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DRAINAGE FROM SLOPING LAND USING OBLIQUE DRAINS

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16. ABSTRACT
A sand tank model study of drainage from sloping land using oblique drains was made in a 60-ft-long (18.29 m), 2-ft-wide (610 mm), and 2½-ft-deep (762 mm) flume. The oblique drains were tested at angles of 90, 45, 30 and 0 degrees to the water table gradient. Water table gradients of 0, 5, 7½, and 10 percent were tested in the study. It was apparent from the test results that the narrow flume produced boundary effects which would not permit application of test results to oblique drains on agricultural fields. However, the laboratory test results are a valuable contribution to the study of oblique drains and can be used to verify future three-dimensional mathematical models.

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INTRODUCTION

In most agricultural lands in the arid Western United States, where applied irrigation water is required for crop production, drainage capability must be available. Practically all arid soils require more water than that used by the crops to maintain the salt balance in the soil and to achieve high plant productivity. Drainage of the excess water can be provided by open channel drains, by natural creeks or ditches, or by buried pipe (or tube) drains. Buried pipe drains are normally used so that the land above the drains can be cultivated.

Most agricultural land chosen to grow valuable food or forage crops has a surface slope, whether natural or artificial, which provides natural storm runoff drainage. On arid land, where irrigation is required to grow crops, the excess water leaching the root zone must be removed for salt control. Such drainage is necessary to prevent the water table from encroaching on the root zone, thus making the land unproductive. A pipe drainage and collection system is usually provided to ensure that the water table stays below the root zone.

Pipe drains are installed at right angles to the water table gradient, where possible, to serve as relief or interceptor drains to maintain the water table at the desired level. Interceptor drains on sloping land, installed at right angles to the water table gradient, provide the most hydraulically efficient drainage. However, it is often necessary to install drains at an oblique angle to the water table gradient. Unsymmetrical property lines, odd shapes of fields, varying topography, and natural drainage conditions sometimes necessitate the installation of oblique drains.

PRESS (Program Related Engineering and Scientific Studies) coordinated with the Drainage and Groundwater Branch, were conducted by the Hydraulics Branch to study drainage from level and sloping land (PRESS allocation No. DR-414). The tests were conducted with drains placed at a right angle to the water table gradient. After the initial research was completed and reports [1,2]* were published, further research was conducted, using the excellent research facilities in place, to learn about the technique for using oblique drains on sloping land.

Although some problems were apparent in studying the three-dimensional condition with a two-dimensional test facility, several series of tests were conducted and valuable information was obtained.

Most drainage installations constructed where the land is sloping require drains oblique to the water table gradient. A major question was to determine the most efficient spacings of these

* Numbers in parentheses refer to entries in the bibliography.

oblique drains. Without guidelines, drain spacings could be less than the optimum for efficient operation, making the drainage system cost more than necessary.

SLOPING SAND TANK (FLUME) MODEL

The sloping sand tank flume (figs. 1 and 2) used for the study was 60 feet (18.29 m) long, 2 feet (610 mm) wide, and 2½ feet (762 mm) deep. Plastic panels, ⅜-inch (9.53 mm) thick, formed one side of the flume. For ease in tilting, the flume was built on two 16WF36 continuous steel beams, each supported at two points. The downslope beam support was a pivot, and the upslope support was the lifting mechanism. Supports were spaced along the beams to give equal deflection at the ends and the center of the flume. The design load on the beams was 900 lb/ft (1339.3 kg/m), 450 lb/ft (669.7 kg/m) on each beam; this load considered the weight of the flume and attached test equipment, the sand, water, beams, and the people standing on the walkway on the side of the flume. One end of the flume was lifted to achieve the desired slope by two 8-ton (7.26-metric ton) motorized chain hoists. Templates were used to determine the flume slope. For safety, screwjacks were placed under the cross beams provided for the upslope lifting hoists. Because of headroom limitations, the maximum slope obtainable was about 12 percent (about 6 degrees 50 minutes).

Simulated Agricultural Drains

To simulate pipe drains, ⅝-inch (15.9-mm) o.d. by ½-inch (12.7-mm) i.d. plastic tubes were used. These plastic tubes were slotted with a band saw to simulate perforated plastic pipe drains used in the field. The flume length was divided into four zones (A, B, C, and D), whose respective drains were installed at angles of 90, 45, 30 and 0 degrees to the water table gradient. The drains were installed level across the flume and longitudinally on a plane 2.0 feet (0.61 mm) above the flume floor when the flume was set to the zero slope position (see fig. 3). After the drains were installed, their placement was checked with an engineer's level and rod. The discrepancies between levels of the drains and between their distances above the flume floor were within a few hundredths of an inch, which was considered well within the overall accuracy of the tests.

Floor Drains

Eleven floor drains, used only to drain and fill the flume at the end of a series of tests, were placed along the centerline of the flume. The first drain was 1 foot (305 mm) from the downslope end. The drains were spaced 6 feet (1.83 m) apart with exception of the last two drains on the upslope end, which were 4 feet (1.22 m) apart; this caused the last drain to be 1 foot (305 mm) from the upslope end of the flume. The floor drains were made from ½-inch (12.7-mm) galvanized pipe with the vertical end of each drain passing through the floor of the flume. A valve in each drainline led to a common 1½-inch (38.1-mm) pipe manifold beside the flume floor that extended the entire length of the flume. Each floor drain was covered by 100-mesh screen and a 1-inch (25.4-mm) thick layer of No. 16 medium sand.

Piezometer Wells

Piezometer wells were used to define the height of the water table above and between adjacent pairs of drains. They were made of ⅝-inch (15.9-mm) o.d. by ½-inch (12.7-mm) i.d. plastic tubes 7½ inches (190.5m-mm) long. The bottom end of each tube was plugged, and the bottom 2 inches (50.8 mm) was slotted in the same manner as the drain tubes. A small cylinder of 100-mesh bronze screen was placed inside each piezometer to keep out the sand. The bottom of each piezometer well was set ½ inch (12.7 mm) below the centerline of the plane of the drains.

The water table was measured between four adjacent pairs of drains, 3A to 7A, for the 90-degree configuration; between three adjacent pairs of drains, 5B to 8B, for the 45 degree configuration; between three adjacent pairs of drains, 5C to 8C, for the 30- degree configuration; and between two adjacent drains, right and left between collectors 2D and 4D, for the 0-degree configuration (see fig. 3). The water table height was measured at right angles to adjacent drains for each drain configuration.

The 90-degree drains were located between stations 0 and 12 feet (0 and 3.66 m) in the flume, the 45-degree drains between stations 12 and 27 feet (3.66 and 8.23 m), the 30-degree drains between stations 27 and 45 feet (8.23 and 13.72 m), and the 0-degree drains between stations 45 and 60 feet (13.72 and 18.29 m). As shown on figure 3, water table measurements in each zone were made between adjacent drains that would receive a minimum of influence from other zones or from the vertical end drains. The water table measurements were made where a uniform flow net would be established.

One-quarter-inch plastic tubing connected each piezometer tube to a scanivalve which, in turn, was connected to a sensitive pressure transducer and digital voltmeter and recorder. The scanivalve had 52 piezometer connections. All of the piezometers for each of the A, B, and C drain sets could be read without changing the piezometer connections.

Water Recirculation System

The water supply for the flume was a closed-circuit flow system. Recharge water was pumped from a covered storage reservoir, 7 by 7 by 4 feet (2.13 by 2.13 by 1.22 m) deep, through a manifold piping system to plastic recharge modules (figs. 4 and 5). The recharge water passed through a stainless steel screen filter and a 1½-inch (38.1-mm) plastic pipe manifold to vertical ½-inch (12.7-mm) plastic pipes. Each of the 10 pipes fed a separate recharge module. Drainage water from all drains was collected in a galvanized trough, from which it flowed into a tank at the downslope end of the 60-foot (18.29 m) flume, where it was pumped back to the covered storage reservoir.

The test facility was not in a temperature- or humidity-controlled environment and, consequently, followed the ambient temperature and humidity of the laboratory. However, because of the large amount of water and sand used, temperature changes in the model were very small and very slow and had no effect on the test results.

Recharge Modules

Each recharge module consisted of three plastic tubes, ½ inch (12.7 mm) o.d. by ⅜ inch (9.52 mm) i.d. by 6 feet (1.83 m) long. The tubes were placed side by side, 0.70 foot (213 mm) apart and 0.30 foot (91 mm) away from the flume walls on each side. The recharge tubes were kept horizontal when the flume was tilted. The tubes were drilled with 12 holes, 0.020 inch (0.508 mm) in diameter, 1 foot (305 mm) apart on the upper side of the tubes. Each hole had an inverted cup over it. The water squirted up into the cup and then dripped onto the sand aquifer. By having the holes on top of the tubes, air could escape and the holes did not clog with foreign matter. The inverted cups eliminated spray as water left the ½-inch (12.7-mm) supply tubes.

Water Recharge Measuring System

In the earlier tests, the water that recharged the aquifer was measured as it flowed to each recharge module with small stainless steel orifices and water manometers; needle valves controlled the flow. However, in the oblique drain tests, glass rotameters made by Schutte and Koerting were used for the recharge water measurement. The rotameters were 10 inches (254 mm) long and were connected to the ½-inch (12.7 mm) plastic pipes with rubber hose connectors. Rotameters were selected that would measure approximately 1.26 gal/min (0.08 l/s) to fit the range of desired recharge for each module. Measurements could be set much more quickly and more accurately with the rotameters than with the small orifices used in the earlier tests.

Measurement of Water Table

The most important factor to consider when designing an agricultural drainage project is the maximum height of the water table between drains. Therefore, very accurate measurements of the water table between drains were made in the model. Piezometers were placed between drains so the water table shape with its highest free-water surface between adjacent drains could easily be defined.

To measure the water table between drains, a pressure measuring system was connected to the water piezometers with ¼-inch (6.4-mm) plastic tubing. A sensitive pressure transducer with a scanivalve (fig. 6) made it possible to read multiple piezometer pressures quickly. Twenty-eight piezometers were installed in the 90-degree (A-drain) zone, 45 piezometers in both the 45-degree (B-drain) and the 30-degree (C-drain) zones, and 84 piezometers in the 0-degree (D-drain) zone (fig. 3). The actual pressures were read from the transducer with a digital voltmeter and printed on strip paper. This method was much more rapid, accurate, and efficient than the water manometer board method used in the earlier tests.

Aquifer Sand

With the exceptions described below, the flume was filled with a uniform rounded silica sand having a medium particle size of slightly less than 0.2 mm. A sieve analysis of the sand is shown on figure 7. A circular envelope of No. 16 medium sand, 0.1 foot (30.5 mm) in outside diameter, was placed around the pipe drains. At both ends of the flume a ½-foot (152-mm) deep layer of No. 16 medium sand was installed to assist in determining the hydraulic conductivity of the aquifer sand and to control the water level and water removal at the downslope end of the flume.

