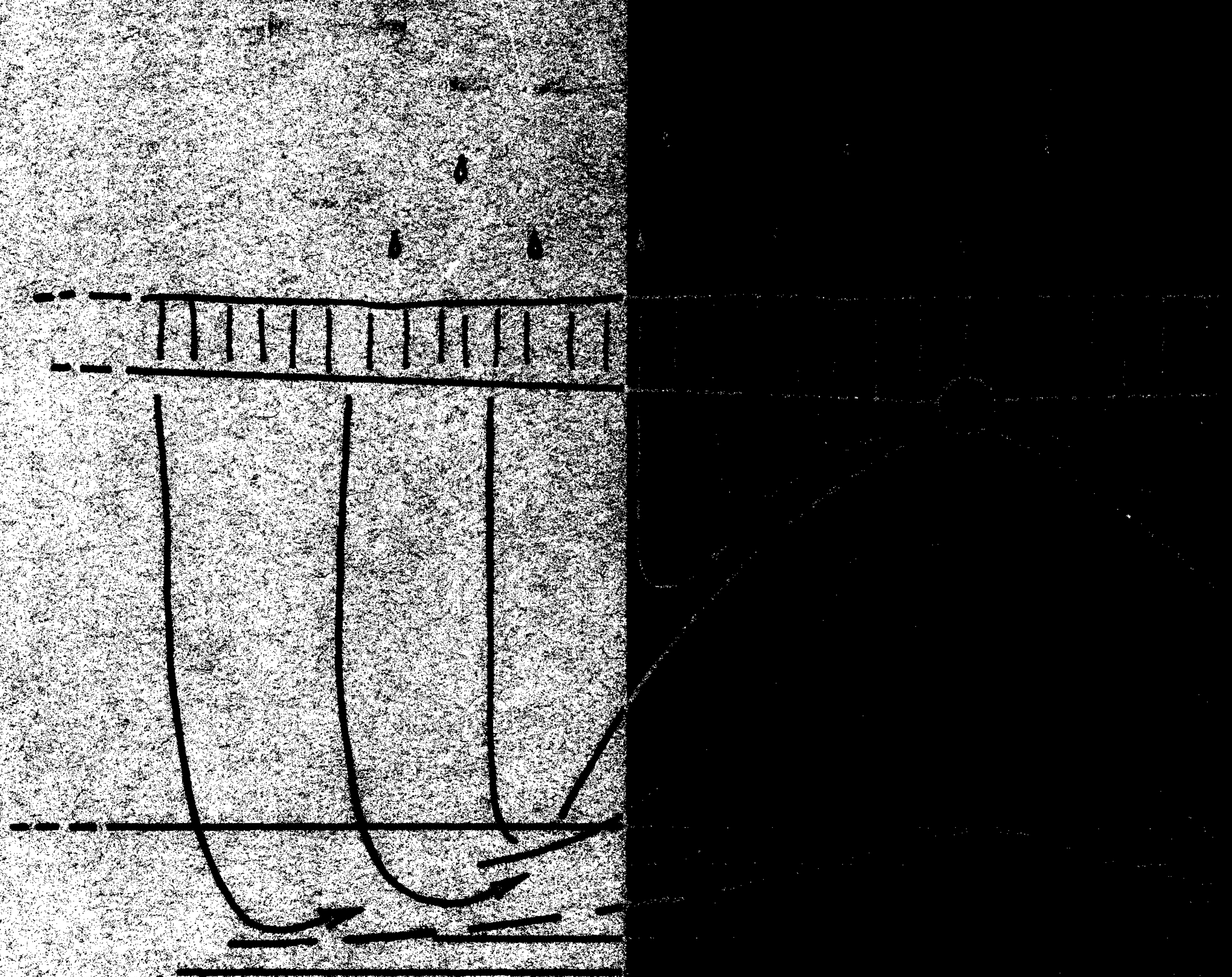
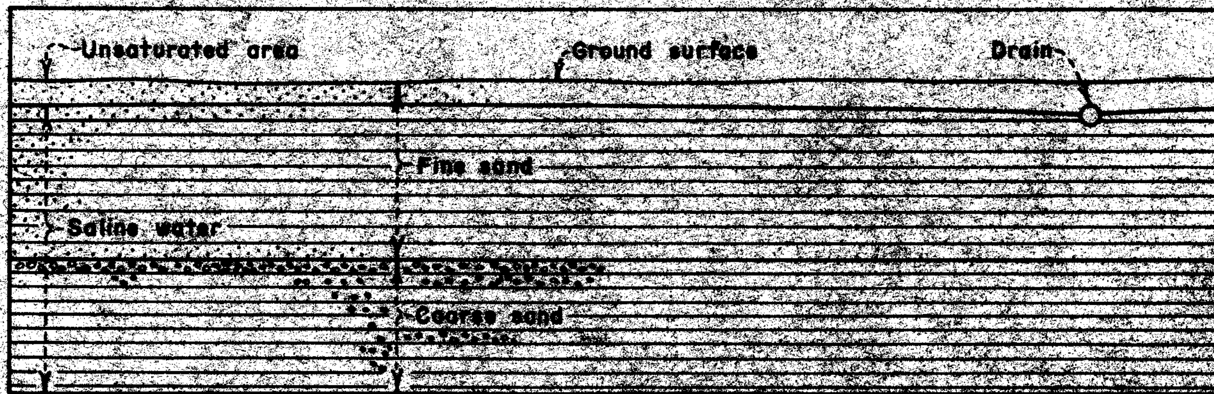


Removal of Saline Water from Aquifers



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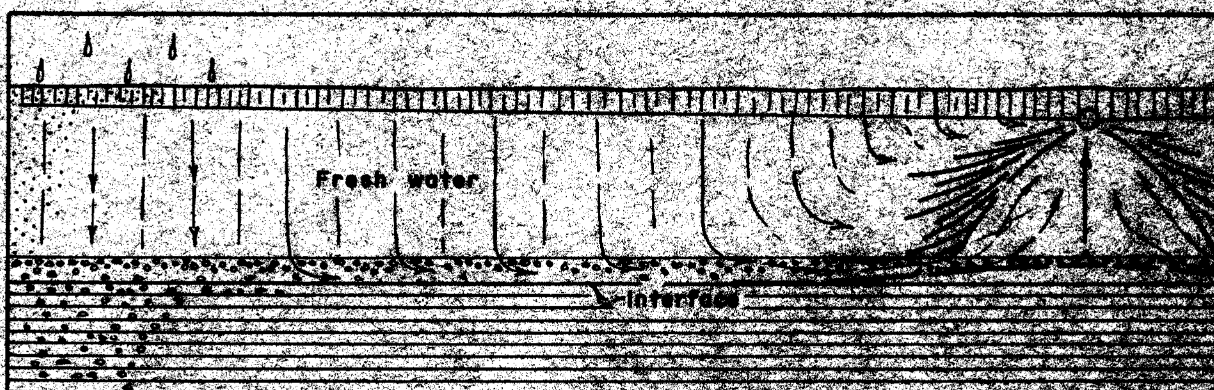
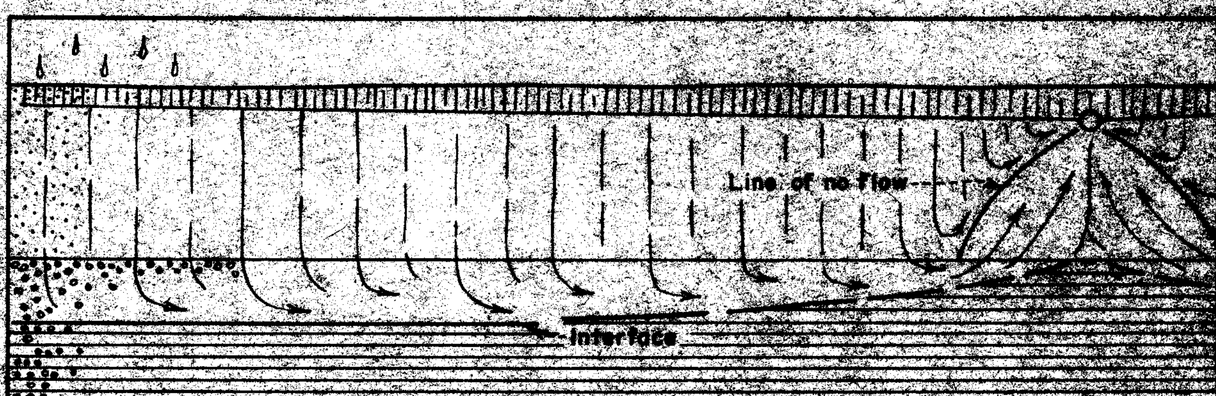
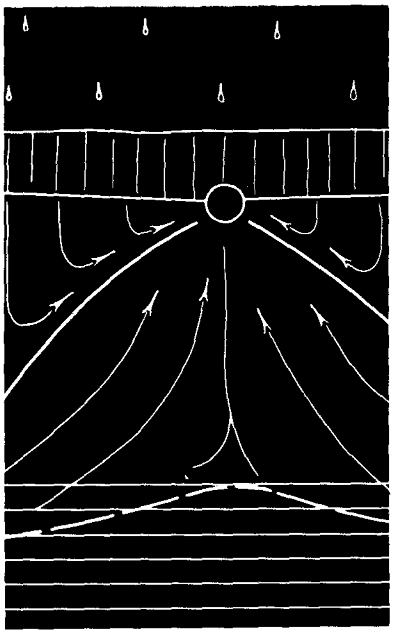


WITH IRRIGATION



WITH STABILIZED INTERFACE

Drainage patterns of saline water in two-part aquifer under irrigation.



Removal of Saline Water from Aquifers

By Enos J. Carlson
Hydraulics Branch
Division of Research
Office of Chief Engineer

UNITED STATES DEPARTMENT OF THE INTERIOR

BUREAU OF RECLAMATION

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering the wisest use of our land and water resources, protecting our fish and wildlife, preserving the environmental and cultural values of our national parks and historical places, and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to assure that their development is in the best interests of all our people. The Department also has a major responsibility for American Indian reservation communities and for people who live in Island Territories under U.S. administration.

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PREFACE

The corollary of good irrigation practice is proper land drainage. Too often the surplus ground water removed from irrigated land through tile drains simply raises the salinity, and consequently the pollution, of the stream into which it is discharged. Already containing dissolved salts, irrigation water increases in salinity during movement on or in the ground.

The situation at once compromises the national effort to improve the water quality of streams and rivers. How then can this pollution be corrected?

This report, *Removal of Saline Water From Aquifers,* based on extensive Bureau of Reclamation research, shows conclusively in what is believed a "first time" investigation that sweet water will be discharged if saline water is first flushed from the aquifer and a stable interface or barrier formed between the fresh and remaining stagnant water. Tile drains placed near the surface of aquifers will not intercept and discharge fresh water if all or part of the aquifer above a stable interface is saline. A formula for computing the depth to a saline water-fresh water interface was derived from the work.

The research findings, documented in this publication, can be of immeasurable value to engineers, designers, and planners concerned with irrigation and drainage, especially with curtailment of downstream saline pollution. The booklet is also useful for academic studies.

The hydraulic model studies were conducted in the Hydraulics Branch, Division of Research, Office of Chief Engineer, Bureau of Reclamation, Denver, Colo. Several engineers from the branch assisted in the many tests. Others from the Division of Drainage and Groundwater Engineering and the Division of Project Investigations furnished the necessary technical data. They also observed the model studies as the testing program progressed.

This research report is based on earlier laboratory reports by A. J. Peterka and R. E. Glover, by E. J. Carlson, and on papers PAP 205 by E. J. Carlson, and PAP 20 by R. E. Glover, both of which were presented at the ASCE Hydraulics Division Conference, Tucson, Ariz., August 25-27, 1965.

Included in this publication is an informative abstract and list of descriptors, or keywords, and identifiers. The abstract was prepared as part of the Bureau of Reclamation's program of indexing and retrieving the literature of water resources development. The descriptors were selected from the *Thesaurus of Descriptors,* which is the Bureau's standard for listings of keywords.

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INTRODUCTION

Waters of natural streams usually contain dissolved salts. When used for irrigation, the water percolating below the root zone increases in salinity because of transpiration and evaporation. Within a few years the problem can become intolerable. If a permanent irrigation agriculture is to be maintained, water in excess of that needed by the crops must generally be applied to provide drainage to carry away these salt concentrations. This creates or intensifies a second problem, draining the land.

To prevent waterlogging, drainage systems may need to be installed to collect and dispose of the excess water. During passage of the drainage waters through the ground, additional salt may be picked up. Usually, no practicable way exists to dispose of drainage flows except a return to the stream of origin.

Where streams traverse arid areas with little or no tributary inflow, and diversions are made for irrigation along their length, it is not surprising to find the salinity of the water increasing downstream. As the water demands approach complete utilization, the salinity level in the lower reaches of the stream may be so high that only salt-tolerant crops can be grown.

Irrigated areas sometimes have some capacity for natural drainage, but when an increase in the use of irrigation water begins to exceed the natural drainage capability, rising water tables will necessitate the installation of drainage systems; otherwise, intolerable soil salinity will result. Immediately after the drainage system is constructed, there will be a more saline drainage effluent, because of the salts accumulated in the soil, than will occur after equilibrium is reached.

Whenever the quality of the river water becomes poor, the problem of salt balance may become critical because of the inability to achieve a salt balance with the available water supply. To design and construct an efficient drainage system, and to predict within reasonable limits the quality of the effluent, the engineer needs to know the mechanism of ground-water movement within the system.

Tests on a 1:40 scale model of an idealized cross section of a typical irrigated valley were made to determine the hydraulic action of tile drains placed 8 feet below the ground surface.[1] Irrigation water was applied to the gravel surface at regular intervals. Water discharging from the drains was sampled for salinity and measured to determine rate of flow. The water table was measured using wells and point gages, and the position of the saline water-fresh water interface was recorded periodically by photography.

Tests in two-part and single-part aquifers initially charged with salt water dyed blue demonstrated that the tile drains will not intercept and discharge the fresh water applied to the soil surface. Only after saline water is flushed from the aquifer and a stable interface is formed between the moving fresh water and the remaining stagnant salt water will fresh water be discharged from the drains.

A time scale for the model was established by comparing the time required to replace the original water content in the idealized section of the typical valley with the time required to replace the original water content in the model. A time of 8 hours of operation in the model represented approximately 1 year in the prototype when the total recharge rate to the surface of the model was 2.73 gallons per hour.

As far as can be determined, there were no previous investigations of this type and, consequently, there were no established principles to offer guidance in designing or testing a model. Construction and testing procedures were, therefore, modified as necessary before, during, or after accomplishment in an attempt to develop techniques.

[1] Numbers refer to references listed at the end of this report.

Part I. Removal Of Saline Water From Two-Part Aquifers Using Tile Drains

Parallel Drains—Two-Part Aquifer

It is common to find river valley aquifers which show an increasing permeability with depth. In some instances, the transition between the surface or near surface permeabilities and the deep permeability is sharp. This is the point of interest here. The aquifer in this case is designated a two-part aquifer, with fine sand material 40 feet deep overlaying coarse sand material 40 feet deep.

If such an aquifer contains saline water, and parallel tile drains are installed near the ground surface, application of irrigation water causes an interface to form in the aquifer separating the fresh irrigation water and the saline water. Water above this interface moves to the tile drains as irrigation water is applied, and the saline water below the interface is stationary and remains in storage.

Whether the interface is established in the upper (fine) part of the aquifer or in the lower (coarse) part depends upon the depth of the upper part of the aquifer, the drain spacing, the irrigation recharge rate, and the difference in density between the saline ground water and the fresh irrigation water. For the case considered here, the upper fine part of the aquifer was 40 feet deep. Drain spacings and irrigation recharge rates were such that the interface always fell below the lower edge of the upper aquifer.

Deep percolation water between the drains moves toward the tile drains by the path of least resistance. It generally moves vertically downward through the fine sand until it reaches the lower coarse sand material. The water then flows horizontally along the coarse material until it is directly under the tile drain, where it moves almost vertically upward to the drain. Resistance to flow through the coarse material is much less than through the fine material, which explains why the water takes the longer path to the drain but which is the path of least resistance.

Percolation water above and close to a tile drain will flow directly to the drain. A stagnation line (line of no flow) forms between the water flowing to the drain from the lower (coarse) part of the aquifer, and the water moving directly to the drain from above. The location of this stagnation line indicates that substantially all of the deep percolation water passes through the upper part of the aquifer into the lower part of the aquifer before flowing to the drain.

The Model

Model Construction

The model of an idealized cross section of an aquifer in a typical irrigated valley was constructed to a linear scale of 1:40 in a glass-walled tank. The tank containing the aquifer was 2.5 feet wide and deep and had transparent walls on both long sides. The primary purpose of the scale was to establish the thickness of the model aquifer in terms of the typical aquifer and the size and location of drains. The scale did not apply to the aquifer particle sizes or to the time factors used to interpret the test results in terms of a prototype. These scale factors are discussed later at the time they are used. Of the entire length of the tank, a portion 15.71 feet long was isolated and used to represent half the distance between two lines of drains. To scale, this then would represent a drain spacing of approximately 1,260 feet.

To represent a two-part aquifer, two laboratory prepared sands were selected on the basis that the coarse sand was 50 times as permeable as the fine sand. The coarse sand was placed in the bottom of the tank to a depth of 11 inches and the fine sand was placed over this to an additional depth of 1 foot, figure 1. Before placing the upper layer, an intermediate size sand was installed in a 1-inch layer to prevent the upper fine sand from working down into the coarse sand below. As placed, these sands repre-

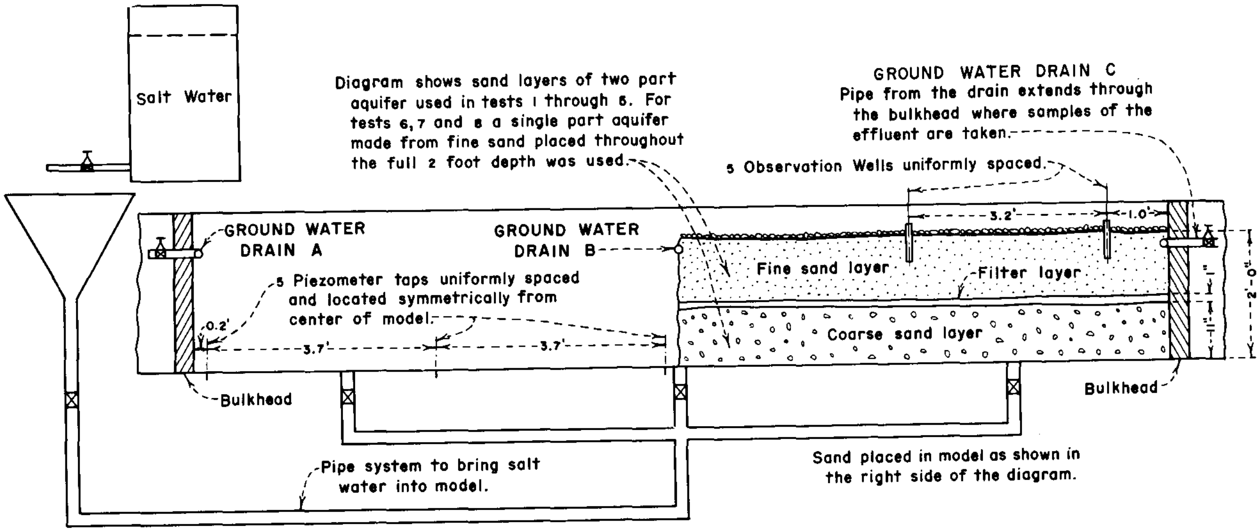


Figure 1.—Ground-water model.

sent a prototype thickness of about 40 feet each in a total aquifer depth of 80 feet.

In an idealized model using homogeneous aquifers, it can be assumed that there is no flow across a vertical plane located midway between drains, or through the centerline of the drainline. Therefore, at the midpoint between lines of drains an impermeable bulkhead (a plane of symmetry) formed one end of the model and a vertical bulkhead through the drainline terminated the model at the other end, without affecting the flow patterns shown by the model. A 2-foot-diameter tile drain, which could be used in the field, was represented by a perforated copper tube about five-eighths inch in diameter, wrapped with fine brass screen to prevent clogging of the perforations. A T-fitting placed at midlength of the copper tube was connected to a short length of pipe which was passed through the bulkhead. The pipe conveyed the drainage flows through the bulkhead to permit sampling, flow measurement, and disposal. On the aquifer side of the bulkhead, a small quantity of intermediate size sand (larger particles than the aquifer sand) was placed around the pipe and against the bulkhead to locate effectively the exact point of drainage at the face of the bulkhead.

Prior to placing the aquifers, piezometer taps had been installed on the centerline of the floor of the tank at each end, in the middle, and between the middle and each end. Flexible plastic tubes attached to these taps were connected to five glass manometer tubes mounted vertically on the middle supporting post of the tank. These manometers are visible in all the photographs. A scale behind the tubes permitted reading the pressures on the bottom of the tank. Directly above each of the piezometer taps, an observation well was installed. Each well consisted of a short, open-end glass tube extending down about halfway into the upper aquifer. The position of the water table during a test could be read by lowering a point gage, mounted on a traveling carriage, into the tube from above. A comparison was made of water depths from well readings and pressures from manometer readings.

A 1-inch layer of coarse sand was placed on top of the upper part of the aquifer to distribute uniformly the water applied to the aquifer during a test, and to prevent displacement of the fine aquifer sand. A valved pipe distribution system was also installed along the centerline of the bottom of the tank to introduce the dyed salt water into the tank at approximately the one-third points of the model to prime the aquifer prior to a test.

Model Operation

Tests 1 through 5 were made using the two-part aquifer and tile drains described to represent an idealized cross section of a portion of an irrigated valley not having natural drainage. Tests 6 through 8–3 were conducted using a single-part aquifer (made from the fine sand used in the upper member of the aquifer tests).

In the first tests, saline water was introduced (through the valved distribution system on the bottom of the tank) only into the lower aquifer. To facilitate

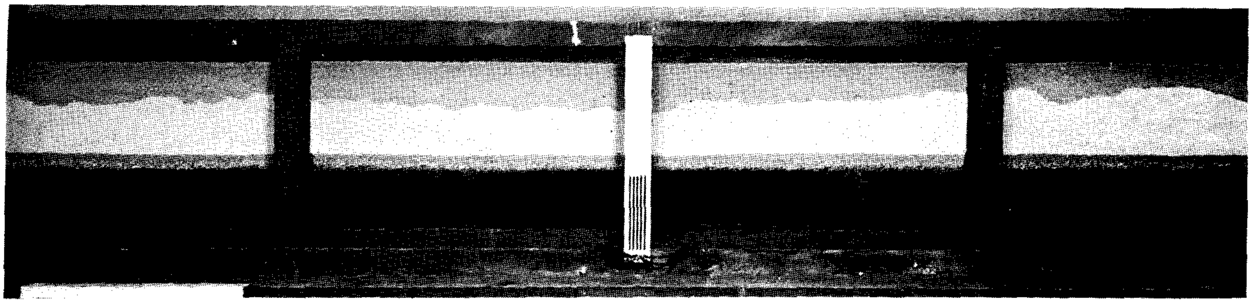


Figure 2.—Lower coarse sand part of aquifer is almost filled with blue salt water introduced through the bottom of the tank, and upper part of fine sand is partially wetted with fresh water introduced onto upper surface of the aquifer prior to start of Test 1. Center lighter-colored areas are still dry. Manometer tubes indicate the level of the salt water.

observations of the salt water movements in the lower aquifer, the salt water was dyed with "patent blue" dye. Sodium chloride (NaCl) was the salt added to provide the proper density; some potassium chloride (KCl) was added in the early tests to provide a tracer and for a secondary analysis to check the sodium chloride content of the drain samples. It was found, however, that the sodium chloride concentration could be determined accurately by the flame photometer, and therefore the potassium chloride tracer was not used in later tests. The mixture varied from test to test, but the salt water contained approximately, by weight:

Tests 1 to 5 .... Approximately 250 ppm (parts per million) patent blue dye.
6,200 to 7,050 ppm sodium chloride.
Approximately 100 ppm potassium chloride.

