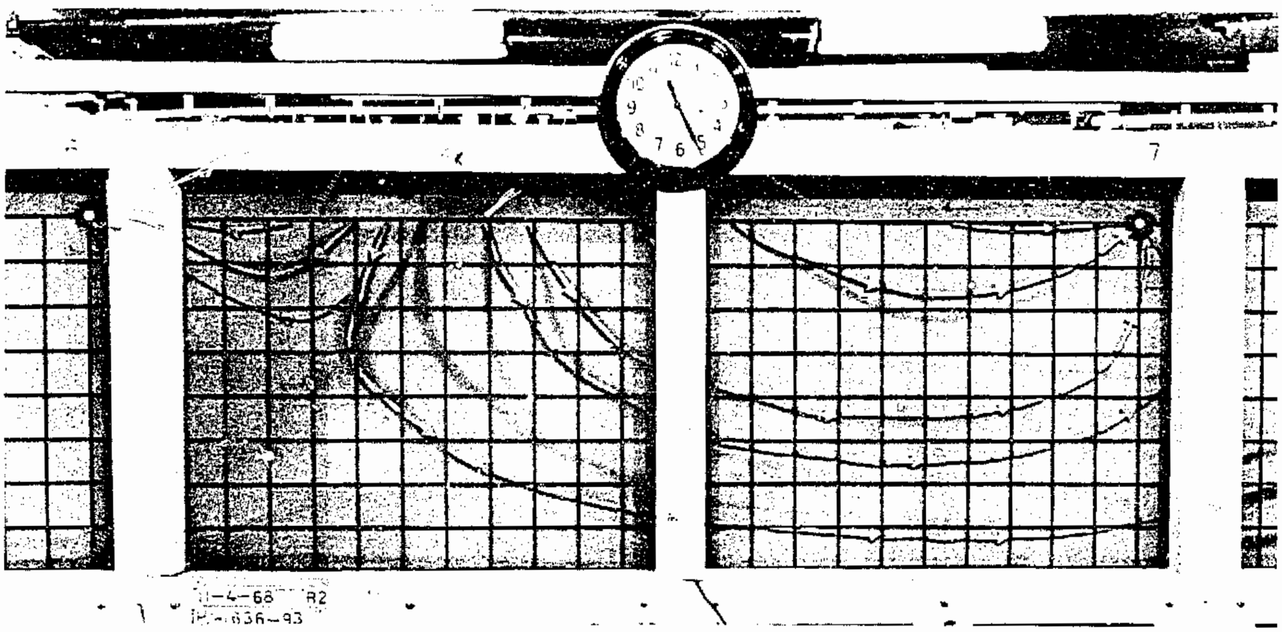


Completion of test. Photo PX-D-70817

Figure 8. Streak-line tests showing formation of streamlines.
Slope 2-1/2 percent—Recharge rate 10 ml/sec

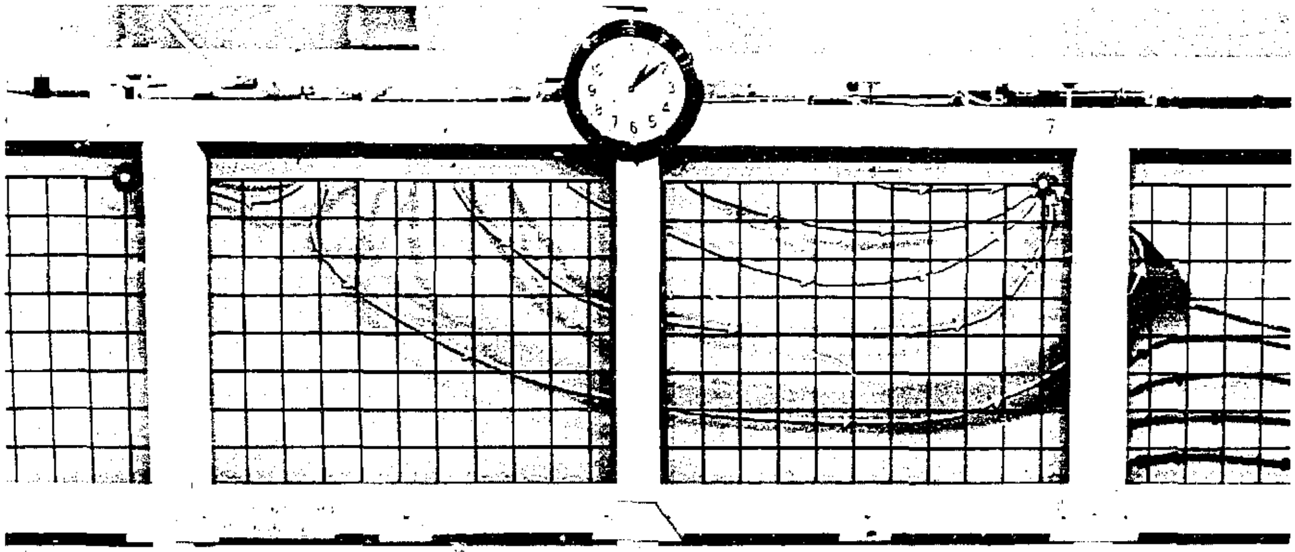


Recharge rate 10 ml/sec. Photo PX-D-70800

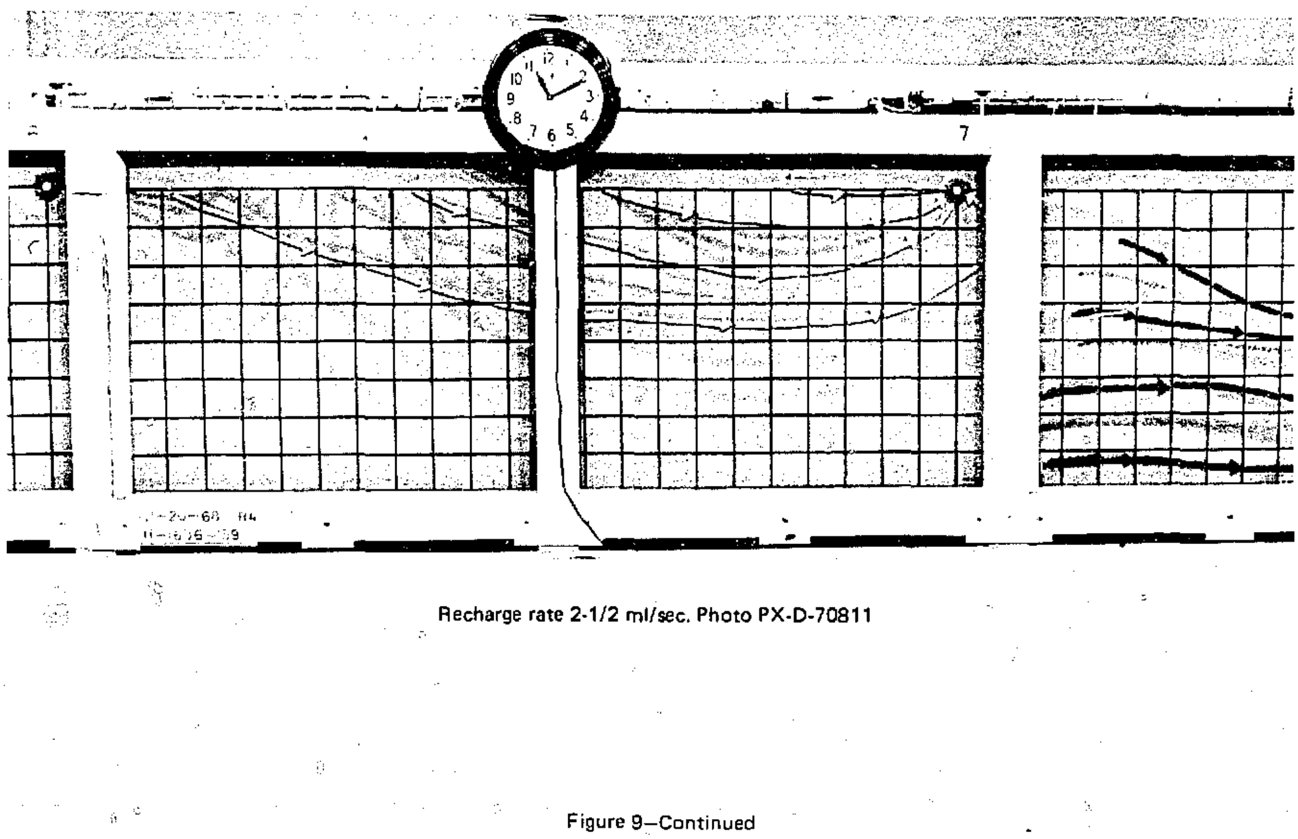


Recharge rate 7-1/2 ml/sec. Photo PX-D-70805

Figure 9. Streak-line tests showing the flow system of the recharge flowing into the drains—6-foot drain spacing and 2-1/2 percent slope.

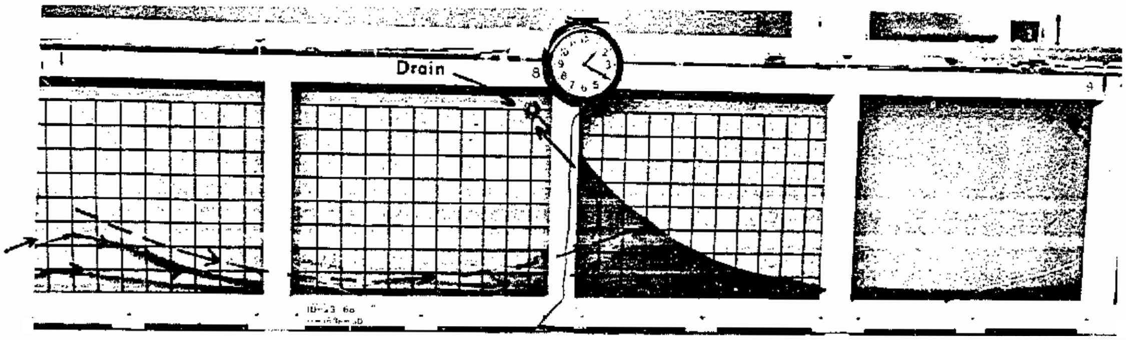


Recharge rate 5 ml/sec. Photo PX-D-70807

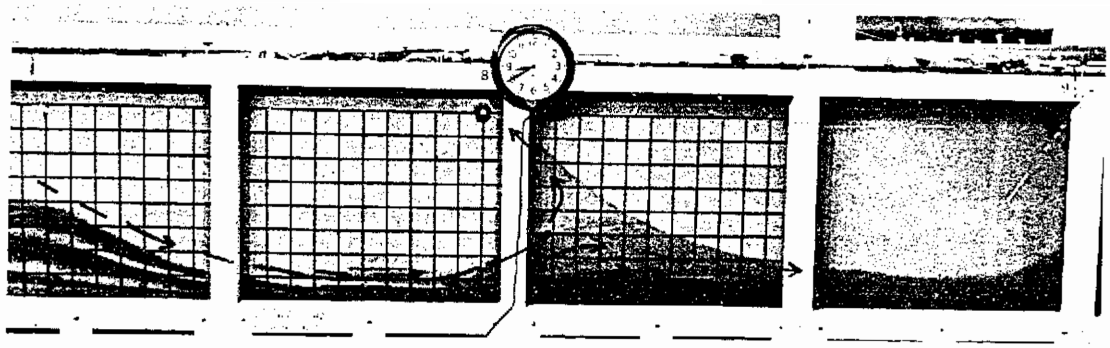


Recharge rate 2-1/2 ml/sec. Photo PX-D-70811

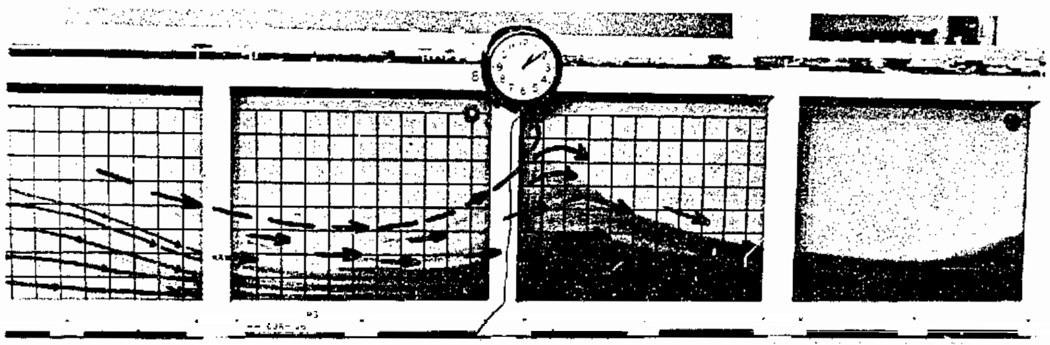
Figure 9—Continued



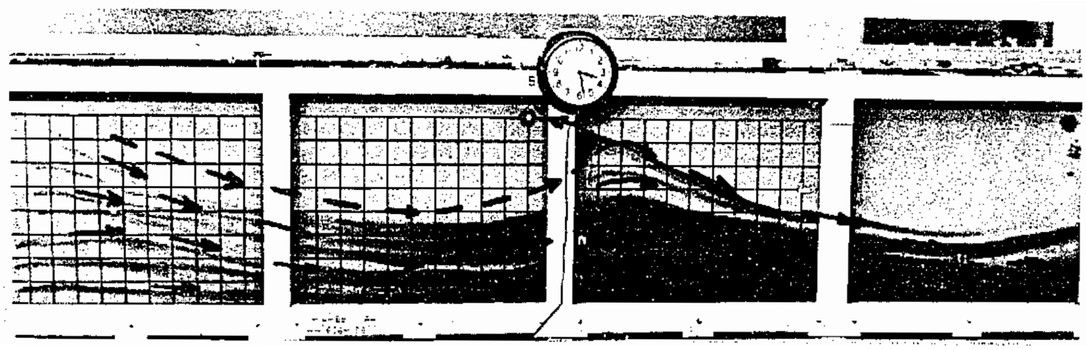
Recharge rate 10 ml/sec. Photo PX-D-70799



Recharge rate 7-1/2 ml/sec. Photo PX-D-70804



Recharge rate 5 ml/sec. Photo PX-D-70808



Recharge rate 2-1/2 ml/sec. Photo PX-D-70810

Figure 10. Streak-line tests showing the flow system of water passing beneath the drains—6-foot drain spacing and 2-1/2 percent slope.