Hydraulic conductivity tests were conducted by measuring the discharge, hydraulic gradient, and cross-sectional area of water moving down the sloping flume. The average hydraulic conductivity of several tests was 48.902 feet (14.905 m) per day for the sand material installed in the flume. During this long testing program there was no settlement in the sand. When the sand was removed from the flume in February 1986, it appeared to be in excellent condition. It was dense, had no cavities, and showed no signs of algae or other foreign growth.

GENERAL PLAN OF TESTS

In the previous tests [1,2], all drains were placed at 90 degree angles to the water table gradient (i.e., Alpha = 90 degrees in the flume). These earlier tests were conducted with 6- and 12-foot (1.83 and 3.66 m) drain spacings. To compare drainage parameters of oblique drains with those placed at 90 degrees to the water table gradient, it was necessary to use smaller spacings. For the A, B, and C drains (at 90-, 45-, and 30-degree angles, respectively, to the gradient), a spacing of 1.5 feet (456 mm) along the side walls was selected. This gave drain spacings perpendicular to the drains as follows:

Drain number	Angle to gradient, degrees	Perpendicular drain spacing, ft	Length of drain between walls, ft
1A-7A	90	1.50	2.00
1B-9B	45	1.06	2.83
1C-10C	30	0.75	4.00

Figure 8 is a definition sketch showing that the water table between drains is measured at a right angle to the drains and perpendicular to the plane of the drains. This is true for all zones whether or not the drains are oblique to the sloping water table gradient.

The D drains, which had a 0-degree angle to the water table gradient (straight down the slope), were spaced 1.0 foot (305 mm) apart to allow the water table to rise between the drains and adjacent to the flume wall and to make the flow net near the drains similar to a flow net in a field installation. Five collection tubes (1D-5D) spaced 3 feet (915 mm) apart collected drain water by gravity from the D drains and passed it through the left flume wall (looking downslope). The collection tubes carried drain water to the outlet trough, which carried the water to the tank at the downslope end of the flume. The collection tubes prevented the drains from being submerged, which would have changed the flow net around the drains from normal flow conditions.

For the A drains, seven piezometers were placed along the centerline between each of four sets of adjacent drains (3A-7A) and at right angles to the drains (fig. 9). For the B drains, 15 piezometers, five in each of three rows, spaced 0.25 foot (76.2 mm) apart, were centered in the flume between adjacent drains (5B-8B) and at right angles to the drains (fig. 10). The number and configuration of piezometers for the C drains were similar to those for the B drains (fig. 11). For the D drains, six rows of piezometers were installed between collection tubes at right angles to the drains (fig. 11).

All piezometers for each set of drains being tested were read so the water table between drains could be defined. Recharge water was added to the entire flume and drains in all zones were operating when tests were conducted for one or more sets of drains. This ensured a continuous operating flow net over the entire flume when each set of drains was tested.

The parameters that could be varied in the model were the recharge (deep percolation) rate and the slope of the flume (angle Beta). The other parameters that affect drainage relationships are the hydraulic conductivity (coefficient of permeability) of the aquifer material, the spacing of the drains, the distance between the level of drains and the impermeable barrier in the geological formation below the agricultural land, and the sum of the drain radius plus the thickness of the gravel envelope around it. All of these parameters were fixed in the model test setup and remained constant as shown below:

Radius of drains plus gravel envelope	0.05 feet
Distance below drains to impermeable barrier	2.00 feet
Hydraulic conductivity (coefficient of permeability)	48.902 feet/day

Variation in Water Table Slope

The test flume was constructed so it could be raised and pivoted to give a maximum angle of 12 percent, about 6 degrees 50 minutes from the horizontal. Tests were made at 0, 5, 7½, and 10 percent to show the variation of the water table between drains as the water table gradient varied. As the testing progressed, the piezometer readings revealed the three-dimensional nature of the flow. Recharge (deep percolation) water applied by the recharge modules percolated vertically downward until it reached the water table, and then flowed to the drains according to the pressure distribution in the saturated flow net.

Recharge (Deep Percolation)

Water reaching agricultural drains that are located below the root zone is deep percolation water that is not used by the plants. This water carries excess salts from the root zone to the drains and prevents salt buildup in the soil. In the hydraulic model no agricultural plants were used and all recharge water was deep percolation water. The rate of recharge could be varied to yield a water table height between drains that was high enough to allow accurate water table measurements, but was not extremely close to the ground surface.

For the A, B, and C drains, recharge was maintained at approximately 7.5 cubic feet of water per square foot per day (feet per day) (2.29m/day) to maintain a reasonable water table height for steady flow conditions. At this rate the drains would not become flooded. A recharge rate of approximately 4.5 feet per day (1.37 m/day) was used for the D drains.

Drain Discharge Measurements

Discharge from pipe drains, which extended through the left wall of the flume, was measured by collecting individual drain outflows in a graduated cylinder and timing them with a stopwatch. Each drain discharge was collected for nearly a minute and timed to 0.1 second. Flow rates from the drains ranged from 5 to 15 mL per second (15.26 to 45.70 ft^3 per day). Flow from the downslope end of the flume during the sloping aquifer tests was removed by drains installed in the vertical layer of No. 16 medium sand at the end of the flume.

DRAIN TEST DATA

General

The D drains, placed at a 0-degree angle to the water table gradient, were at the limit angle of oblique drains used for drainage. Drains placed in this configuration could not perform as true interceptor drains, particularly for the steeper slopes, because they were parallel to the water table gradient. On first thought, to have the drains run down the slope would seem to be the best way to drain sloping land. But upon closer analysis of the flow net, and considering accretion vertically from the root zone above and the water flowing according to the pressure at every point in the saturated flow, it became obvious that drains placed at 90 degrees to the gradient are preferable. The drain is the line sink and gravity is the driving force. Because the flow lines become curved in three dimensions, analysis and interpretation of the data taken on the two-dimensional model was most difficult. A three-dimensional mathematical model is needed to supplement the two dimensional hydraulic model data.

In the hydraulic model, pressures and water levels could be measured at a point or at several consecutive points, and the discharge could be measured from the drains or from a drain collection system, as for the D drains. To measure differential changes in potential in three dimensions would require an infinite number of monitoring instruments placed very close together, an impossible test setup. The best practical test setup used included a single pressure-measuring instrument with a large number of piezometers placed at close intervals to define the water table between drains, and then to measure the discharge from adjacent drains for each test.

For drains sets A and D (fig. 3), the flume simulates a slice of land parallel to the water table gradient in a wide sloping field. The sides of the flume do not cause boundary influence to the flow net in the A and D drains because they are perpendicular and parallel, respectively, to the water table gradient (figs. 9 and 12). Drain sets B and C, 45 and 30 degrees, respectively, to the gradient, have three-dimensional flow nets. Data for these oblique drains show the influence of the flume sides, even though piezometers were installed as far as practical from the flume walls (figs. 10 and 11).

Tests were conducted for the A drains by setting the recharge rate for the entire flume, then waiting until equilibrium flow from the drains was established. Equilibrium was usually apparent within 1 hour. Piezometer readings were made for each slope, 0, 2½, 5, 7½, and 10 percent, using the same recharge on each set of drains for each slope setting. Piezometer connections were then changed to the B, C, and D sets of drains, in order, and the same procedure was followed. Drain discharge was measured for all drains in each set as data were taken to ensure that equilibrium continued in the test. For the D drains, which were installed straight down the slope (with a different drain collection system), a different recharge rate was required to have the water table height within the range of the test setup.

Data From A (90-degree) Drains

There were seven drains in the A set. Twenty-eight piezometers were used between drains 3A and 7A, seven in each space between adjacent pairs of drains. The recharge modules over the entire flume were kept operating to maintain continuity and equilibrium.

The maximum water table height between drains was the important value for designing drain spacings. The maximum water table heights between drains were taken from smooth curves drawn through piezometer pressures measured perpendicular to the plan of the drains. Recharge rate and drain discharge were converted to recharge infiltration in feet per day over the area of the soil surface being considered (see tables 1 through 5).

The maximum water table height between the 90-degree A drains varied a small amount for each slope tested. The only trend noticed was that the average height of the water table between the A drains decreased as the water table slope increased. However, this decrease was less than the variation in the water table between drains for a given test. The water table heights for the A drains on a zero slope (horizontal) were within the range of experimental accuracy of the water table heights measured when the water table was sloped 2½ to 10 percent (table 1). These data showed results similar to the data obtained from previous tests [1, 2] with 6- and 12-foot (1.83 m and 3.66 m) spacings.

Data From B (45-degree) Drains

The same recharge inflow rates were used for the B drains as for the A drains. A slightly different area contributing to the different drain sets made the converted recharge rates differ slightly between drain sets. The drain spacing was shorter for the B drains than for the A drains, so the water table height above the drains was less. The average maximum water table heights above the plane of the drains were very close for slopes, 2½ to 10 percent. However, the water table was always higher on the left side of the flume looking downslope (table 2). The influence of the boundaries of the flume sides are clearly shown where the drains are truly at oblique angles to the water table gradient. The effect is greater between drains 5B and 6B than between 6B and 7B.

Data From C (30-degree) Drains

Because the perpendicular distance between the C drains (0.75 ft) was less than that for either the A drains (1.50 ft) or the B drains (1.06 ft), the water table heights for the C drains were lower (figs. 9, 10, 11 and table 3). The effect of the flume boundaries was apparent when observing the plots of each row of piezometer pressures. However, the piezometer pressures between drains 6C and 7C had a pattern that showed the water table to be considerably lower close to drain 7C than in the areas between drains 5C and 6C and between drains 7C and 8C. This could be caused by drain 7C deflecting when it was installed, making the piezometer pressures lower in this location. Although the water table was lower near drain 7C, as shown on piezometer pressure plots of 6C-R, 6C-C, and 6C-L, the maximum water table height between drains 6C and 7C was very close to the pattern of water table heights between drains 5C and 6C and between drains 7C and 8C. The 30-degree angle of drains made them act more like the D drains (placed straight down the slope) where the water table built up higher the farther down the slope the water traveled before reaching a drain outlet.

Data From D (0-degree) Drains

The water table profile for the D drains was lower toward the upslope drain exit. This is the opposite of the profile of water table between the 90-degree A drains. For a wider drain spacing, such as 6 and 12 feet (1.83 and 3.66 m) [2], it is more noticeable. Table 4 shows a comparison of drain discharge from each of the five D drains and discharge from the downslope flume end drain. As the water table slope increased from 2½ percent, discharge from the end drain increased. Table 4 also shows the water table profile between drain exits 2D and 3D and between drain exits 3D and 4D. After water drains from 3D, the water table downslope drops abruptly. For the 10-percent gradient, the water table drops below the plane of the drains for piezometers 1 and 2. These data show how inefficient drains placed at a 0-degree angle are for slopes above 2½ percent. The excess end drain discharge for slopes above 2½ percent indicates flow passing downslope between the plane of the drains and the barrier.