Test 6 .... Approximately 250 ppm patent blue dye.
Approximately 4,000 ppm sodium chloride.
No potassium chloride.

Test 7 .... Approximately 250 ppm patent blue dye.
Approximately 79,800 ppm sodium chloride.
No potassium chloride.

Tests 8–1, 8–2, and 8–3 .... Approximately 250 ppm patent blue dye.
Approximately 75,200 ppm sodium chloride.
No potassium chloride.

The salts and dye in granular form were added to water in a 50-gallon drum and thoroughly mixed using a pneumatic propeller mixer. The mixture from the drum was fed into the valved distribution system at the bottom of the testing tank and allowed to slowly rise to displace the air in the lower aquifer interstices and the film of moisture covering each sand particle.

Several days were required to raise the level of the blue salt water to near the top of the lower aquifer. To prevent capillary action from pulling salt water up into the upper aquifer, the inflow of blue salt water was stopped before it reached the separating sand layer used in the two-part aquifer tests. Fresh water (Denver tap water) was then added to the surface of the upper aquifer and allowed to permeate the upper sand. The lower salt water flow was then restarted, the process being repeated until the lower aquifer was full of blue salt water and the upper aquifer was full of fresh water up to the level of the drain, 0.2 foot below the surface. Figure 2 shows the bottom aquifer almost full of blue salt water and the upper aquifer partially wetted with fresh water.

In the first test, water representing the irrigation water applied to crops was applied to the surface of the upper aquifer by means of an ordinary garden sprinkling can. Three gallons of Denver tap water were applied in less than a minute at 1-hour intervals. The water was uniformly distributed over the entire surface of the model; the quantity was sufficient to raise the water table about 0.1 foot (model dimension) above the level of the drain. The water table level was closely controlled and was never allowed to reach the top of the upper sand. At the end of each test the entire model was flushed with tap water.

In Tests 2 through 7 a perforated garden soaker hose was used to apply a uniform and continuous supply of irrigation water at the rate of 3 gallons per hour. The soaker replaced the sprinkling can method of application. The hose was laid along the longitudinal centerline of the model on the coarse sand covering previously described; the water issued from pinholes uniformly spaced along the underside. The coarse sand distributed the water laterally.

For Tests 8–1, 8–2, and 8–3, the garden soaker hose was replaced with a modified toilet flush tank and clock-controlled timer, which discharged the desired quantity of water into two perforated stainless steel troughs spaced to distribute the water uniformly over the aquifer surface. The tank float was positioned so the tank capacity was approximately 3 gallons. With this adjustable arrangement, water was applied at three rates: 2.77 gallons each 2-hour interval, Test 8–1; 2.89 gallons each 1-hour interval, Test 8–2; and 2.77 gallons each ½-hour interval, Test 8–3.

In constructing the model the fine sand aquifer was left bare of the coarse sand cover for about 6 inches across the width of the tank at the drain ends of the model. It was, therefore, possible to visually determine that no free water was ever present in this zone.

Measurements were made systematically of the levels in the observation wells throughout the period of the test. Samples of the drain effluent were taken at scheduled times for chemical and colorimetric analysis to determine the concentration (salt content) of the drain effluent. The salinity values were determined by flame photometer measurements in the Bureau's Chemical Engineering Laboratory. Measurements of the rate of flow (timed volumetric determinations) from the drain were made at regular intervals, and photographs on 35-mm color film and 4- by 5-inch black and white film were taken at frequent intervals. A 16-mm timed-sequence motion picture film was also made; individual frames were taken at 1-, 3-, or 6-minute intervals, day and night throughout the test.

In later tests a second drain assembly was placed at the other bulkhead to represent a drain spacing of 630 feet; a third drain was placed at the center of the test tank to represent a drain spacing of 315 feet. Modifications were made to the model and testing procedures as testing progressed. Variations are discussed as they occur in each test but, in general, the procedures were as described.

The Investigation

Results of Tests 1 and 2

Test 1.—Almost immediately after the first application of 3 gallons of water to the top aquifer the saline (blue) water began to flow through the fine sand layer toward and out of the drain, figure 3. After a few hours (3 gallons added every hour), a wedge of blue water, having a triangular shape with the hypotenuse at an angle of about 45° to the horizontal, had formed near the drain in the upper aquifer.

After 11 hours, the hypotenuse began to show a convex shape. This configuration was maintained until sufficient water had been added to the upper aquifer (50 hours) to make visible clear water areas in the lower aquifer which indicated that the blue water was being flushed out, figure 4. As the testing proceeded, the blue water was confined to a narrow wedge in the lower sand and a very narrow band in the upper sand.

After 4 days of operation, most of the blue saline water had been flushed out of the lower aquifer except close to and below the drain where the height of the blue water wedge in the lower sand always occupied the full depth of the lower sand. The face

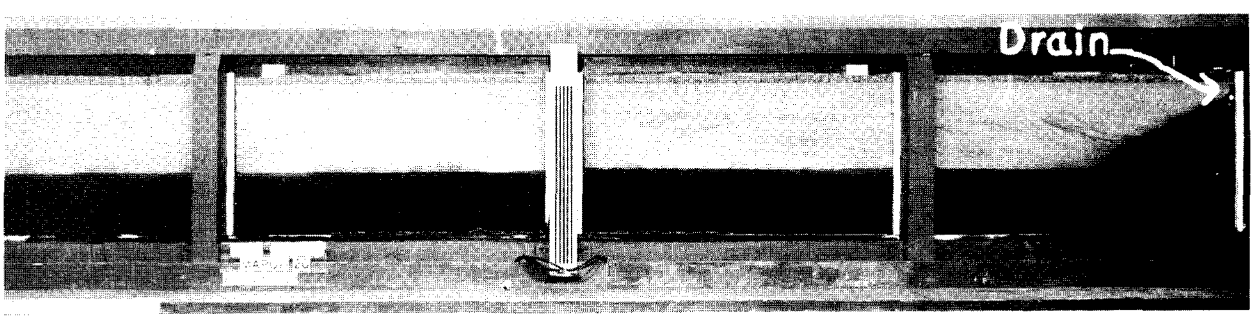


Figure 3.—Flow pattern of salt water through aquifer to drain is well established only a few hours after the start of Test 1. Manometers indicate the level of the water table in the aquifer.

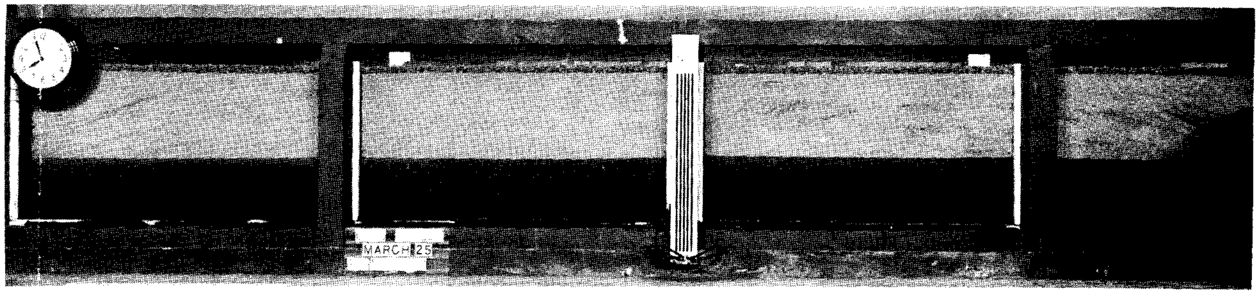


Figure 4.—Flow of salt water to the drain continues after 67 hours of operation, Test 1. Lower part of aquifer is being flushed with fresh water.

of this wedge was concave upwards. Two more days of operation failed to dissipate the wedge.

Figure 5 is a record of Test 1 operations and results plotted against the days of the month (which indicates the duration of the testing). The water application curve (also the water discharge curve) indicates that water was added during the regular working hours on the 19th, 20th, and 21st of March; no water was added during the 16 off-hours. Starting on the afternoon of March 21, water was added day and night; every hour 3 gallons of water were sprinkled over the surface. The drain effluent (sodium chloride) concentration curve rose rapidly for the first 2 days of the testing, declined at a rather rapid rate for about 3 days, then gradually approached a fresh water condition, although a fully fresh condition was not reached after 8 days of testing. The potassium chloride curve indicates a similar action.

Figure 6 shows water surface profiles as determined from water surface observations made in the wells during one water cycle application, about 1 hour. The scale sketch at the bottom of the figure shows the stations at which wells were located, the drain location, and the relative height of the water level change in terms of the total depth of aquifers.

The upper curves in the figure show the water surface plotted to an exaggerated vertical scale. The top curve labeled "zero minutes" indicates the water table surface, beneath the surface of the upper aquifer, immediately after application of 3 gallons of water

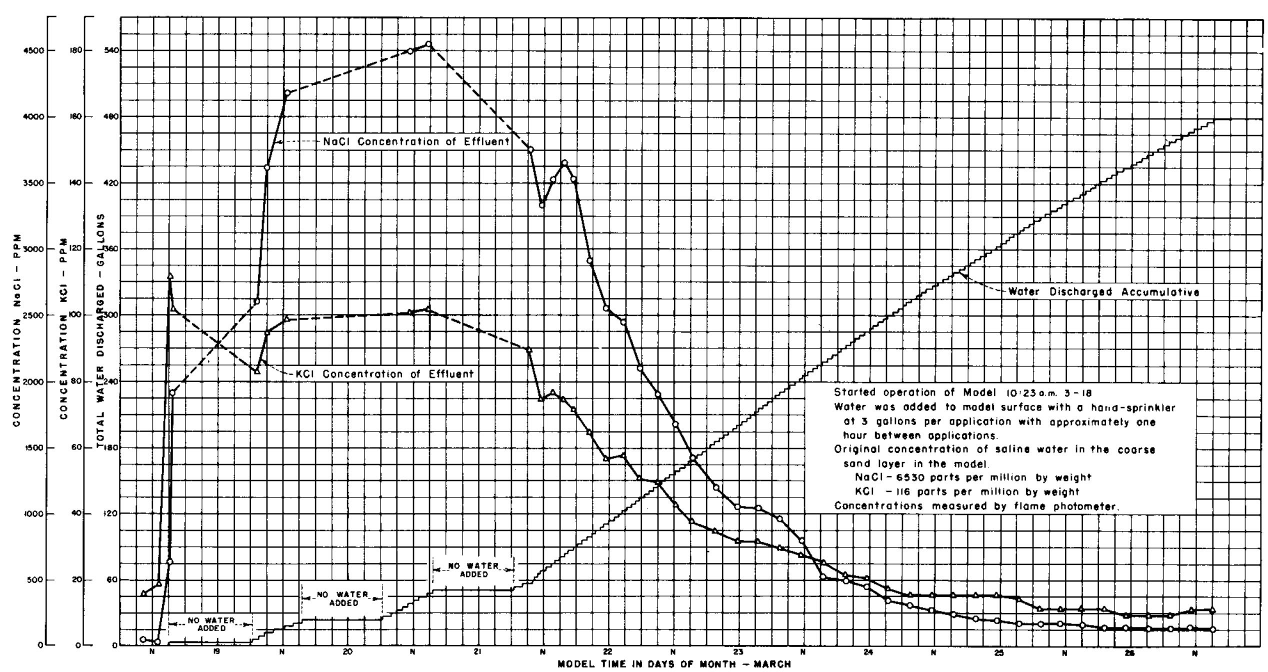


Figure 5.—Water discharged and salinity of drain effluent, Test 1.

over the upper aquifer surface. The next curve below was taken 15 minutes later, the next 30 minutes later, the next 45 minutes, and the bottom curve 60 minutes later. At this time, the cycle was repeated and more measurements were taken.

The convex upward curve of the water surface found in all profile measurements, figure 6, was a reality and not the result of poor measurement techniques. The rise in water surface indicated between the plane of symmetry bulkhead and the high point in the water surface was about one-eighth inch in the model.

The results of Test 1 indicate that a single drain placed 8 feet below the surface of the upper aquifer will not intercept only fresh water applied to the upper aquifer surface. This is true even when there is a sufficient quantity of fresh water to raise the average water table level above the level of the drain. Instead, the fresh water tends to follow a path of least resistance to the drain by working its way into the lower aquifer, where flow resistance is considerably less, and displacing salt water up through the upper aquifer to the drain. The drain effluent is thereby contaminated with salt water. Analysis of the drain effluent indicates that the salt concentration rose as high as 4,500 ppm, and for a period of over 2 test days (model time) stayed above 1,500 ppm.

Test 2.—Test 2 was a rerun of Test 1, except that the method of applying irrigation water was changed. In this test, water was applied to the upper aquifer continuously at a uniform rate (2.93 gallons per hour) through a perforated garden hose laid along the centerline on the top of the model. Figure 7 shows the drain effluent discharge rate in gallons per hour plotted against model time in days. Although the rate of water application should have been constant, the variations indicated are the result of clogging of needle valve control and the line pressure variations. The large sudden increase at noon on April 8 was caused by opening the needle valve to clear the clogging prior to resetting of the desired quantity.

A study of the salt concentration of effluent and rate of application curves indicates that there is, in general, an increase in salt concentration when there is an increase in fresh water application, and that the effect is apparent almost immediately.

Salt concentration in the drain effluent throughout Test 2 was practically the same as for Test 1, and the overall test results were practically identical. For a direct comparison of Tests 1 and 2, the salt concentration curve for Test 1 has been replotted in figure 8, after making time adjustments to compensate for the differences in the method of application of the fresh water. The slight displacement of the curves of Tests 1 and 2 is not significant in drawing

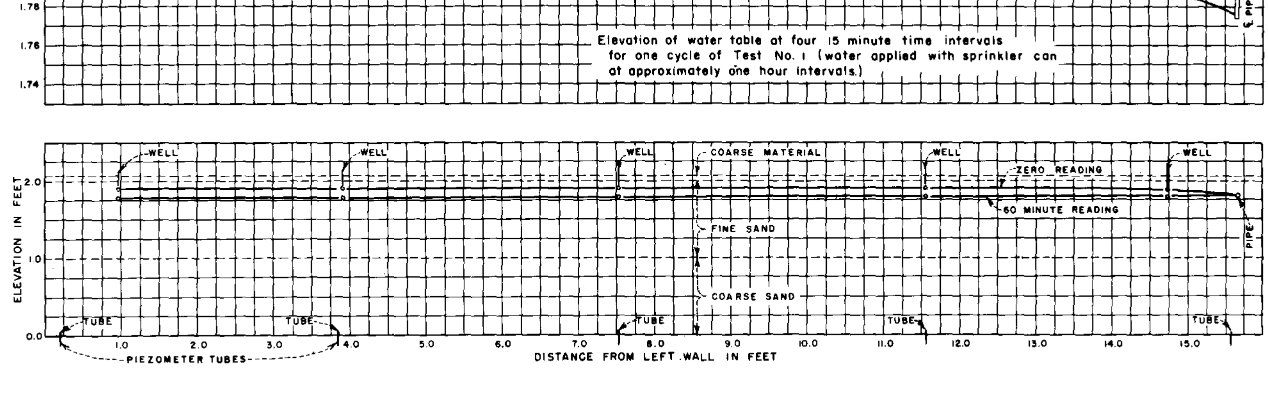


Figure 6.—Water table variation for intermittent recharge, Test 1.

general conclusions from these tests.

Near the end of the second test, crystals of potassium permanganate were used to indicate flow direction in various parts of the model. The crystals

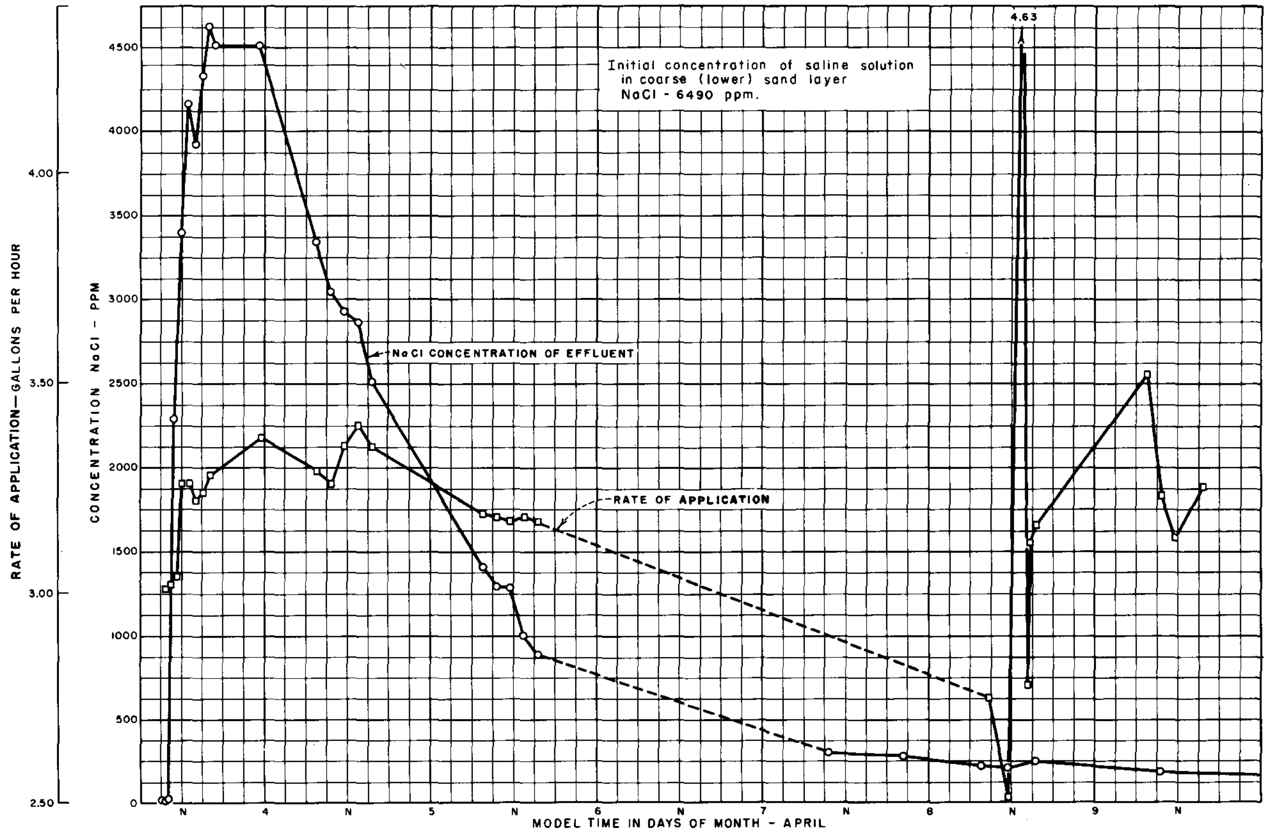


Figure 7.—Water application rate and salinity of drain effluent, Test 2.

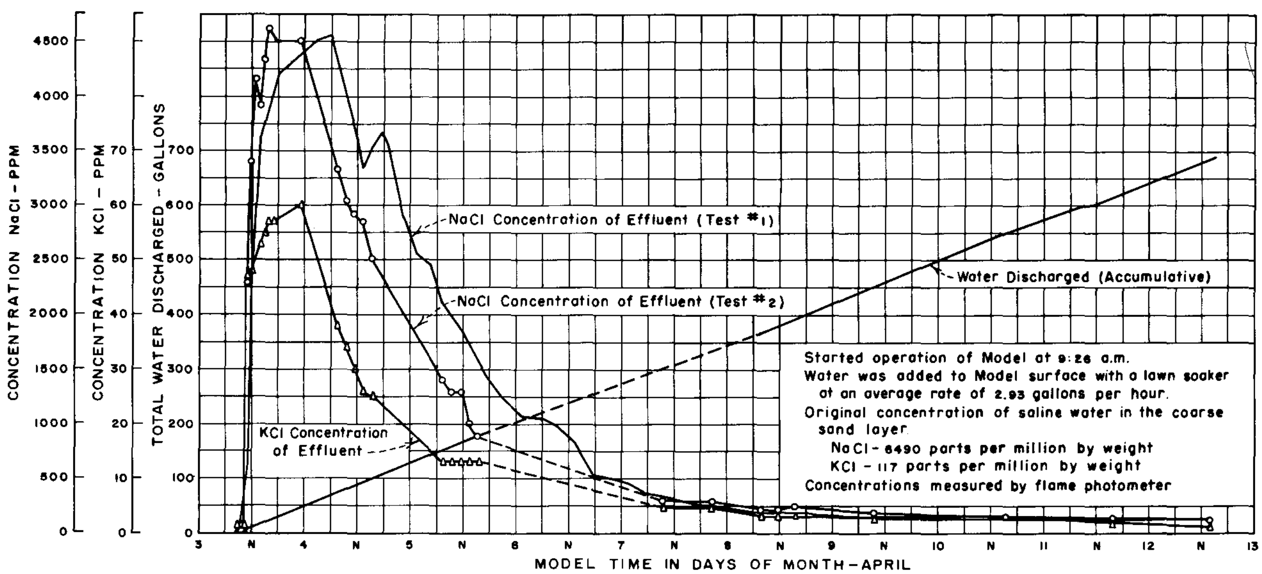


Figure 8.—Comparison of salinity of drain effluents for Tests 1 and 2.

were placed against the glass wall of the tank by inserting a glass tube downward through the sand until the bottom was at the desired elevation, dropping the crystals down the tube and pushing them out into the sand through the bottom with a rod, and then withdrawing the tube so that the sand closed in around the hole. Flow past the crystals left color trails which, if traced and timed at regular intervals, indicated flow direction and velocity. Crystals introduced below the drain and inside the blue wedge indicated that the flow direction was toward the drain.

Elsewhere, the dye streaks indicated the flow direction to be downward through the upper sand and into the lower sand, horizontally through the lower sand, and upward to the drain. Such a flow path represents essentially the flow path of least resistance between the crystal and the drain. Figure 9 shows three vertical dye traces, one in each of the three upstream panels, and two dye traces in the downstream panel approaching the drain in the upper part of the aquifer. The third dye trace in the downstream panel shows flow downward through the upper part into the lower part even though the starting point for this flow trace was just a fraction of an inch upstream from the end of the blue wedge.

Time Correlation

The prediction of prototype times from the 1:40 scale model could not be based on the usual Froude number relationship because of the lack of similarity with regard to particle sizes. Therefore, correlation of model and prototype times was made on the basis of comparative aquifer volumes. The prototype aquifer, 80 feet deep, with a 40-percent total porosity would contain (80) (0.4) = 32 feet of water. Deep percolation of 3 feet per year (a value obtained from the typical field project) would replace the original water content in a period of 32/3 = 10⅔ years. The model is 15.71 feet long, 2.5 feet wide, and 2 feet deep, making the volume (15.71) (2.5) (2) = 78.6 cubic feet. With a total porosity of 40 percent, the water content would be (78.6) (0.4) = 31.4 cubic feet. An inflow of 3 gallons per hour for an 8-hour period would supply

$$\frac{(3)(8)}{7.48} = 3.21 \text{ cubic feet.}$$

On this basis, the time required to replace the original water content in the model would be 31.4/3.21 = 9.78 periods of 8 hours each. A comparison of these values will indicate that 7.34 or about 8 hours of model time represents a year of prototype time for the recharge rate of 3 gallons per hour to the model. This comparison is valid, however, only for an area irrigated over the entire surface at regular intervals or at a uniform steady rate.