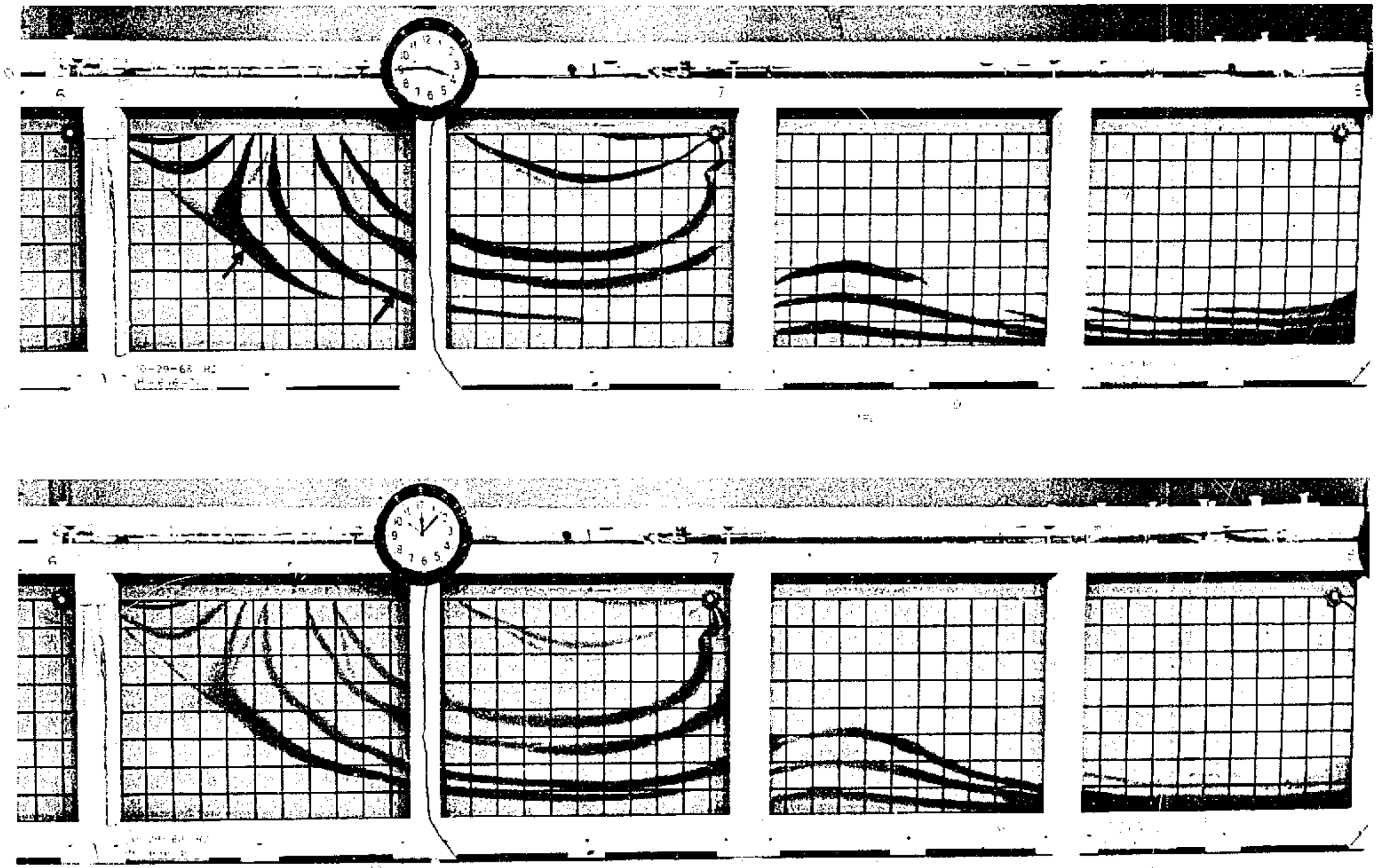
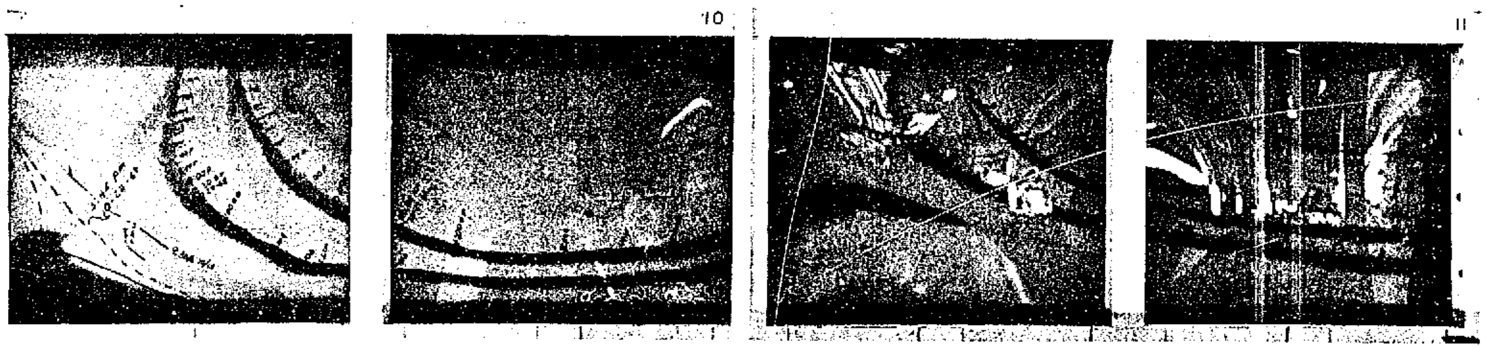
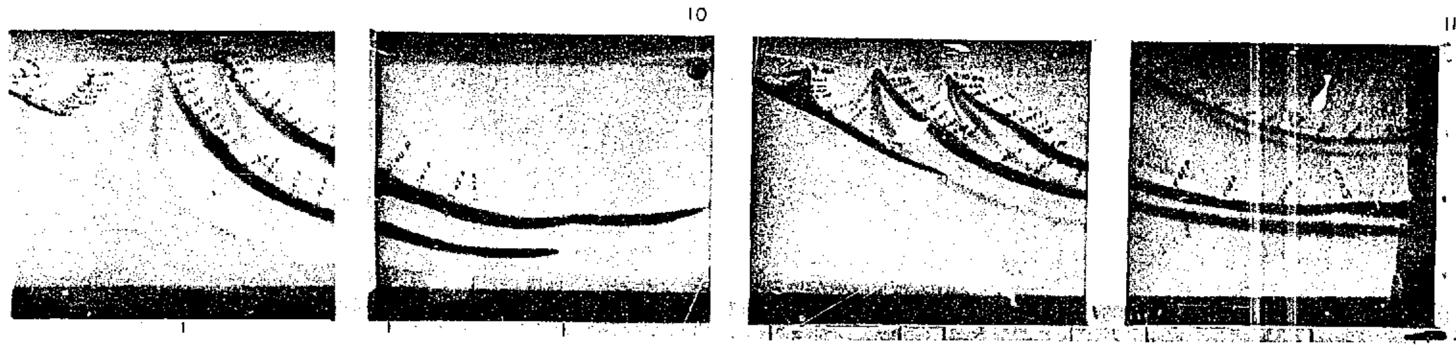


Figure 11. Streak-line tests showing recharge flowing beneath the drain.

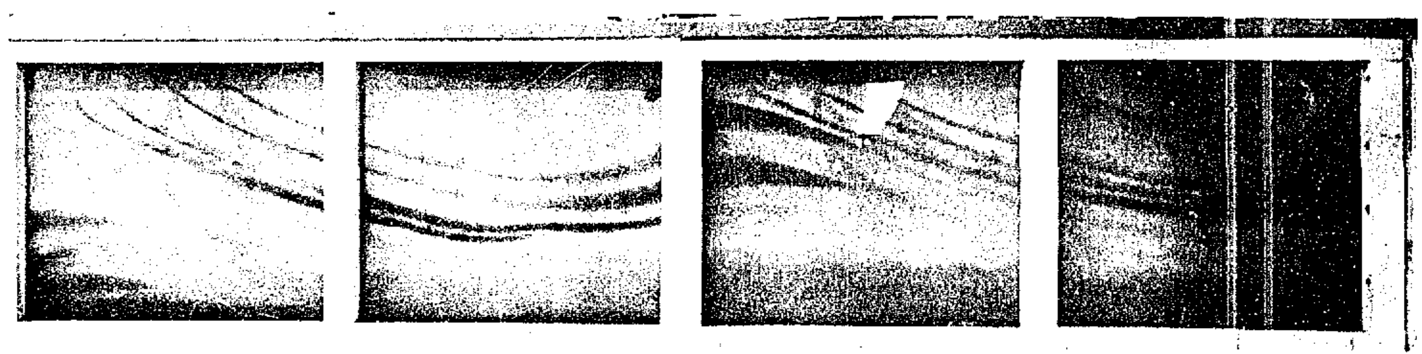
Streak lines for 2-1/2 percent slope and 7-1/2 ml/sec recharge rate test. The upper photograph was after 32 hours of operation and the lower photograph was after 52 hours of operation. Photo PX-D-70801. The two panels between Drains No. 6 and 7 show streak lines formed from recharge entering the water table. The two panels between Drains No. 7 and 8 show streak lines of water flowing downslope and passing beneath the drains. Note the two streak lines in the upper photograph that were designated by arrows. These two streak lines started near the dividing point of the water table between Drains No. 6 and 7. For a perfect equilibrium condition these two streak lines would flow into Drain No. 7. The bottom photograph shows where the two streak lines passed beneath Drain No. 7 and flowed downslope. Photo PX-D-70802



Recharge 7-1/2 ml/sec. Photo PX-D-70803



Recharge 5 ml/sec. Photo PX-D-70806



Recharge rate 2-1/2 ml/sec. Photo PX-D-70809

Figure 12. Streak-line tests showing streamlines entering the end drain envelope—6-foot drain spacing and 2-1/2 percent slope.

The upper two photographs have marks and notes which were made on the plexiglass sides. During these tests streak-line locations were marked at given times to help follow the movement of the dyed water.

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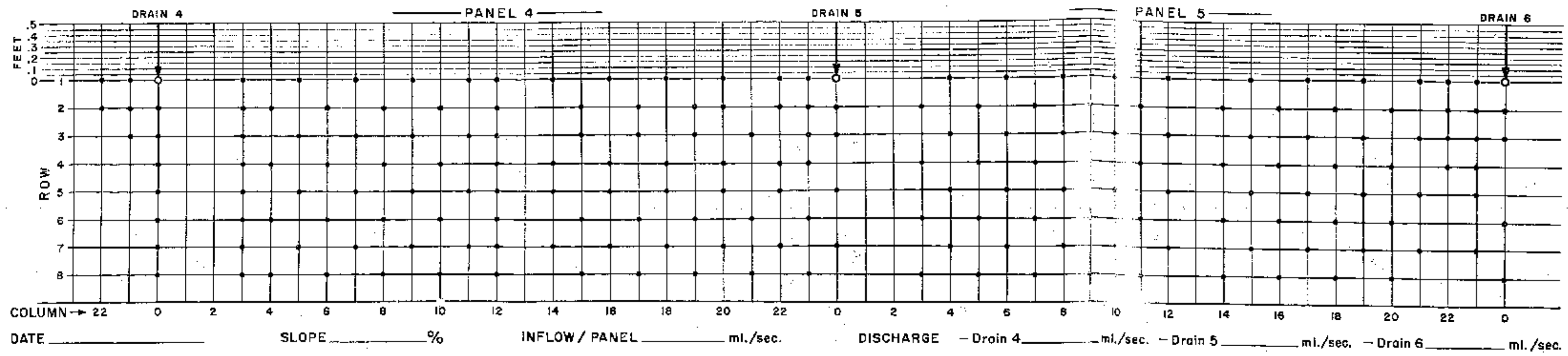


Figure 13A. Location of the piezometer taps are shown by dots on the grid. Spacing of the grid was 3 inches. The piezometer taps were identified by panel, row, and column numbers. The absence of piezometer taps at Columns No. 1 and 2 was due to the vertical wooden structure members which supported the plexiglass sides. This form was used to record the pressure measurements.

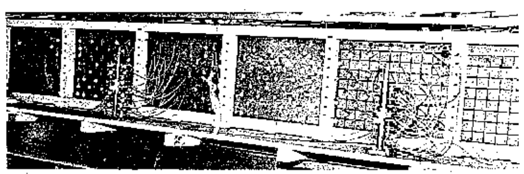


Figure 13B. Photograph showing plexiglass side of the sand tank where the pressure measurements were made. The two manifolds are connected to a group of the piezometer taps. The manifolds were also connected to one side of the pressure transducer. Each piezometer tap had an identification tag. When connecting the taps to the manifold the individual tags were transferred to the corresponding manifold valves. The identification tags helped prevent a mixup among the 60 different flexible tubes from the manifolds. Photo PX-D-70812

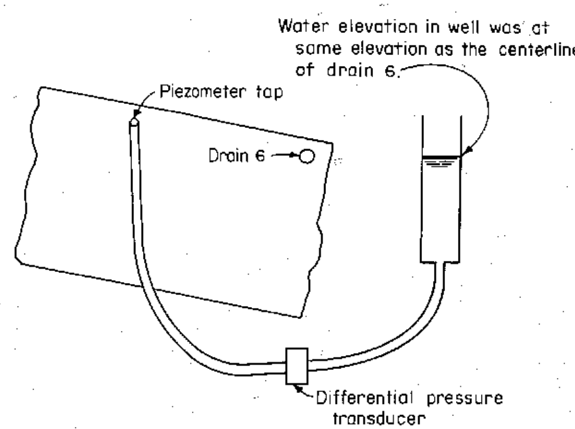


Figure 13C. Schematic showing reference datum of pressure measurements and hydraulic connection of differential pressure transducer.

Figure 13. Pressure measurements.

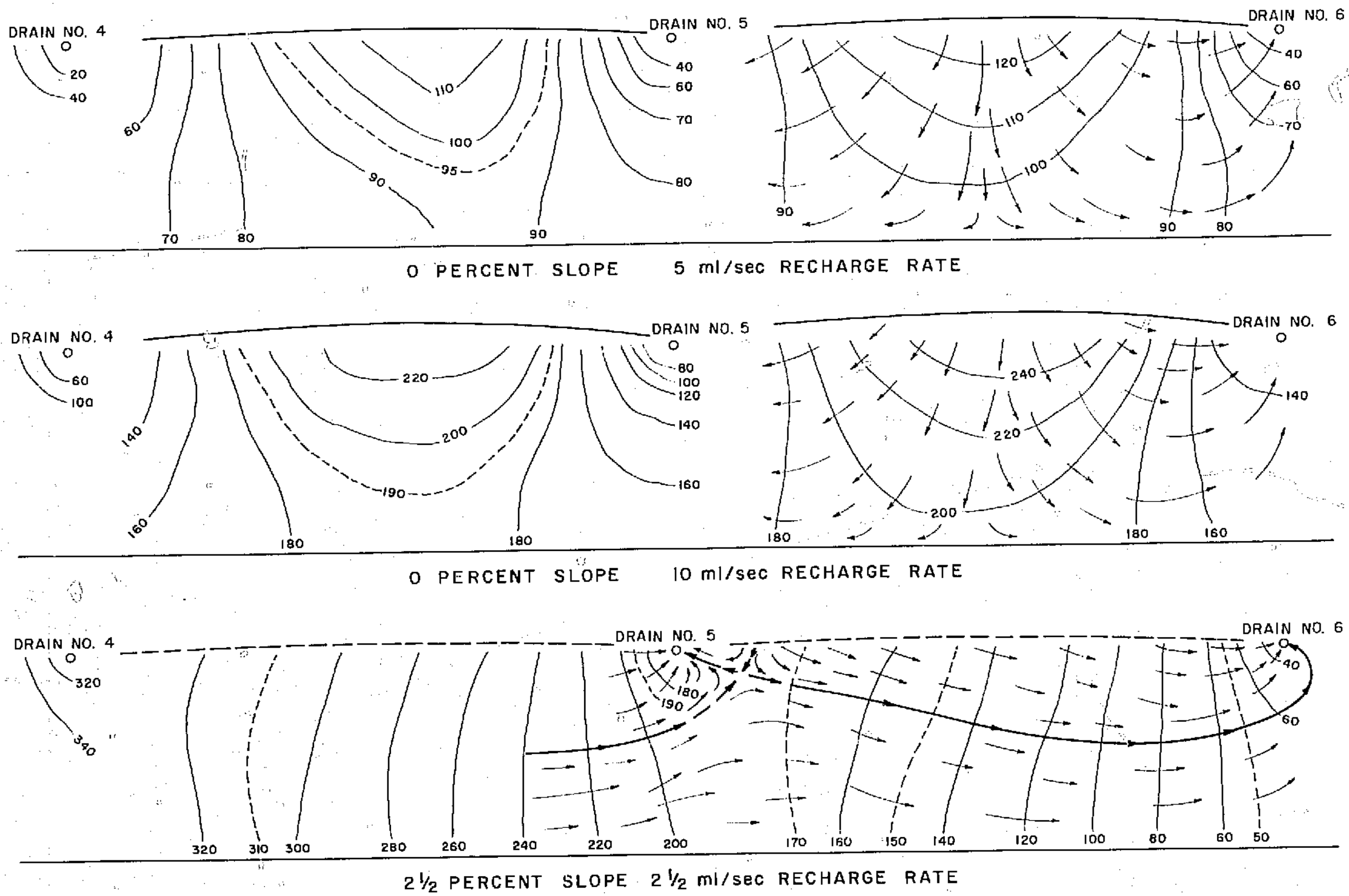


Figure 14. Equal potential and flow lines determined from pressure measurements.