SUMMARY AND ANALYSIS OF TESTS

Table 1 shows the maximum water table heights between A drains for water table gradients 0, 2-½, 5, 7-½, and 10 percent. The maximum water table height between adjacent drains from drains 3A to 7A are taken from seven piezometers between each of four pairs of adjacent drains. Discharge rates from all seven A drains are also shown. The pattern of maximum water table heights is similar for all water table gradients. Pressures in piezometer sets 3A and 6A were higher than those in piezometer sets 4A and 5A. Sets 4A and 5A show maximum water table heights about 82 percent of the water table heights in 3A and 6A. There is no apparent reason for this trend except the drain discharge from the next drain downslope would generally increase as the upslope water table would increase and the drain discharge would decrease as the upslope water table would decrease. Averaging the water table heights in the four sets of piezometers showed that the average maximum water table heights decreased as the slope of the water table gradient increased: 0.171 feet (52 mm) for a 2-½ percent slope and 0.144 feet (44 mm) for a 10 percent slope.

Water table heights for the B drains (45 degrees to the water table gradient) were higher on the left side of the flume looking downslope, than on the right side (table 2). This trend was more prominent for the B drains than for the C (30-degree) drains. In a large agricultural field with a water table of uniform slope, a uniform maximum water table between drains would be expected over the entire drained area. It is apparent that the flume side walls had a boundary influence on the pattern of the water table between drains in the model.

The pattern of water table heights was similar for all slopes of gradient, 2-½ to 10-percent. With accretion from uniform irrigation water, or recharge in the model study, water flowing vertically downward would follow a flow net affected by gravity and the line sink of each drain. The B drains, aligned at a 45-degree angle downslope to the left (fig. 10), caused the accretion water to move to the left and build up against the left flume wall.

The discharge from each of the nine B drains is also shown in table 2. The flow varies from drain to drain, but the pattern of each of the four slopes of water table gradient tested was the same. Variations are very likely due to slight differences in the levels of the drains and their alignments, or due to possible deflections of the drains in the model during installation. A similar variation in discharges from individual drains in each drain set can be seen in the tables for each set. Upslope drain 1B and downslope drain 9B had higher discharges than drains 2B through 8B. Excess discharge in the upslope and downslope drains was apparently due to the change of pattern of drains installed between the A and B drain sets and between the B and C drain sets.

The C drains (30 degrees to the water table gradient) had a pattern of maximum water table heights between drains similar to that for the B drains, except that the water table did not build up on the left side. The small angle between the drains and the gradient did not have a great effect on the flow net.

Water table heights for the D drains (0 degrees to the water table gradient) increased going downslope from a drain collector to the next downslope drain collector. Drain discharge increased from the upslope drain collector, 1D, to the downslope drain collector 5D. For every test considerable flow reached the vertical drain at the end of the flume (table 4). It was obvious that considerable flow was moving downslope in the aquifier below the plane of the drain sets as described below.

INFILTRATION RECHARGE VS. DRAIN DISCHARGE

A summary of a typical set of measurements showing infiltration recharge and discharge from all drain sets for all water table gradients tested is given in table 5. A test for the A drains with the water table gradient set at zero slope (flume level) shows considerable flow, 31.66 ft^3 per day (0.90 m^3/day), discharging from the upslope vertical end drain. At zero slope and at 2-½ percent slope, a small discharge came from the upslope end drain.

As the water table gradient was increased, 5 to 10 percent, considerable flow from accretion to the A-drain zone flowed down the slope under the drains. Column 5 on table 5 shows that the difference between total infiltration and drain discharge was comparatively small. The difference between infiltration and drain discharge for the C drains was larger, and for the D drains it increased dramatically.

MAXIMUM WATER TABLE BETWEEN DRAINS

Because the perpendicular spacings between drains was different for each set of drains, it was necessary to use a normalizing computation to compare water table heights. In report [1] the development of a computer program, EJC16M (app. A), is described relating to the various parameters that influence drain spacing design for steady recharge conditions. Donnan's tile spacing formula [3] was used with Hooghoudt's correction for convergence [4] in developing this computer program. These formulas have been used extensively for drainage design in steady-state conditions and for a first estimate for transient drainage conditions [5, 6]. The steady-state drain spacing formulas are based on the Dupuit-Forchheimer idealization, which involves the assumption that the gradient at the water table is effective through the entire saturated thickness of an unconfined aquifer. The drainage design parameters are the coefficient of permeability (hydraulic conductivity) of the aquifer material, drain spacing, radius of the drain plus gravel envelope, depth between drains and impermeable barrier, infiltration recharge (deep percolation), and the maximum water table height between drains. The formulas are based on drainage from level land.

Another computer program, EJC20M (app. B), used to compute permeability when the other variables were known, was adapted from EJC16M. Using the A-drain test for zero water table gradient gives a permeability of 38.02 feet per day (11.59 m/day). This is less than the permeability of 48.902 feet per day (14.91 m/day) measured in the 60-foot-long (18.29 m) flume because of the small drain spacing and the Dupuit-Forchheimer idealization. Using a permeability of 38.02 feet per day and computing water table heights for the B, C, and D drain sets with respective drain spacings of 1.06, 0.75, and 1.0 feet (320,229, and 305 mm) gave a way to compare water table heights among the different oblique drains. The comparison is shown on table 6 for all drain sets and for all water table gradients tested.

CONCLUSIONS AND RECOMMENDATIONS

From the data taken in the narrow, 2-foot- (610 mm) wide flume, it was apparent that the flume sides had a boundary effect on steady-state ground water flow to oblique drains. Using the flume data, comparable efficiencies of oblique drains could not be determined for drains installed at various angles to the water table gradient and for a variation of the water table gradient.

A three-dimensional mathematical model is needed to relate the physical changes of flow to the influencing variables: aquifer permeability, infiltration (deep percolation), drain spacing, radius of the drain plus gravel envelope, depth of drains to impermeable barrier, water table gradient, and angle of drains to water table. Data from the study of the hydraulic model with its restrictive boundary conditions could be used to verify the mathematical model.

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APPENDIX A

COMPUTER PROGRAM EJC16M
FOR DETERMINING MAXIMUM WATER TABLE HEIGHT
BETWEEN AGRICULTURAL PIPE DRAINS

```
      PROGRAM EJC16M(INPUT,OUTPUT)
C     COMPUTATIONS FOR MAXIMUM WATER TABLE BETWEEN DRAINS -
C     STEADY RECHARGE - DONNAN"S FORMULA WITH HOOGHOUDT"S
C     CORRECTION FOR CONVERGENCE
C     IF Ø < D/S <= .312 USE FORMULA A, IF .312 < D/S USE
C     FORMULA B
      DIMENSION P(1Ø)
      DIMENSION R(1Ø)
C     INPUT VALUES
C     NN = NUMBER OF R VALUES
C     R = RECHARGE RATE ... FT. PER DAY
C     MM = NUMBER OF P VALUES
C     P = PERMEABILITY ... FT. PER DAY
C     S = DRAIN SPACING - FT
C     R1 = RADIUS OF DRAIN + GRAVEL PACK - FT
C     D = DEPTH - DRAINS TO BARRIER - FT
      PRINT 1Ø
   1Ø FORMAT(/*..NN..R,,MM,,P*)
      READ*, NN,(R(IN),IN=1,NN),MM,(P(IN),IN=1,MM)
      PRINT 2Ø
   2Ø FORMAT(/*...SS...R1...DD*)
      READ*, S,R1,D
      PRINT 3Ø,S,R1,D
   3Ø FORMAT (    17X,
     +        5ØHCOMPUTATIONS FOR MAX WATER TABLE - STEADY RECHARGE/
     +        15X,38HDONNAN"S FORMULA WITH HOOGHOUDT"S CORR
     +        16H FOR CONVERGENCE/
     +        15X,34HFOR Ø < D/S <= .312 OR .312 < D/S,/
     +        15X,21HDRAIN SPACING, S - FT F8.3/
     +        15X,38HRADIUS OF DRAIN + GRAVEL PACK, R1 - FT F5.2/
     +        15X,33HDEPTH - DRAINS TO BARRIER, D - FT F8.1//
     +        5X,44HPERMEABILITY     AVG RECHARGE     MAX WATER
     +        6H TABLE/
     +        8X,4ØHFT/DAY P(K)/R(I)  FT/DAY               FT
     +        15H           D/S //)
C     START FORMULA A (FOR Ø<D/S<=.312)
      DO 1ØØ K = 1,MM
        IF (P(K).EQ. Ø.) GO TO 11Ø
        DO 7Ø I = 1,NN
          IF (R(I).EQ. Ø.) GO TO 8Ø
          T = P(K)/R(I)
          V = D/S
          IF ( V .GT. Ø.312) GO TO 5Ø
          A = 1 + (2.546*D/S)*ALOG(D/R1)
          B = -3.55*(D/S) + 1.6*(D**2./S**2.)
     +    - ((2.*D**3.)/(S**3.))
          C = D/(A+B)
          E = SQRT(C**2. + (S**2.*R(I))/(4.*P(K)))
          H = -C + E
          PRINT 4Ø,P(K),T,R(I),H,V
   4Ø     FORMAT (4X,F7.3,2X,F8.2,2X,F8.4,9X,F1Ø.4,8X,F8.4)
```

```
      GO TO 70
C     START FORMULA B (FOR .312<D/S)
   50 A1 = 2.546*(ALOG(S/R1) - 1.15)
      B1 = (S/A1)
      C1 = SQRT(B1**2. + (S**2.*R(I))/(4.*P(K)))
      H = -B1 + C1
      PRINT 60,P(K),T,R(I),H,V
   60 FORMAT (4X,F7.3,2X,F8.2,2X,F8.4,9X,F10.4,5X,F8.4)
   70 CONTINUE
   80 PRINT 90
   90 FORMAT(* *)
  100 CONTINUE
  110 STOP
      END
```