Results of Test 3

For Test 3 an additional drain was installed at the bulkhead at the opposite end of the tank and another was installed at the midpoint. With three drains the model extended throughout two adjacent drain spacings. With reference to the prototype, the drain spacing would be about 315 feet. Test 3 was run with a continuous and uniform water supply at a rate of about 13 gallons per hour applied through the perforated hose. The initial depth of blue salt water (concentration 6,200 ppm) introduced into the lower aquifer was 1 foot.

After the fresh water irrigation was initiated, the salinity of the effluent from Drains A and C, located on the bulkheads, quickly rose to a peak of about 3,125 and 3,000 ppm, respectively, as shown on figure

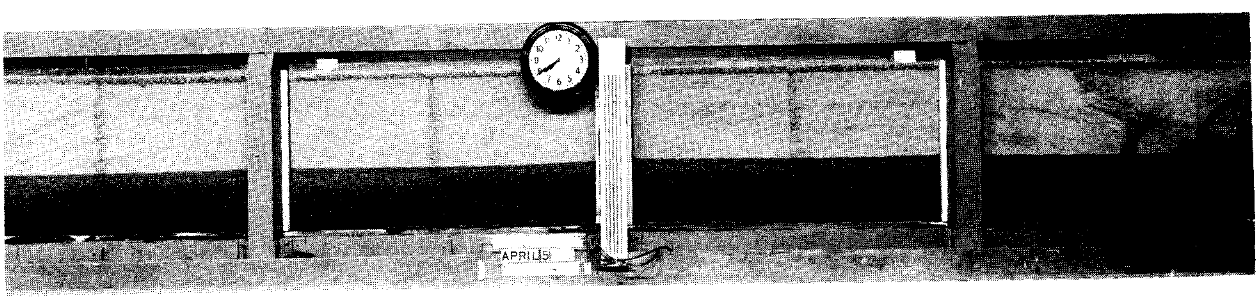


Figure 9.—Dye paths in center of panels show that path of fresh water is vertically downward from surface to lower aquifer, horizontally to vicinity of drain, then vertically into drain. Two dye traces at extreme right show flow from upper aquifer is directly into drain on a curved path, Test 2.

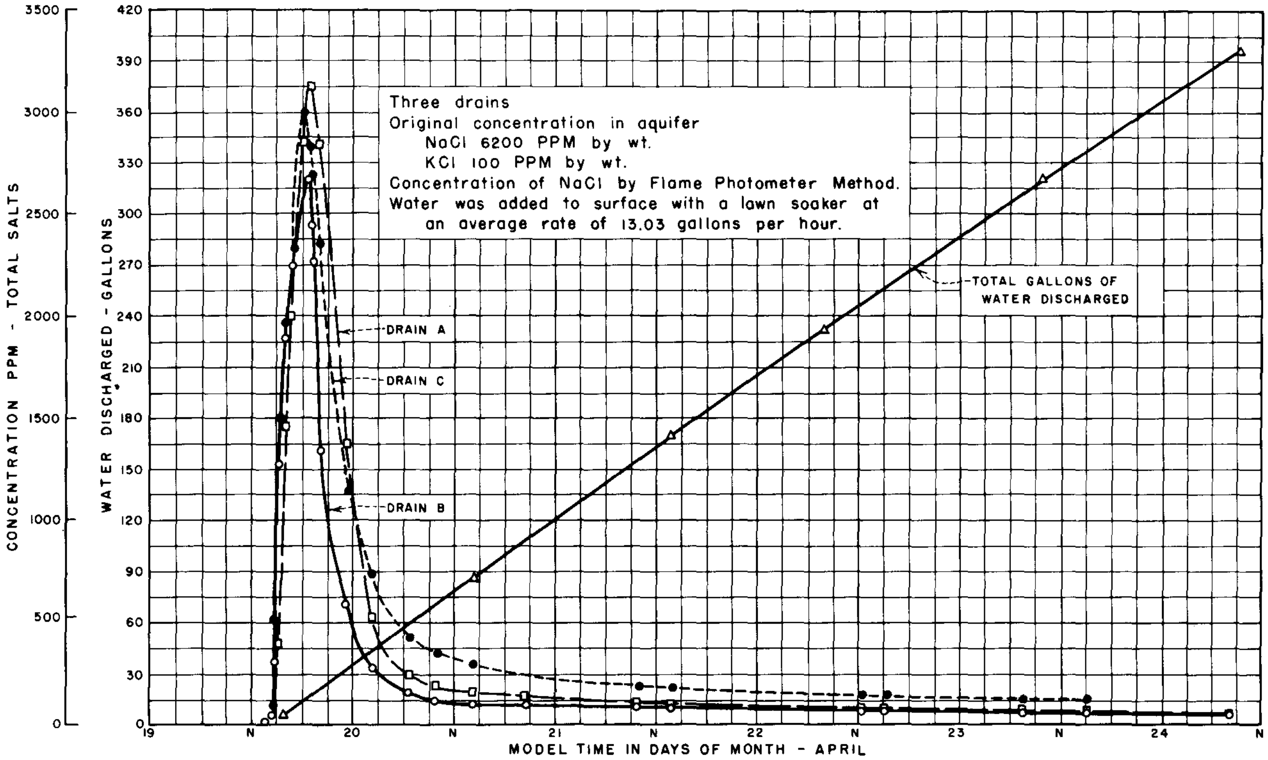


Figure 10.—Water discharged and salinity of effluents in Drains A, B, and C, Test 3.

10, and then declined. The concentration of the saline solution in the lower part of the aquifer was 6,200 ppm at the beginning of Test 3.

The average discharge from Drain A was 3.42 gallons per hour; from Drain C, 2.87 gallons per hour. The average discharge from Drain B (middle) was 6.74 gallons per hour. The middle drain could draw water from both horizontal directions, which accounts for its larger discharge. The effluent from Drain B reached a maximum salt concentration of 2,660 ppm.

Figure 11 shows water table profiles of Test 3 for times and dates as indicated. The variations in profile shape are minor and indicate the probable range of profile differences throughout the testing period.

Figure 12 shows the blue salt water starting to approach the center drain after only 1 hour and 5 minutes of the test.

Figure 13 shows the blue wedges at the drains and a well developed flow pattern 50 minutes later.

Figure 14 shows the reduction in color in the wedges and the beginning of the sharp interface in the lower aquifer, indicating complete displacement of the movable salt water and an approach to equilibrium in the water profiles. The hypotenuse of the wedge seems to have a darker line than the interior of the wedge. This is because there is almost negligible flow along the hypotenuse and the dye (salt) near this line is the last to be flushed out.

At the completion of the test (after almost 4 days) a sharp and stable interface was present in the lower gravel layer, figure 15. The blue salt solution remaining below the interface occupied about half of the volume of the gravel layer, or one-fourth the volume of the entire model. At this time, the effluent still contained over 100 ppm of salt.

This test indicated that a closer spacing of drains does reduce the salt concentration of the drain effluent, but a very close spacing would be required to produce a salt-free effluent in a short time.

Results of Test 4

The three drains described in Test 3 were again used in Test 4. In this test, however, the salt water level was brought to the upper surface of the upper aquifer and before the start of the test occupied the entire volume of the tank.

The initial concentration of salt used in this test was 7,050 ppm, by weight. The fresh water application rate was approximately 3 gallons per hour, ap-

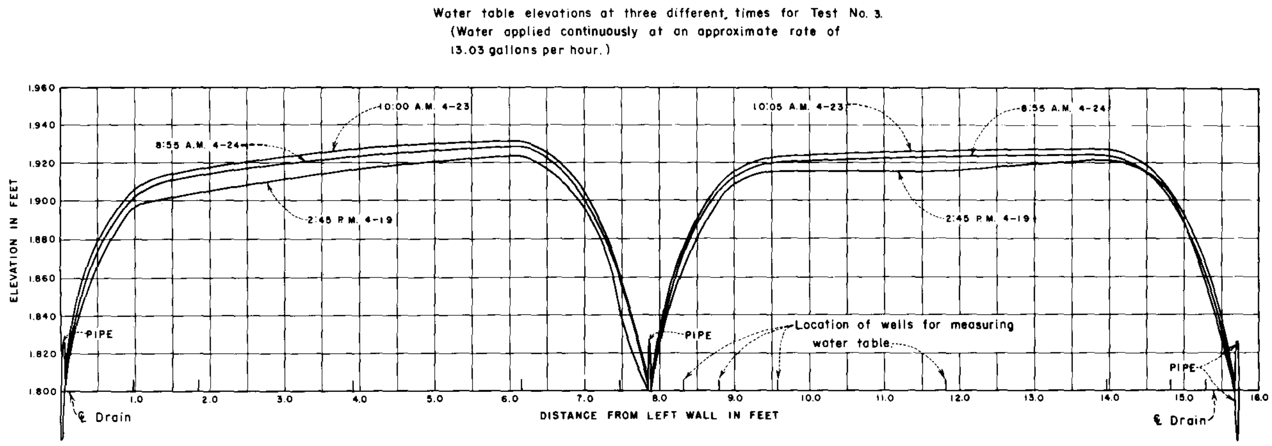


Figure 11.—Water table elevations, three drains, Test 3.

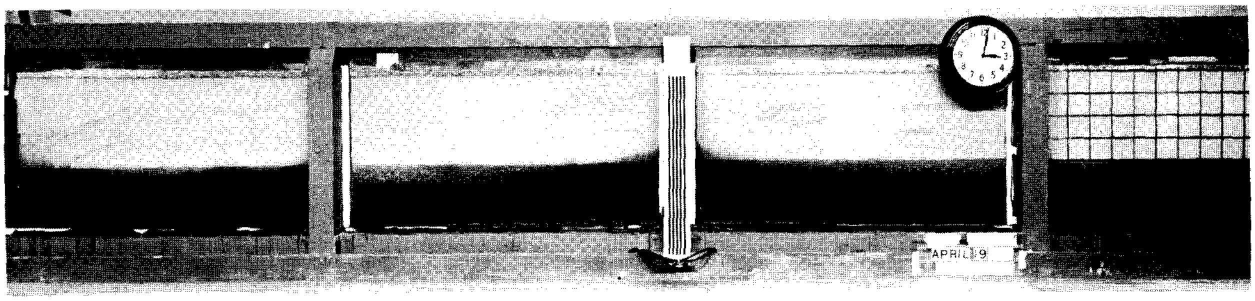


Figure 12.—One hour and five minutes after the start of Test 3, the blue salt water could be seen approaching the three drains, located at each end and the middle of model.

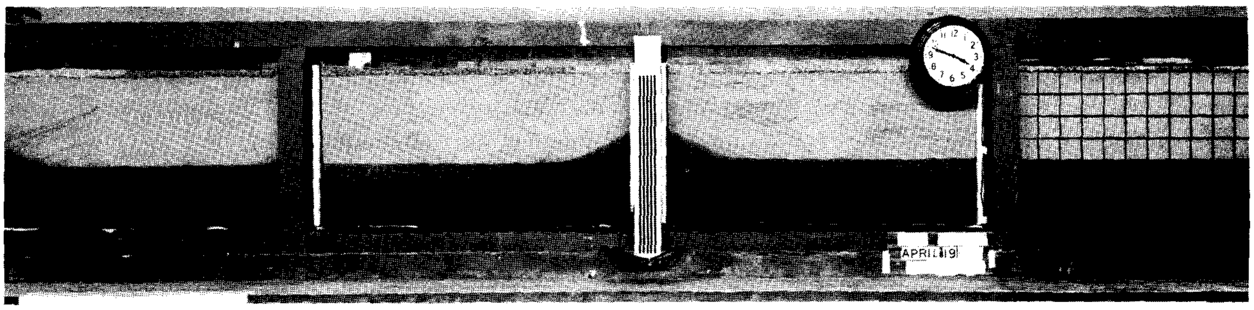


Figure 13.—One hour and fifty-five minutes after start of Test 3, a well-developed flow pattern toward the drains is evident. Clearing of the lower aquifer has begun and a curved interface is evident.

plied uniformly and continuously through the perforated hose. By comparing the results obtained from this test with those obtained from Test 3, it was hoped to get some indication of the effect of different initial concentrations of salt solution and of different irrigation water application rates.

Immediately after the start of Test 4 (on May 10), a salt concentration of 7,050 ppm occurred in the drain effluent. As the test progressed, it was evident that the operation was erratic since the right-hand end of the model (as shown in photographs) was cleared of blue salt water long before the left side was. There were two reasons for this, determined after the conclusion of the test: (1) the hose was

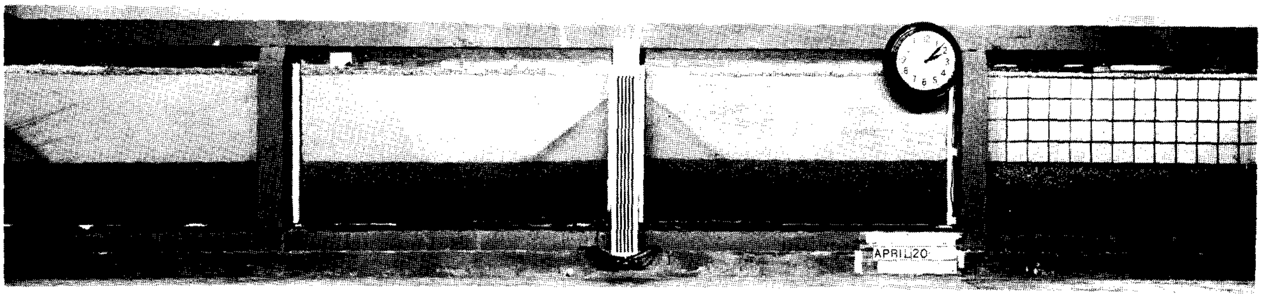


Figure 14.—After only about 24 model hours of operation, Test 3, a large quantity of the salt water in the lower aquifer has been displaced and discharged through the drains. The characteristic sharp line of demarcation between fresh and salt water areas is evident.

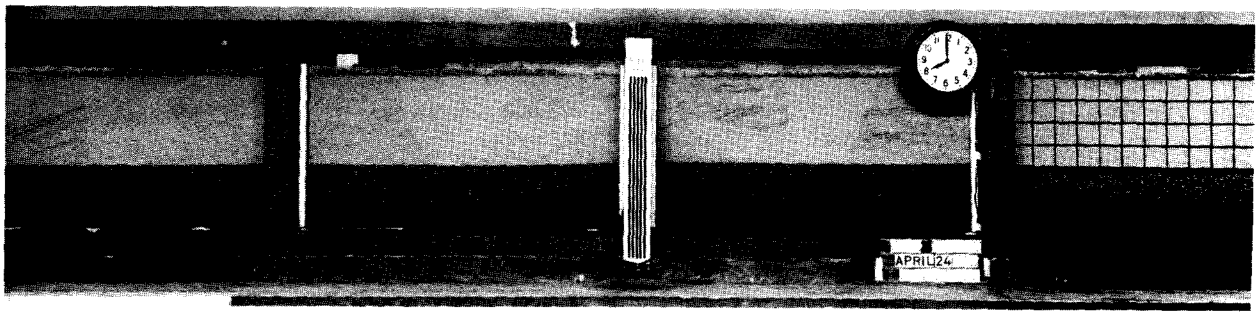


Figure 15.—After almost 4 days of operation, Test 3, about half of the salt water in the lower aquifer has been replaced; the drain effluent still contains over 100 ppm of salt. This represents an almost stable state in the aquifer.

inadvertently delivering more than half of the water to the right side of the model, and (2) the drains were at slightly different elevations. Figure 16 shows the erratic clearing of the blue salt water from the upper part of the aquifer and the beginning of the formation of a visible flow pattern at the middle "B" drain and right "C" drain, May 12. By May 20, a well established pattern for Drain A was apparent, and the C drain pattern was no longer visible. By May 28, the A and B drain flow patterns were beginning to disappear and the position of the salt water in the lower aquifer was sharply defined, figure 17. Testing was then discontinued.

As terminal conditions are approached during a test, a stagnation line becomes visible, shown in figures 16 and 17 as lines radiating from the drains. The line separates the downward flowing waters in the upper bed, supplied by infiltration, from the upward flowing waters coming from the lower bed and moving toward the drain. As there is no flow at the stagnation line, the color remains in the line long after it has been washed out of the adjacent areas. The position of this line indicates that substantially all of the infiltrating irrigation water passes through the upper bed and into the lower bed before flowing to the drain.

Figure 18 shows the salt concentration in the effluent from the three drains plotted against model time, Test 4. This test disclosed that the drainage pattern is sensitive to slight variations of drain elevations, inflow, and aquifer conditions.

Results of Test 5

The middle drain (described for Test 4) was plugged, leaving the two end drains operative for Test 5. This arrangement of the model represents a prototype spacing between drains of 630 feet. The entire depth of both aquifers was saturated with blue salt water as in Test 4, but with a salt concentration of 6,830 ppm. The fresh water flow rate was maintained at 3.32 gph (gallons per hour). Test 5 was started at 8:30 a.m., June 11. As irrigation water was applied to the surface, blue salt water began discharging from Drains A and C with concentrations of 6,728 and 6,845 ppm, respectively.

Average discharges, throughout the test, measured from the two drains was 1.87 gph for Drain A and

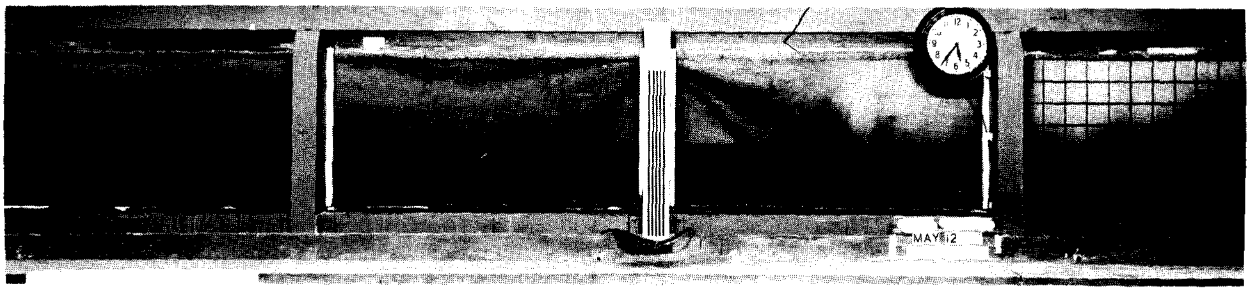


Figure 16.—Test 4. Blue salt water, which occupied entire volume of model at start of test, is being cleared from the upper part of the aquifer, particularly in right-hand area. Flow patterns indicating path of salt water to drains are evident.

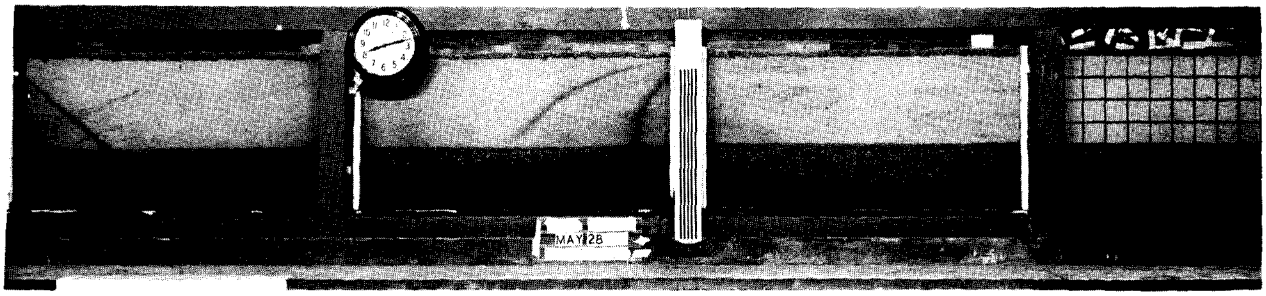


Figure 17.—End of Test 4. Permanent storage of salt water in lower part of the aquifer is indicated. Storage pattern in lower part is not symmetrical about centerline of model because water was inadvertently applied more rapidly to right-hand side (in photograph).

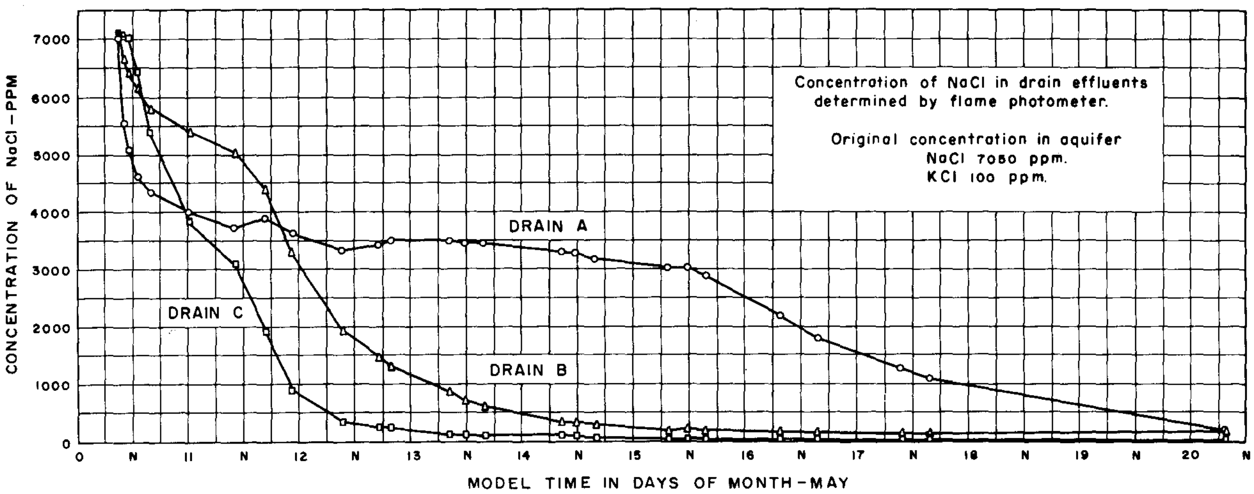


Figure 18.—Salinity of effluents from three drains, Test 4.

1.45 gph for Drain C. The difference in discharge from the two drains was due to the nonuniformity of water coming from the garden soaker. A slightly higher proportion of the water was discharged toward Drain A than toward Drain C. This nonuniformity of inflow and outflow from the model caused a slight nonuniform evacuation of saline solution and shape of the stable interface.

TABLE 1.—*Draining saline water from two-part aquifers with agricultural tile drains—data from all tests—ground-water model*

1	2	3	4	5	6	7	8	9	10
Test No.	Date and time		Drains operating	Average discharge from drains, gph	Average salt concentration start of test, ppm	Top of salt solution at start of test	Model and prototype drain spacing, feet	Model distance of interface below ground at equilibrium, feet	Model days to reduce effluent concentration to one-tenth of original aquifer saline concentration, days
	Start test	Finish test							
1	3–18	3–26	C	Transient 3.0	6,530	Top of lower	31.42	Below bottom of	3.5
	10:23 a.m.	3:30 p.m.				aquifer	1,260	model	
2	4–13	4–16	C	Steady 2.93	6,490	.... do	31.42	.... do	3.5
	9:26 a.m.	8:00 a.m.					1,260		
3	4–19	4–24	A	Steady 3.42	6,200	.... do	7.86	1.5 left side	.5
	1:55 p.m.	10:00 a.m.	B	6.74			315	1.5 right side	.4
			C	2.87					.6
				Total .. 13.03					
4	4–10	4–27	A	Steady .... .82	7,050	Top of upper	7.86	1.35 left side	8.8
	8:50 a.m.	8:30 a.m.	B	1.75		aquifer	315	1.5 right side	3.0
			C	.62					1.8
				Total .. 3.19					
5	6–11	7–1	A	Steady 1.87	6,830	.... do	15.71	1.7	3.0
	8:30 a.m.	12:30 p.m.	C	1.45			630		5.0
				Total .. 3.32					

Figure 19 shows a graph of the effluent salinity concentration from Drains A and C in parts per million. The graph also gives a mass diagram of discharge in gallons from Drains A and C. Salt (NaCl) concentration in Drain A was reduced to one-tenth of the original concentration at 8:30 a.m. on June 14, after 3 model days of operation. Discharge from Drain C was reduced to one-tenth the original concentration after 5 model days of operation at 8:30 a.m. on June 16. These time intervals represented approximately 11 and 18 prototype years, respectively. Figure 20 shows the model on June 14 and June 16. Figure 21 shows the position of the interface on July 1, just before the test was stopped, 20 days and 2 hours (approximately 73 prototype years) after the beginning of the test. The concentration of the effluents just before the test was stopped was 56 ppm and 136 ppm for Drains A and C, respectively, as shown on figure 19.