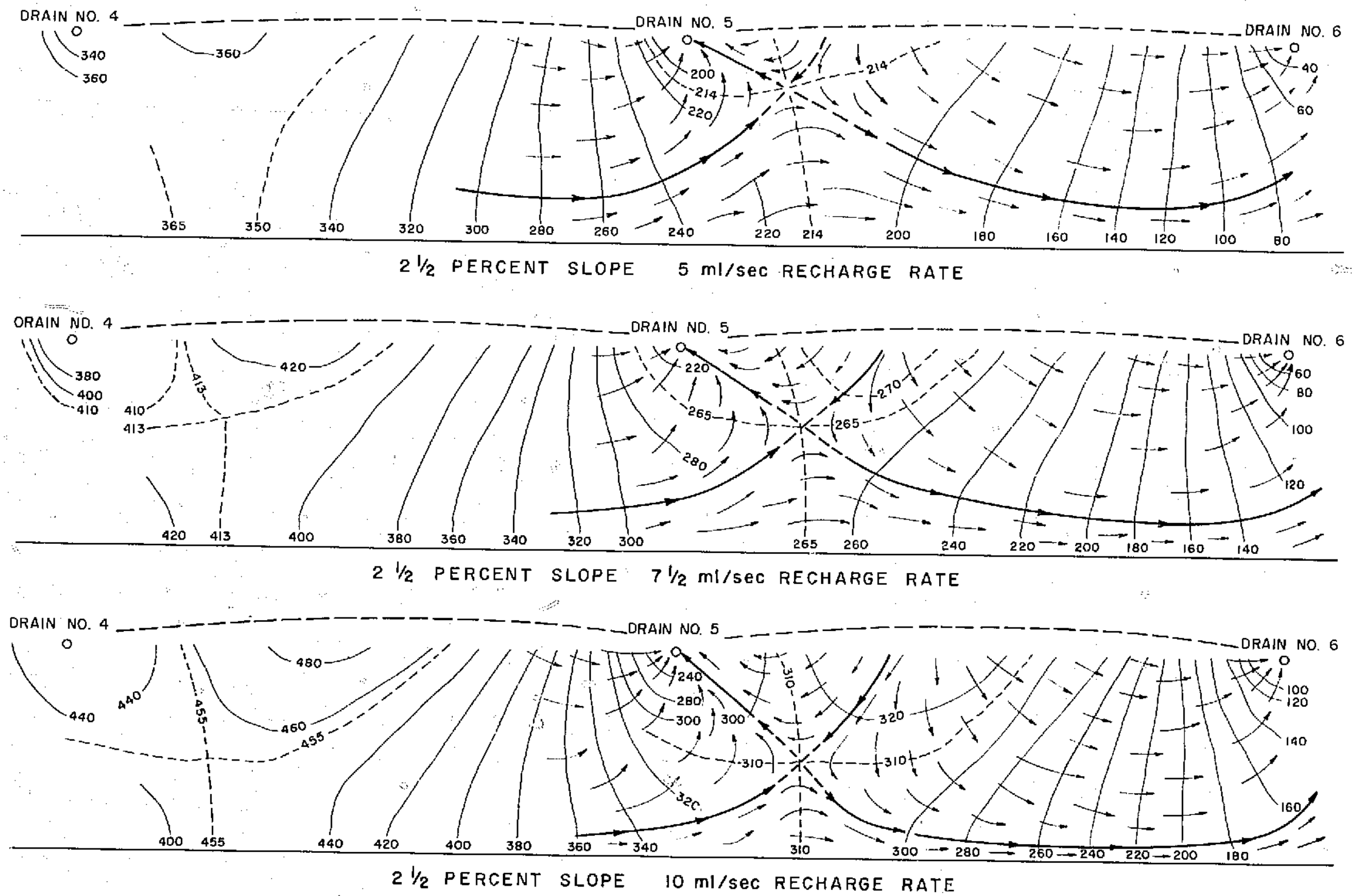


Figure 15. Equal potential and flow lines determined from pressure measurements.

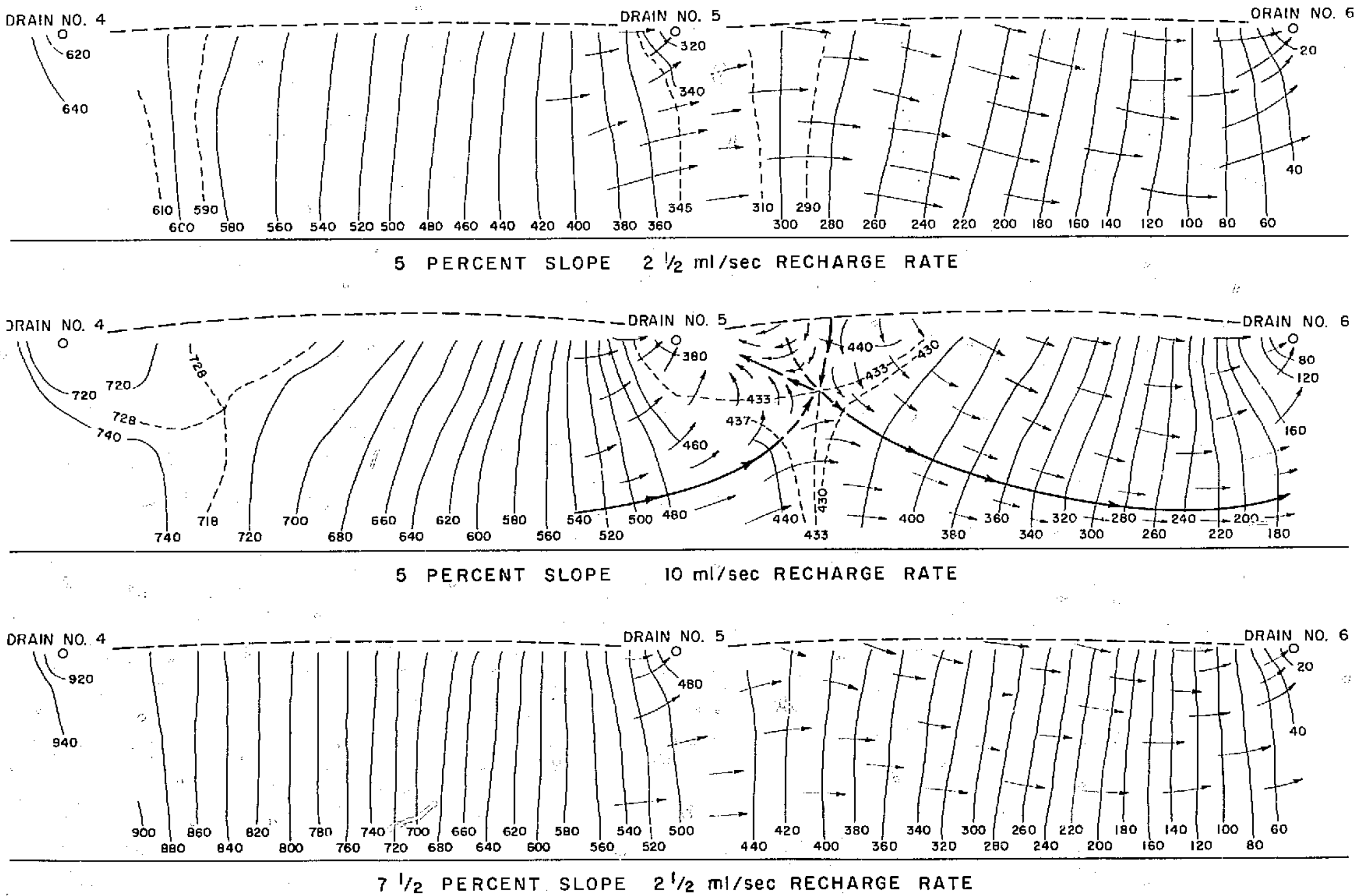


Figure 16. Equal potential and flow lines determined from pressure measurements.

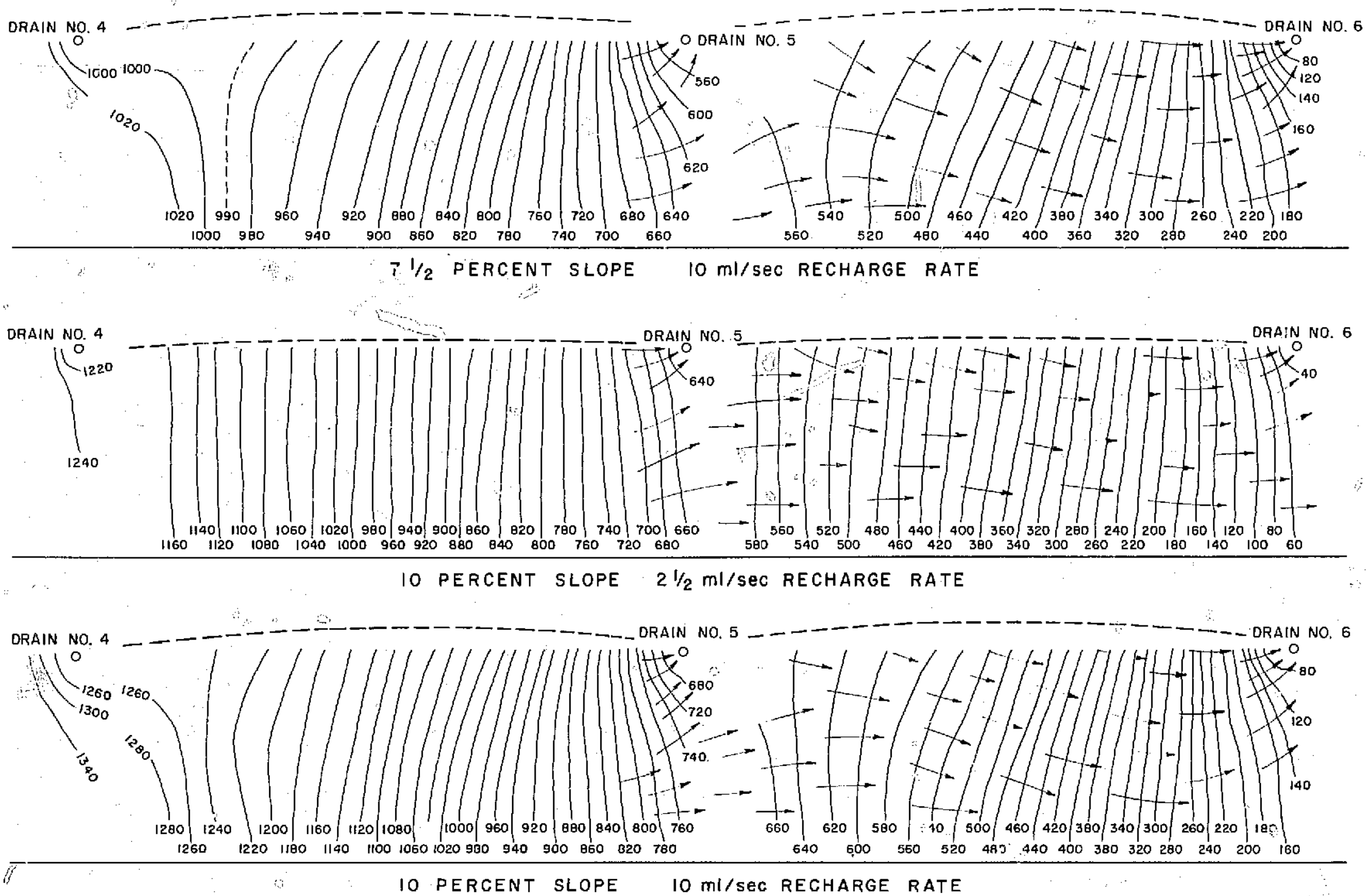


Figure 17. Equal potential and flow lines determined from pressure measurements.

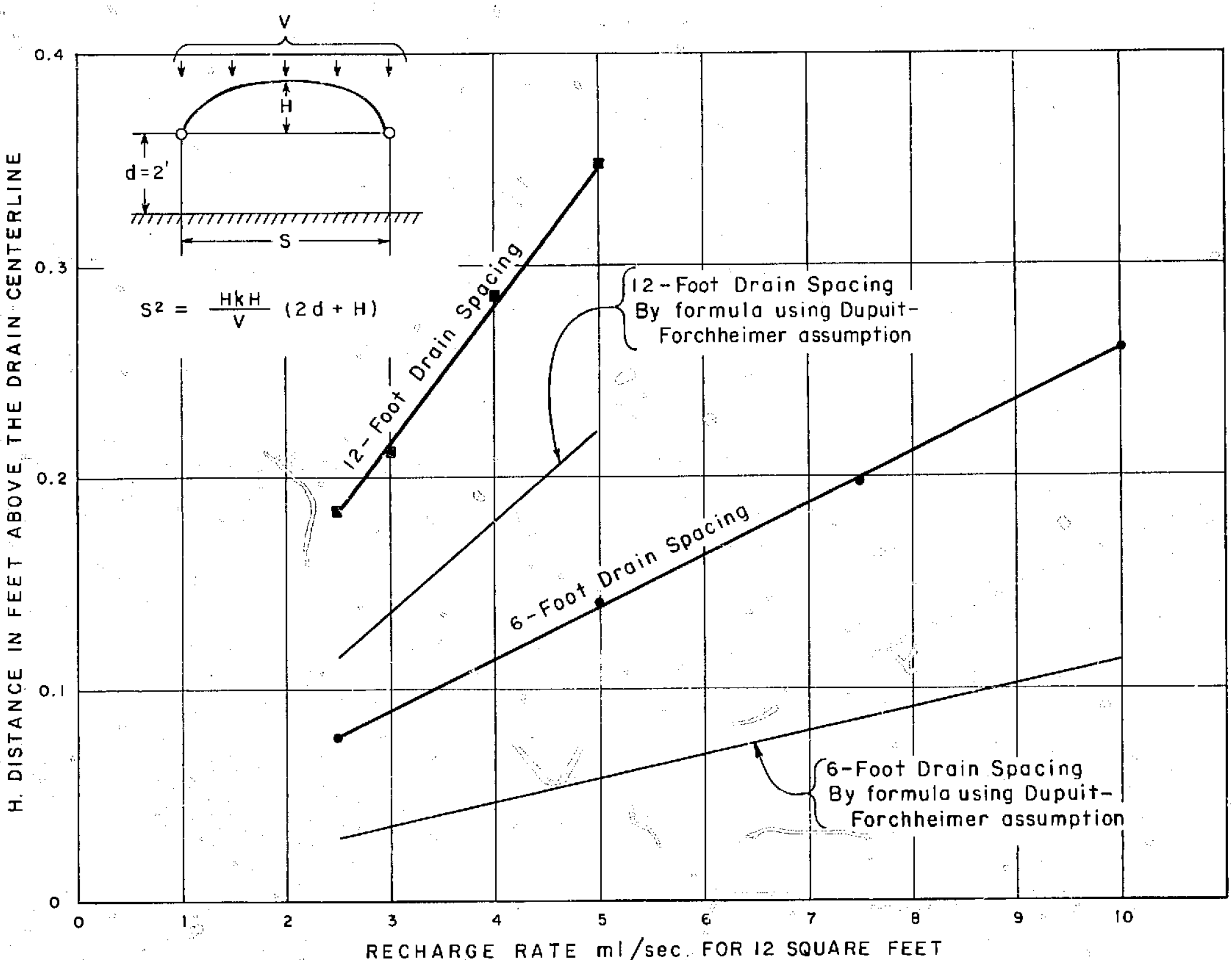


Figure 18. Recharge rate—Water table elevation midway between the drains at 0 percent slope.

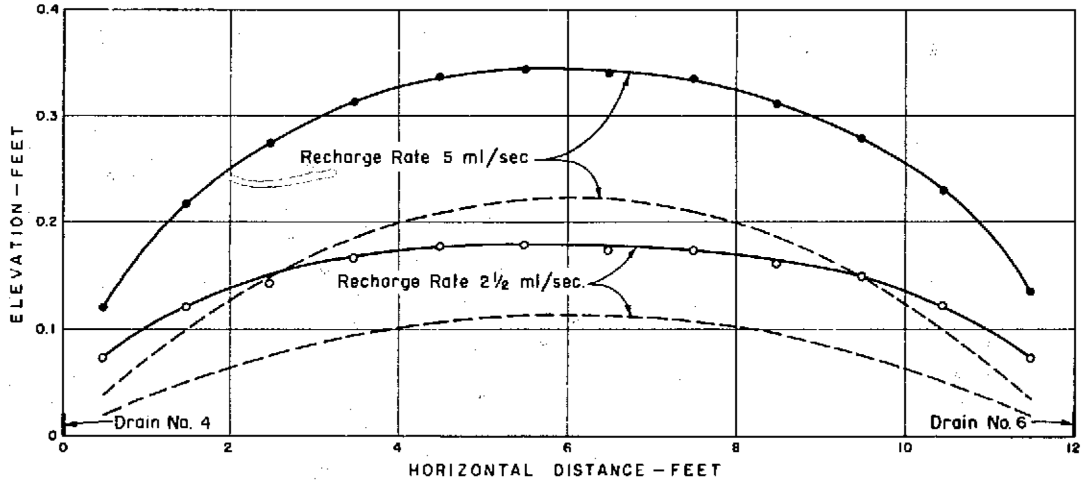


Figure 19A. Water table profiles for 12-foot drain spacing.