APPENDIX B

COMPUTER PROGRAM EJC20M FOR DETERMINING PERMEABILITY OF AQUIFER WHEN MAXIMUM WATER TABLE BETWEEN AGRICULTURAL PIPE DRAINS IS KNOWN

```
      PROGRAM EJC20M(INPUT,OUTPUT)
C     COMPUTATIONS TO CALCULATE PERMEABILITY
C     DOONAN"S FORMULA WITH HOOGHOUDT"S CORRECTION FOR CONVERGENCE
      DIMENSION R(5),S(5),H(5)
      COMMON R1,D
    5 DO 10 I=1,5
      R(I)=0.0
      S(I)=0.0
      H(I)=0.0
   10 CONTINUE
C     READ INPUT FROM CRT
      WRITE(1, 20)
   20 FORMAT(/29HRECHARGE RATE (FT/DAY) - R(I) / 1X,
     + 47H  TYPE IN NUMBER OF RECHARGE RATES, THEN VALUES)
      ACCEPT NR, (R(I), I=1, NR)
      IF(NR.GT.5)  WRITE(1, 25 )
   25 FORMAT(45H***MAXIMUM NUMBER OF VALUES ALLOWED IS 5 -- B,
     + 10HEGIN AGAIN)
      IF(NR.GT.5) GO TO 5
      WRITE(1, 30)
   30 FORMAT(/41HHEIGHT OF WATER TABLE ABOVE CENTER LINE O
     + 20HF DRAINS (FT) - H(I) / 1X,30H  TYPE IN NUMBER OF HEIGHTS, T
     + 10HHEN VALUES)
      ACCEPT NH,(H(I),I=1,NH)
      IF(NH.GT.5) WRITE(1, 25)
      IF(NH.GT.5) GO TO 5
      WRITE(1, 40)
   40 FORMAT(/29HSPACING OF DRAINS (FT) - S(I) /1X,
     + 41H  TYPE IN NUMBER OF SPACINGS, THEN VALUES)
      ACCEPT NS,(S(I),I=1,NS)
      IF(NS.GT.5) WRITE(1, 25)
      IF(NS.GT.5) GO TO 5
      WRITE(1, 50)
   50 FORMAT(/39HRADIUS OF DRAIN + GRAVEL PACK (FT) - R1/1X,
     + 15H  TYPE IN VALUE)
      ACCEPT R1
      WRITE(1, 60)
   60 FORMAT(/42HDEPTH FROM CENTER LINE OF DRAINS TO BARRIE
     + 10HR (FT) - D / 1X,15H  TYPE IN VALUE)
      ACCEPT D
C     PRINT HEADINGS
  100 WRITE(1, 110 )
  110 FORMAT(///23X,27HCOMPUTATION OF PERMEABILITY / 7X,10HDONNAN"S F
     + 50HORMULA WITH HOOGHOUDT"S CORRECTION FOR CONVERGENCE / 23X,
     + 28HFOR 0<D/S<0.312 OR D/S>0.312 /)
      WRITE(1, 120)  R1, D
  120 FORMAT(6X,29HRADIUS OF DRAIN + GRAVEL PACK,F5.3,3H FT /6X,
     + 28HDEPTH FROM DRAINS TO BARRIER,F6.1,3H FT //)
      WRITE(1, 130 )
  130 FORMAT(4X,8HRECHARGE,7X,5HDRAIN,9X,5HWATER,8X,3HD/S,9X,
```

```
     + 10HCALCULATED / 6X,4HRATE,8X,7HSPACING,8X,5HTABLE,7X,5HRATIO,7X,
     + 12HPERMEABILITY/4X,8H(FT/DAY),7X,4H(FT),10X,4H(FT),23X,
     + 8H(FT/DAY) )
C     CHECK TO DETERMINE BEST ORGANIZATION OF OUTPUT
C     AND CALCULATE PERMEABILITY FOR ALL COMBINATIONS OF PARAMETERS
      IA=NR+NS
      IB=NR+NH
      IC=NS+NH
      ID=NR+NH
      IF(IA.EQ.2) GO TO 140
      IF(IB.EQ.2) GO TO 140
      IF(IC.EQ.2) GO TO 140
      IF(ID.EQ.3) GO TO 140
      IF(NR.EQ.1) GO TO 180
      IF(NH.EQ.1) GO TO 200
      GO TO 180
  140 WRITE(1, 150 )
  150 FORMAT(/)
      DO 170 I=1,NR
      DO 170 J=1,NS
      DS=D/S(J)
      DO 170 K=1,NS
      IF(DS.LE.0.312) GO TO 151
      CALL PERM2(R(I),S(J),H(K),P)
      GO TO 152
  151 CALL PERM1(R(I),S(J),H(K),P)
  152 CONTINUE
      WRITE(1, 160) R(I),S(J),H(K),DS,P
  160 FORMAT(5X,F6.4,7X,F7.2,6X,F7.4,7X,F5.3,7X,F9.4)
  170 CONTINUE
      GO TO 220
  180 DO 190 I=1,NR
      DO 190 J=1,NS
      DS=D/S(J)
      WRITE(1, 150 )
      DO 190 K=1,NH
      IF(DS.LE.0.312) GO TO 181
      CALL PERM2(R(I),S(J),H(K),P)
      GO TO 182
  181 CALL PERM1(R(I),S(J),H(K),P)
  182 CONTINUE
      WRITE(1, 160) R(I),S(J),H(K),DS,P
  190 CONTINUE
      GO TO 220
  200 DO 210 I=1,NR
      WRITE(1, 150 )
      DO 210 J=1,NS
      DS=D/S(J)
      IF(DS.LE.0.312) GO TO 201
      CALL PERM2(R(I),S(J),H(K),P)
      GO TO 202
  201 CALL PERM1(R(I),S(J),H(K),P)
  202 CONTINUE
      WRITE(1, 160) R(I),S(J),H(1),DS,P
  210 CONTINUE
```

```
  220 WRITE(1, 150 )
      END
      SUBROUTINE PERM1(RR,SS,HH,P)
C     THIS SUBROUTINE CALCULATES PERMEABILITY FOR Ø<D/S<=Ø.312
C     FORMULA (4Ø), PAGE 8, DRAINAGE FROM LEVEL AND SLOPING LAND
C     P=PERMEABILITY (FT/DAY)
C     RR=RECHARGE RATE (FT/DAY)
C     SS=DRAIN SPACING (FT)
C     HH=HEIGHT OF WATER TABLE ABOVE DRAIN CENTER LINE (FT)
C     R1=RADIUS OF DRAIN + GRAVEL PACK (FT)
C     D=DEPTH FROM CENTER LINE OF DRAINS TO BARRIER (FT)
      COMMON R1,D
      PART1=SS+D*(2.54648*ALOG(D/R1)-3.4)
      PART2=PART1/(2.Ø*D*SS+HH*PART1)
      P=(SS**2)*RR*PART2/4.Ø/HH
      RETURN
      END
      SUBROUTINE PERM2(RR,SS,HH,P)
C     THIS SUBROUTINE CALCULATES PERMEABILITY FOR D/S>Ø.312
C     FORMULA (41), PAGE 8, DRAINAGE FROM LEVEL AND SLOPING LAND
C     P=PERMEABILITY (FT/DAY)
C     RR=RECHARGE RATE (FT/DAY)
C     SS=DRAIN SPACING (FT)
C     HH=HEIGHT OF WATEABLE ABOVE DRAIN CENTER LINE (FT)
      COMMON R1,D
      PART1=ALOG(SS/R1)-1.15
      PART2=PART1/(3.1416*SS+4.Ø*HH*PART1)
      P=(SS**2)*RR*PART2/HH
      RETURN
      END
```

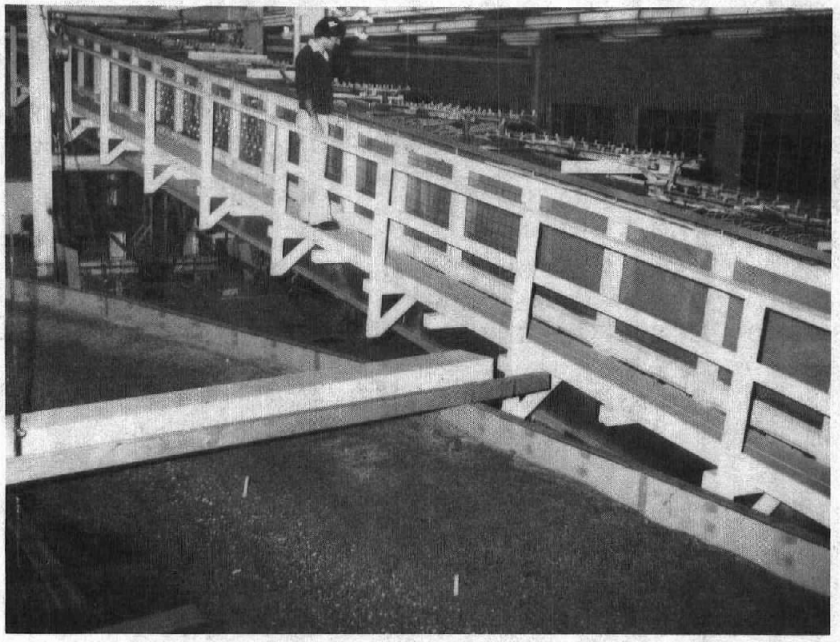


Figure 1. – Hydraulic model sloping flume used for oblique drain tests. Photograph H-1882.

Figure 2. – Test flume tilted to its maximum slope, 12 percent. Photograph PX-D-70132

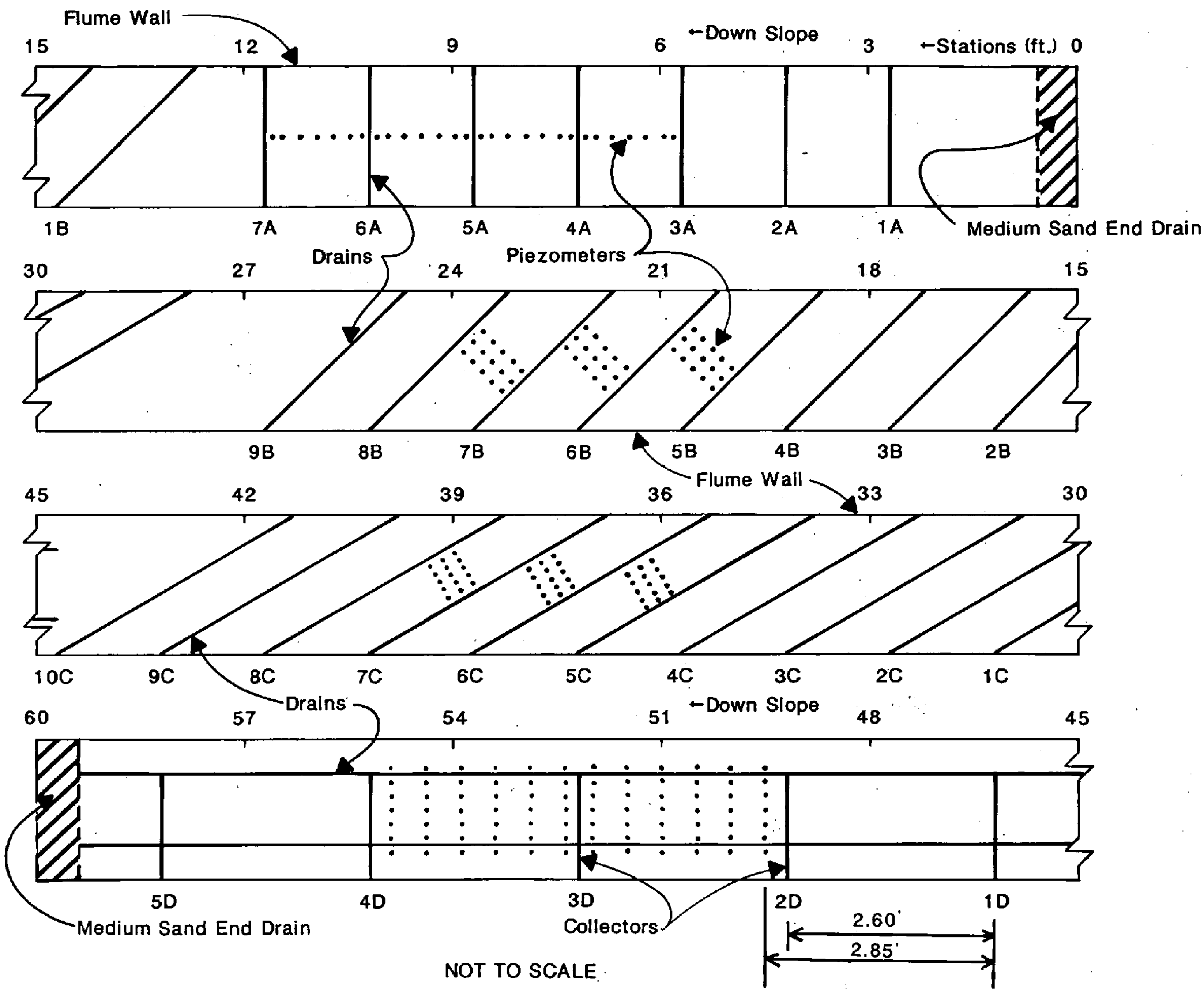


Figure 3. – Designations and locations of drains and piezometers in test flume.