Saline Water Displacement

The rate at which the saline water contained in an aquifer is replaced by fresh water is an important factor in the determination of quality of return flows. Table 1, column 10, shows the model time required for each test to reduce the salinity of the drain effluent to one-tenth of that originally placed in the aquifer.

The time required is based on a rigid water application schedule as described in each test and assumes that water is applied over the entire surface. In a prototype, conditions are seldom as ideal; the irrigated area does not include the entire area above the entire aquifer, nor is the application of irrigation water as regular and uniform as in a model. The salt concentration in the drain effluent at the time one full water replacement volume had entered the aquifer, and similar concentration values for various fractions of one replacement volume would be significant information that would help in understanding the process of flushing saline water by application of irrigation water.

A method of evaluating the dilution of saline water under these conditions would be to compute the percentage of saline water in the total drain effluent and plot this value versus the ratio of the cumulative quantity of water discharged to the total water stored in the aquifer. Figures 22 through 26 show these plots for Tests 1 through 5. When the cumulative discharge of the drain effluent equals one on the abcissa, the water added is equal in volume to the total water volume originally stored in the aquifer. The concentration of effluent indicates the extent that salt water was forced ahead of the fresh water (without mixing) and the amount of the latter that moved directly to the drain.

A plot was made for each test relating percent of saline water in the drain effluent with cumulative discharge in units of volume of water stored in the aquifer. Differences exist in cumulative discharge from test to test, depending on: (a) whether the saline water was placed to the top of the upper aquifer (Tests 4 and 5) or to the top of the lower aquifer at the beginning of the test (Tests 1, 2, and 3); (b) the concentration of salt solution in the aquifer at the

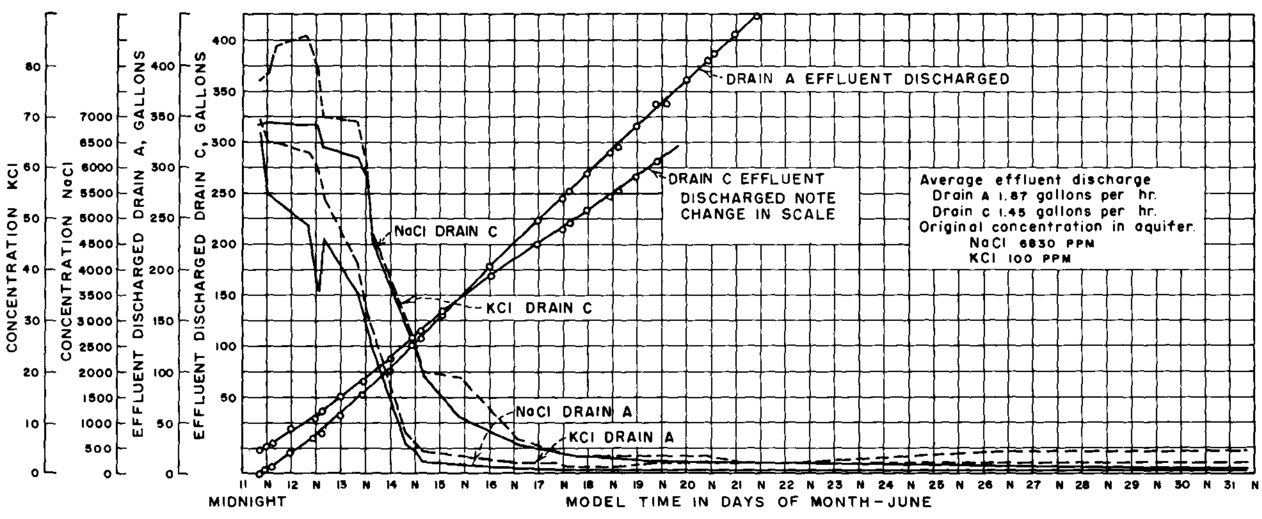
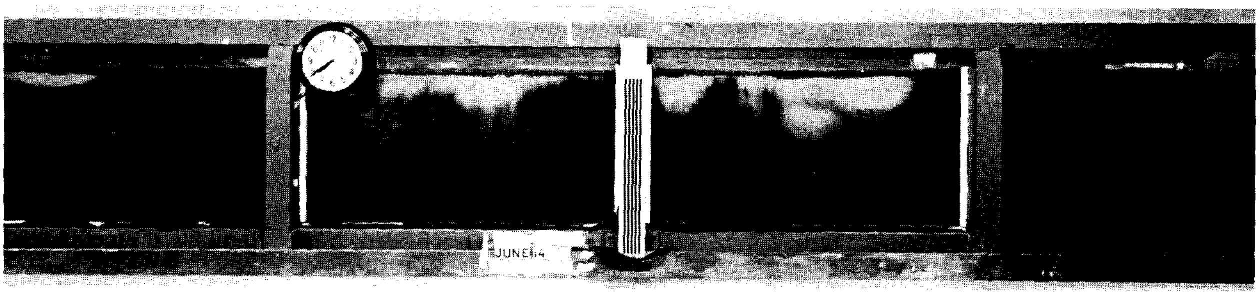
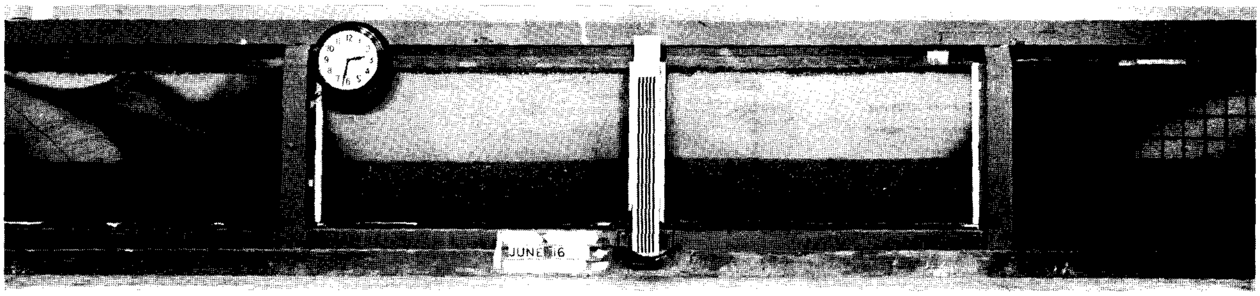


Figure 19.—Water discharged and salinity of effluents from two drains, Test 5.



A. Position of interface on June 14, when concentration in effluent from Drain A was one-tenth (683 ppm) of that initially placed in the aquifer (6,830 ppm).



B. Position of interface on June 16, when concentration in effluent from Drain C was one-tenth (683 ppm) of that initially placed in the aquifer (6,830 ppm).

Figure 20.—Appearance of model interface during Test 5, when drain effluents contain one-tenth of initial salt concentration.

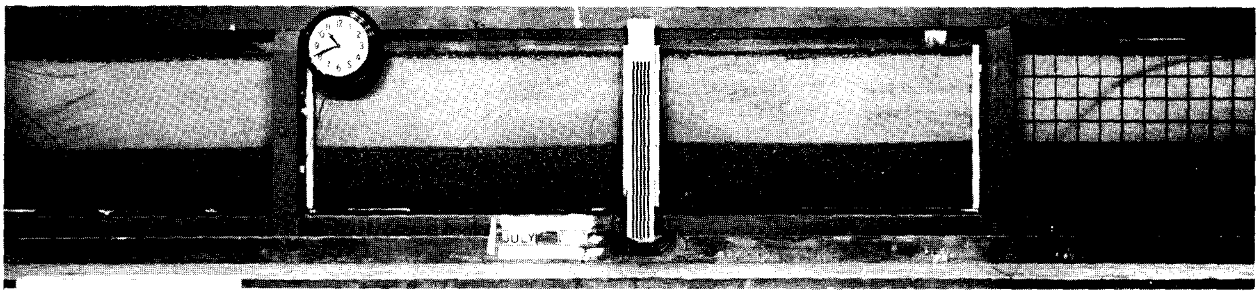


Figure 21.—At the end of Test 5, salt water remains in permanent storage in about one-third of the volume of the lower part of the aquifer. Effluents from Drains A and C contain 56 and 136 ppm of salt, respectively, after 20 days and 2 hours of model operation.

beginning of the test; (c) the number of drains operating; and, (d) the rate of water application to the model and discharge from the drains.

In Tests 1 and 2, the permeability ratio of the upper aquifer to the lower aquifer P_u/P_L was 1/50.

Figures 22 and 23 show the relationships resulting from Tests 1 and 2 in which the lower aquifer was charged with saline water having concentrations of 6,530 and 6,490 ppm, respectively. Tests 1 and 2 gave the same general curves although they were different in detail. The percent of salt water in the drain effluent for both Tests 1 and 2 reached a maximum of slightly above 70 percent when 0.2 of a model porosity volume had discharged from the drain. Also, when 1.0 model porosity volume of accumulated discharge had discharged from the drain, the effluent

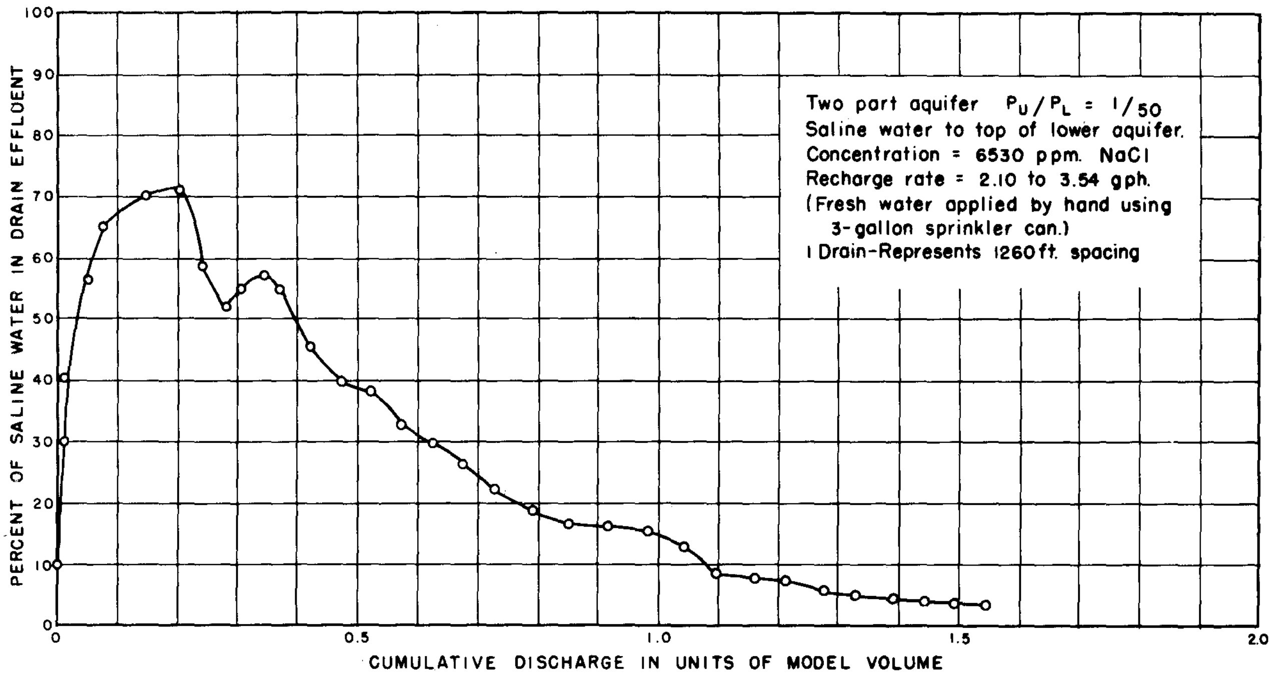


Figure 22.—Graph of cumulative discharge and percent of saline water in drain effluent, Test 1.

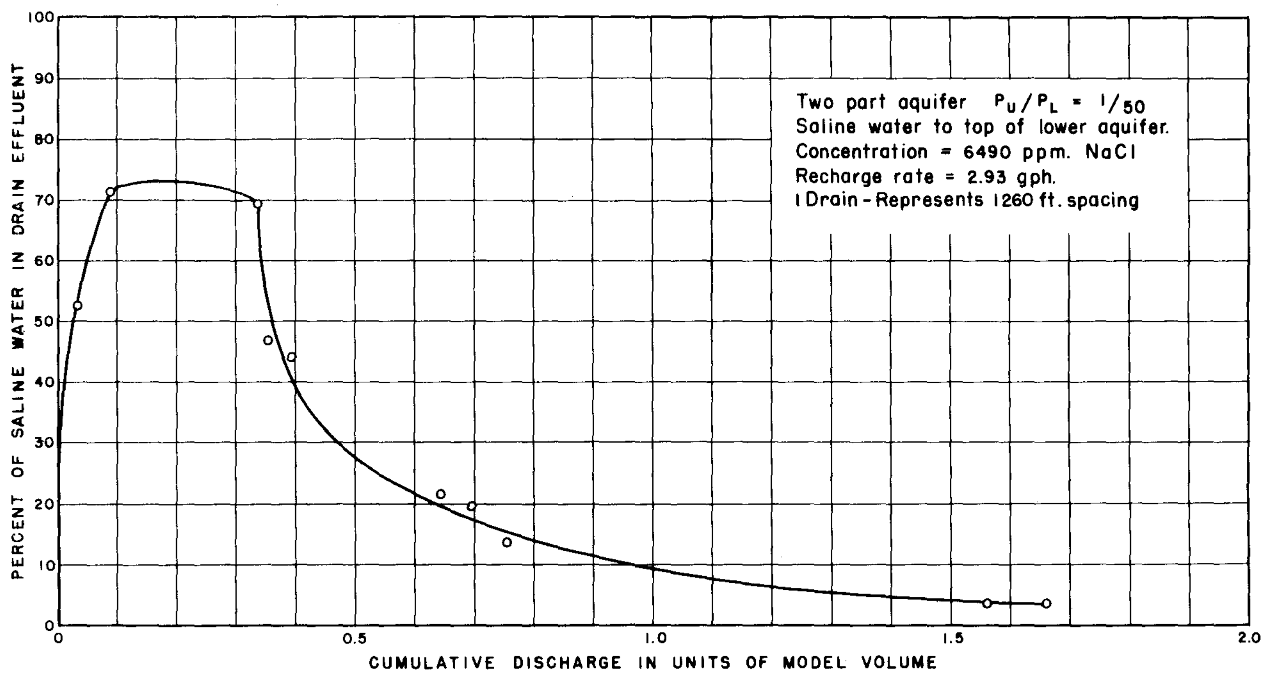


Figure 23.—Cumulative discharge and percent of saline water in drain effluent, Test 2.

contained only about 10 percent of the original aquifer saline water.

The comparison is very good even though the water was applied to the model in two different ways: (a) by intermittent application of irrigation water using a 3-gallon sprinkler can giving an average rate which varied from 2.10 to 3.54 gph in Test 1, figure 22, and (b) by application of water continuously at an average rate of 2.93 gph using a garden soaker hose, Test 2. In this test, the peak concentration of

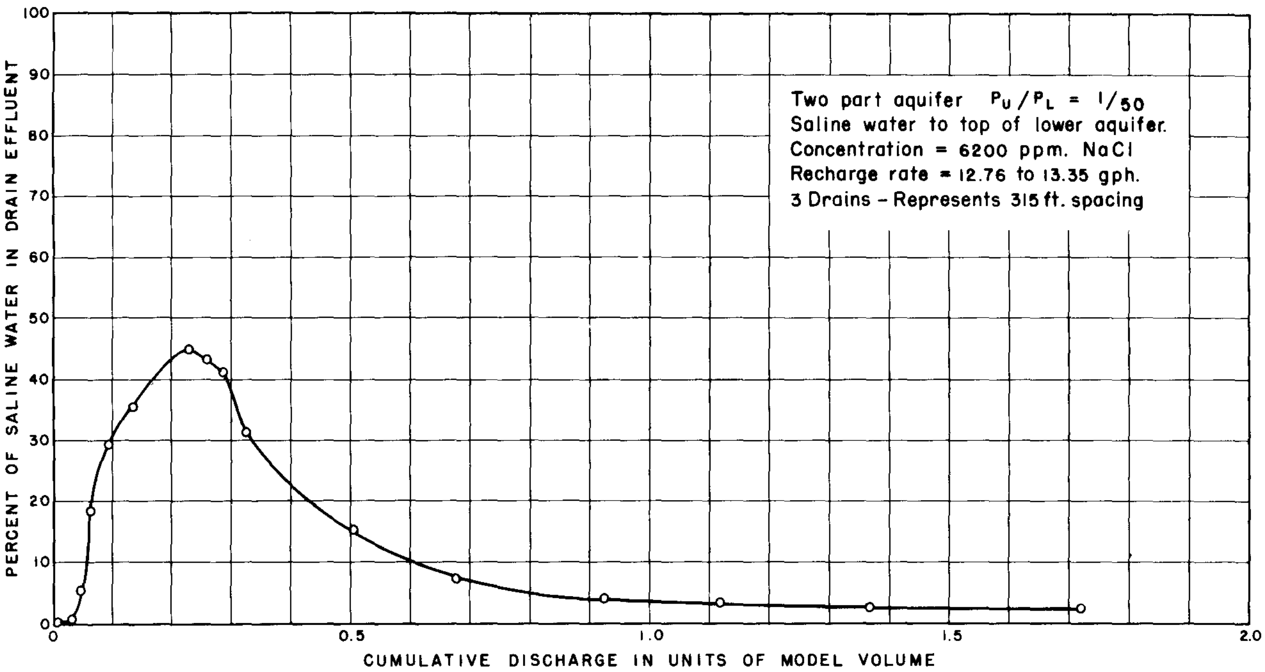


Figure 24.—Cumulative discharge and percent of saline water in drain effluent, Test 3.

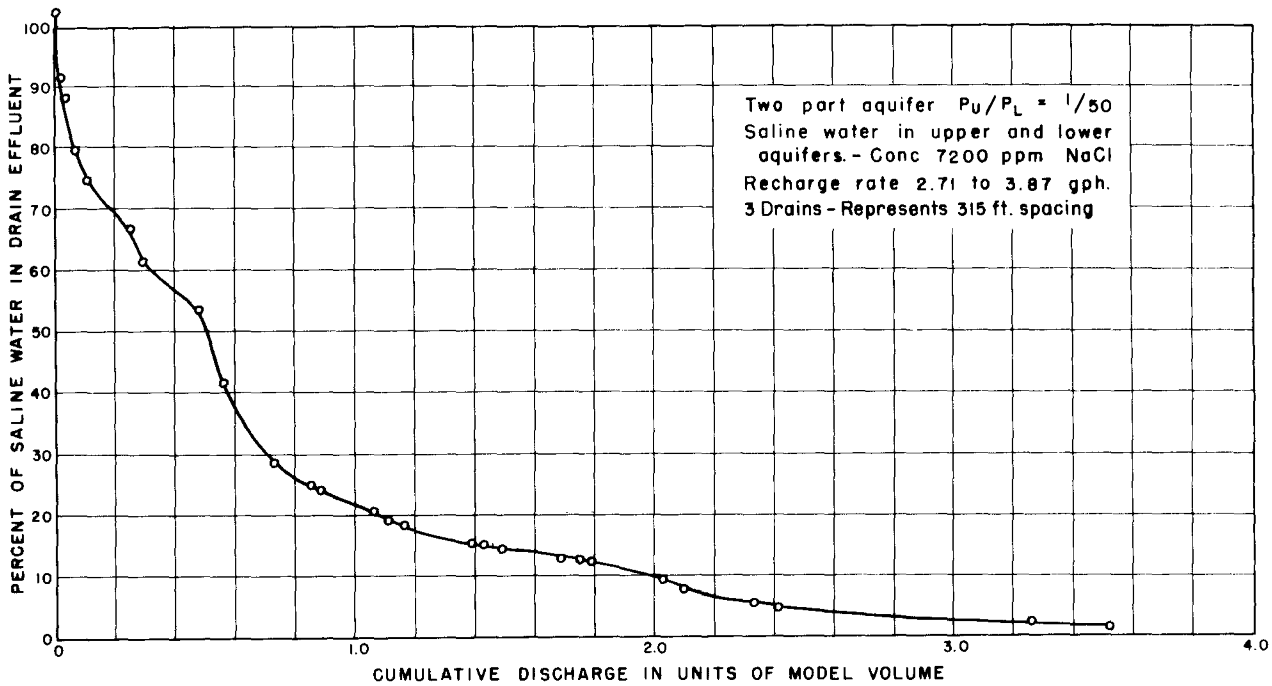


Figure 25.—Cumulative discharge and percent of saline water in drain effluent, Test 4.

salt remained at a level slightly above 70 percent during the time required for 0.1 to 0.35 of a model porosity volume to be discharged from the drain. The salt water concentration then dropped rapidly. In Test 1, the peak concentration of salt continued for a shorter period but did not drop as rapidly as in Test 2. The differences between the two curves, figures 22 and 23, is attributable to the different rates of applying the recharge water. The average recharge rate for Test 2 during the first 3 days of operation was

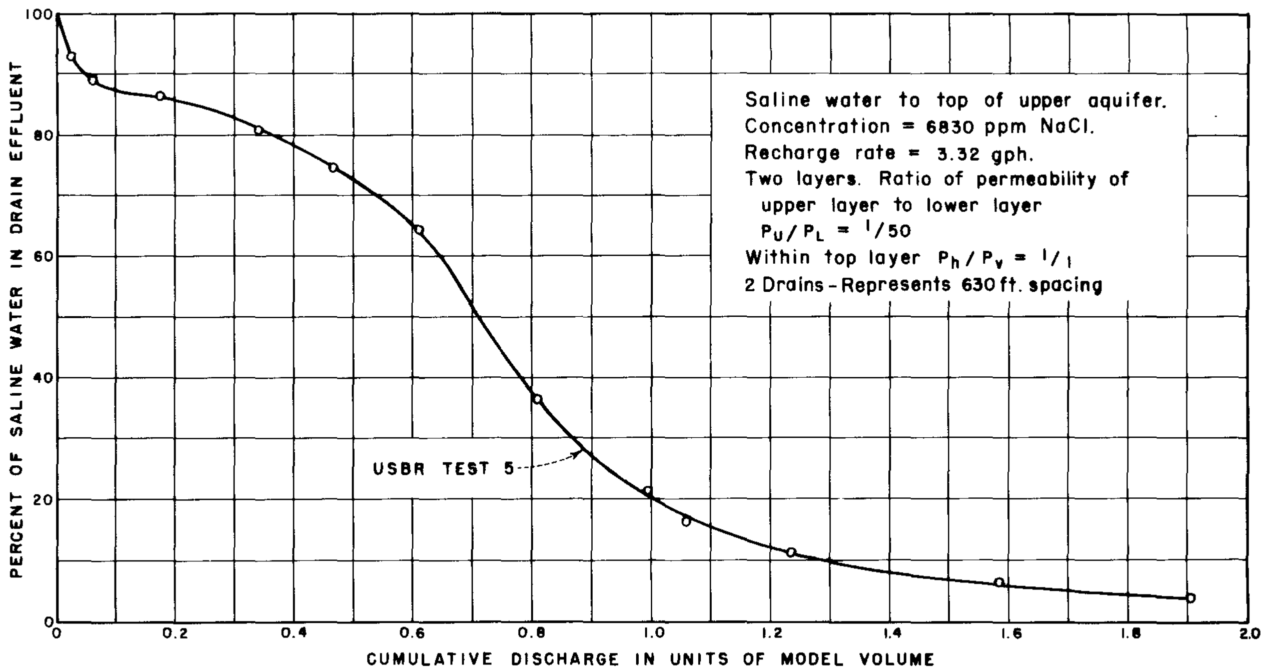


Figure 26.—Cumulative discharge and percent of saline water in drain effluent, Test 5.

higher than for Test 1, which accounts for the faster removal of salt water in Test 2. The overall average recharge rate for the entire tests was higher for Test 1 than for Test 2.