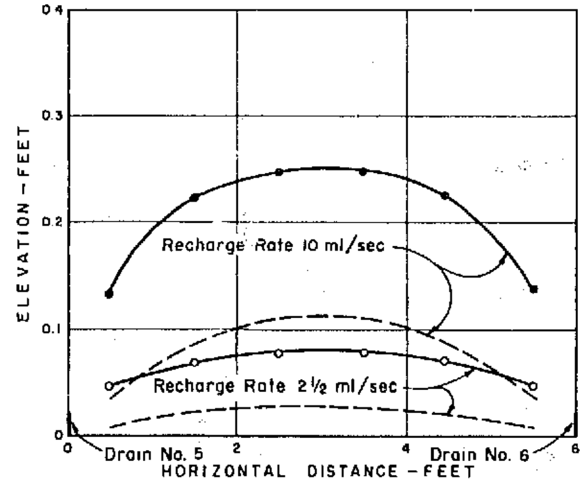
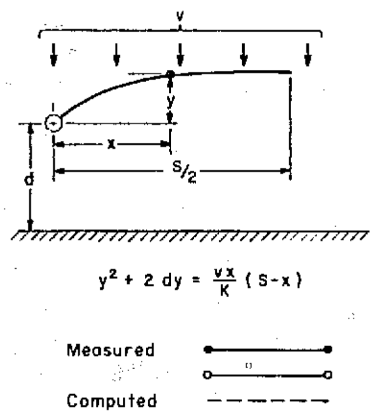


Figure 19B. Water table profiles for 6-foot drain spacing.



$$y^2 + 2\,dy = \frac{vx}{K}(S-x)$$

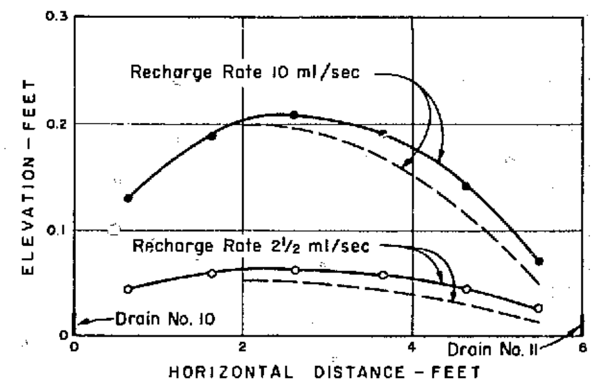


Figure 19C. Water table profiles for 6-foot drain spacing showing the influence of the end drain envelopes.

Figure 19. Comparison of measured water table profiles with water table profiles computed by using Dupuit-Forchheimer assumptions–Zero percent slope tests.

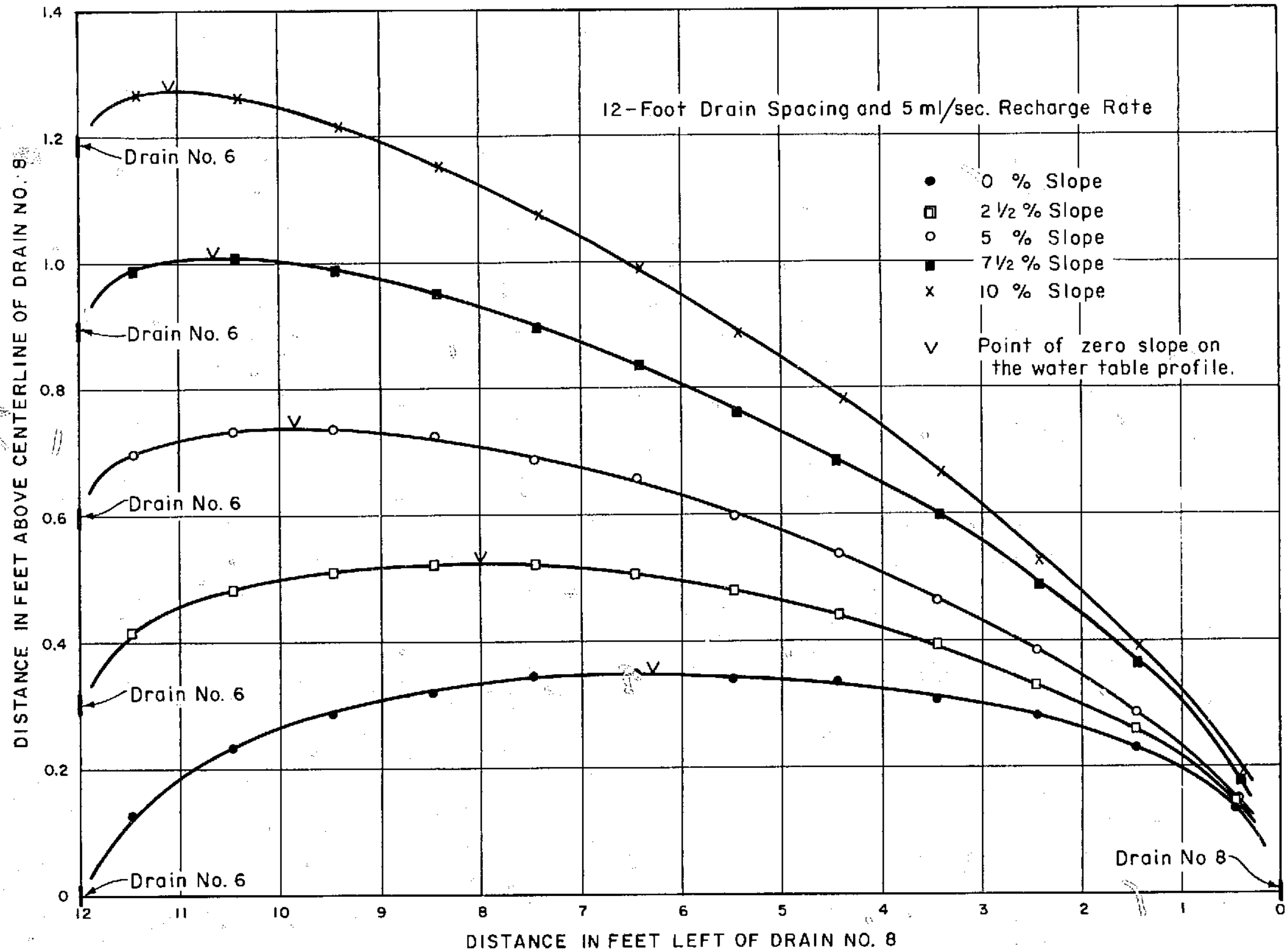


Figure 20. Water table profiles between Drains No. 6 and 8 by slope.

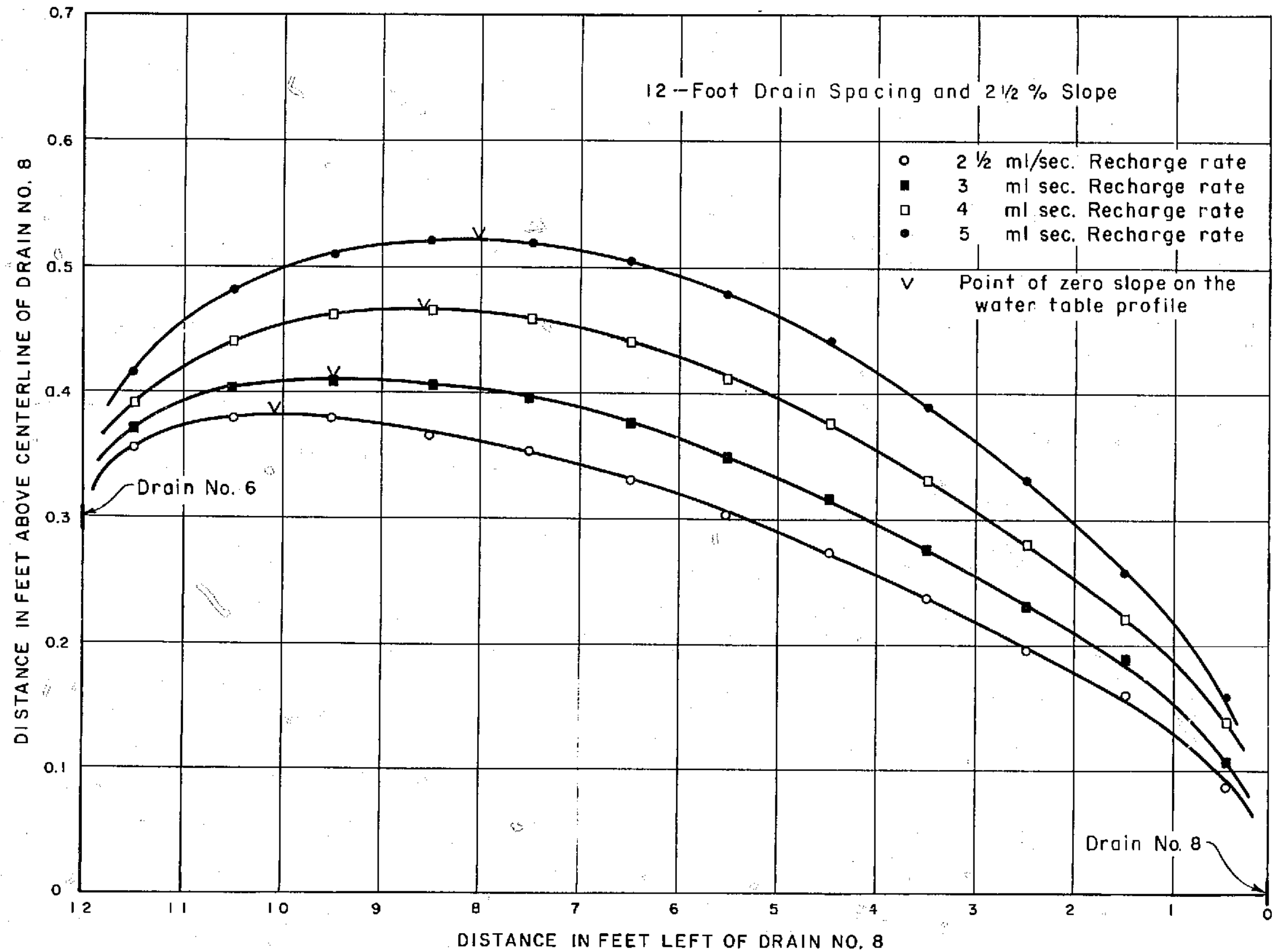


Figure 21. Water table profiles between Drains No. 6 and 8 by recharge rete.

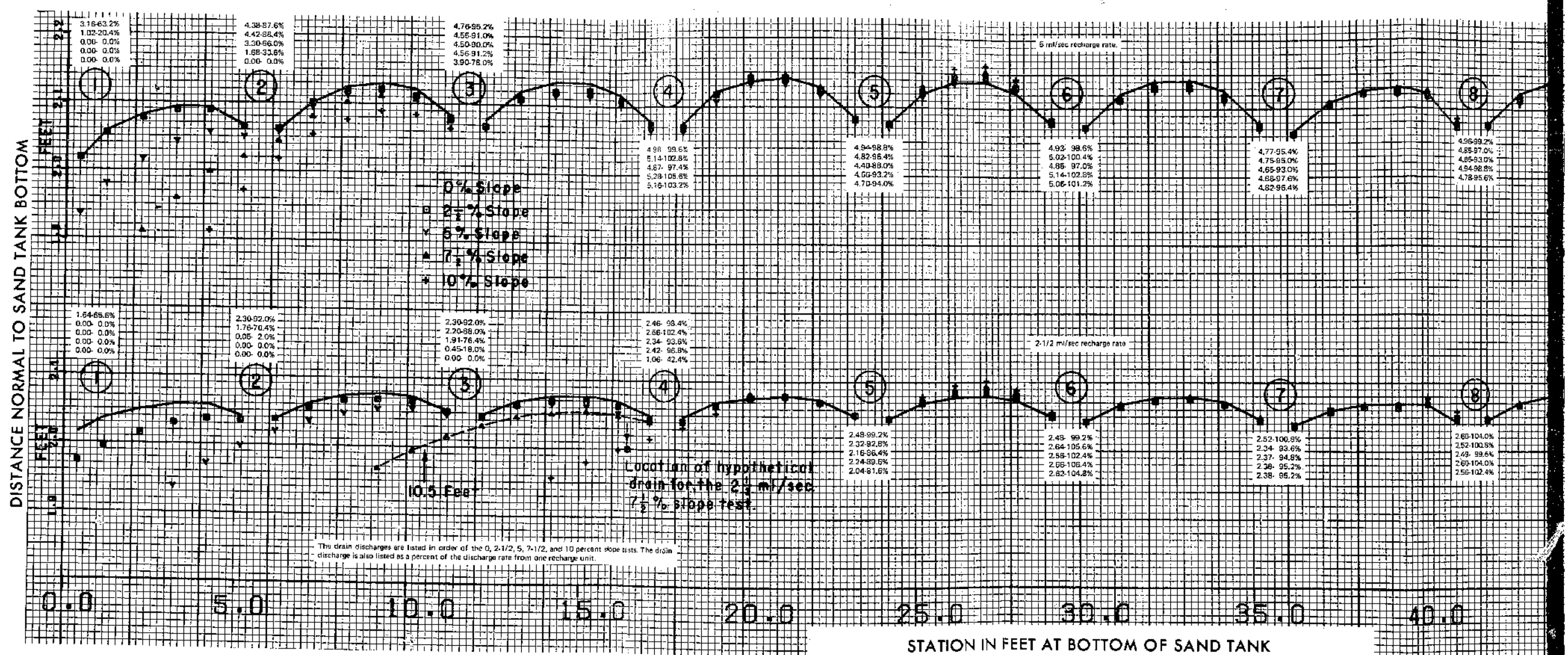


Figure 22. Water table profiles normal to the tank bottom—6-foot drain spacing.

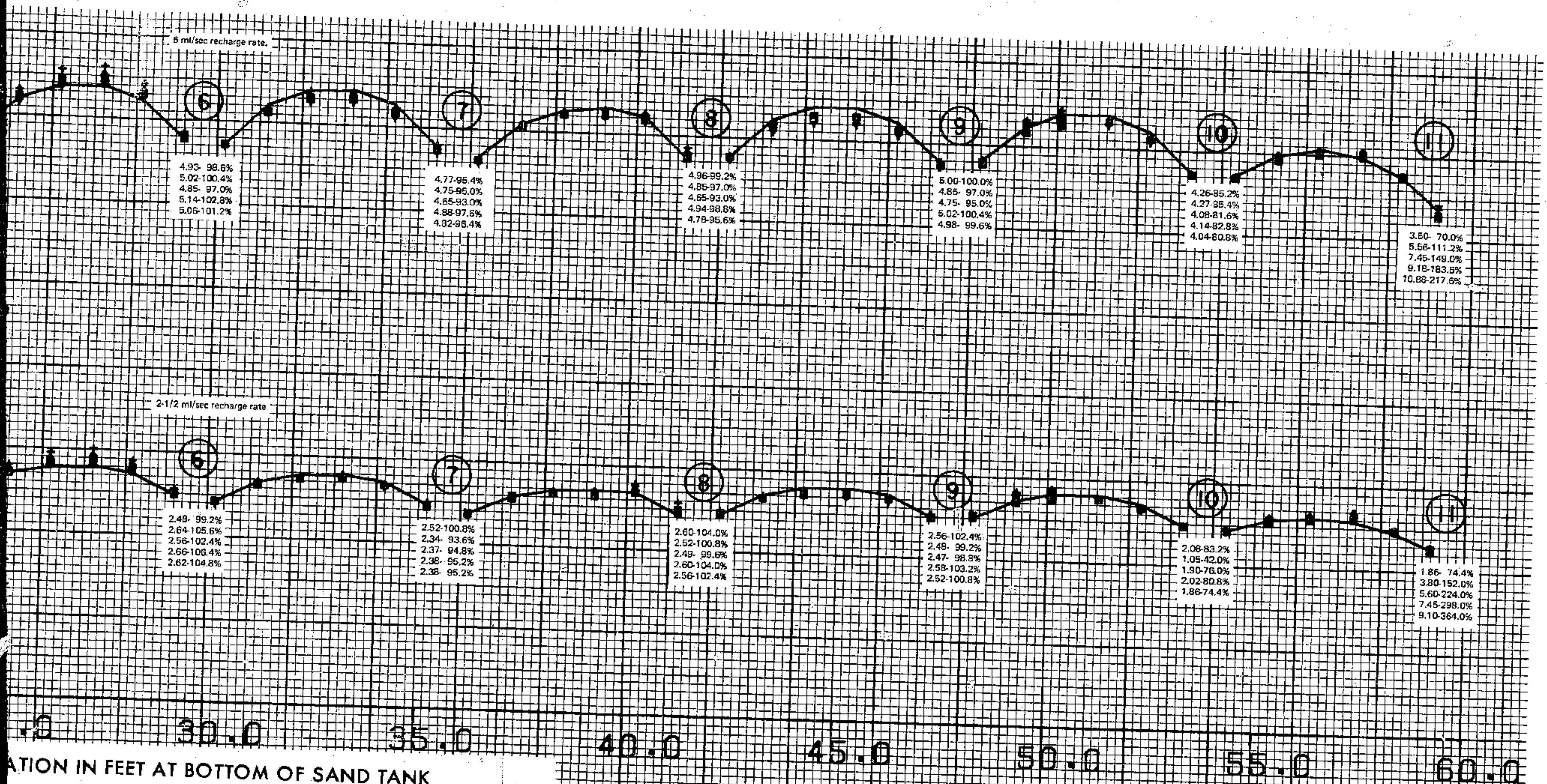


Figure 22. Water table profiles normal to the tank bottom—6-foot drain spacing.