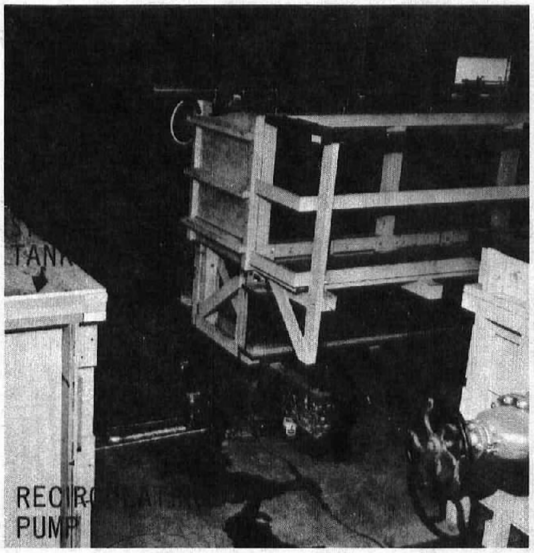


Figure 4. – Water recirculation system. Water is recirculated in the drainage system to maintain a uniform water temperature and a uniform dissolved air content in the water. Photograph PX-D-70127

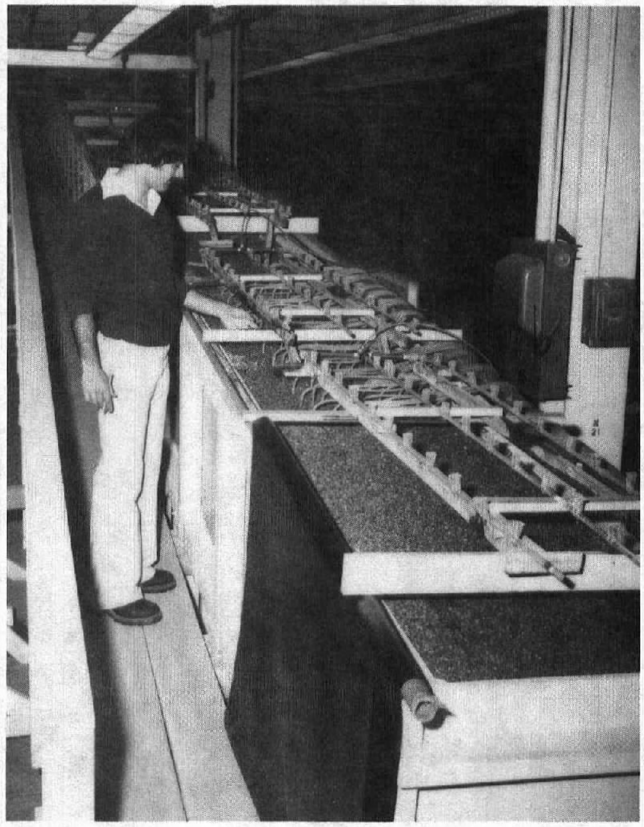


Figure 5. – Water recharge modules. Drainage water is provided through 10 recharge modules, each 6 feet long. Photograph H-1881-5

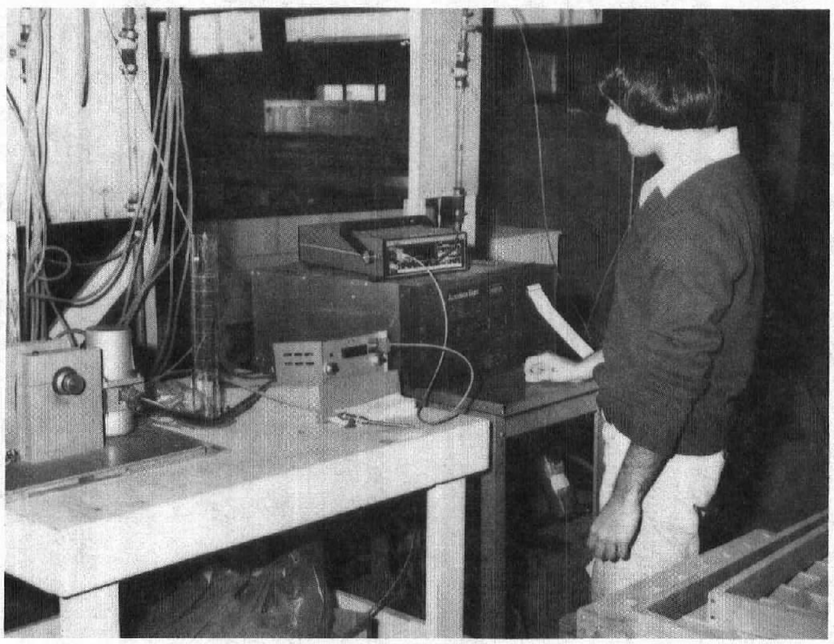


Figure 6. – Pressure measuring and recording system for piezometers. Sensitive pressure transducer, scanivalve, digital voltmeter, and strip paper printer. Photograph H-1881-10

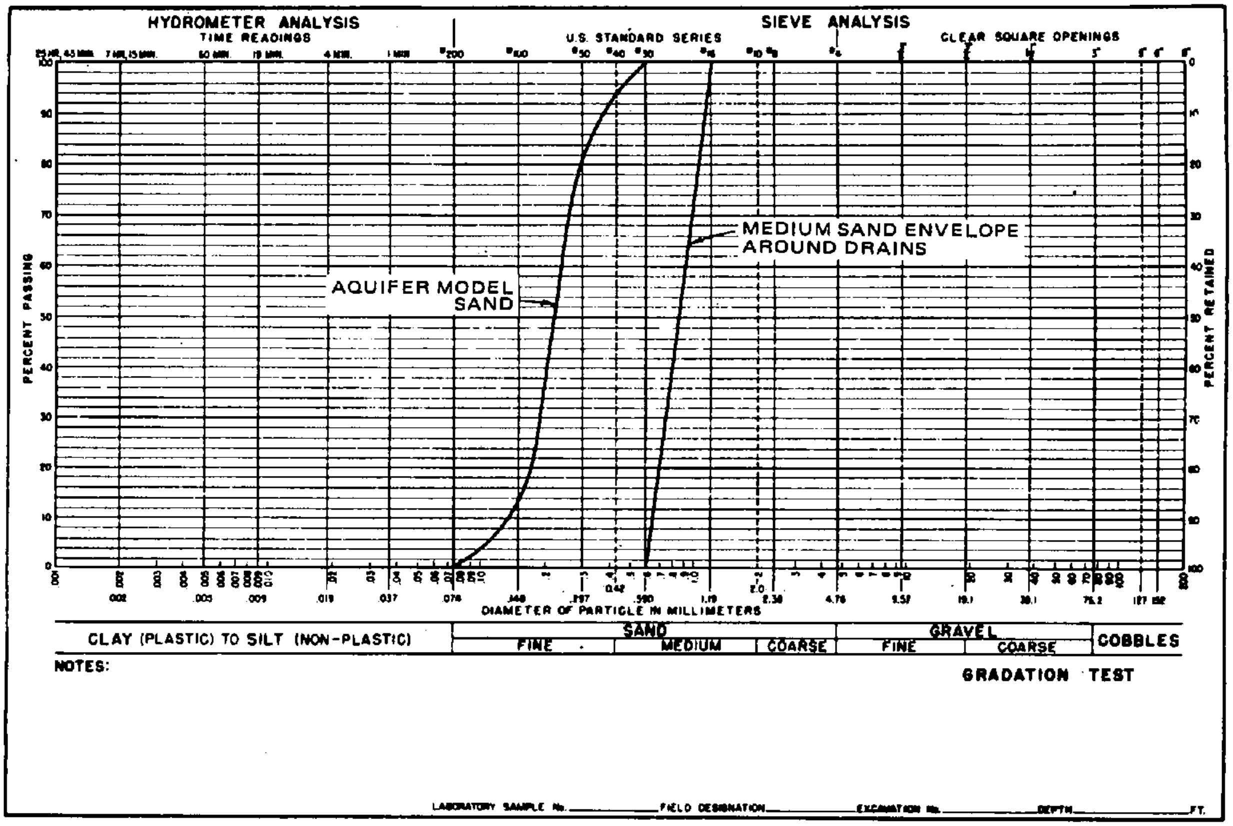


Figure 7. – Sieve analysis of sand used for aquifer and drain envelope material.