The materials which were used to form the aquifers were placed in the model in a dry condition and in a random manner, and therefore it is believed that in all tests the horizontal permeability P_h and the vertical permeability P_v for both aquifers was the same, making the ratio

$$\frac{P_h}{P_v} = 1.$$

Test 3 was made in the same two-part aquifer model as were Tests 1 and 2. Salt water with a similar concentration, 6,200 ppm, was placed to the top of the lower aquifer to start the test. In Test 3, the application rate of irrigation water varied between 12.76 and 13.35 gph and three drains, prototype spacing 315 feet, were used. The spacing was 1,260 feet for Tests 1 and 2. For these different conditions in Test 3, the curve of figure 24 showed that more salt water was forced out of the lower aquifer with less total irrigation water being applied than for Tests 1 and 2. The concentration of salt water in the drain effluents reached a peak of approximately 45 percent of that placed in the lower aquifer at the time 0.22 of a model porosity volume had been discharged through the three drains. After 1.0 model porosity volume of accumulative discharge had flowed through the model, the concentration of salt in the effluents was about 3.0 percent.

The rate of removal of salt water from the two-part aquifer model in Tests 4 and 5 is shown in figures 25 and 26. Initial conditions for the two tests were very similar except that in Test 4 three drains were used, giving a prototype drain spacing of 315 feet; in Test 5 the prototype drain spacing was 630 feet. In both tests the upper and lower aquifers were filled with salt water to the top of the upper aquifer. At the beginning of each test the drain effluents therefore consisted of approximately 100 percent salt water.

In both Tests 4 and 5, the percentage of salt water in the drain effluents was reduced to 20 percent by the time 1.0 model porosity volume had discharged through the drains. However, in Test 5 the saline water concentration did not drop as rapidly as in Test 4 because of the closer drain spacing in Test 4. For example, at the time that 0.2 of a model porosity volume had discharged through the drains, the Test 5 drain effluents contained 85 percent salt water and the Test 4 effluents contained only 70 percent. At the time that 0.6 of a model porosity volume had discharged through the drains in Test 5, 65 percent salt water was in the effluent, in Test 4 only 38 percent. The differences between the curves plotted for Tests

4 and 5, figures 25 and 26, are attributable to the different drain spacing in the two tests.

Summary and Conclusions for Part I—Two-Part Aquifers

For the first series of tests, a 1:40 scale model of an idealized cross section of a valley was constructed and tested to determine the hydraulic action of tile drain(s) placed 8 feet below the ground surface. Two-part aquifer tests were made with an upper aquifer 40 feet thick, composed of fine sand placed over a lower aquifer 40 feet thick. The lower aquifer was composed of coarse sand having a permeability about 50 times as great as the fine sand in the upper aquifer. The model was contained in a testing tank 15.71 feet long and 2.5 feet wide and deep. The lower aquifer (and in some tests the upper aquifer also) was charged with salt water, colored blue for visual identification. Fresh irrigation water was applied, continuously in some tests and intermittently in others, to the upper aquifer surface. The drain effluent was regularly sampled, analyzed, and used to determine the flow patterns in the model. In each test the model was operated continuously for days, keeping a continuous supply of fresh irrigation water flowing into the upper aquifer and a continuous flow of drainage water from the drain(s).

The statements below are conclusions based on analyses of data from the 5 tests made in the Bureau of Reclamation Hydraulics Laboratory and described in this paper. No record of previous tests of this kind could be found in the literature; the conclusions are, therefore, based upon the few tests made and described in this test series.

1. A tile drain(s) placed 8 feet below the top surface of a two-member aquifer will not intercept and discharge fresh water if the lower aquifer contains salt water. The drain discharge will have a maximum salt concentration of about two-thirds to three-fourths of the salt concentration existing in the lower aquifer.

2. An interface will develop between the saline water (original aquifer water) and the fresh irrigation replacement water. This interface will reach a stable configuration which is determined by the geometry of the aquifer, the permeabilities of the aquifer materials, the inflow and outflow rates, and the difference in densities between the saline and fresh water. The saline water above the final configuration of the interface will move to the drain and will be replaced by fresh water. The saline water below the final position of the interface remains relatively undisturbed and in semipermanent storage.

3. Decreasing the drain spacing will reduce the upper limit of salt concentration in the drain effluent and will increase the amount of saline water left in storage. However, it does not appear that a substantial amount of salt water storage could be realized unless the drain spacing is made comparable to (or less than) the thickness of the upper part of the aquifer. Increasing the number of drains will reduce the time required to flush the aquifer free of the salt water that can be moved to the drains. Drain spacings ranging from prototype equivalents of about 1,260 to 315 feet were investigated in the model tests.

4. The reduced quantity of salt water which flows to the drains from the lower aquifer, as a result of decreasing the drain spacing, is associated with a corresponding increase in the amount of salt water remaining in semipermanent storage in the aquifer. The reason that a portion of the original salt water contained in the aquifer remains in storage is that the saline water has a greater density than the fresh water and a balance of forces develops in which the saline water reaches a condition of complete stagnation with regard to motion. From visual estimates, the salt remaining in semipermanent storage for a 1,260-foot drain spacing was very small for the aquifer assumed in the model, for 630 feet was about one-sixth of the original volume, and for 315-foot spacing was about one-fourth of the original volume.

5. The aquifer is flushed substantially free of salt water when the quantity (volume) of fresh water applied to the ground surface (irrigation water) becomes equal to the volume of salt water originally present in the aquifer. Based on model test results and on an estimated time correction factor to account for nonirrigated areas, the time necessary to flush the aquifer used in the tests would be in the order of 25 to 35 years. The time scale used to obtain these values is: one 24-hour model day represents approximately 3.0 prototype years.

6. In two-part aquifer tests, the path followed by the fresh irrigation water applied on the ground surface to the tile drain located in the upper aquifer is, in general, vertically downward through the upper aquifer and into the lower aquifer, horizontally through the more permeable lower aquifer to an area beneath and extending out from the drain, then vertically upward to the drain. Only slight mixing of the fresh and salt waters occurs during the flushing process. The fresh water tends to drive the salt water ahead of it to the drain.

7. The depth to which a stable interface forms below the ground surface between adjacent horizontal tile drains depends on the difference in density between the fresh and salt water and on the height to which the water table is maintained above the drains. The latter value depends on the rate of application of water and on the permeability of the aquifer.

8. After the interface has reached its semistable configurations, slowly acting mechanisms such as molecular diffusion and disturbances due to changing infiltration rates may continue the removal of salt water at a greatly reduced rate.

Part II. Removal Of Saline Water From Single-Part Aquifers Using Tile Drains

Parallel Drains—Uniform Aquifer

At the conclusion of Test 5, the two-part aquifer was removed and the tank refilled to a depth of 2 feet with a single-part aquifer consisting of fine sand (the same type of sand previously used in the upper part of the two-part aquifer). A 1-inch layer of coarse sand was again placed on the fine sand surface to help distribute the applied irrigation water and prevent erosion of the fine sand aquifer. The three bottom pipe inlets had previously been prepared by covering with fine brass screen and a layer of medium sand about 1 inch deep to form a reverse filter between the pipe inlets and the fine sand aquifer. Two horizontal drains (perforated copper tubing) were placed 0.2 foot below the sand surface (8 feet prototype) and covered with fine brass screen. The drains were surrounded with medium sand to form a reverse filter to prevent clogging. The distance between the drains was 15.71 feet, simulating a prototype distance of about 630 feet.

The Investigation

Results of Test 6

On August 5, salt water dyed blue and having a sodium chloride concentration of approximately 4,000 ppm was introduced into the model, table 2. No potassium chloride tracer was used for Tests 6, 7, and 8 because the results of previous tests had shown that the changes in concentration of sodium chloride in the effluent paralleled very closely the changes in the concentration of the potassium chloride tracer.

Specific gravity of the dyed salt water was 1.0034 at 70.5° F and for Denver tap water 1.0002 at 69° F, measured with precision hydrometers previously checked for accuracy by the National Bureau of Standards. Ten 55-gallon barrels full of dyed salt water were required to completely fill the aquifer with salt water. The salt water moved from the inflow pipes slowly through the fine sand of the upper aquifer.

Difficulty was encountered in filling areas remote from the inlet pipes because of the greater resistance to the inflow. Because allowing the salt water to rise uniformly across the entire fine sand aquifer would take a very long time, the filling operation was forced. This was done by drawing salt water off the aquifer surface between the inlet pipes, and ponding the blue salt water directly about the inlet pipes until it had completely saturated the areas farthest from the inflow pipes.

Test 6 was started at 10:05 a.m., August 12, using a new garden soaker. Because of pressure changes in the water supply line and the accumulation of foreign particles in the soaker hose pinholes, the application rate changed slightly during the test. At the beginning of the test, a uniform flow rate of approximately 2.36 gph was applied to the total surface. The average discharge during the entire test was 1.29 gph from Drain A, left, and 1.14 gph from Drain C, right, giving a total of 2.43 gph. Figure 27 is a graph showing the discharge and concentration of the effluent from Drains A and C. The concentration in Drain A was reduced from the original concentration of 4,000 ppm to approximately 400 ppm (one-tenth of the original concentration) in 7½ days. Drain C had one-tenth of the original concentration after operating 8½ days, figure 27.

Figure 28 shows the interface on August 20 and 21, when the effluent reached a concentration of one-tenth the original salt concentration in Drains A and C, respectively.

Time sequence photographs were again taken with a 16-mm motion picture camera. Single frames were exposed at 6-minute intervals and a motion picture

TABLE 2.—*Draining saline water from single-part aquifers with agricultural tile drains—data from all tests—ground-water model*

1	2	3	4	5	6	7	8	9	10
Test No.	Date and time		Drains operating	Average discharge from drains, gph	Average salt concentration start of test, ppm	Top of salt solution at start of test	Model and prototype drain spacing, feet	Model distance of interface below ground at equilibrium, feet	Model days to reduce effluent concentration to one-tenth of original aquifer saline concentration, days
	Start test	Finish test							
6	8–12 10:05 a.m.	8–26 1:20 p.m.	A C	Steady ...... 1.29 1.14 Total 2.43	4,000	Top of aquifer	15.71 630	Below bottom of model (80.0 ft. by computation)	7.5 8.6
7	10–2 10:00 a.m.	10–15 11:30 a.m.	A B C	Steady .... .53 1.67 .56 Total 2.76	79,770	.... do	7.86 315	1.4 left side .... 1.45 right side	5.2 4.8
8–1	11–6 8:30 a.m.	11–19 9:30 a.m.	A B C	Transient 2.77 each 2 hours	75,190	.... do	7.86 315	1.08 right side .... 1.00 left side	5.8 7.0
8–2	11–19 9:30 a.m.	12–2 10:30 a.m.	A B	Transient 2.89 each hour	75,190	Continued from Test 8–1	7.86 315	1.42 right side .... 1.25 left side	....
8–3	12–2 10:30 a.m.	12–23 8:35 a.m.	A B C	Transient 2.77 each ½ hour	75,190	Continued from Test 8–2	7.86 315	Below bottom of model	....

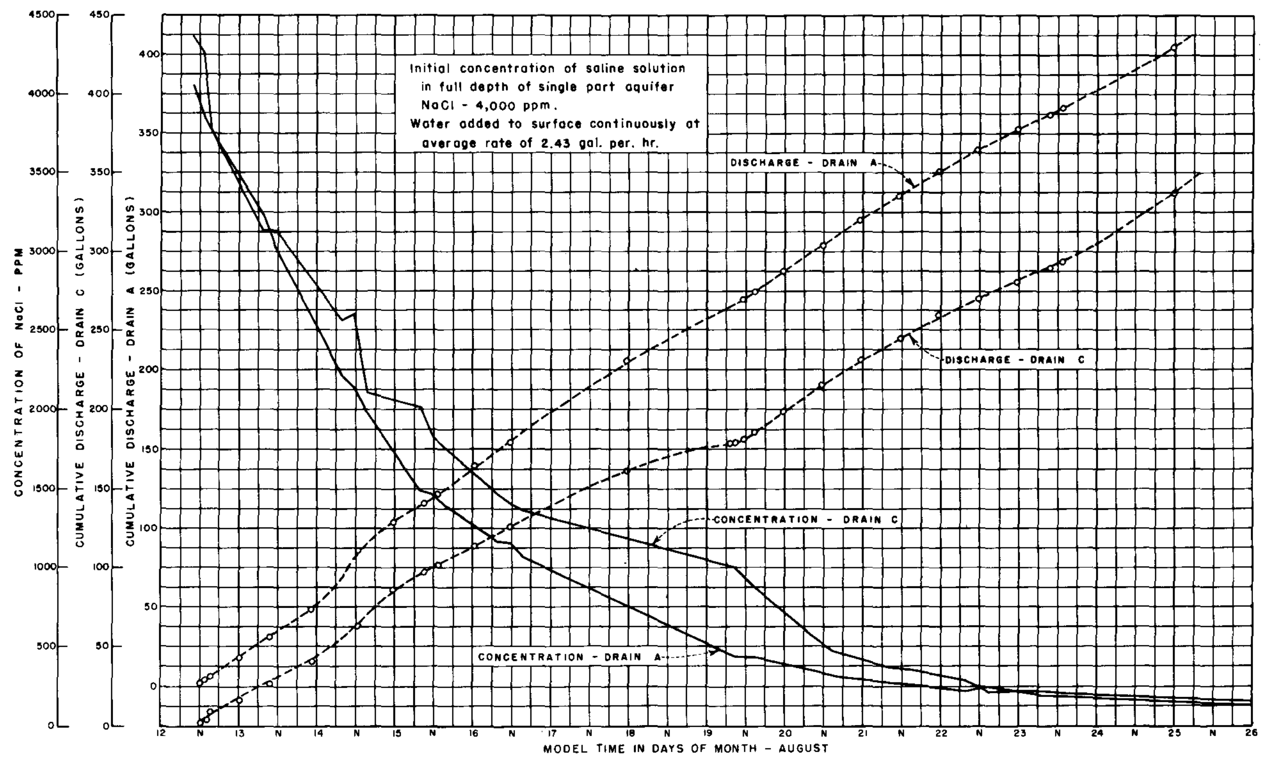


Figure 27.—Salinity and quantity of water discharged from two drains.

of the entire operation of Test 6 (13 days) can be projected at normal speed and viewed in a period of approximately 5 minutes.

At the conclusion of Test 6, the interface had moved downward so far that its apparent position was below the bottom of the sand in the model. The only salt water remaining was contained in the small wedges under each of Drains A and C, figure 29.

Ghyben-Herzberg Relationship

More than 60 years ago, W. Badon Ghyben [2] and A. Herzberg [3] working independently along the European coast, discovered that salt water was to be found underground, not at sea level but rather at a depth below sea level equivalent to about 40 times the height of the fresh water table above sea level. Dynamic equilibrium existing between the sea water and the fresh water supplied by precipitation influences the distribution of the saline and fresh water. Analytical studies [4 5 6 8 9] have disclosed the reason for this relationship. The equation derived to explain the phenomenon is referred to as the Ghyben-Herzberg relationship shown below, figure 30:

$$h_s = \frac{\rho_f}{\rho_s - \rho_f} h_f$$

where h_s is the depth to salt water below the sea level (depth to fresh water-saline water interface)

h_f is the height of the water table above sea level

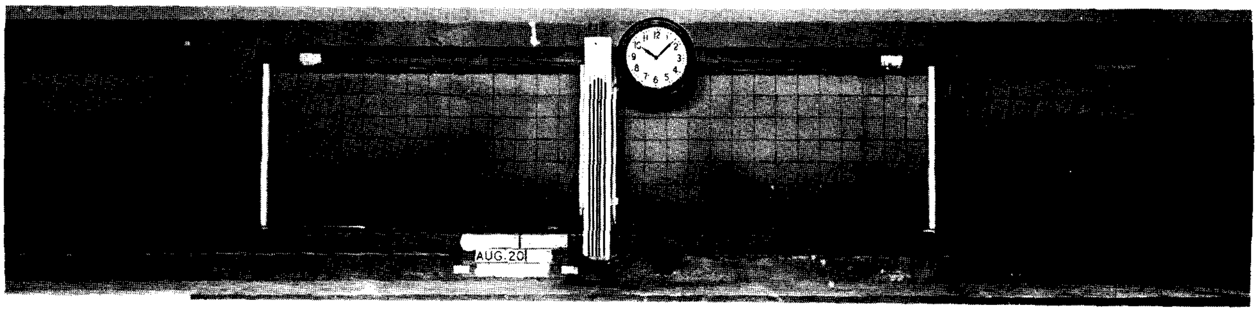
ρ_f is the specific gravity of the fresh water, and

ρ_s is the specific gravity of sea water.

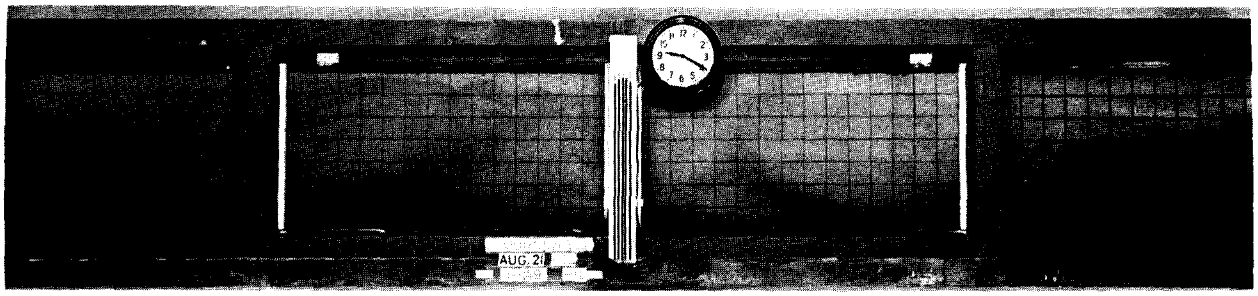
If $\rho_s = 1.025$ g/cm^3 and $\rho_f = 1.00$ g/cm^3, then $h_s = 40\ h_f$.

When the Ghyben-Herzberg relationship is applied to the case of drainage by tile drains, the saline aquifer water replaces the sea water, irrigation water replaces rainfall infiltration, and the tile drain replaces the coastline. The depth that the saline water-fresh water interface will reach and become stable is determined by the spacing between drains, the infiltration rate, the permeability of the aquifer, and the difference in density between the saline aquifer water and the fresh irrigation water. When stability occurs, the saline water below the interface is stagnant, and the fresh water above the interface moves toward the drain.

Where the flow to unit length of drain is sustained by an infiltration rate, *i,* over a drain spacing of



A. Interface when Drain A, left, effluent had a salt concentration one-tenth (400 ppm) of original concentration 7½ days after beginning of test.



B. Interface when Drain C, right, effluent had a salt concentration one-tenth (400 ppm) of original concentration 8½ days after beginning of test.

Figure 28.—Appearance of fresh water-salt water interface in Test 6 when drain effluents contain one-tenth of original aquifer salt concentration.

length, L, continuity requires that

$$q=i\left(\frac{L}{2}-x\right) \tag{1}$$

where x represents the distance from the drain and q represents the flow to the drain from one side.

The density differential between the saline and replacement waters will be expressed by a quantity, m, defined by the relation

$$m=\frac{\rho_f}{(\rho_s-\rho_f)} \tag{2}$$

where ρ_s represents the density of the saline water, and ρ_f represents the density of the fresh replacement water.

If K represents the permeability of the soil and h the head driving the water toward the drain, then the flow to the drain may be expressed in the form:

$$q=K\left(1+m\right)h\frac{dh}{dx} \tag{3}$$

This expression conforms to the requirement that the greater static pressure of the stagnant saline water must be counterbalanced by the pressures sustaining the flow of the replacement waters to the drain.

Elimination of q between equations (1) and (3) yields the differential equation:

$$h\frac{dh}{dx}=\frac{i\left(\frac{L}{2}-x\right)}{K(1+m)} \tag{4}$$

An integration, subject to the requirement that $h=h_o$ when $x=0$, yields the solution:

$$h=\sqrt{\frac{iL^2}{4(1+m)K}-\frac{i\left(\frac{L}{2}-x\right)^2}{(1+m)K}+h_o^2} \tag{5}$$

In most cases, $h_o=0$.

The quantity, h, reaches its maximum value midway between the drains where $x=L/2$. This value is, when $h_o=0$,

$$h_m=\sqrt{\frac{iL^2}{4(1+m)K}} \tag{6}$$

Equation 5 was applied to Test 6 and computations indicated the interface would occur 80.2 feet below the drains in the model. The small wedges of dyed

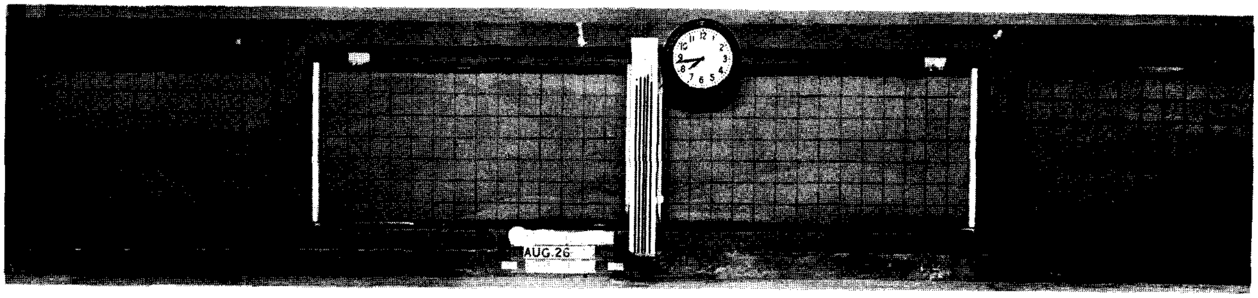


Figure 29.—Only small wedges of salt water in the lower corners beneath the drains remain in the aquifer of Test 6 on August 26, after 13 days (58½ prototype years) of model operation.

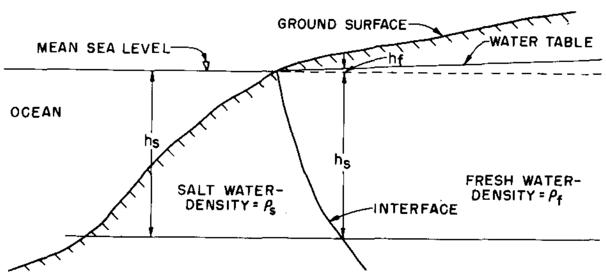


Figure 30.—Idealized portrayal of fresh water-salt water interface in a coastal aquifer to illustrate the Ghyben-Herzberg relationship.

salt water remaining under each drain at the end of Test 6, figure 29, verify the computation to the extent that the interface would have occurred far below the bottom of the model floor.