FRAME 2

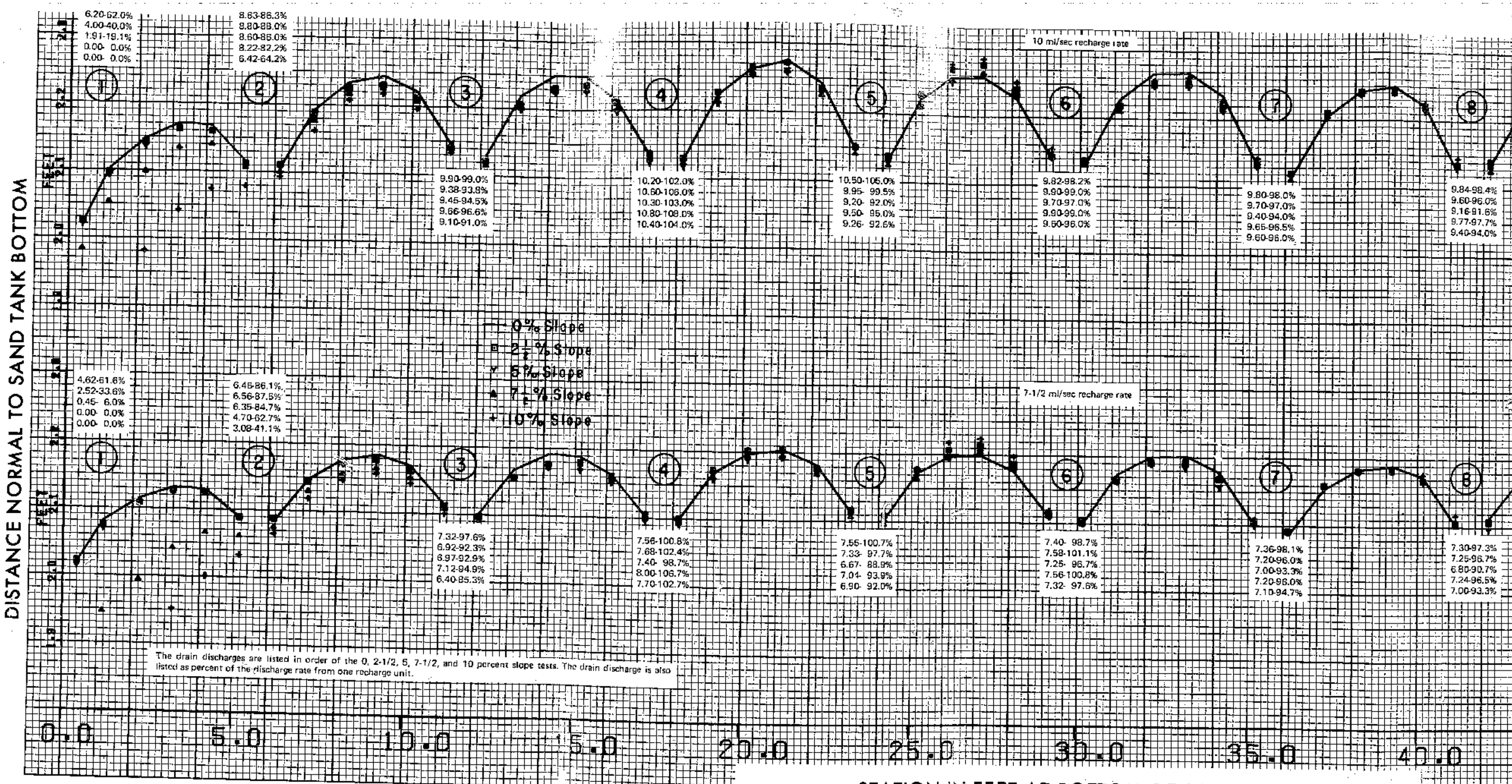


Figure 23 Water table profiles normal to the tank bottom—6-foot drain spacing.

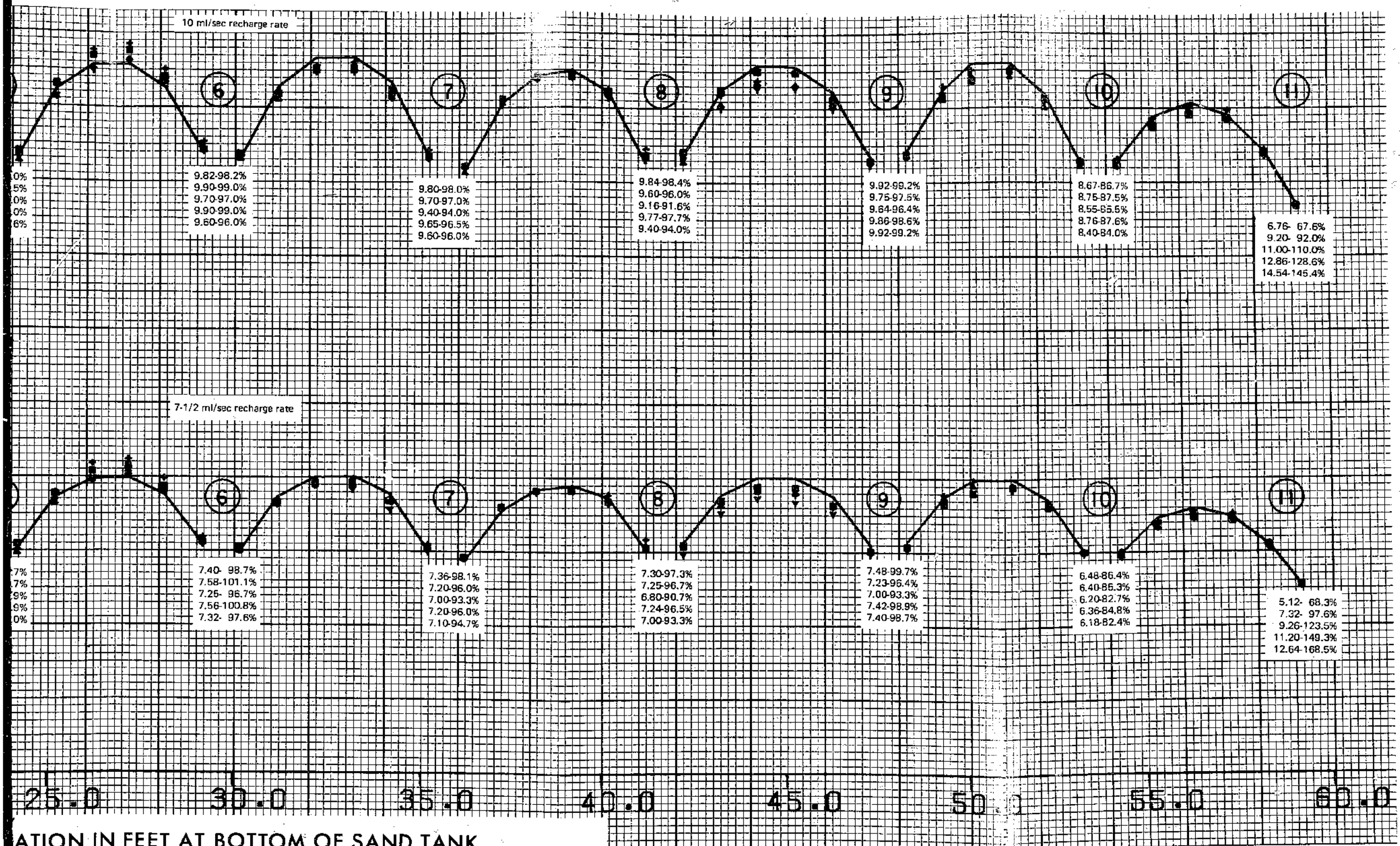


Figure 23. Water table profiles normal to the tank bottom—6-foot drain spacing.

FRAME 2

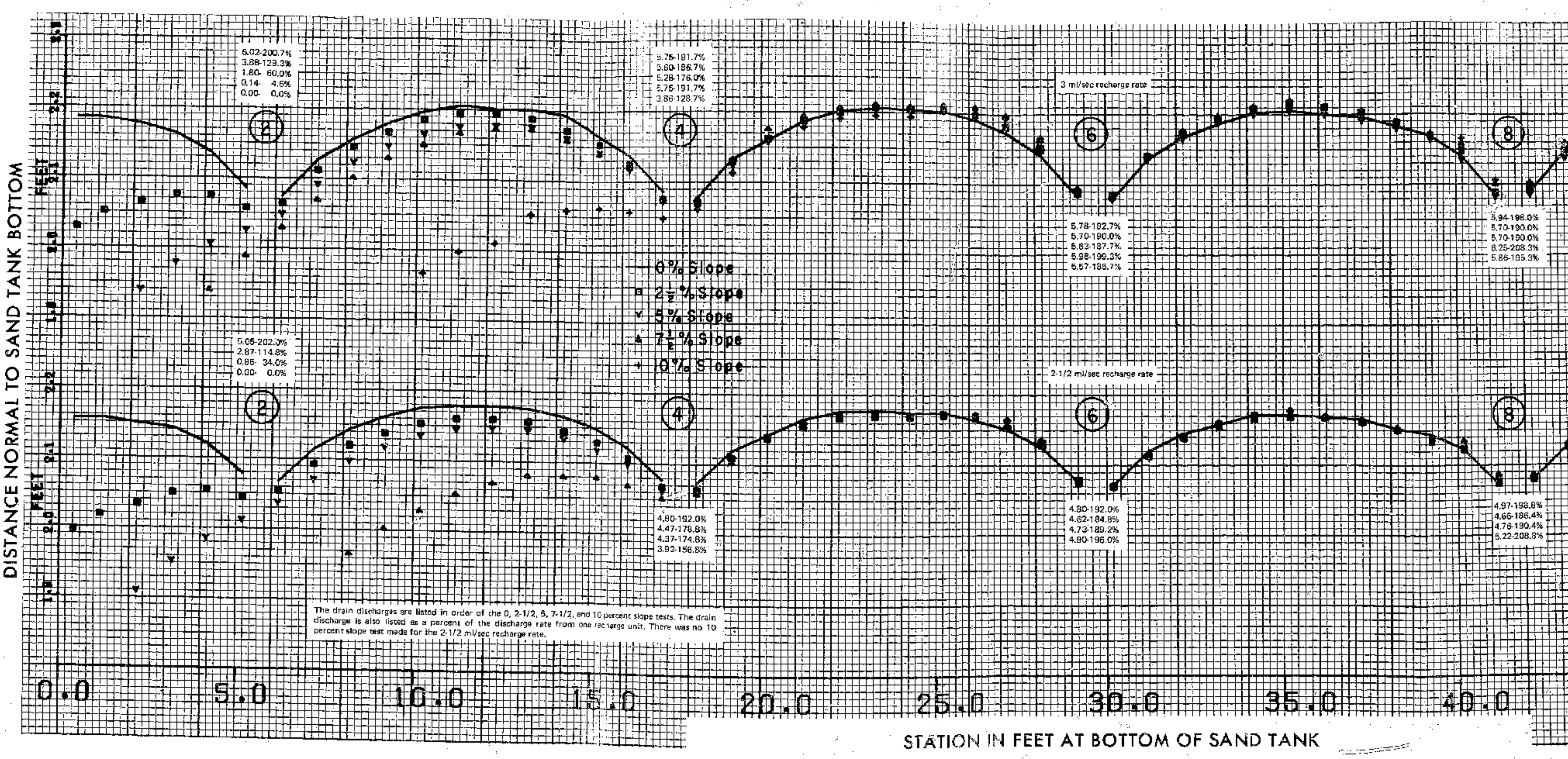
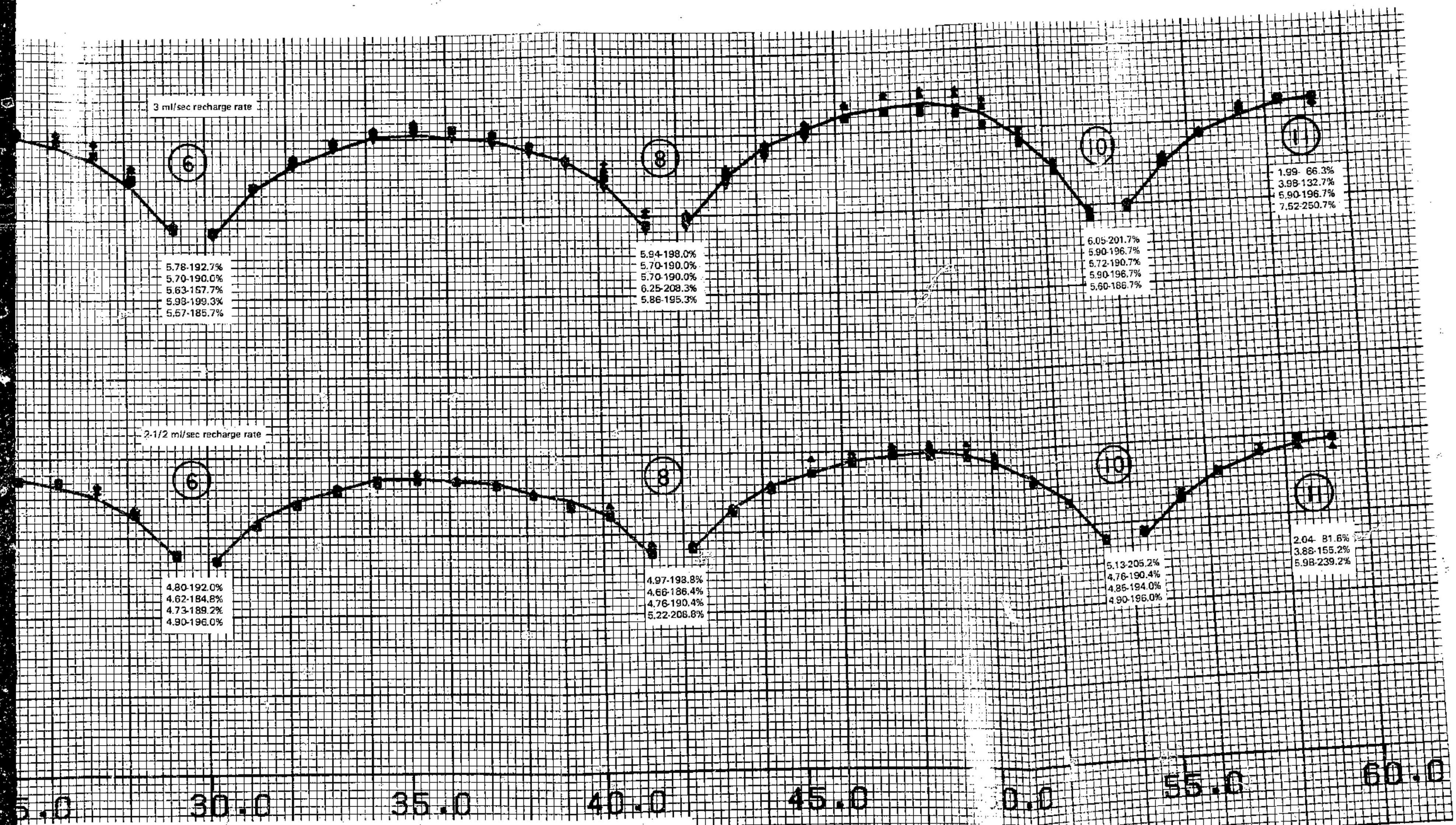


Figure 24. Water table profiles normal to the tank bottom—12-foot drain spacing.