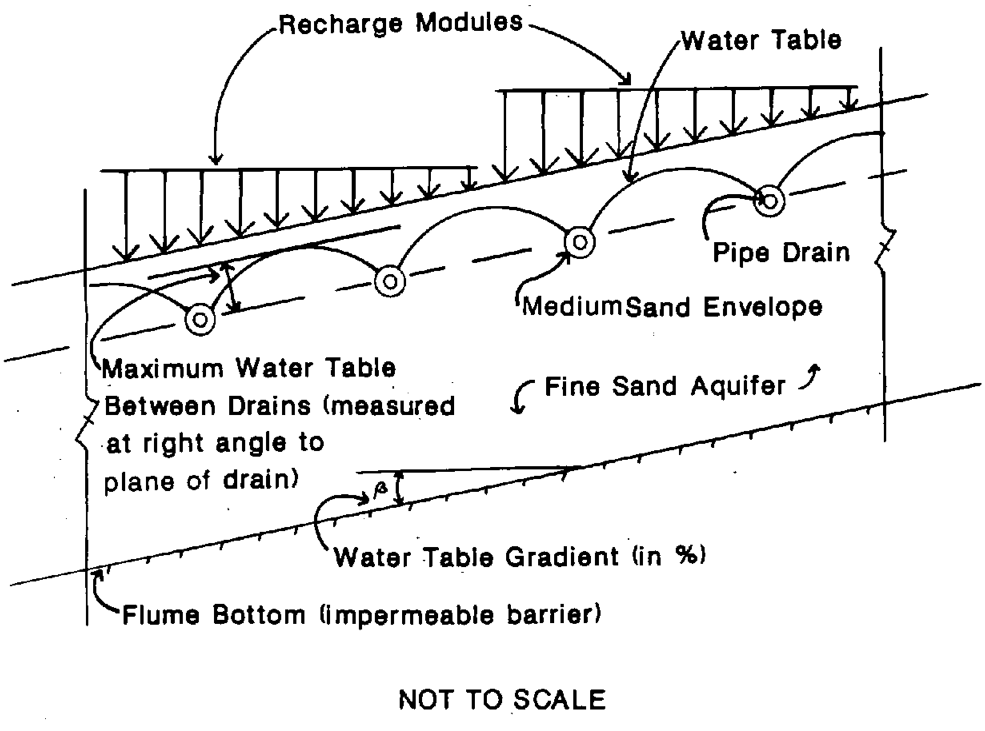
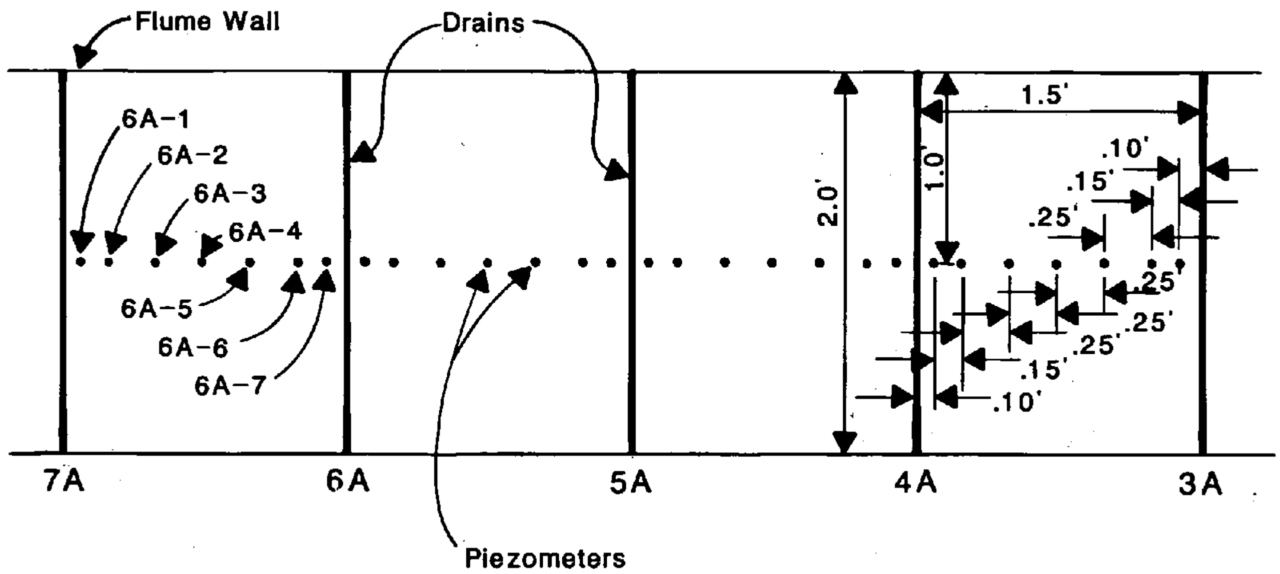
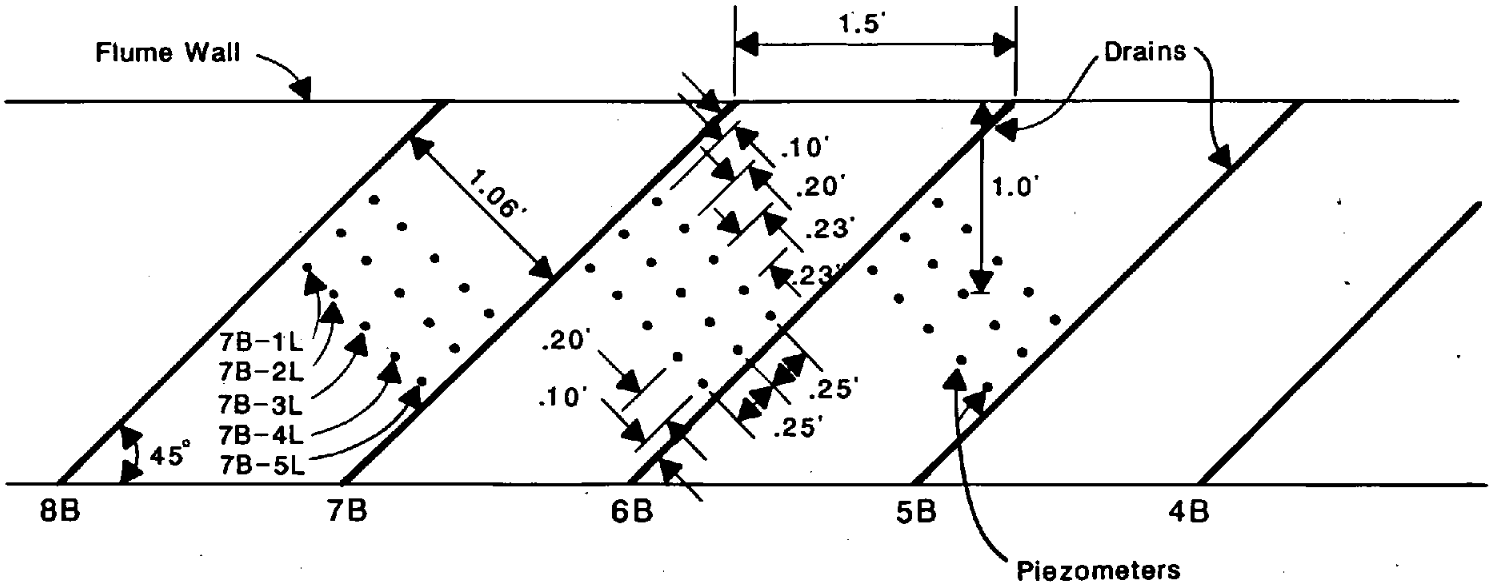


Figure 8. – Typical cross section showing the water table between drains for the 90-, 45-, 30-, and 0-degree (A, B, C, and D) drains. Cross section is perpendicular to direction of the drains (see fig. 3).



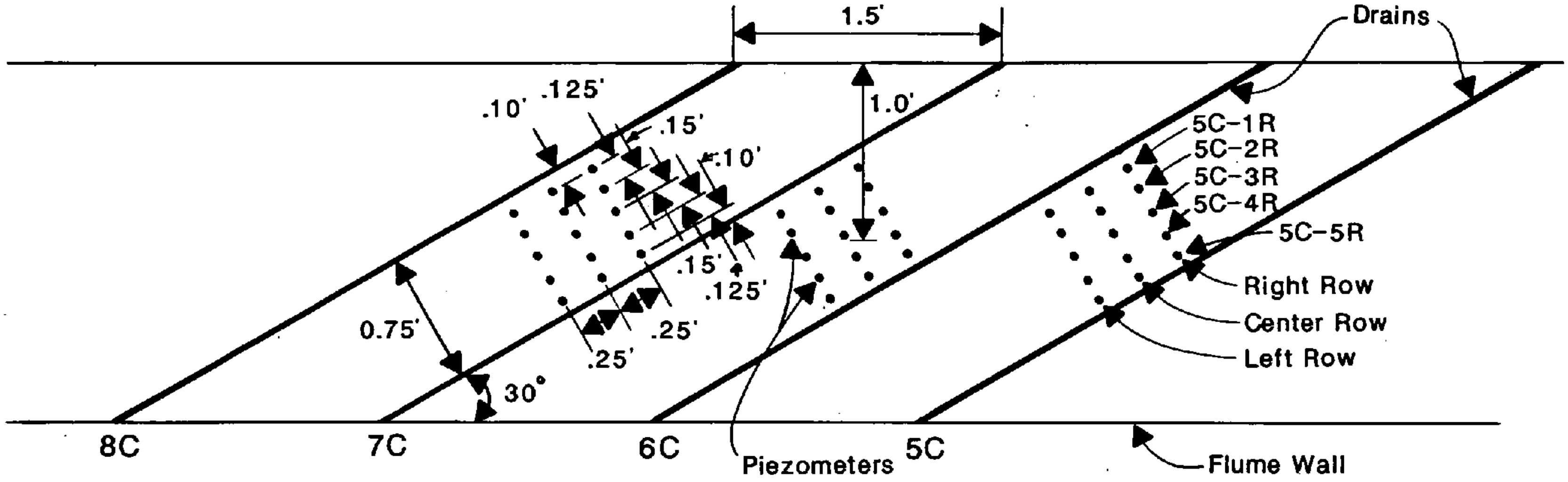
NOT TO SCALE

Figure 9. – Locations of piezometers for A drains.



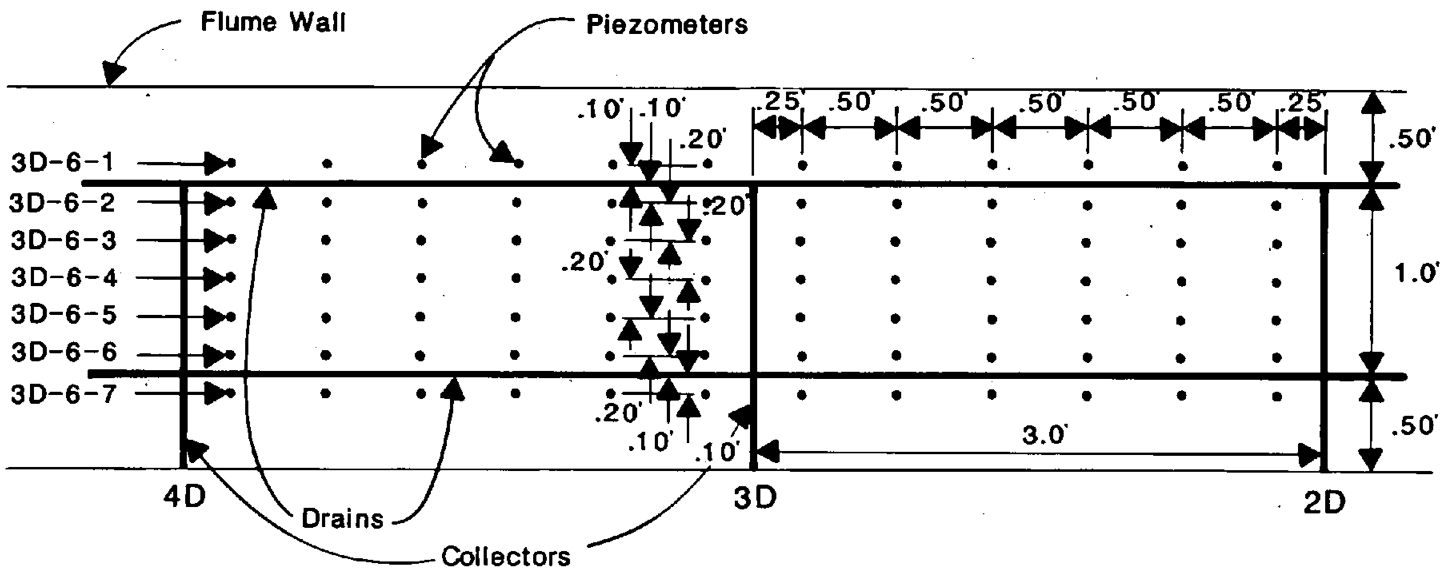
NOT TO SCALE

Figure 10. – Locations of piezometers for B drains.



NOT TO SCALE

Figure 11. – Locations of piezometers for C drains.



NOT TO SCALE

Figure 12. – Locations of piezometers for D drains.