Tests 7 and 8 were then conducted to check the equation and to determine if the Ghyben-Herzberg principle could be applied to an aquifer drained by agricultural tile drains placed near the ground surface. A high concentration of salt was used to make a large difference in specific gravity between the saline water and the fresh irrigation water, and thereby cause the stable interface to form at a higher elevation above the floor of the model.

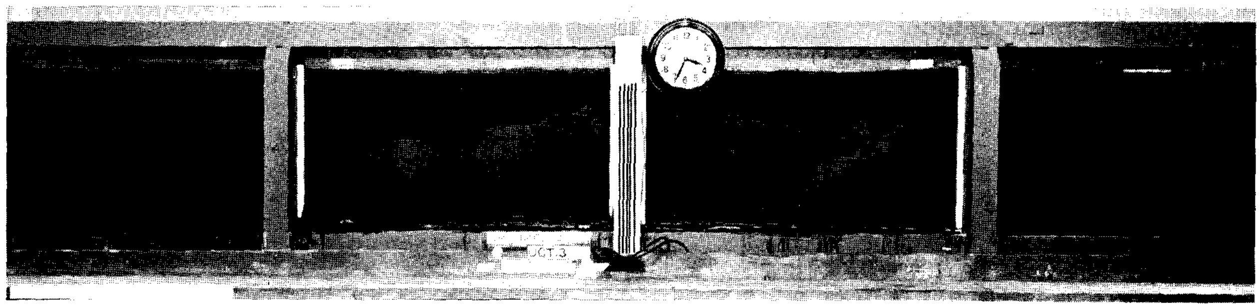
Results of Test 7

At the conclusion of Test 6 the fine sand single-part aquifer was flushed with tap water. The model aquifer was then charged with salt water having an average concentration of 79,770 ppm. The salt water was again dyed blue with 250 ppm of patent blue dye. No potassium chloride tracer was used in Test 7. To reduce the depth of the saline water-fresh water interface, three drains were used giving a spacing of 7.86 feet between drains, simulating a drain spacing in the field of 315 feet.

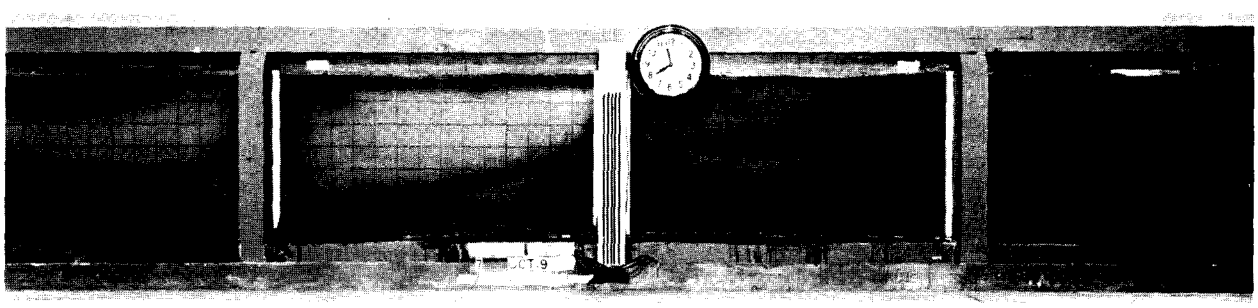
Blue salt water was introduced into the model beginning at 12:20 p.m. on September 4 and on September 27, after 13 barrels (55 gallons per barrel) of dyed salt water had been used, the sand aquifer was completely (as seen through the observation panels) filled with saline water. The perforated garden soaker was again used to add fresh water to the sand surface at a uniform rate. The test was started at 10 a.m. on October 2. The average total discharge from the three drains was 2.76 gph, divided as follows: 0.53 gph from Drain A, 1.67 gph from Drain B, and 0.56 gph from Drain C.

The high concentration of salt caused the dyed water to have a light greenish-blue color instead of the deep blue color seen with lower salt concentrations. As more fresh water became mixed with the highly concentrated salt water, the solution became darker and bluer in color. When the latter color was washed out of the model, the sand cleared to its natural white color. The photograph in figure 31A shows the dark blue color as the upper dark area on the black and white photograph and the lighter greenish-blue color in the lower part of the aquifer. Figure 31B shows the dark blue band at the interface, with the lighter greenish-blue color below the interface. Sand, washed clear of dyed salt water, may be seen above the interface.

Using the formula described previously, the position of the interface for an equilibrium condition was computed. A plot of this computed interface position, figure 32, is compared with the actual interface position as the interface appeared on October 8, after 5.9 days of model operation, figure 33, and on October 15, after 12.9 days of model operation, figure 34. The slight displacement of the interface in 7 days of model operation in the interval between the times of



A. The high concentration of salt (approximately 79,770 ppm) caused the blue dye to have a light bluish-green color (lower part of aquifer) at the beginning of Test 7. As fresh water mixed with the highly concentrated salt water, the solution became dark blue.



B. The dark blue band (interface) separates the fresh water above and the saline water below after 7 days of operation of Test 7. Original concentration of salt was approximately 79,770 ppm.

Figure 31.—Test 7 at the beginning and after 7 days of operation.

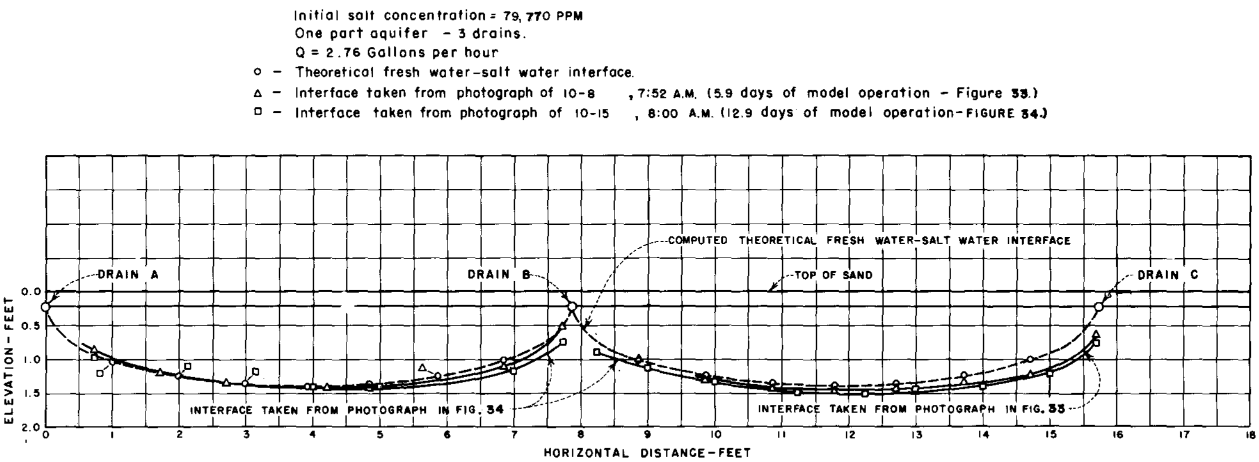


Figure 32.—Comparison of observed and computed position of fresh water-saline water interface in Test 7.

the two photographs shows that the interface had reached a stable position. Inasmuch as the computed position of the interface is very close to the actual interface position, the validity of the formula has been demonstrated for a uniform aquifer.

Figure 35 shows the rate of discharge from the

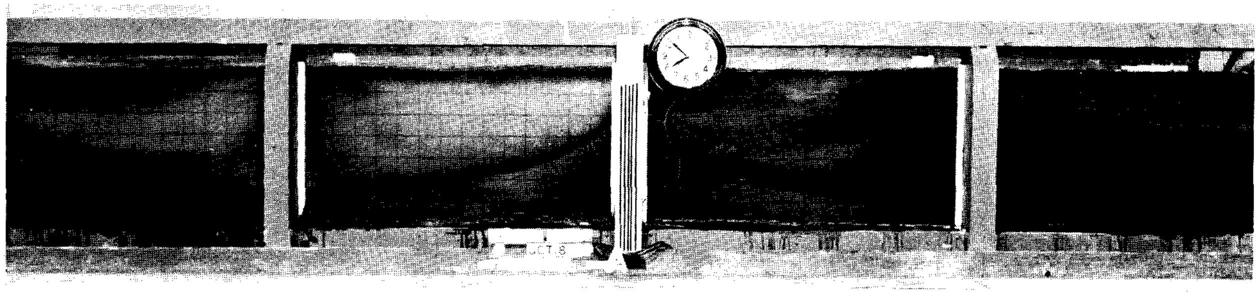


Figure 33.—Test 7, with single-part aquifer, showing saline water-fresh water interface on October 8. Interface is in same general position as computed using the Ghyben-Herzberg principle shown on figure 32. Salt concentration in the aquifer at the beginning of the test was approximately 79,770 ppm.

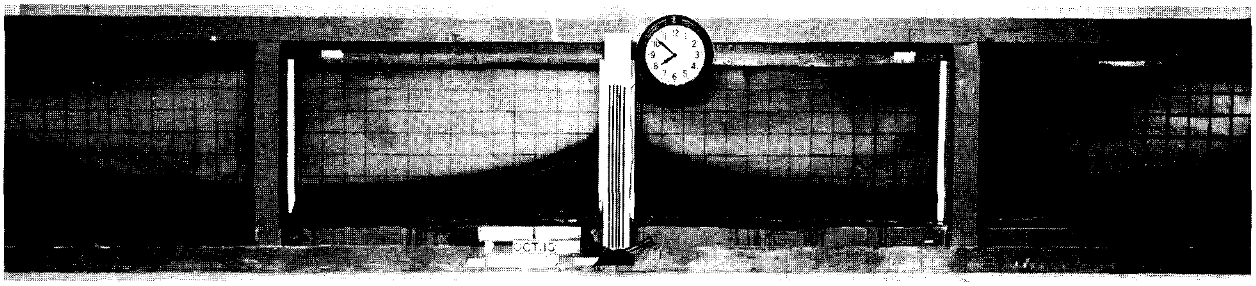


Figure 34.—Saline water-fresh water interface of Test 7 after 12 days and 20 hours of operation of model.

three drains measured at intervals throughout Test 7. Figure 36 shows the rate of change of salinity of effluents from Drains A, L, and C.

The time required for the effluent to be reduced to one-tenth the original concentration was 5¼ days for Drain A, 4¾ days for Drain B, and 3¼ days for Drain C. Discharge from the garden soaker was higher between Drains B and C, causing the salt water to be flushed from that end of the model in a shorter time.

A pressure-reducing system was used to maintain a low pressure on the garden soaker but some of the fine holes in the plastic tube became partially clogged with foreign particles from the supply line, causing slight variations in discharge along the longitudinal axis of the model and some variation in average discharge with time. However, despite minor difficulties, the garden soaker gave generally good results.

Figure 34 shows the position of the interface on October 15, 3½ hours before the application of irrigation water was stopped. The curved interface started to flatten after application of irrigation water was stopped and the heavy salt water began to form a level surface. Figure 37 shows the interface on October 18, 3 days after the application of irrigation water was stopped.

Results of Tests 8-1, 8-2, and 8-3

Test 8 was conducted in three parts (three different rates of water application) for the purpose of checking the validity of the formula 5 for the three different intermittent recharge rates. The single-part aquifer consisting of fine sand was used.

Salt water, dyed blue and having an average concentration of 75,190 ppm sodium chloride, was added to the sand aquifer until it was filled. Twelve barrels of salt water were used to replace the fresh water in the aquifer between October 24 and November 4 in the filling operation. The average specific gravity of the salt water, measured with a hydrometer, was 1.0550 at 60° F; tap water was 1.0002 at 60° F.

To overcome the difficulties encountered in obtaining uniform discharges from the garden soaker, a toilet flush tank was modified and arranged to operate with a timer to supply given quantities of water at any desired time interval. The system consisted of a toilet tank containing the flushing mechanism, an

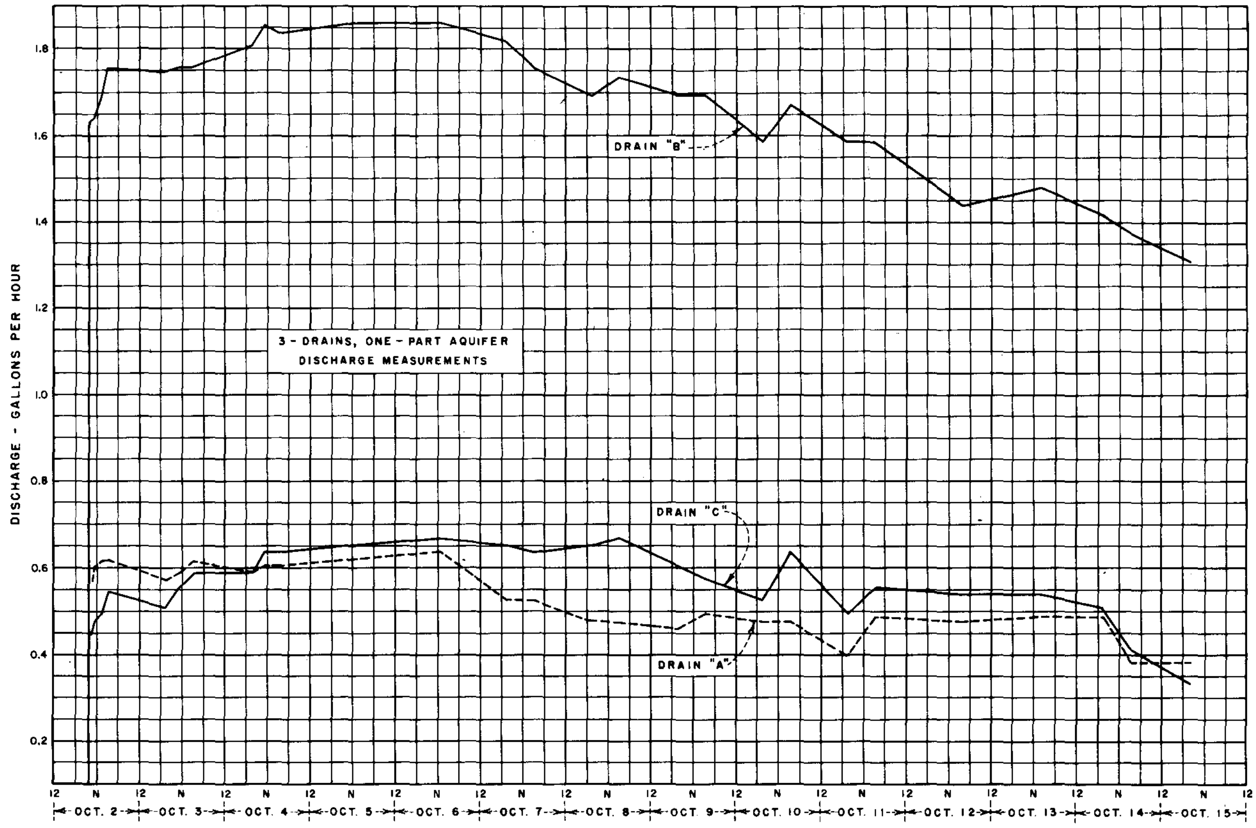


Figure 35.—Effluent discharge measurements from three drains in Test 7.

assembly of plastic pipe, two perforated stainless steel troughs to distribute the water over the model surface, and a solenoid relay activated by an adjustable timer to trip the flushing mechanism. The interval between applications of replacement water is very short compared to the time required for the interface to level out after application of irrigation water is stopped, figure 37. Therefore, in this respect at least, the intermittent applications of replacement water are equivalent to steady flow.

For Test 8–1, 2.77 gallons of fresh water were applied to the aquifer surface every 2 hours. The troughs were perforated at 1-foot intervals to distribute the water uniformly over the aquifer surface. The holes were large enough to be unclogged with foreign particles in the supply water. The flush tank and distribution system had previously been adjusted and calibrated to discharge equal quantities of water to all areas. The time interval between applications could be varied to give different application rates. Figure 38 shows the automatic distributing system.

In Test 8–1 the interface between the saline water and fresh water formed soon after water was first applied to the surface at 8:30 a.m., November 6. Figure 39 shows the position of the interface on November 8, 12, 14, and 19.

Samples of effluents from the three drains were taken at various time intervals, and an analysis of their salt content was made using the flame photometer. A graph of the variation of salt content with time for Test 8–1 is shown on figure 40. The salt concentration of the effluent was reduced to a value of one-tenth the original salt concentration in the aquifer (75,190 ppm) in 5-5/6 days for Drain A, 7 days for Drain B, and 5-1/3 days for Drain C. The time required for the interface to reach a stable position and a concentration of one-tenth the original concentration in the aquifer does not vary appreciably whether a two-part or a single-part aquifer is used. The time required in either case for the interface to reach a stable position is influenced by the drain spacing and the water application and/or effluent flow rate. The ratio, density of the fresh irrigation water divided by the difference in densities between the fresh and saline water, determines the position of the stable interface between the two liquide. The time to evacuate the required volume of saline water to form a stable interface is

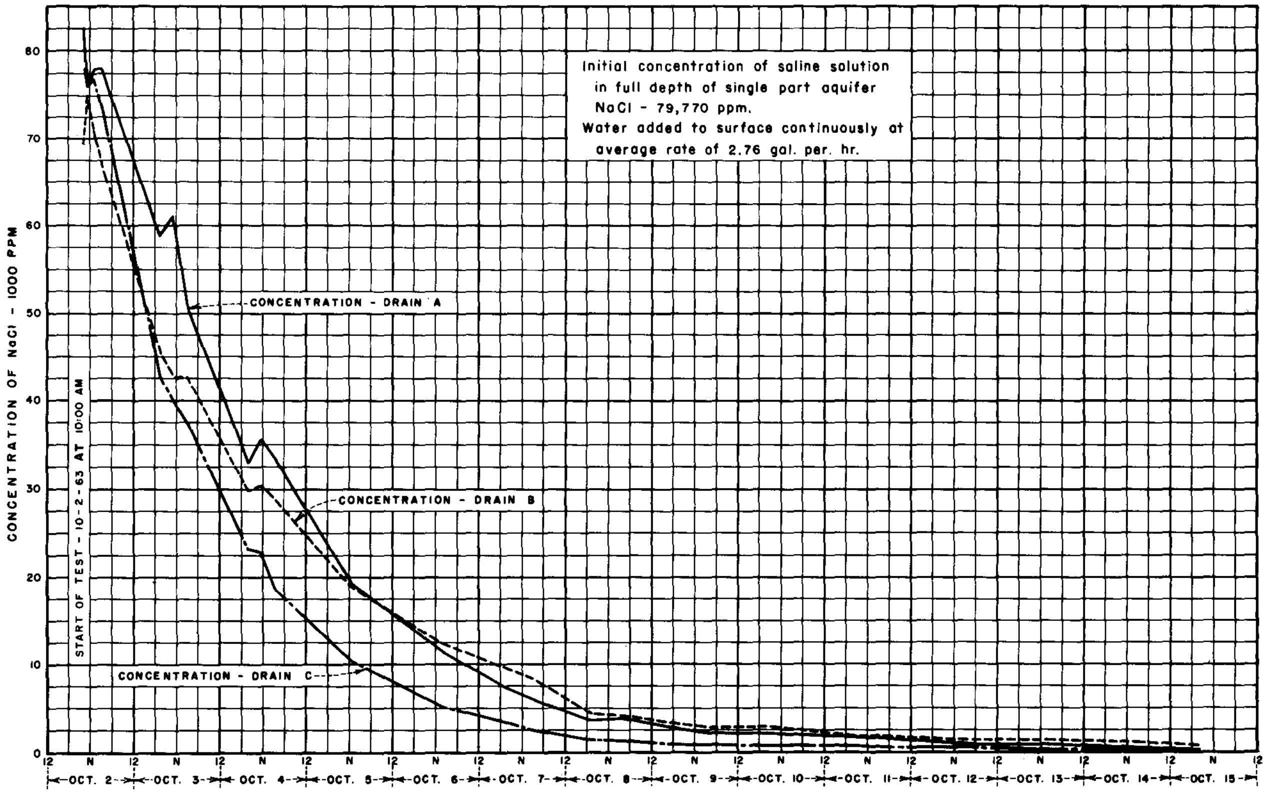


Figure 36.—Salinity of effluents from three drains in Test 7.

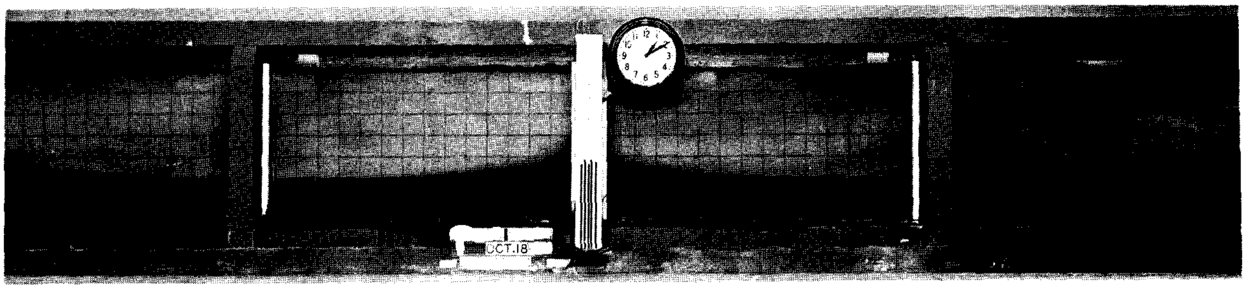


Figure 37.—Saline water-fresh water interface of Test 7, 3 days (13.8 prototype years) after the application of irrigation water was stopped. Comparison with figure 36 shows that the interface has not leveled completely.

influenced by the depth that the stable interface forms below the level of the drains, and the rate of application of fresh water.

Figure 41 shows the equilibrium position of the interface for Test 8–1 as measured in the model and the comparative interface position as computed by the formula based on the Ghyben-Herzberg principle. The two lines show good agreement.

In Test 8–1 the irrigation water inflow was added intermittently, producing transient conditions, whereas the formula for computing the interface assumes a steady state condition of inflow and outflow. The good comparison between the computed and observed position of the interface in the model, figure 41, shows that the stable interface forms at the same depth whether irrigation water is applied intermittently or whether it is applied continuously. The pressures near the stable interface may vary slightly with time, but it is quite obvious that variations occur so slowly for the conditions under which the model was operated that the location of the interface was the same for transient conditions as for steady state conditions. For a 6,000 ppm solution in the aquifer, the interface would form at an even greater depth where pressure conditions would be even slower to change. Also, in the prototype, the long time average application rate

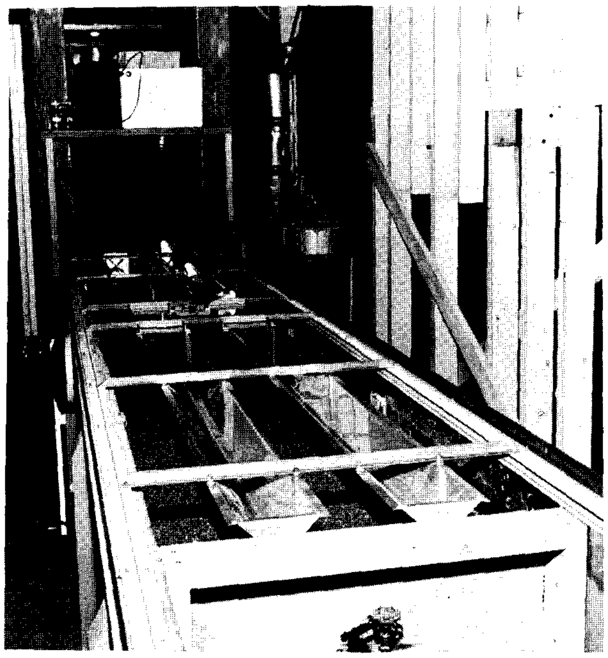


Figure 38.—Sand tank model with automatically operated flush tank and stainless steel troughs installed for Test 8, to apply irrigation water at regular intervals and distribute it uniformly over the aquifer surface.

of irrigation water would probably be less than used in the model and again pressure conditions would be slower to change. Without a doubt, therefore, it may be concluded that intermittent or uniform application of irrigation water as discussed will produce the same final result.