TION IN FEET AT BOTTOM OF SAND TANK

Figure 24. Water table profiles normal to the tank bottom—12-foot drain spacing.

FRAME 2

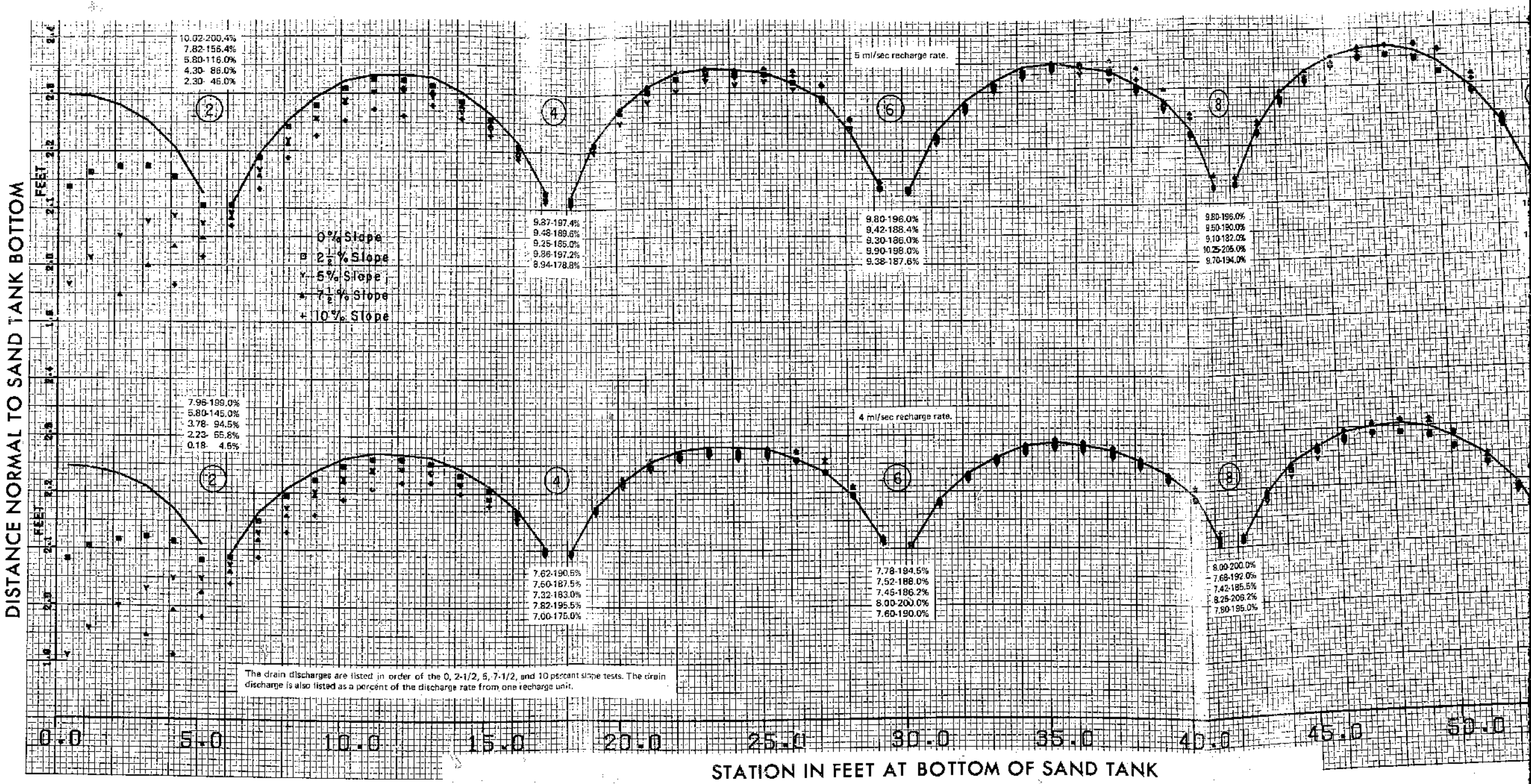


Figure 25. Water table profiles normal to the tank bottom—12-foot drain spacing.

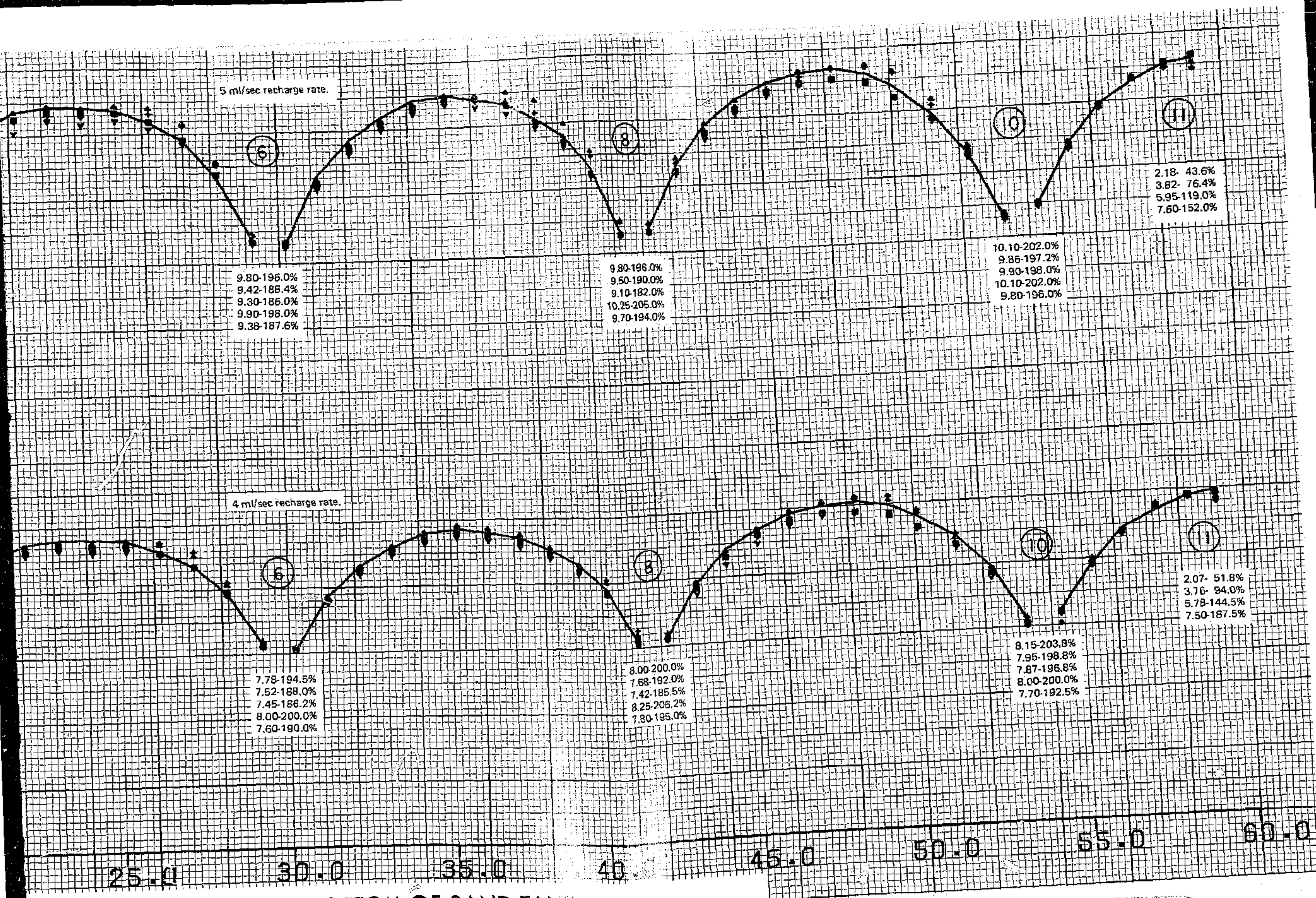


Figure 25. Water table profiles normal to the tank bottom—12-foot drain spacing.

FRAME 2

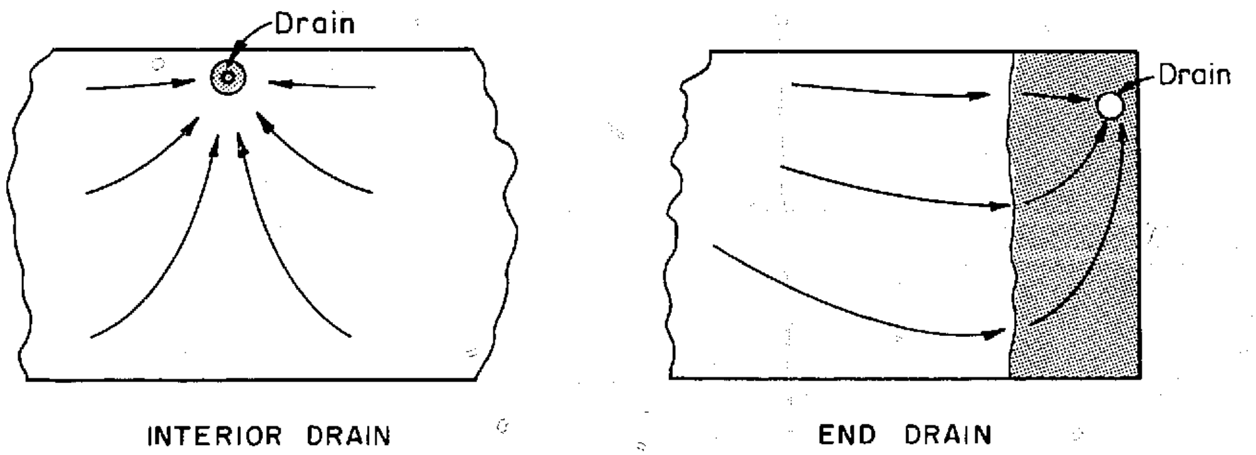


Figure 26A. Diagram showing streamlines of flow entering an interior and an end drain envelope. Drain envelopes are the shaded area.

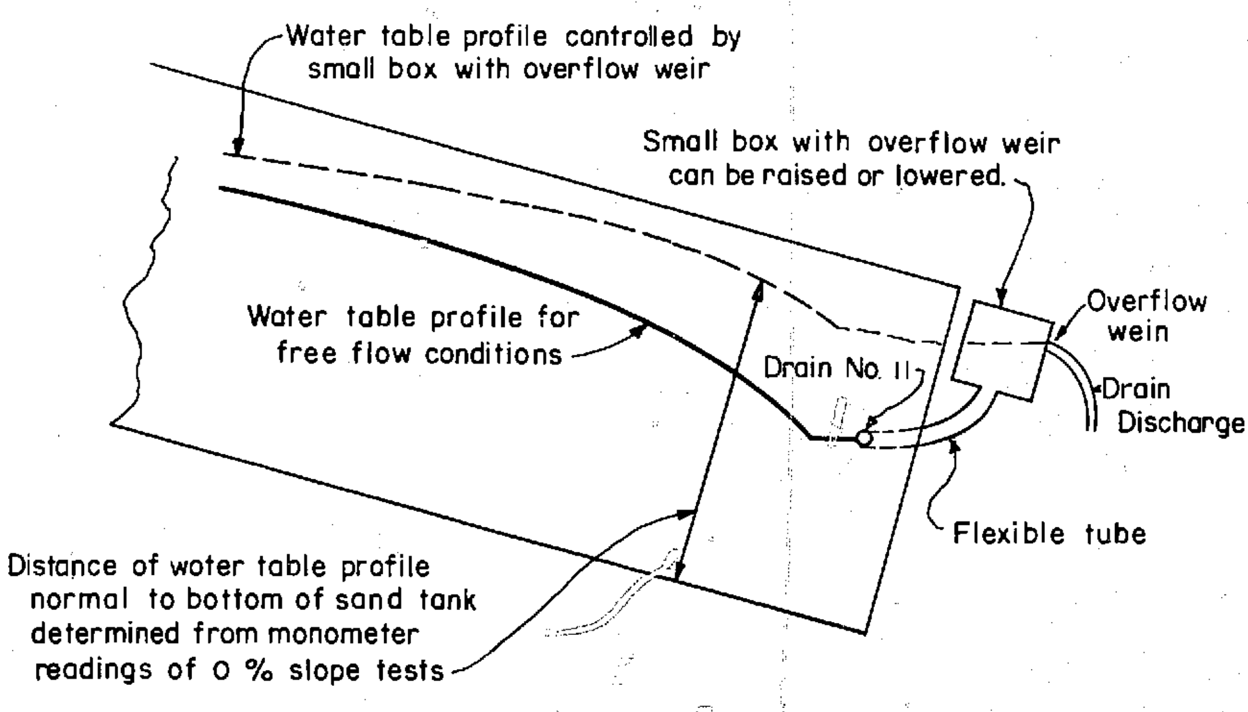
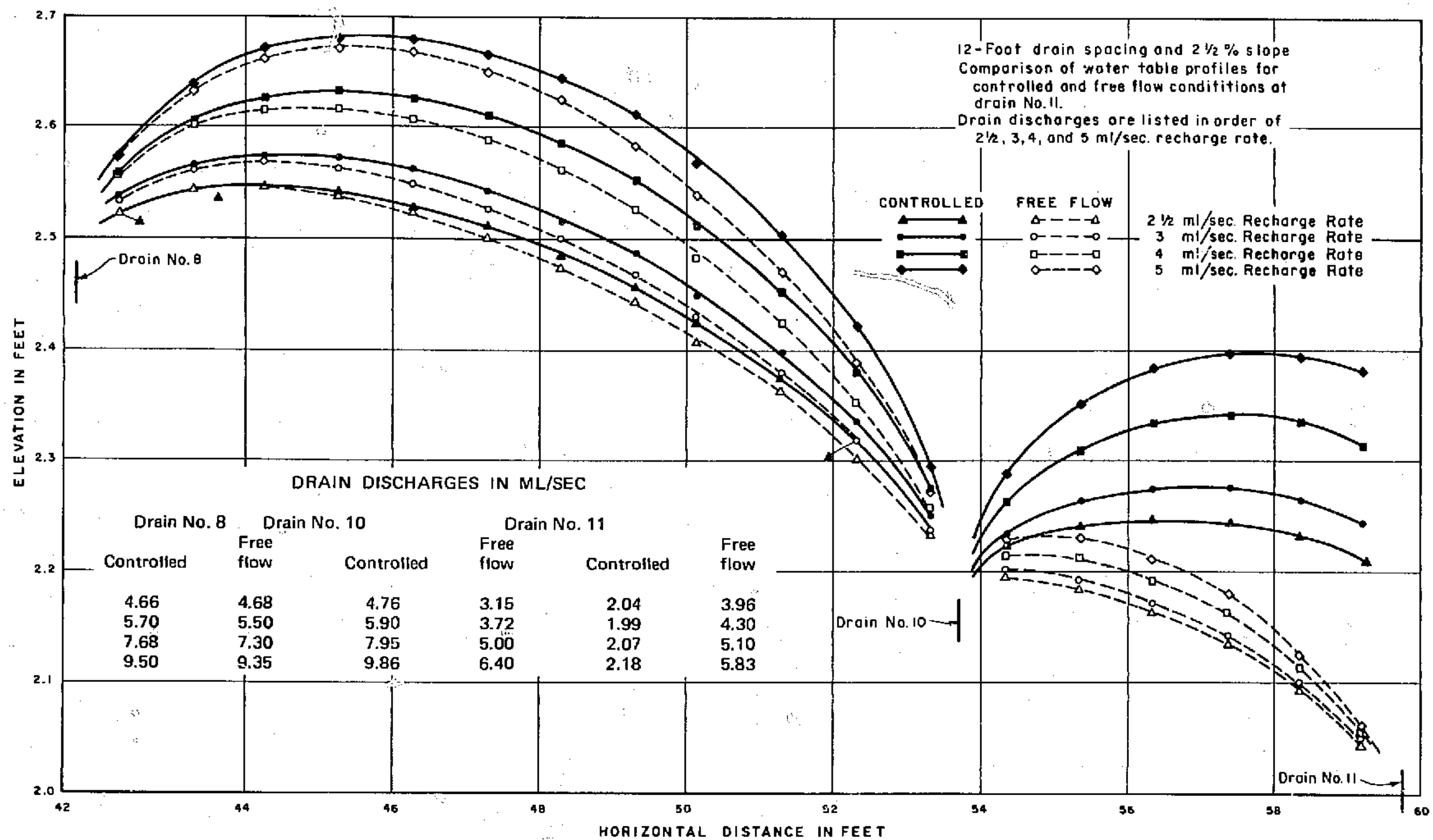
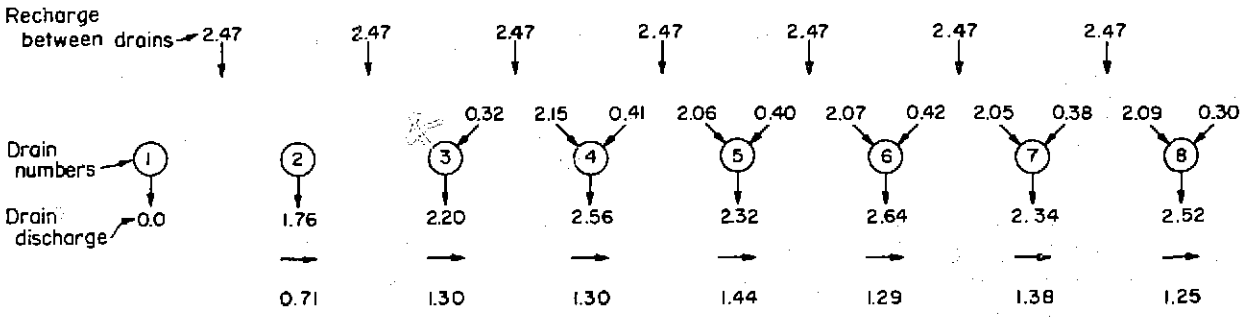


Figure 26B. Diagram showing method for controlling height of water table profile near End Drain No. 11.