Description of Table Column Headings

The dates in all six tables refer to when the data was taken.

Tables 1, 2, and 3. – Column 2, "Drain piezometer row," refers to the drains as numbered on figure 3. Column 3, "Measured maximum water table, ft," gives the measured maximum water table height (measured perpendicular to the plane of the drains as shown on figs. 3 and 8) between the drain in column 2 and the next downslope drain. Drain sets B and C had three rows of piezometers, right (R), center (C), and left (L) looking downslope, as shown in tables 2 and 3 and on figure 3. The average maximum water table height for each slope tested is given at the bottom of each set of measurements taken. Column 4, "Drain Q infiltration rate, ft/day," shows the discharge from each drain converted to infiltration over the surface area contributing to the individual drain in cubic feet per square foot per day (ft/day). Column 5, "Drain discharge, ft^3/day," gives the discharge from each drain in cubic feet per day. Discharge from the US (upslope) end of the flume (vertical medium sand layer) is given in table 1. Total discharge for all drains in each set, including the flume ends where appropriate, is given at the bottom of column 5.

Table 4. – Columns 1, 2, and 3 are similar to those in tables 1, 2, and 3. Column 4 is the drain collector number. Columns 5 and 6 are similar to columns 4 and 5 in tables 1, 2, and 3. Column 7 gives total drain discharge for only the two D drains and excludes drain water going to the vertical coarse sand layer at the downslope end of the flume.

Table 5. – Column 3, "Total infiltration recharge, ft^3/day," is the recharge infiltration over the entire area for each set of drains in cubic feet per square foot per day (ft per day). Column 4, "Total drain discharge, ft^3/day," is the total discharge for all drains in the particular set in cubic feet per square foot per day (ft per day). Column 5, "Infiltration minus drain discharge, ft^3/day," is the difference between columns 3 and 4, which show the amount of water going to the flow downslope below the drains.

Table 6. – Column 3 gives the measured maximum average water table height between adjacent pairs of drains for each test. Column 4 gives the maximum water table height between drains computed using computer programs EJC16M and EJC20M, for a level water table gradient.

Table 1. – Hydraulic model data for A drains (Alpha = 90 degrees to water table gradient).

Width of flume = 2.0 ft; depth of drains to barrier = 2.0 ft; radius of drains + gravel envelope = 0.05 ft; perpendicular drain spacing = 1.50 ft; area contributing to all drains = 24.74 ft^2; infiltration recharge = 61.8 mL/s = 188.56 ft^3/day = 7.619 ft/day.

(1) Date of test	(2) Drain piez-ometer row	(3) Measured maximum water table, ft	(4) Drain Q infil-tration rate, ft/day	(5) Drain discharge, ft^3/day
WATER TABLE GRADIENT BETA = 0%				
02-26-79	US end			31.66
	1A	—	7.65	22.96
	2A	—	7.32	21.95
	3A	0.180	8.30	24.89
	4A	0.148	8.44	25.31
	5A	0.154	6.87	20.62
	6A	0.175	7.32	21.95
	7A	—	7.73	23.19
	Average	0.164	Total	192.52
WATER TABLE GRADIENT BETA = 2-½%				
01-30-79	1A	—	12.50	37.51
	2A	—	12.42	37.25
	3A	0.190	7.21	21.62
	4A	0.158	8.84	26.53
	5A	0.150	6.78	20.34
	6A	0.187	7.73	23.19
	7A	—	7.82	23.46
	Average	0.171	Total	189.90
WATER TABLE GRADIENT BETA = 5%				
01-30-79	1A	—	11.72	35.15
	2A	—	8.86	26.57
	3A	0.190	7.49	22.48
	4A	0.120	8.95	26.85
	5A	0.145	6.70	20.09
	6A	0.165	7.35	22.04
	7A	—	5.51	16.53
	Average	0.155	Total	169.71

Table 1. – Hydraulic model data for A drains
(Alpha = 90 degrees to water table gradient). – Continued

(1) Date of test	(2) Drain peiz-ometer row	(3) Measured maximum water table, ft	(4) Drain Q infil-tration rate, ft/day	(5) Drain discharge, ft^3/day
WATER TABLE GRADIENT BETA = 7-½%				
01-30-79	1A	—	12.79	38.36
	2A	—	10.30	30.89
	3A	0.178	7.74	23.21
	4A	0.143	7.80	23.40
	5A	0.135	6.12	18.36
	6A	0.155	7.76	23.28
	7A	—	6.47	19.40
	Average	0.153	Total	176.90
WATER TABLE GRADIENT BETA = 10%				
01-30-79	1A	—	11.91	35.72
	2A	—	9.88	29.63
	3A	0.170	7.67	23.00
	4A	0.135	8.92	26.77
	5A	0.125	6.66	19.99
	6A	0.145	7.78	23.35
	7A	—	6.10	18.30
	Average	0.144	Total	176.75

Table 2. – Hydraulic model data for B drains
(Alpha = 45 degrees to water table gradient).

Width of flume = 2.0 ft; depth of drains to barrier = 2.0 ft; radius of drains + gravel envelope = 0.05 ft; perpendicular drain spacing = 1.06 ft; area contributing to all drains = 29.24 ft²; infiltration recharge = 72 mL/s = 219.69 ft³/day = 7.513 ft/day.

(1)	(2)	(3)			(4)	(5)
Date of test	Drain piez-ometer row	Measured maximum water table, ft Piezometer Rows			Drain Q infil-tration rate, ft/day	Drain discharge, ft³/day
		R	C	L		
WATER TABLE GRADIENT BETA = 2-½%						
01-22-79	1B	—	—	—	10.087	30.261
	2B	—	—	—	7.676	23.028
	3B	—	—	—	6.527	19.581
	4B	—	—	—	7.479	22.437
	5B	0.110	0.120	0.135	8.737	26.211
	6B	0.090	0.108	0.110	8.276	24.828
	7B	0.090	0.100	0.100	5.806	17.418
	8B	—	—	—	7.654	22.962
	9B	—	—	—	10.242	30.726
	Average	0.097	0.109	0.115	Total	217.452
WATER TABLE GRADIENT BETA = 5%						
01-22-79	1B	—	—	—	10.741	32.223
	2B	—	—	—	7.456	22.368
	3B	—	—	—	6.942	20.826
	4B	—	—	—	6.781	20.343
	5B	0.110	0.112	0.118	8.320	24.960
	6B	0.089	0.100	0.120	8.889	26.667
	7B	0.095	0.105	0.102	5.903	17.709
	8B	—	—	—	7.946	23.838
	9B	—	—	—	10.016	30.048
	Average	0.098	0.106	0.113	Total	218.982

Table 2. – Hydraulic model data for B drains
(Alpha = 45 degrees to water table gradient). – Continued

(1)	(2)	(3)			(4)	(5)
Date of test	Drain piez-ometer row	Measured maximum water table, ft Piezometer Rows			Drain Q infil-tration rate, ft/day	Drain discharge, ft^3/day
		R	C	L		
WATER TABLE GRADIENT BETA = 7-½%						
01-22-79	1B	—	—	—	10.992	32.976
	2B	—	—	—	7.704	23.112
	3B	—	—	—	7.440	22.320
	4B	—	—	—	7.997	23.991
	5B	0.120	0.125	0.136	7.998	23.994
	6B	0.105	0.115	0.110	9.555	28.665
	7B	0.085	0.084	0.090	5.638	16.914
	8B	—	—	—	6.370	19.110
	9B	—	—	—	9.103	27.309
	Average	0.103	0.108	0.112	Total	218.391
WATER TABLE GRADIENT BETA = 10%						
01-22-79	1B	—	—	—	11.280	33.840
	2B	—	—	—	7.015	21.045
	3B	—	—	—	7.873	23.619
	4B	—	—	—	8.002	24.006
	5B	0.110	0.120	0.138	8.216	24.648
	6B	0.095	0.105	0.112	8.689	26.067
	7B	0.100	0.100	0.100	6.134	18.402
	8B	—	—	—	6.120	18.360
	9B	—	—	—	8.741	26.223
	Average	0.102	0.108	0.117	Total	216.210

Table 3. – Hydraulic model data for C drains
(Alpha = 30 degrees to water table gradient).

Width of flume = 2.0 ft; depth of drains to barrier = 2.0 ft; radius of drains + gravel envelope = 0.05 ft; perpendicular drain spacing = 0.75 ft; area contributing to all drains = 32.92 ft²; infiltration recharge = 82.17 mL/s = 250.72 ft³/day = 7.616 ft/day.

(1)	(2)	(3)			(4)	(5)
Date of test	Drain piez-ometer row	Measured maximum water table, ft Piezometer Rows			Drain Q infil-tration rate, ft/day	drain discharge, ft³/day
		R	C	L		
WATER TABLE GRADIENT BETA = 2-½%						
01-18-79	1C	—	—	—	13.495	40.485
	2C	—	—	—	7.611	22.833
	3C	—	—	—	8.065	24.195
	4C	—	—	—	6.589	19.767
	5C	0.025	0.022	0.033	7.865	23.595
	6C	0.042	0.048	0.053	5.829	17.487
	7C	0.060	0.060	0.055	8.476	25.428
	8C	—	—	—	7.272	21.816
	9C	—	—	—	6.809	20.427
	10C	—	—	—	6.187	18.561
	Average	0.042	0.043	0.047	Total	234.594
WATER TABLE GRADIENT BETA = 5%						
01-18-79	1C	—	—	—	13.446	40.338
	2C	—	—	—	8.038	24.114
	3C	—	—	—	5.329	15.987
	4C	—	—	—	7.459	22.377
	5C	0.020	0.028	0.035	8.944	26.832
	6C	0.040	0.042	0.038	4.942	14.826
	7C	0.057	0.053	0.053	9.928	29.784
	8C	—	—	—	6.780	20.340
	9C	—	—	—	6.357	29.071
	10C	—	—	—	5.594	16.782
	Average	0.039	0.041	0.042	Total	230.451

Table 3. – Hydraulic model data for C drains
(Alpha = 30 degrees to water table gradient). – Continued

(1) Date of test	(2) Drain piezometer row	(3) Measured maximum water table, ft Piezometer Rows R	C	L	(4) Drain Q infiltration rate, ft/day	(5) Drain discharge, ft^3/day
WATER TABLE GRADIENT BETA = 7-½%						
01-19-79	1C	—	—	—	12.636	37.908
	2C	—	—	—	8.922	26.766
	3C	—	—	—	4.291	12.873
	4C	—	—	—	8.199	24.597
	5C	0.018	0.025	0.032	10.171	30.513
	6C	0.030	0.031	0.028	3.139	9.417
	7C	0.045	0.043	0.046	9.323	27.969
	8C	—	—	—	9.945	29.835
	9C	—	—	—	4.843	14.529
	10C	—	—	—	2.792	8.376
	Average	0.031	0.033	0.035	Total	222.783
WATER TABLE GRADIENT BETA = 10%						
01-19-79	1C	—	—	—	13.512	40.536
	2C	—	—	—	9.894	29.682
	3C	—	—	—	5.683	17.049
	4C	—	—	—	4.041	12.123
	5C	0.020	0.023	0.025	12.300	36.900
	6C	0.032	0.028	0.028	2.534	7.602
	7C	0.040	0.039	0.052	13.105	39.315
	8C	—	—	—	5.684	17.052
	9C	—	—	—	6.655	19.965
	10C	—	—	—	6.733	20.199
	Average	0.031	0.030	0.035	Total	240.423

Table 4. – Hydraulic model data for D drains
(Alpha = 0 degrees to water table gradient).