Variations in the water table elevation with time, between applications of irrigation water, were measured in the model, and a typical example of the changing water table surface is shown in figure 42. These relationships were developed from data obtained in Test 8–1 by making water table measurements at the drains and at five points between adjacent drains. Data were taken at measured time intervals after an application of water was made through the flush tank and stainless steel trough equipment. Figure 43 shows the variation of water table surface at each observation well plotted against time. Figure 44 is a plot of the variation of discharge from Drains A, B, and C during a 30-minute period following the application of 2.77 gallons of water. The data of figures 43 and 44 were used to develop figure 42.

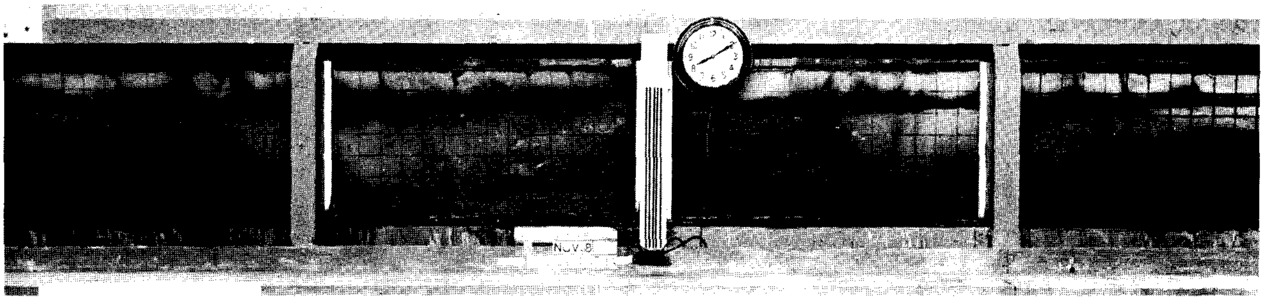
To verify that the Ghyben-Herzberg principle could be applied to a single-part aquifer and to show that the interface would move downward with an increased water application rate, Tests 8–2 and 8–3 were made as a continuation of Test 8–1 without stopping the irrigation application and without adding additional salt water. For Test 8–3, the rate was again roughly doubled by applying 2.77 gallons of fresh water to the model each one-half hour. Figure 45 shows the position of the interfaces that formed at the end of Tests 8–1, 8–2, and 8–3. The interface position is seen to be successively lower as the average rate of application of irrigation water was increased.

Saline Water Displacement

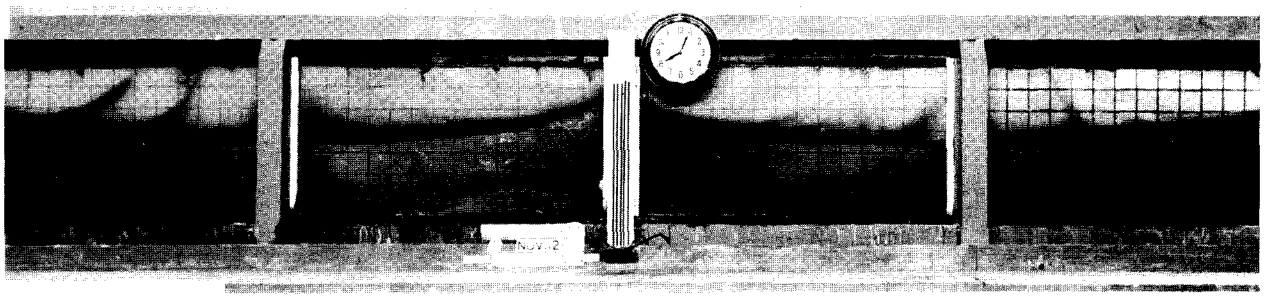
Test 6 was conducted using a single-part aquifer made of the fine sand used in the upper aquifer for Tests 1 through 5. Salt water with 4,000 ppm concentration was used to completely fill the aquifer prior to the start of the test. The average application rate of fresh water was 2.43 gph. Two drains, A and C, 15.71 feet apart were in operation. At the beginning of the test, the drain effluents contained approximately 100 percent salt water. After 1.0 model porosity volume had discharged through the drains, the effluent contained approximately 40 percent of saline water.

Figure 46, Test 6, shows the relationship between percent of saline water in drain effluent and the cumulative discharges from the drains in terms of total amount of saline water placed in the aquifer (model porosity volume).

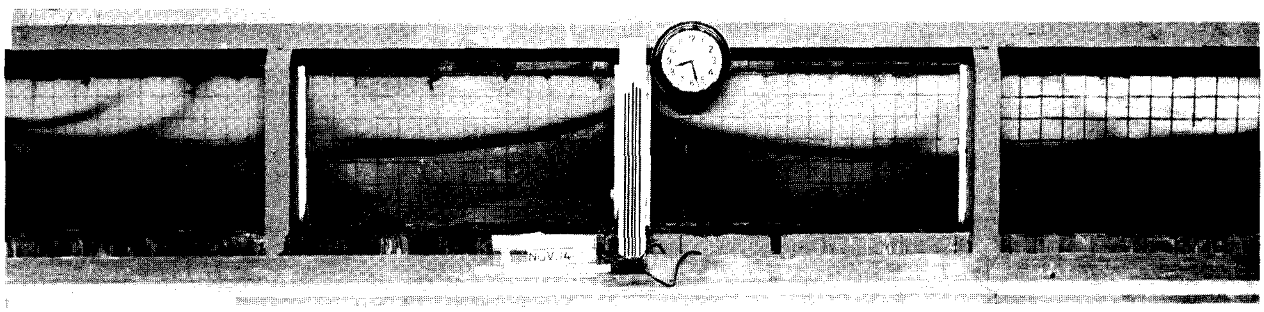
Results of Tests 7 and 8–1 are shown on figures 47 and 48. These two tests were conducted in the same single-part fine sand aquifer, filled to the top of the aquifer with 79,770 and 75,190 ppm salt water, respectively, prior to the start of the test. Test 7 had an application rate of 2.76 gph with three drains being used, and Test 8–1 had an application rate of 2.77 gallons each 2 hours with three drains being used. The percent of salt water in the combined effluents from Drains A, B, and C at the beginning of Tests 7 and 8–1 was slightly less than 100 percent, probably because of the small amount of fresh water remaining on the sand particles of the aquifer when it was charged with salt water. Test 7, figure 47, showed that the percent of salt water in the drain effluents was about 20 percent at the time 1.0 model porosity volume of effluent had discharged from the drains. Test 8, figure 48, showed that at the time 1.0 model porosity volume of effluent had discharged from the drains, the percent of salt water in the effluent was about 10 percent. The difference in salt water content in the effluent for Tests 7 and 8 is attributable to the different fresh water application rates used in the tests.



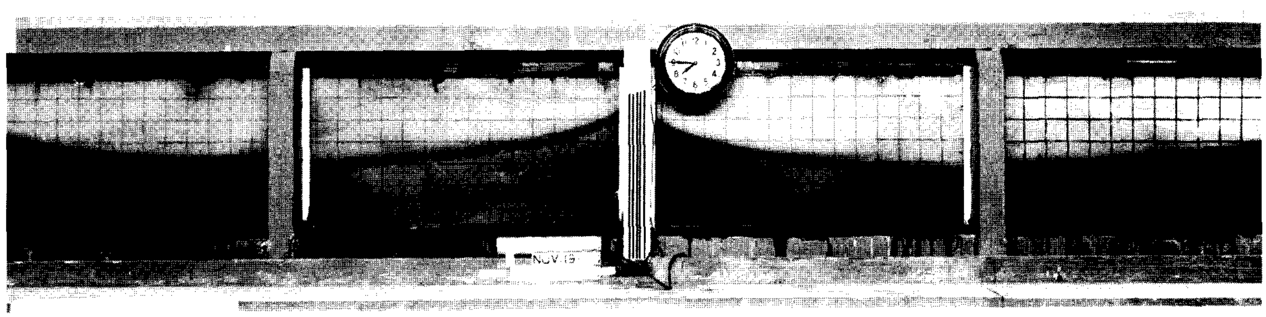
November 8



November 12



November 14



November 19

Figure 39.—Test 8–1, single-part aquifer was filled with approximately 75,190 ppm salt water before beginning of test; photographs show movement of interface from November 8 to November 19.

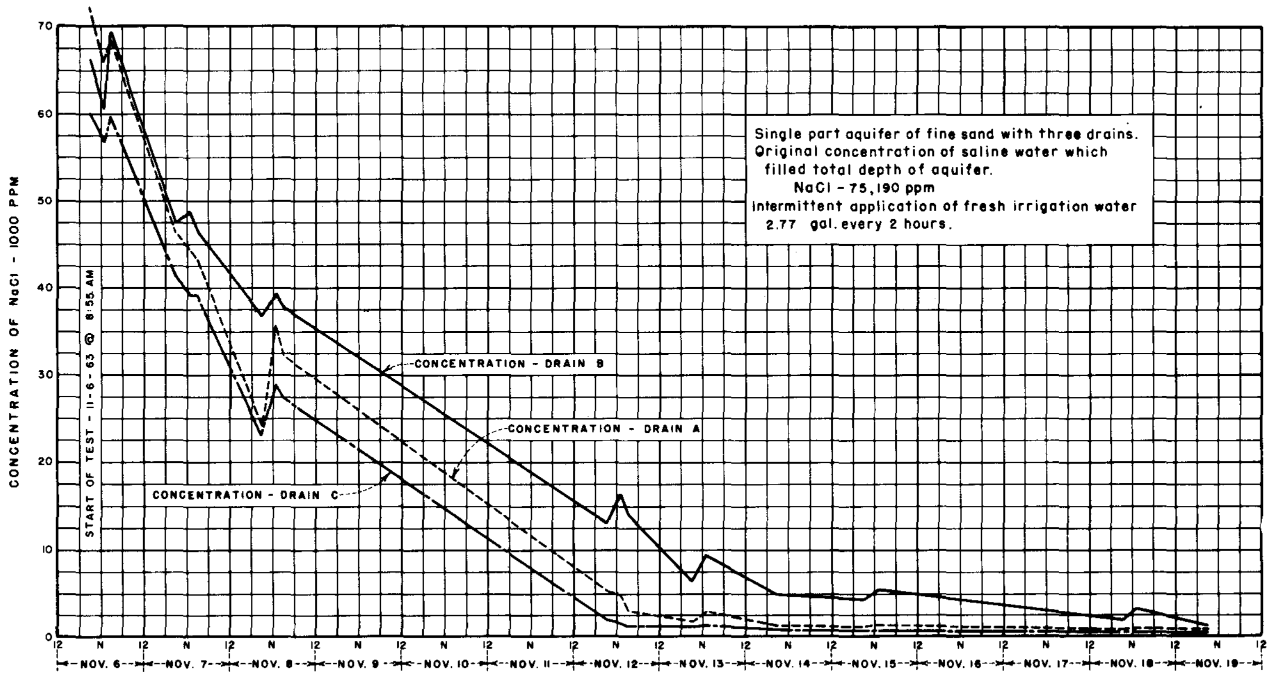


Figure 40.—Salinity of effluents from three drains in Test 8–1.

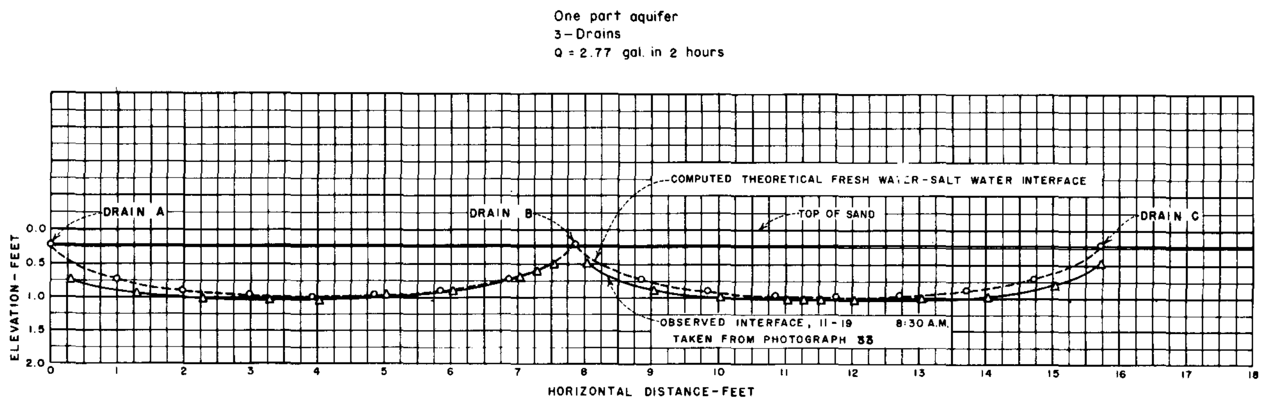


Figure 41.—Comparison of observed and computed positions of fresh water-saline water interface for Test 8–1.

Plots relating the percent of salt water in the drain effluent with accumulative discharges from the drains could not be made for Tests 8–2 and 8–3 because these tests were a continuation of Test 8–1 and were not started with the aquifer full of salt water.

Salt Removed by Drains in the Field

For field installations where drains are installed at depths and spacing to keep the water table out of the root zone, calculations generally indicate that the ultimate position of the interface will be below the bottom of the aquifer at a point midway between the drains. In such cases, only a wedge of saline water remains below the drain. For shorter spacings, the two wedges join and the interface is continuous between drains. If the drain spacing is reduced until the distance is comparable to the aquifer depth, considerable amounts of salt could be left in semipermanent storage. Laboratory and analytical investigation indicate this possibility, but there is some question whether it could be realized in the field because of the presence there of disturbing influences not accounted for in the laboratory and analytical studies. In river valley aquifers, for example, there is a down-

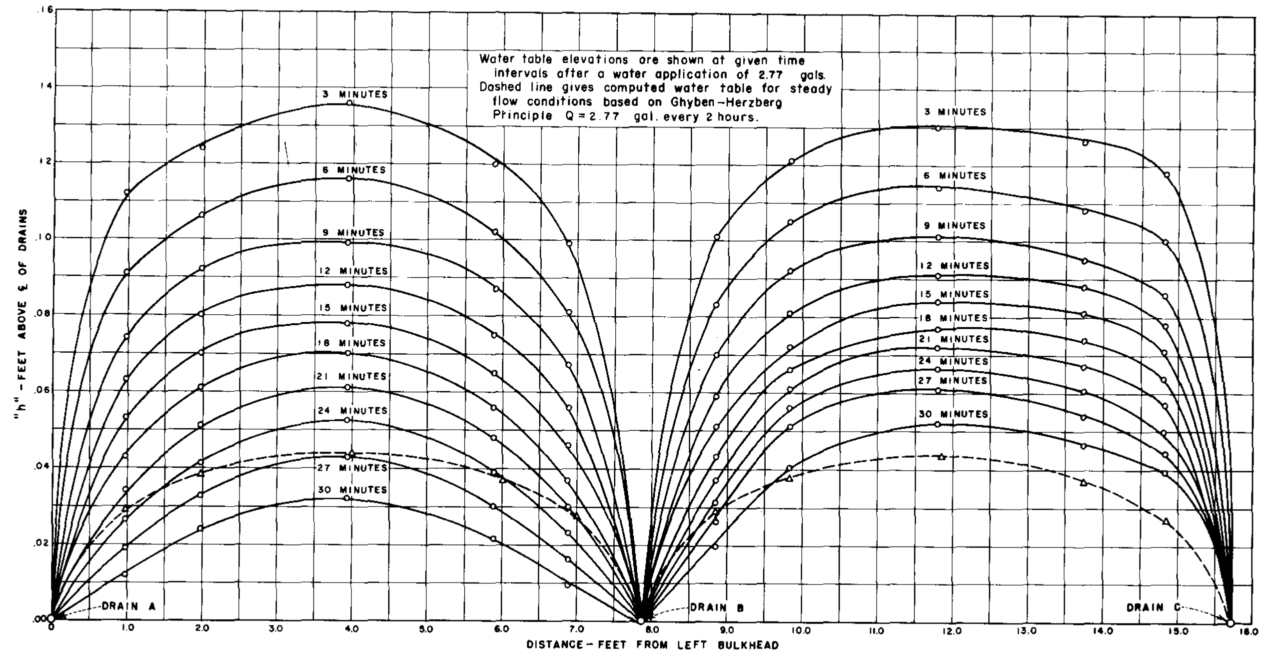


Figure 42.—Water table elevations at various time intervals for transient inflow conditions in Test 8–1.

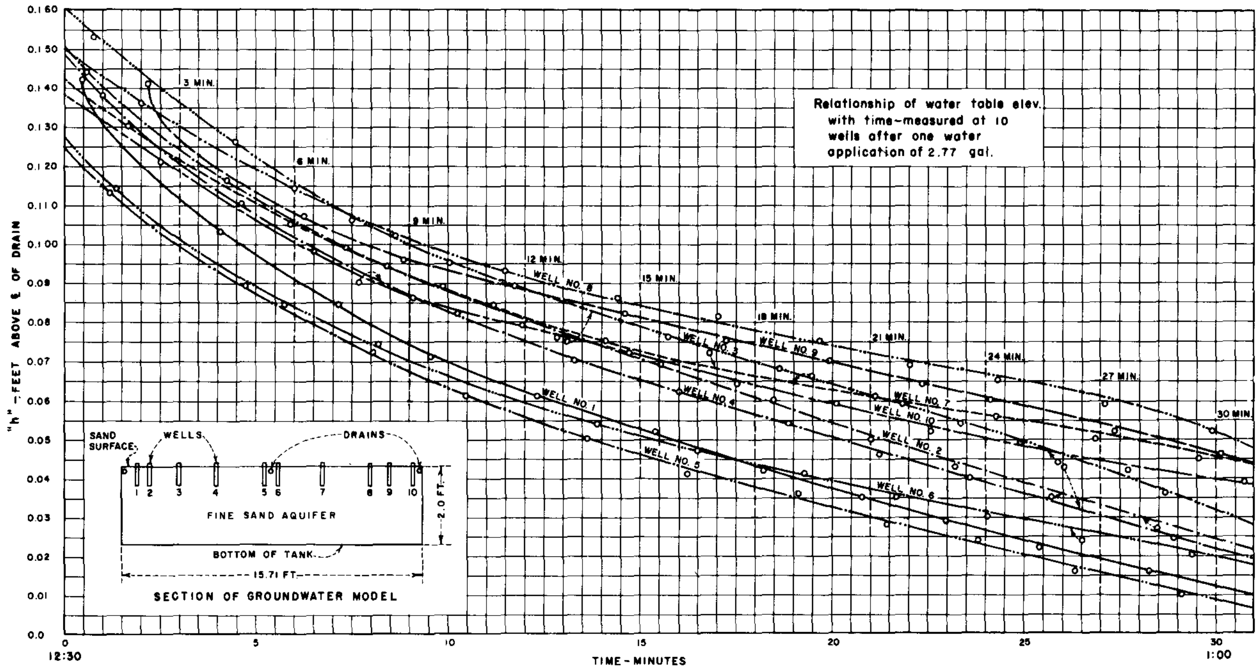


Figure 43.—Transient water table heights measured from 10 wells in Test 8–1.

valley movement of the ground water due to the valley gradient. In addition, the irregular pattern of irrigation on adjacent parcels of land creates groundwater mounds that cause a continual shifting of the ground waters. When an interface between saline and replacement waters is moved in this way, there is a diffusion of salinity across the interface which is favorable to the removal of salt. [7 8] Molecular diffusion across the interface also favors salt removal.

There are, therefore, slow mechanisms of salt removal other than the relatively rapid one described in this study. Considering all factors, it seems certain

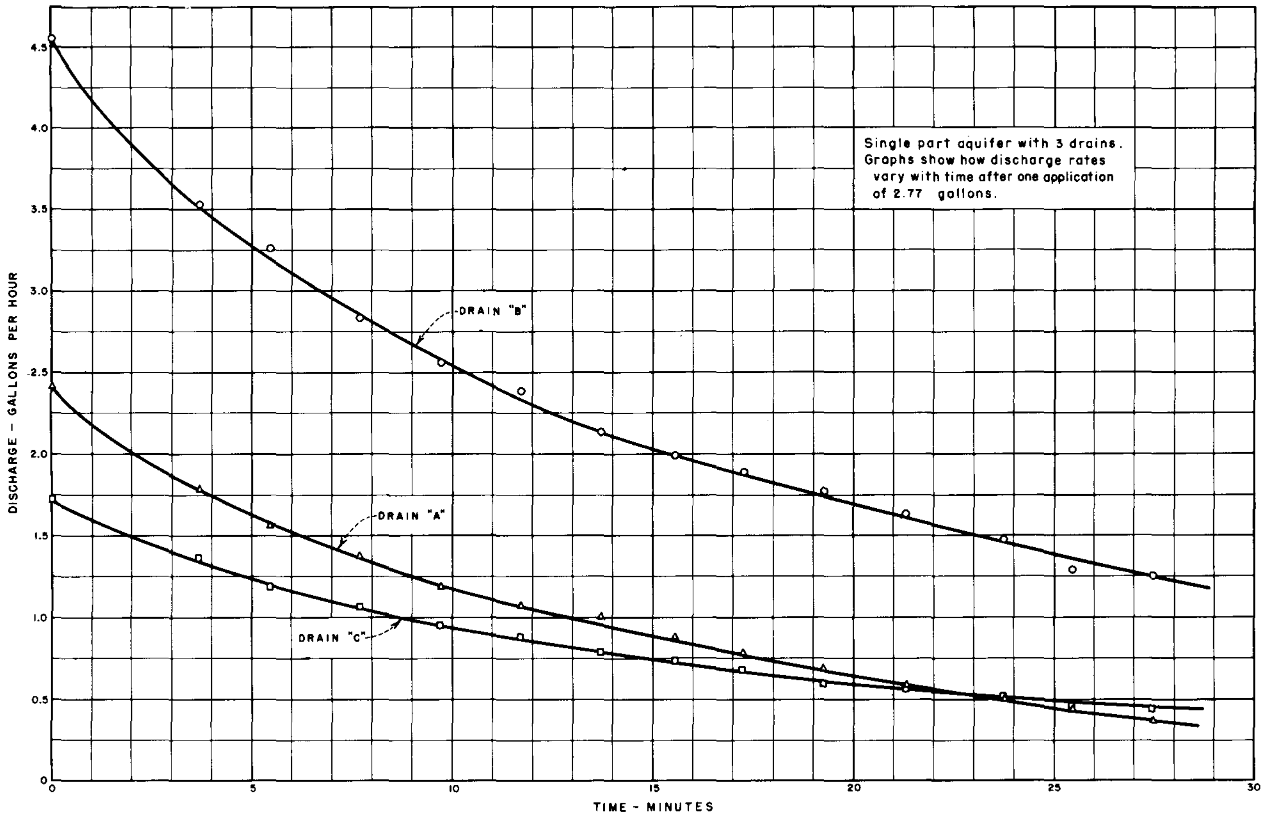


Figure 44.—Transient discharge rates from three drains in Test 8–1.

that all of the saline water will utimately be removed, but it is also reasonable to suppose that aquifer sweetening is complete for all practical purposes when the first phase, as shown in the model study and treated analytically herein, has come to an end.