Drain No. 8		Drain No. 10		Drain No. 11	
Controlled	Free flow	Controlled	Free flow	Controlled	Free flow
4.66	4.68	4.76	3.15	2.04	3.96
5.70	5.50	5.90	3.72	1.99	4.30
7.68	7.30	7.95	5.00	2.07	5.10
9.50	9.35	9.86	6.40	2.18	5.83

Figure 27. Water table profiles between Drains No. 8, 10, and 11 by recharge rate.

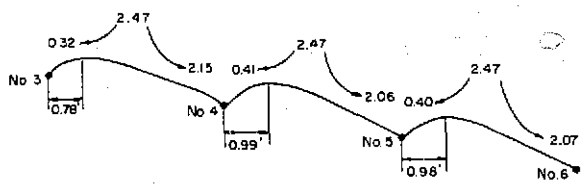


Numbers designate flow, expressed in ml/sec. Example is shown only up to drain No. 8. Results for drains No. 9, No. 10 and No. 11 are similar.

1. Total drain discharge 24.72 ml/sec. For 10 recharge units, 2.47 ml/sec per recharge unit. For the 60-foot sand tank length the recharge per linear foot along the tank is 24.72 ml/sec ÷ 60 ft = 0.412 ml/sec-ft.

2. Determine location of the zero slope point or dividing point for the water table profiles between drains. Get distance between zero slope point and the uphill drain. The location of zero slope points was obtained from working graphs or large-size plots of the water table profiles which are not included in this report. Only the distance for Drains No. 3, 4, and 5 are given for this example. The distances are Drain No. 3--0.78 ft, Drain No. 4—0.99 ft, and Drain No. 5—0.98 ft.

3. Determine amount of water from the recharge unit that flows up slope, the remaining water flows downslope.



Drains No.

3–4	0.78 ft x 0.412 ml/sec-ft = 0.32 ml/sec (up slope) 2.47 – 0.32 = 2.15 ml/sec (downslope)
4–5	0.99 ft x 0.412 ml/sec-ft = 0.41 ml/sec (up slope) 2.47 – 0.41 = 2.06 ml/sec-ft (downslope)
5–6	0.98 ft x 0.412 ml/sec-ft = 0.40 ml/sec (up slope) 2.47 – 0.40 = 2.07 ml/sec (downslope)

4. Input-output analysis to determine flow of water passing downslope beneath the drains.

Drain No. 1. The drain is next to the up-slope end of the sand tank, therefore no flow downslope.

Drain No. 2. Flow into the drain comes entirely from downslope flow which is the recharge between Drains No. 1 and 2. (2.47 – 1.76) ml/sec = 0.71 ml/sec.

Drain No. 3. Flow into the drain comes from (1) flow beneath Drain No. 2 – 0.71 ml/sec, (2) downslope flow between Drains No. 2 and 3 – 2.47 ml/sec, (3) up-slope flow between Drains No. 3 and 4 – 0.32 ml/sec. (0.71 + 2.47 + 0.32 – 2.20) ml/sec = 1.30 ml/sec.

Drain No. 4. Flow into the drain comes from (1) flow beneath Drain No. 3 – 1.30 ml/sec, (2) downslope flow between Drains No. 3 and 4 – 2.15 ml/sec, (3) up-slope flow between Drains No. 4 and 5 – 0.41 ml/sec. (1.30 + 2.15 + 0.41 – 2.56) ml/sec = 1.30 ml/sec.

Drain No. 5	(1.30 + 2.06 + 0.40 – 2.32) ml/sec = 1.44 ml/sec
Drain No. 6	(1.44 + 2.07 + 0.42 – 2.64) ml/sec = 1.29 ml/sec
Drain No. 7	(1.29 + 2.05 + 0.38 – 2.34) ml/sec = 1.38 ml/sec
Drain No. 8	(1.38 + 2.09 + 0.30 – 2.52) ml/sec = 1.25 ml/sec

Figure 28. Example of input—Output analysis to determine flow downslope passing beneath the drains.

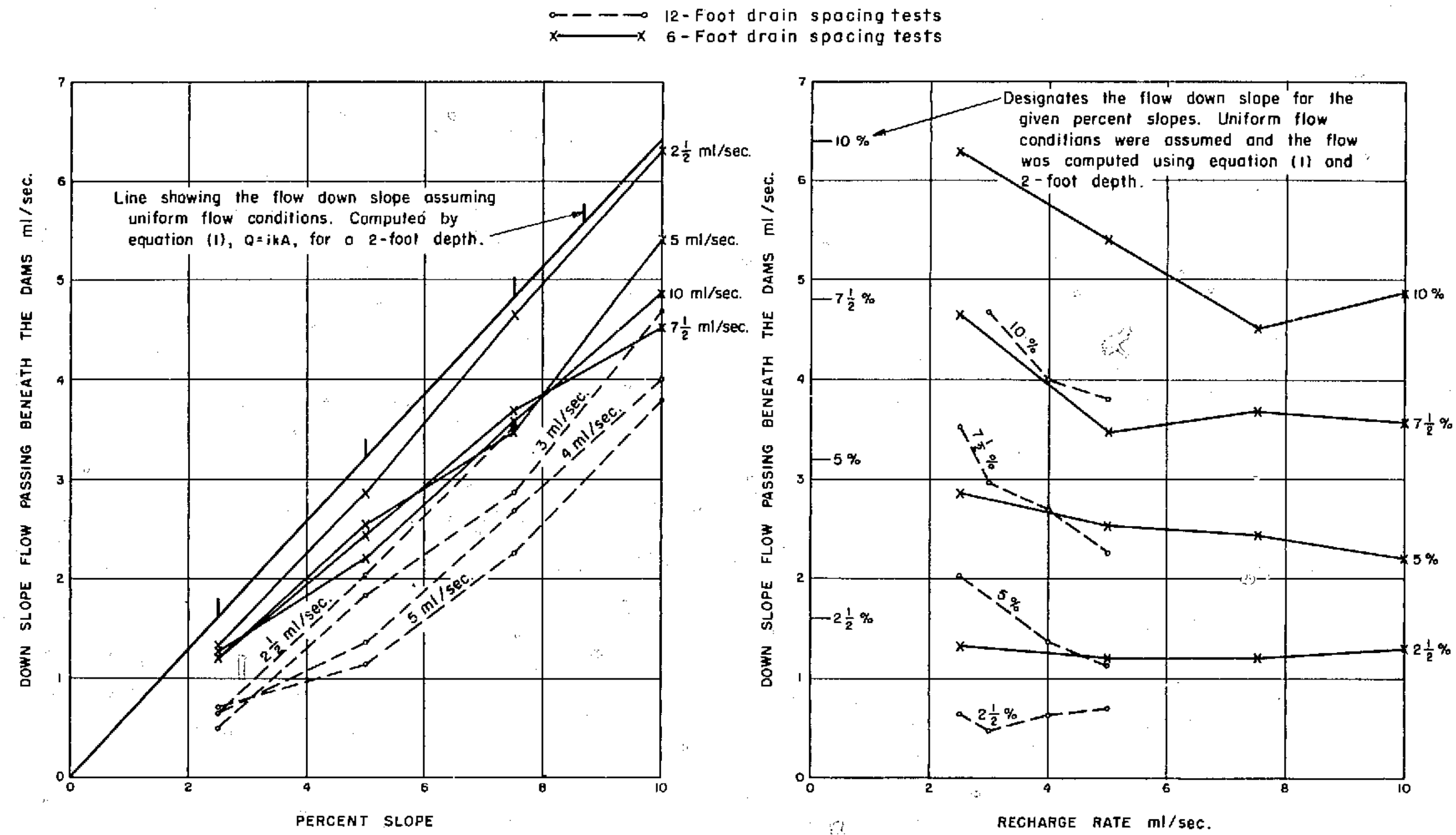


Figure 29A. Lines of constant recharge rate.

Figure 29B. Lines of constant percent slope.

Figure 29. Downslope flow passing beneath the drains.

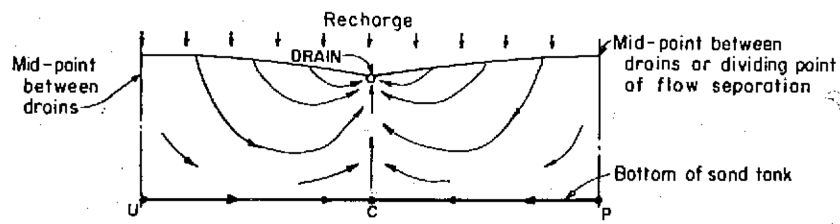


Figure 30A. Streamlines of flow for a level drainage system.

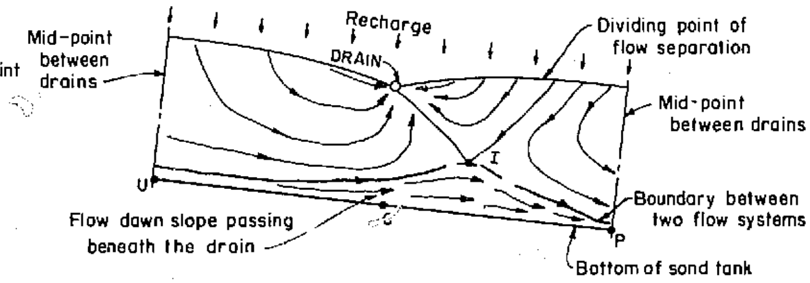


Figure 30C. Illustration of two flow systems.

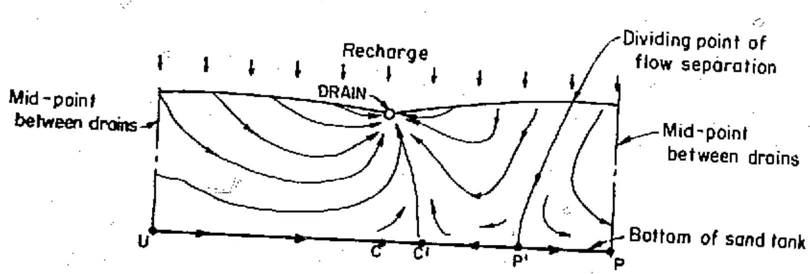


Figure 30B. New location of stagnation points.

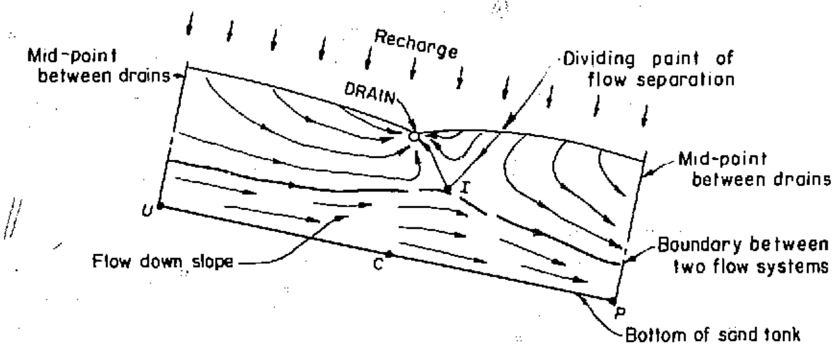


Figure 30D. Increase in slope increases amount of flow downslope passing beneath the drain.

Figure 30. Streamlines of flow for a constant recharge rate and varying slopes.

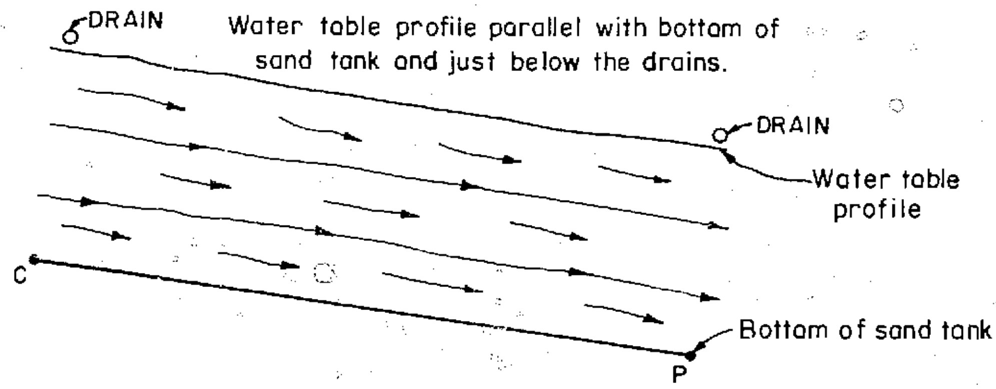


Figure 31A. Uniform flow downslope.

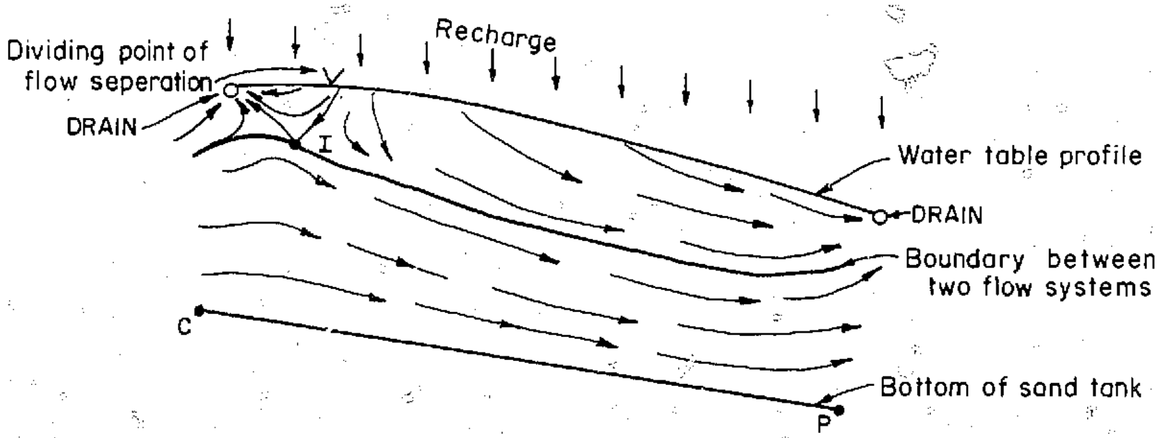


Figure 31B. Illustration of two flow systems.

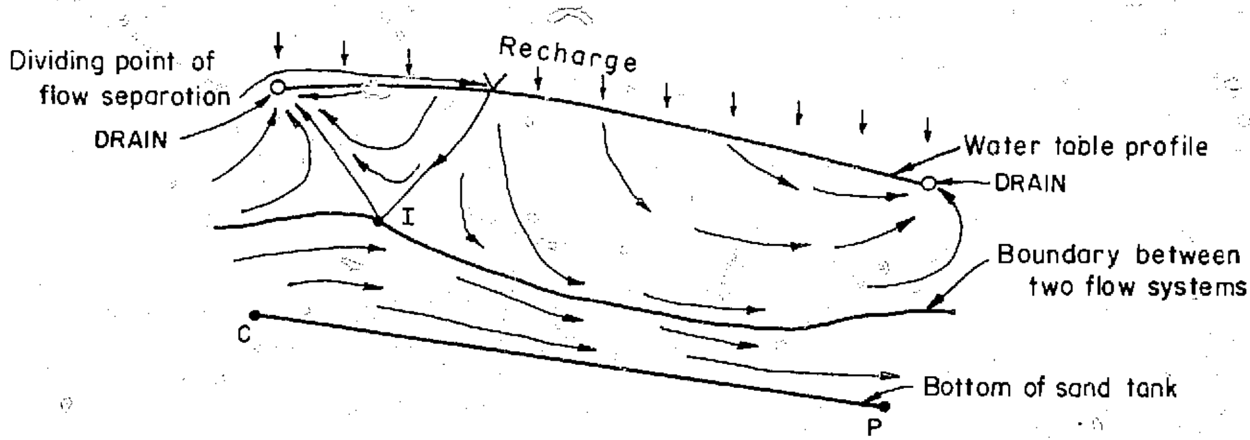


Figure 31C. Increase in recharge rate decreases amount of flow downslope passing beneath the drain.