Width of flume = 2.0 ft; depth of drains to barrier = 2.0 ft; radius of drains + gravel envelope = 0.05 ft; perpendicular drain spacing = 1.0 ft; area contributing to all drains = 33.09 ft²; infiltration recharge = 46.92 mL/s = 143.16 ft³/day = 4.338 ft/day; drain collectors spacing = 3.0 ft.

(1) Date of test	(2) Drain piezometer row	(3) Measured maximum water table, ft	(4) Drain collector number	(5) Drain Q infiltration rate, ft/day	(6) Drain discharge, ft³/day	(7) Drain total discharge, ft³/day
WATER TABLE GRADIENT BETA = 2½%						
01-17-79	2D-1	0.045	1D	1.374	8.244	–
	2D-2	0.068	2D	2.906	17.436	–
	2D-3	0.072	3D	3.769	22.614	–
	2D-4	0.083	4D	3.945	23.670	–
	2D-5	0.100	5D	5.157	30.942	102.906
	2D-6	0.113	End	–	30.204	–
	Average	0.080		Total	133.110	–
01-12-79 & 01-15-79	3D-1	0.026	1D	3.240	19.440	–
	3D-2	0.042	2D	3.678	22.068	–
	3D-3	0.059	3D	2.626	15.756	–
	3D-4	0.070	4D	4.220	25.320	–
	3D-5	0.080	5D	4.680	28.080	110.664
	3D-6	0.098	End	–	23.677	–
	Average	0.063		Total	134.341	–
WATER TABLE GRADIENT BETA = 5%						
01-17-79	2D-1	0.080	1D	2.366	14.196	–
	2D-2	0.095	2D	2.293	13.758	–
	2D-3	0.090	3D	2.877	17.262	–
	2D-4	0.099	4D	2.945	17.670	–
	2D-5	0.100	5D	5.805	34.830	97.716
	2D-6	0.098	End	–	33.208	–
	Average	0.063		Total	130.924	–
01-12-79 & 01-15-79	3D-1	0.015	1D	2.379	14.274	–
	3D-2	0.030	2D	3.192	19.152	–
	3D-3	0.065	3D	2.374	14.244	–
	3D-4	0.070	4D	4.107	24.642	–
	3D-5	0.085	5D	5.599	33.594	105.906
	3D-6	0.105	End	–	34.492	–
	Average	0.062		Total	140.398	–

Table 4. – Hydraulic model data for D drains
(Alpha = 0 degrees to water table gradient). – Continued

(1) Date of test	(2) Drain piez-ometer row	(3) Measured maximum water table, ft	(4) Drain collector number	(5) Drain Q infil-tration rate, ft/day	(6) Drain discharge, ft³/day	(7) Drain total discharge, ft³/day
WATER TABLE GRADIENT BETA = 7½%						
01-17-79	2D-1	0.099	1D	2.682	16.092	–
	2D-2	0.115	2D	2.315	13.890	–
	2D-3	0.110	3D	2.391	14.346	–
	2D-4	0.109	4D	2.445	14.670	–
	2D-5	0.110	5D	5.884	35.304	94.302
	2D-6	0.098	End	–	41.308	–
	Average	0.107		Total	135.610	–
01-12-79 & 01-15-79	3D-1	0.004	1D	1.508	9.048	–
	3D-2	0.014	2D	2.266	13.596	–
	3D-3	0.035	3D	2.049	12.294	–
	3D-4	0.060	4D	3.978	23.868	–
	3D-5	0.076	5D	6.324	37.944	96.750
	3D-6	0.115	End	–	40.560	–
	Average	0.051		Total	137.310	–
WATER TABLE GRADIENT BETA = 10%						
01-17-79	2D-1	0.097	1D	2.534	15.204	–
	2D-2	0.113	2D	2.026	12.156	–
	2D-3	0.107	3D	2.119	12.714	–
	2D-4	0.108	4D	1.891	11.346	–
	2D-5	0.097	5D	6.090	36.540	87.960
	2D-6	0.094	End	–	52.391	–
	Average	0.103		Total	140.351	–
01-12-79 & 01-15-79	3D-1	–0.038	1D	1.305	7.830	–
	3D-2	–0.015	2D	2.270	13.620	–
	3D-3	0.026	3D	2.062	12.372	–
	3D-4	0.068	4D	3.437	20.622	–
	3D-5	0.102	5D	7.006	42.036	96.480
	3D-6	0.141	End	–	53.510	–
	Average	0.047		Total	149.990	–

Table 5. – Hydraulic model data, infiltration recharge compared with drain discharge for all drain sets and all flume slopes.

(1) Water table gradient, %	(2) Date of test	(3) Total infiltration recharge, ft³/day	(4) Total drain discharge, ft³/day	(5) Infiltration minus drain discharge, ft³/day
A DRAINS (ALPHA = 90 DEGREES TO WATER TABLE GRADIENT)				
0	01-30-79	188.56	160.86	–
		US End	31.66	–
		Total	192.52	−3.96
2½	01-30-79	188.56	189.90	−1.34
5	01-30-79	188.56	169.71	18.85
7½	01-30-79	188.56	176.90	11.56
10	01-30-79	188.56	176.75	11.81
B DRAINS (ALPHA = 45 DEGREES TO WATER TABLE GRADIENT)				
2½	01-22-79	219.69	217.45	2.24
5	01-22-79	219.69	218.98	0.71
7½	01-23-79	219.69	218.39	1.30
10	01-23-79	219.69	216.21	3.48
C DRAINS (ALPHA = 30 DEGREES TO WATER TABLE GRADIENT)				
2½	01-18-79	250.72	234.59	16.13
5	01-18-79	250.72	230.45	20.27
7½	01-19-79	250.72	222.78	27.94
10	01-19-79	250.72	240.42	10.30
D DRAINS (ALPHA = 0 DEGREES TO WATER TABLE GRADIENT)				
2½	01-17-79	143.16	102.91	40.25
		End	30.21	–
		Total	133.12	–
5	01-17-79	143.16	97.72	45.44
		End	33.21	–
		Total	130.92	–
7½	01-17-79	143.16	94.30	48.86
		End	41.31	–
		Total	135.61	–
10	01-17-79	143.16	87.96	55.20
		End	52.39	–
		Total	140.35	–

Table 6. – Hydraulic model data and data computed using programs EJC20M and EJC16M. Maximum water table heights between adjacent drains for all drain sets and all flume slopes.

Width of flume = 2.0 ft; depth of drains to barrier = 2.0 ft; radius of drains + gravel envelope = 0.05 ft.

A DRAINS (ALPHA = 90 DEGREES TO WATER TABLE GRADIENT)

Perpendicular drain spacing = 1.50 ft; area contributing to all drains = 24.75 ft²; infiltration recharge = 61.8 mL/s = 188.56 ft³/day = 7.619 ft/day. Computed permeability = 38.02 ft/day, based on measured average maximum water table height for A drains at water table gradient Beta = 0% on 02-26-79, using program EJC20M. Computed water table heights based on program EJC16M.

(1) Water table gradient %	(2) Date of test	(3) Measured maximum water table, ft	(4) Computed maximum water table, ft
2½	01-30-79	0.171	0.164
5	01-30-79	0.155	0.164
7½	01-30-79	0.153	0.164
10	01-30-79	0.144	0.164

(1) Water table gradient, %	(2) Date of test	(3) Measured maximum water table, ft Piezometer Rows			(4) Computed maximum water table, ft
		R	C	L	
B DRAINS (ALPHA = 45 DEGREES TO WATER TABLE GRADIENT)					
Perpendicular drain spacing = 1.06 ft; area contributing to all drains = 29.24 ft²; infiltration recharge = 72 mL/s = 219.69 ft³/day = 7.513 ft/day.					
2½	01-22-79	0.097	0.109	0.115	0.103
5	01-22-79	0.098	0.106	0.113	0.103
7½	01-23-79	0.103	0.108	0.112	0.103
10	01-23-79	0.102	0.108	0.117	0.103

Table 6. – Hydraulic model data and data computed using programs EJC20M and EJC16M. Maximum water table heights between adjacent drains for all drain sets and all flume slopes. – Continued

(1) Water table gradient, %	(2) Date of test	(3) Measured maximum water table, ft Piezometer Rows			(4) Computed maximum water table, ft
		R	C	L	

C DRAINS (ALPHA = 30 DEGREES TO WATER TABLE GRADIENT)

Perpendicular drain spacing = 0.75 ft; area contributing to all drains = 32.92 ft^2; infiltration recharge = 82.17 mL/s = 250.72 ft^3/day = 7.616 ft/day.

2½	01-18-79	0.042	0.043	0.047	0.064
5	01-18-79	0.039	0.041	0.042	0.064
7½	01-19-79	0.031	0.033	0.035	0.064
10	01-19-79	0.031	0.030	0.035	0.064

Table 6. – Hydraulic model data and data compared using programs EJC20M and EJC16M. Maximum water table heights between adjacent drains for all drain sets and all flume slopes. – Continued

(1) Water table gradient %	(2) Date of test	(3) Drain piez-ometer row	(4) Measured maximum water table, ft	(5) Computed maximum water table, ft
D DRAINS (ALPHA = 0 DEGREES TO WATER TABLE GRADIENT)				
Perpendicular spacing = 1.0 ft; area contributing to all drains = 33.09 ft²; infiltration recharge = 4.92 mL/s = 143.16 ft³/dy = 4.338 ft/day; drain collector spacing = 3.0 ft.				
2½	01-17-79	2D	0.080	0.059
2½	01-12-79 & 01-15-79	3D	0.063	0.059
5	01-17-79	2D	0.094	0.059
5	01-12-79 & 01-15-79	3D	0.062	0.059
7½	01-17-79	2D	0.107	0.059
7½	01-12-79 & 01-15-79	3D	0.051	0.059
10	01-17-79	2D	0.059	0.059
10	01-12-79 & 01-15-79	3D	0.059	0.059

GPO 853-132

Mission of the Bureau of Reclamation

The Bureau of Reclamation of the U.S. Department of the Interior is responsible for the development and conservation of the Nation's water resources in the Western United States.

The Bureau's original purpose "to provide for the reclamation of arid and semiarid lands in the West" today covers a wide range of interrelated functions. These include providing municipal and industrial water supplies; hydroelectric power generation; irrigation water for agriculture; water quality improvement; flood control; river navigation; river regulation and control; fish and wildlife enhancement; outdoor recreation; and research on water-related design, construction, materials, atmospheric management, and wind and solar power.

Bureau programs most frequently are the result of close cooperation with the U.S. Congress, other Federal agencies, States, local governments, academic institutions, water-user organizations, and other concerned groups.

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