Quality of the Effluent From Drains

As a basis for making an estimate of the quality of water issuing from the drains, R. E. Glover made the following analytical analysis.[5] He used the reasonable assumption that the rate of flow of saline water is proportional to the amount of removable saline water remaining in the aquifer. It is first necessary to determine the amount of saline water to be removed.

Formula 5 with $h_0=0$ can be written in the form

$$h=\sqrt{\frac{iL^2}{4(1+m)K}}\ \sqrt{1-\left(1-\frac{2x}{L}\right)^2} \qquad (7)$$

The saline water volume to be removed is

$$W=\int_0^L mh\ dx \qquad (8)$$

then

$$W=m\sqrt{\frac{iL^2}{4(1+m)K}}\ \int_0^L \sqrt{1-\left(1-\frac{2x}{L}\right)^2}\,dx$$

By introducing the change of variable

$$u=\left(1-\frac{2x}{L}\right) \qquad du=-\frac{2dx}{L}$$

The above expression takes the form:

$$W=\frac{mL^2}{4}\sqrt{\frac{i}{(1+m)K}}\ \int_{-1}^{+1}\sqrt{1-u^2}\ du$$

Since

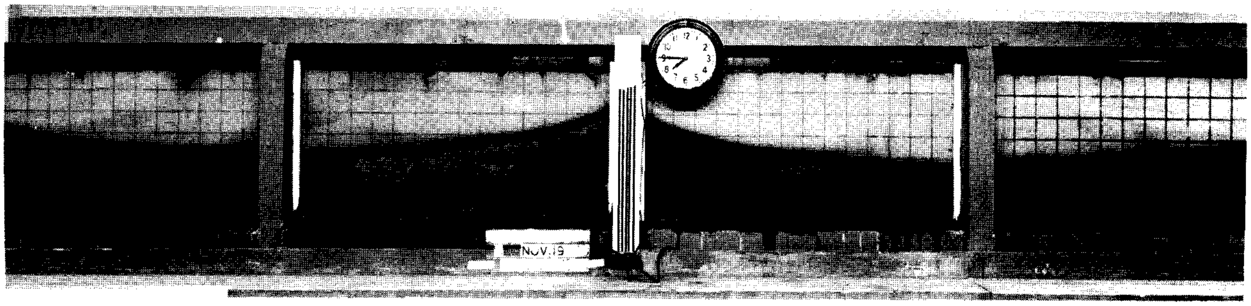
$$\int_{-1}^{+1}\sqrt{1-u^2}\ du=\tfrac{1}{2}\ \Big[u\sqrt{1-u^2}+\sin^{-1}u\Big]_{-1}^{+1}=\frac{\pi}{2}$$

then

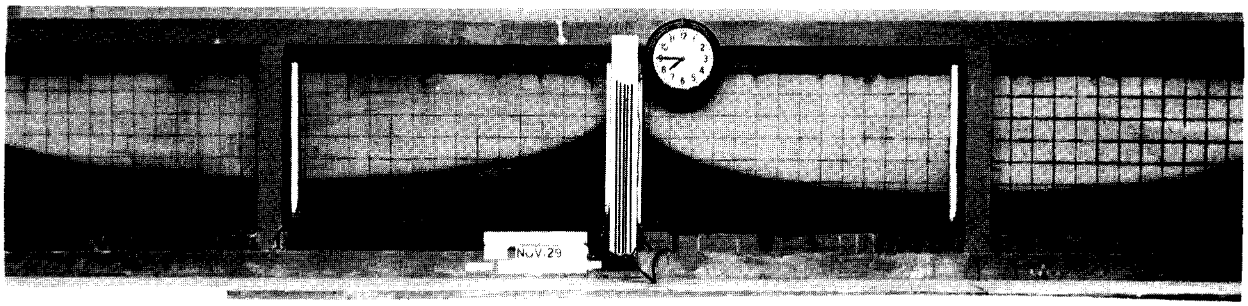
$$W=\frac{m\pi L^2}{8}\ ^2\sqrt{\frac{i}{(1+m)K}} \qquad (9)$$

The condition that salt removed from the aquifer must appear in the drainage water is:

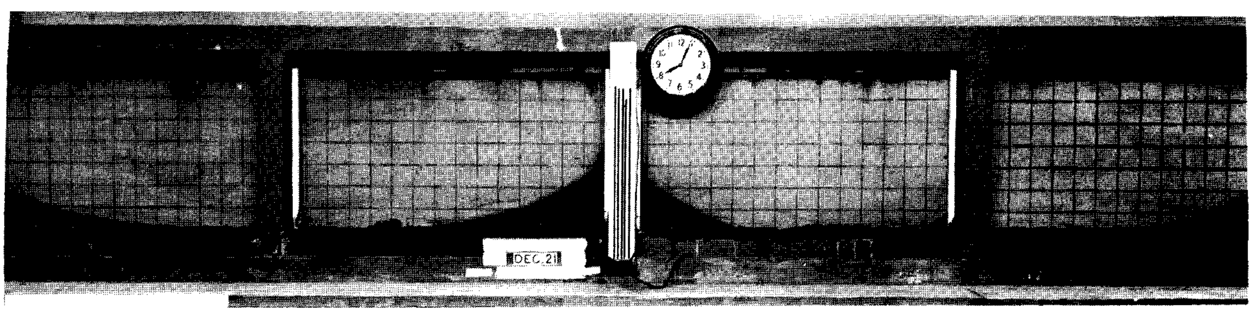
$$\frac{ds}{dt}+\frac{2qs}{VW}=0 \qquad (10)$$



A. The stable interface at the end of Test 8–1 had been achieved by the application of 2.77 gallons of fresh water every 2 hours.



B. The stable interface at the end of Test 8–2 is lower than in A, above. Fresh recharge water had been applied at the rate of 2.89 gallons every hour.



C. The stable interface at the end of Test 8–3 is lower than in A and B, above. Fresh recharge water had been applied at the rate of 2.77 gallons every half-hour.

Figure 45.—Stable interface positions at end of Tests 8–1, 8–2, and 8–3.

This is a differential equation whose solution is

$$s = s_0 e^{\frac{-2qt}{VW}} \tag{11}$$

where s_o represents the salinity s at the time $t=0$. The factor 2 appears in the expression because of the assumption that the drainage flow passes to two drains. This development applies, without modification, to a single-part aquifer in which the ultimate interface is continuous between the drains. In many field situations, there may remain only a wedge of saline water under the drains and W will then approach in value the entire volume of water in the aquifer.

A comparison of observed and computed effluent qualities is shown in figure 49. Data were taken from Test 7, in which a high salt concentration was used to get a continuous interface between drains.

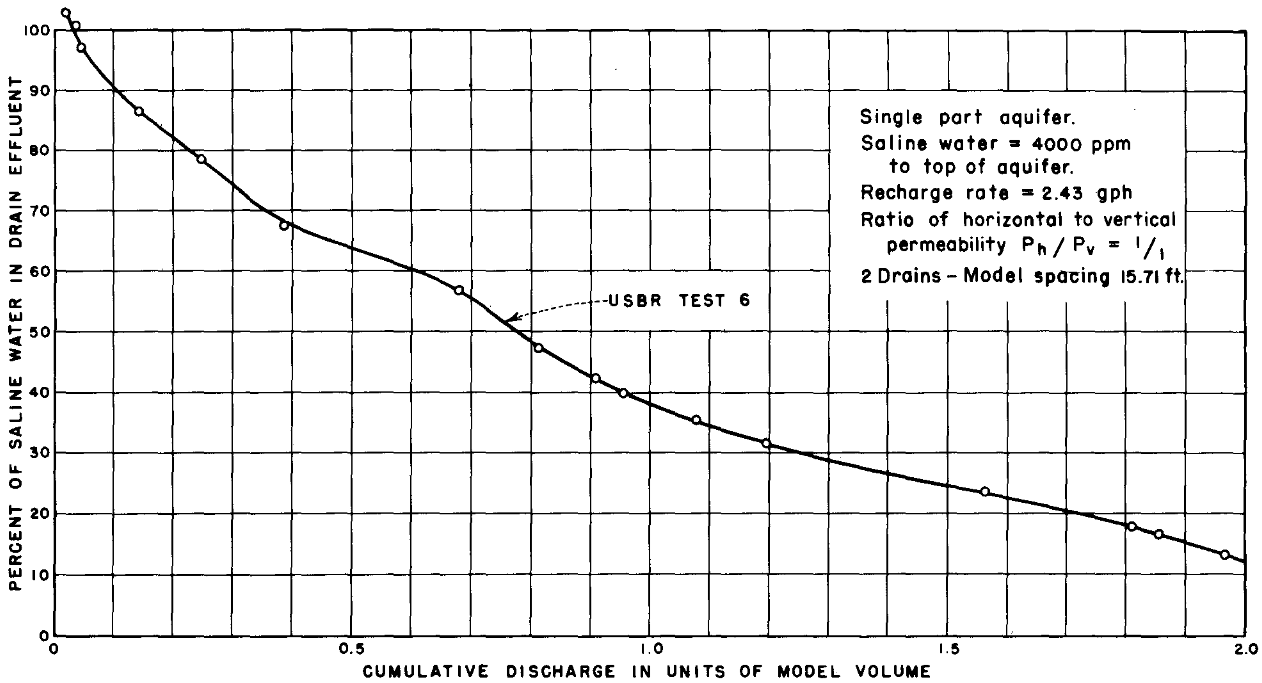


Figure 46.—Cumulative discharge and percent of saline water in drain effluent in Test 6.

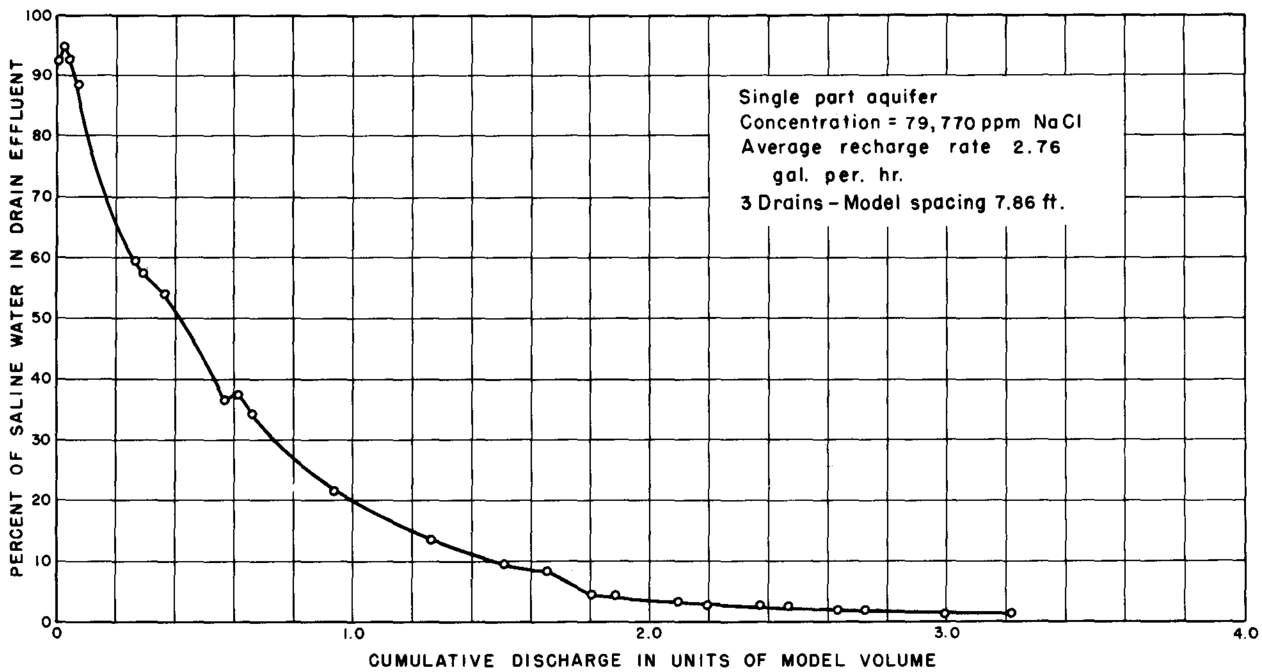


Figure 47.—Cumulative discharge and percent of saline water in drain effluent in Test 7.

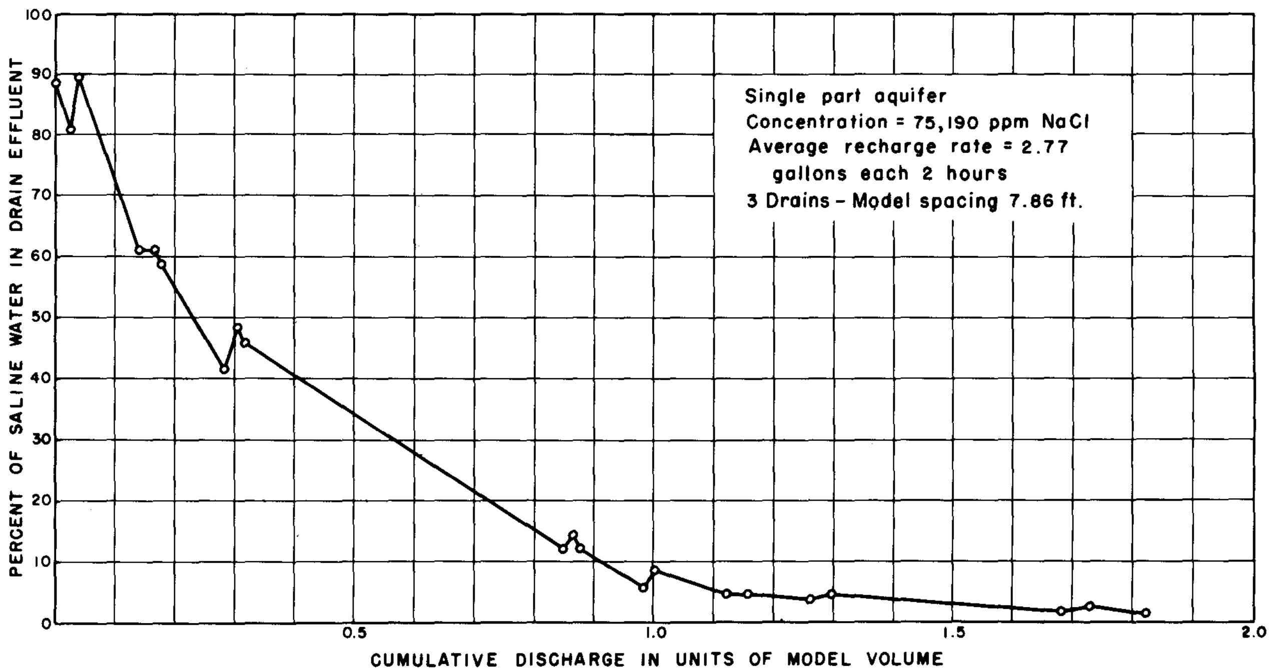


Figure 48.—Cumulative discharge and percent of saline water in drain effluent in Test 8–1.

Conclusions for Part II Single-Part Aquifers

Data from Tests 6 through 8 with single-part aquifers, described in this report, indicate that:

1. The stable interface at the end of a test, between the moving fresh water applied as irrigation water and the stagnant salt water, can be determined very closely by using a formula based on the Ghyben-Herzberg principle. This principle explains why ground water flowing to the sea coast, and fed by precipitation, is found to extend about 40 feet below sea level for each foot the ground-water table is above sea level.

2. Along the curved and sloping interface between the fresh and saline waters the greater hydrostatic pressure of the saline water is counterbalanced by the dynamic forces producing flow along the interface on the fresh water side. A similar balance exists in coastal areas where the seaward-moving ground waters come in contact with the saline ocean water. This balance is a very delicate one and is influenced by the ratio of the densities of the salt and fresh waters, and by the rates at which water is supplied to the area between drains. There is only slight deviation between the observed and computed interface in the vicinity of the drains.

3. The path of the flow of irrigation water to the tile drain is different for every point on the ground surface and is different for a uniform single-part aquifer than for the two-part aquifer. Close to the drain, the flow is vertically downward for only a short distance, then along a curved path to the drain. Farther from the drain, the flow penetrates deeper before turning toward the drain. Thus, the overall flow pattern can be described by a flow net which converges on the drain. The surface of the saline water body curves upward as it approaches the drain, and the saline water below the interface remains stagnant at a very small depth directly below the drain.

The following two conclusions are also true for a two-part aquifer and are included in the "Conclusions" for Part I.

4. The depth to which a stable interface forms below the ground surface between adjacent horizontal tile drains depends on the difference in density between the fresh and salt water and on the height to which the water table is maintained above the drains. The latter value depends on the rate of application of water and on the permeability of the aquifer.

5. After the interface has reached its semistable configurations, slowly acting mechanisms such as molecular diffusion and disturbances due to changing infiltration rates may continue the removal of salt water at a greatly reduced rate.

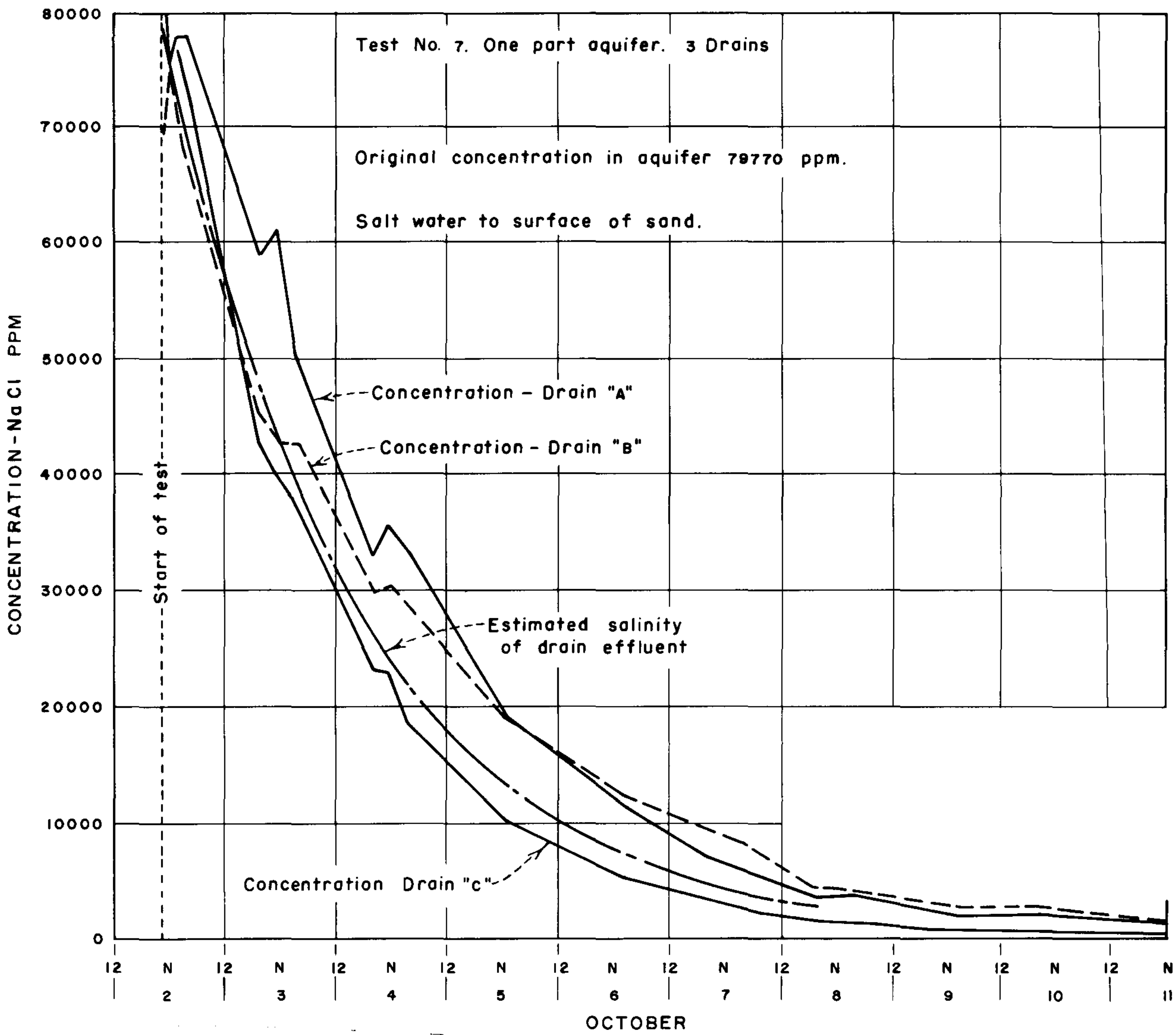


Figure 49.—Observed compared to computed effluent quality discharging from three tile drains in Test 7.

Notations

The notations used in this report are shown below. The appropriate physical dimensions are also indicated.

e	base of natural logarithms	(dimensionless)
h	head driving water to drain	(ft)
h_o	head at point $x=0$	(ft)
h_m	head at midpoint between drains	(ft)
h_f	height of water table above sea level	(ft)
h_s	depth below sea level to salt water-fresh water interface in a coastal aquifer	(ft)
i	infiltration rate	(ft/sec)
K	permeability	(ft/sec)
L	distance between adjacent drains	(ft)
m	$\frac{\rho_f}{\rho_s-\rho_f}$	(dimensionless)
P_h	horizontal permeability	(ft/sec)
P_v	vertical permeability	(ft/sec)
q	flow to a drain, per unit length of drain	(ft^2/sec)
s	salinity, parts per million	(ppm)
s_o	an initial salinity	(ppm)
t	time	(seconds)
u	a variable of integration	(dimensionless)
V	ratio of drainable void volume to the gross volume	(dimensionless)
W	porosity volume above the fresh water-saline water interface	(ft^3)
x	horizontal distance from drain	(ft)
ρ_f	density of replacement water expressed as a ratio to the density of distilled water	(slugs/ft^3)
ρ_s	density of saline water expressed as a ratio to the density of distilled water	(slugs/ft^3)

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Abstract

Aquifer sweetening was studied in the laboratory using a rectangular, glass-walled, sand-filled tank. Two types of aquifers were studied: (1) a 1:40 scale, two-part aquifer (coarse and fine sand) representing a vertical cross section through an idealized portion of an irrigated valley; and (2) a fine sand, single-part aquifer used to evaluate a formula derived from the Ghyben-Herzberg principle for computing depth to a saline-fresh water interface. Salt water was flushed from the aquifers into subsurface drains by applying fresh water to the surface. Test results for both aquifer types showed that tile drains placed near the ground surface will not intercept and discharge surface-applied fresh water if all or part of the aquifer contains salt water. The fresh water displaces the salt water without appreciable mixing and moves it into the drains. A stable fresh-salt water interface is thereby formed in the aquifer. Reducing the spacing of drains reduces the amount of salt water that will be removed from the aquifer. The aquifers were charged with salt water having sodium chloride concentrations of 4,000 to 79,770 ppm, which was colored blue for visual identification. Progress of the tests was recorded in still and timed sequence motion pictures.

DESCRIPTORS—*hydraulic models / model tests / drainage / water table / fresh water / permeability / saline water / fluid flow / tracers / hydrostatic pressures / dyes / flow nets / density / ground water / ground-water flow / tile drains / *aquifers / *subsurface drains.

IDENTIFIERS—two-part aquifers / single-part aquifers / saline ground water / flow rate / Ghyben-Herzberg principle / saline-nonsaline interfaces / drain spacing / salt removal / *aquifer sweetening / interfaces / infiltration rate.

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