Figure 31. Streamlines of flow for a constant slope and varying recharge rates.

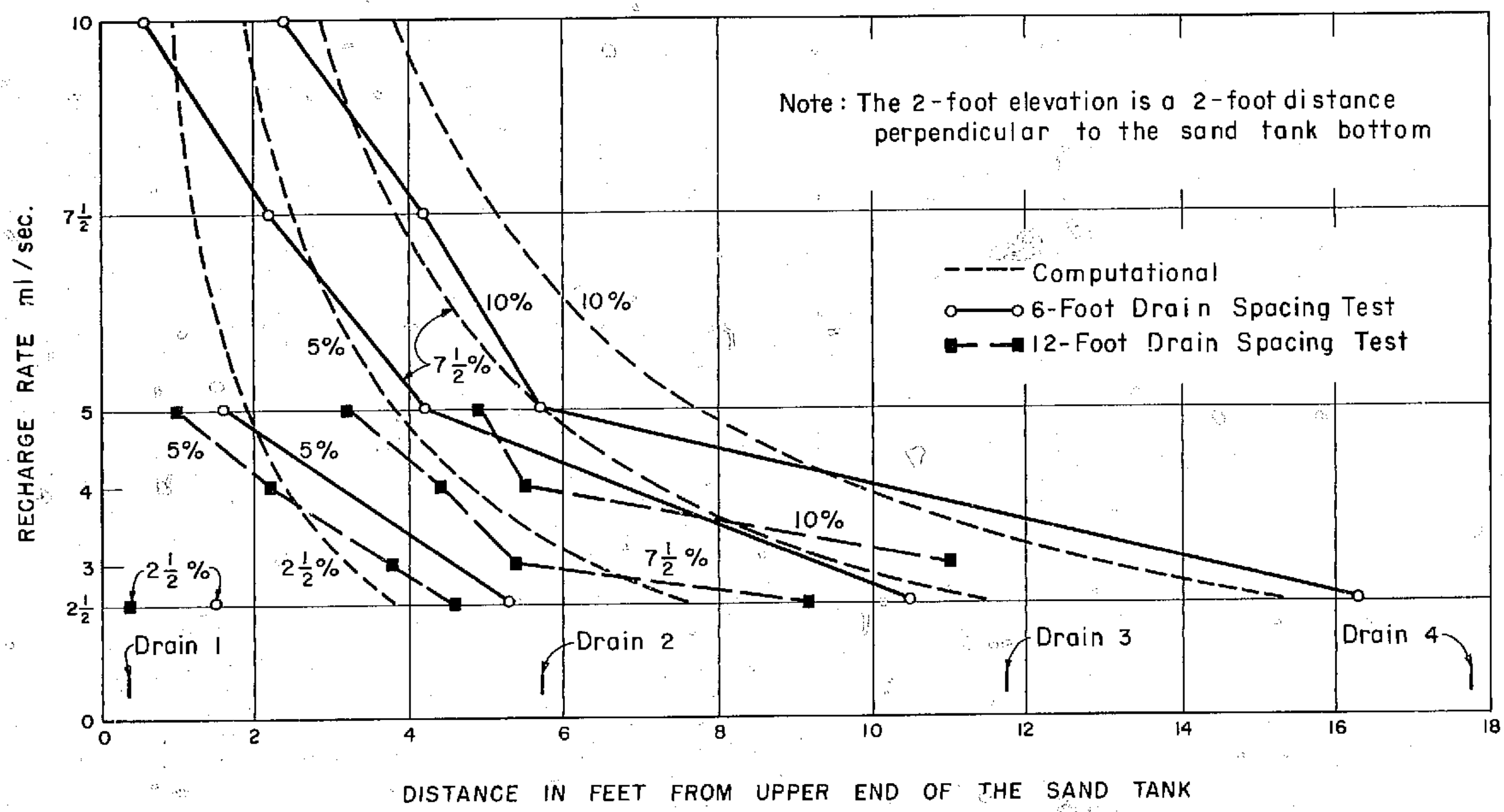


Figure 32. Location of the perpendicular 2-foot elevation for the water table at the up-slope end of the sand tank.

7-1750 (3-71)
Bureau of Reclamation

CONVERSION FACTORS—BRITISH TO METRIC UNITS OF MEASUREMENT

The following conversion factors adopted by the Bureau of Reclamation are those published by the American Society for Testing and Materials (ASTM Metric Practice Guide, E 380-68) except that additional factors (*) commonly used in the Bureau have been added. Further discussion of definitions of quantities and units is given in the ASTM Metric Practice Guide.

The metric units and conversion factors adopted by the ASTM are based on the "International System of Units" (designated SI for Systeme International d'Unites), fixed by the International Committee for Weights and Measures; this system is also known as the Giorgi or MKSA (meter-kilogram (mass)-second-ampere) system. This system has been adopted by the International Organization for Standardization in ISO Recommendation R-31.

The metric technical unit of force is the kilogram-force; this is the force which, when applied to a body having a mass of 1 kg, gives it an acceleration of 9.80665 m/sec/sec, the standard acceleration of free fall toward the earth's center for sea level at 45 deg latitude. The metric unit of force in SI units is the newton (N), which is defined as that force which, when applied to a body having a mass of 1 kg, gives it an acceleration of 1 m/sec/sec. These units must be distinguished from the (inconstant) local weight of a body having a mass of 1 kg, that is, the weight of a body is that force with which a body is attracted to the earth and is equal to the mass of a body multiplied by the acceleration due to gravity. However, because it is general practice to use "pound" rather than the technically correct term "pound-force," the term "kilogram" (or derived mass unit) has been used in this guide instead of "kilogram-force" in expressing the conversion factors for forces. The newton unit of force will find increasing use, and is essential in SI units.

Where approximate or nominal English units are used to express a value or range of values, the converted metric units in parentheses are also approximate or nominal. Where precise English units are used, the converted metric units are expressed as equally significant values.

Table I

QUANTITIES AND UNITS OF SPACE

Multiply	By	To obtain
	LENGTH	
Mil	25.4 (exactly)	Micron
Inches	25.4 (exactly)	Millimeters
Inches	2.54 (exactly)*	Centimeters
Feet	30.48 (exactly)	Centimeters
Feet	0.3048 (exactly)*	Meters
Feet	0.0003048 (exactly)*	Kilometers
Yards	0.9144 (exactly)	Meters
Miles (statute)	1,609.344 (exactly)*	Meters
Miles	1.609344 (exactly)	Kilometers
	AREA	
Square inches	6.4516 (exactly)	Square centimeters
Square feet	*929.03	Square centimeters
Square feet	0.092903	Square meters
Square yards	0.836127	Square meters
Acres	*0.40469	Hectares
Acres	*4,046.9	Square meters
Acres	*0.0040469	Square kilometers
Square miles	2.58999	Square kilometers
	VOLUME	
Cubic inches	16.3871	Cubic centimeters
Cubic feet	0.0283168	Cubic meters
Cubic yards	0.764555	Cubic meters
	CAPACITY	
Fluid ounces (U.S.)	29.5737	Cubic centimeters
Fluid ounces (U.S.)	29.5729	Milliliters
Liquid pints (U.S.)	0.473179	Cubic decimeters
Liquid pints (U.S.)	0.473166	Liters
Quarts (U.S.)	*946.358	Cubic centimeters
Quarts (U.S.)	*0.946331	Liters
Gallons (U.S.)	*3,785.43	Cubic centimeters
Gallons (U.S.)	3.78543	Cubic decimeters
Gallons (U.S.)	3.78533	Liters
Gallons (U.S.)	*0.00378543	Cubic meters
Gallons (U.K.)	4.54609	Cubic decimeters
Gallons (U.K.)	4.54596	Liters
Cubic feet	28.3160	Liters
Cubic yards	*764.55	Liters
Acre-feet	*1,233.5	Cubic meters
Acre-feet	*1,233,500	Liters

Table II

QUANTITIES AND UNITS OF MECHANICS

Multiply	By	To obtain
MASS		
Grains (1/7,000 lb)	64.79891 (exactly)	Milligrams
Troy ounces (480 grains)	31.1035	Grams
Ounces (avdp)	28.3495	Grams
Pounds (avdp)	0.45359237 (exactly)	Kilograms
Short tons (2,000 lb)	907.185	Kilograms
Short tons (2,000 lb)	0.907185	Metric tons
Long tons (2,240 lb)	1,016.05	Kilograms
FORCE/AREA		
Pounds per square inch	0.070307	Kilograms per square centimeter
Pounds per square inch	0.689476	Newtons per square centimeter
Pounds per square foot	4.88243	Kilograms per square
Pounds per square foot	47.8803	Newtons per square meter
MASS/VOLUME (DENSITY)		
Ounces per cubic inch	1.72999	Grams per cubic centimeter
Pounds per cubic foot	16.0185	Kilograms per cubic meter
Pounds per cubic foot	0.0160185	Grams per cubic centimeter
Tons (long) per cubic yard	1.32894	Grams per cubic centimeter
MASS/CAPACITY		
Ounces per gallon (U.S.)	7.4893	Grams per liter
Ounces per gallon (U.K.)	6.2362	Grams per liter
Pounds per gallon (U.S.)	119.829	Grams per liter
Pounds per gallon (U.K.)	99.779	Grams per liter
BENDING MOMENT OR TORQUE		
Inch-pounds	0.011521	Meter-kilograms
Inch-pounds	1.12985×10^6	Centimeter-dynes
Foot-pounds	0.138255	Meter-kilograms
Foot-pounds	1.35582×10^7	Centimeter-dynes
Foot-pounds per inch	5.4431	Centimeter-kilograms per centimeter
Ounce-inches	72.008	Gram-centimeters
VELOCITY		
Feet per second	30.48 (exactly)	Centimeters per second
Feet per second	0.3048 (exactly)*	Meters per second
Feet per year	*0.965873×10^{-6}	Centimeters per second
Miles per hour	1.609344 (exactly)	Kilometers per hour
Miles per hour	0.44704 (exactly)	Meters per second
ACCELERATION*		
Feet per second^2	*0.3048	Meters per second^2
FLOW		
Cubic feet per second (second-feet)	*0.028317	Cubic meters per second
Cubic feet per minute	0.4719	Liters per second
Gallons (U.S.) per minute	0.06309	Liters per second
FORCE*		
Pounds	*0.453592	Kilograms
Pounds	*4.4482	Newtons
Pounds	*4.4482×10^5	Dynes

Table II–Continued

Multiply	By	To obtain
WORK AND ENERGY*		
British thermal units (Btu)	*0.252	Kilogram calories
British thermal units (Btu)	1,055.06	Joules
Btu per pound	2.326 (exactly)	Joules per gram
Foot-pounds	*1.35582	Joules
POWER		
Horsepower	745.700	Watts
Btu per hour	0.293071	Watts
Foot-pounds per second	1.35582	Watts
HEAT TRANSFER		
Btu in./hr ft^2 degree F (k, thermal conductivity)	1.442	Milliwatts/cm degree C
Btu in./hr ft^2 degree F (k, thermal conductivity)	0.1240	Kg cal/hr m degree C
Btu ft/hr ft^2 degree F	*1.4880	Kg cal m/hr m^2 degree C
Btu/hr ft^2 degree F (C, thermal conductance)	0.568	Milliwatts/cm^2 degree C
Btu/hr ft^2 degree F (C, thermal conductance)	4.882	Kg cal/hr m^2 degree C
Degree F hr ft^2/Btu (R, thermal resistance)	1.761	Degree C cm^2/milliwatt
Btu/lb degree F (c, heat capacity)	4.1868	J/g degree C
Btu/lb degree F	*1.000	Cal/gram degree C
Ft^2/hr (thermal diffusivity)	0.2581	Cm^2/sec
Ft^2/hr (thermal diffusivity)	*0.09290	M^2/hr
WATER VAPOR TRANSMISSION		
Grains/hr ft^2 (water vapor) transmission)	16.7	Grams/24 hr m^2
Perms (permeance)	0.659	Metric
Perm-inches (permeability)	1.67	Metric perm-centimeters

Table III

OTHER QUANTITIES AND UNITS

Multiply	By	To obtain
Cubic feet per square foot per day (seepage)	*304.8	Liters per square meter per day
Pound-seconds per square foot (viscosity)	*4.8824	Kilogram second per square meter
Square feet per second (viscosity)	*0.092903	Square meters per second
Fahrenheit degrees (change)*	5/9 exactly	Celsius or Kelvin degrees (change)*
Volts per mil	0.03937	Kilovolts per millimeter
Lumens per square foot (foot-candles)	10.764	Lumens per square meter
Ohm-circular mils per foot	0.001662	Ohm-square millimeters per meter
Millicuries per cubic foot	*35.3147	Millicuries per cubic meter
Milliamps per square foot	*10.7639	Milliamps per square meter
Gallons per square yard	*4.527219	Liters per square meter
Pounds per inch	*0.17858	Kilograms per centimeter

GPO 841-999

ABSTRACT

An investigation was made to study drainage from sloping land. A tilting sand tank (flow tank) 2 ft wide, 2-1/2 ft deep, and 60 ft long was used. Drains to simulate agricultural tile were placed in the sand tank at 6-ft intervals 2 ft above the tank bottom. Water (recharge) was applied at a steady rate on the sand surface to simulate irrigation. Drain discharges and water table profiles were measured for 54 tests with different recharge rates, 6- and 12-ft drain spacings, and sand tank slopes from 0 to 10%. Four tests were made introducing dye into the tank and streak-lines obtained showing directions of water movement in the sand. Pressure measurements were made at points on the tank side to obtain the potential field between drains. An equilibrium area occurred in the middle length of the sloping sand tank where the drain discharges equaled the amount of water applied between two operating drains. This condition occurred during all tests, regardless of slope, recharge rate, or drain spacing. For a given recharge rate and in the equilibrium area, water table profiles measured perpendicular to the tank bottom were the same for slopes between 0 to 10%. The report includes tables of the drain discharges, plots of the water table profiles, photographs of the dye streak-lines, and diagrams showing the potential field occurring between drains. Effects of slope and recharge rate upon drain discharges, water table profiles, and water movement in the sand tank were analyzed.

ABSTRACT

An investigation was made to study drainage from sloping land. A tilting sand tank (flow tank) 2 ft wide, 2-1/2 ft deep, and 60 ft long was used. Drains to simulate agricultural tile were placed in the sand tank at 6-ft intervals 2 ft above the tank bottom. Water (recharge) was applied at a steady rate on the sand surface to simulate irrigation. Drain discharges and water table profiles were measured for 54 tests with different recharge rates, 6- and 12-ft drain spacings, and sand tank slopes from 0 to 10%. Four tests were made introducing dye into the tank and streak-lines obtained showing directions of water movement in the sand. Pressure measurements were made at points on the tank side to obtain the potential field between drains. An equilibrium area occurred in the middle length of the sloping sand tank where the drain discharges equaled the amount of water applied between two operating drains. This condition occurred during all tests, regardless of slope, recharge rate, or drain spacing. For a given recharge rate and in the equilibrium area, water table profiles measured perpendicular to the tank bottom were the same for slopes between 0 to 10%. The report includes tables of the drain discharges, plots of the water table profiles, photographs of the dye streak-lines, and diagrams showing the potential field occurring between drains. Effects of slope and recharge rate upon drain discharges, water table profiles, and water movement in the sand tank were analyzed.

ABSTRACT

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DESCRIPTORS—/ groundwater flow/ subsurface drains/ water table/ steady flow/ horizontal drains/ *subsurface drainage/ *laboratory tests/ *test results/ plastic tubing/ slopes/ water recirculation/ *groundwater movement/ *porous materials/ water measurement/ infiltration rate/ permeability tests/ effects

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