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UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

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LABORATORY INVESTIGATION OF THE
REMOVAL OF SALT WATER FROM
TWO-PART AND SINGLE-PART
AQUIFERS USING TILE DRAINS

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Hydraulics Branch
DIVISION OF RESEARCH



OFFICE OF CHIEF ENGINEER
DENVER, COLORADO

May 5, 1965

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ABSTRACT

Tests were made to study the process of aquifer sweetening (removal of salt water from an aquifer and into drains by applying fresh irrigation water to the surface) in a glass walled testing tank 15.71 feet long, 2.5 feet deep, and 2.5 feet wide, using (1) a 2-part aquifer representing, to 1:40 scale, a vertical cross section through idealized portions of an irrigated valley; and (2) a single-part aquifer consisting of fine sand to evaluate a derived formula based on the Ghyben-Herzberg principle. The formula is used to compute the depth to a saline water-fresh water interface. Test results for a 2-part aquifer and also for a single-part aquifer showed that tile drains, placed near the ground surface will not intercept and discharge fresh irrigation water applied to the surface if all or part of the aquifer contains salt water. The fresh irrigation water replaces the salt water as the salt water moves into the drains and a stable fresh water-salt water interface is eventually formed in the aquifer. Reducing the spacing of drains reduces the amount of salt water that will be removed from the aquifer. Five tests were made using the 2-part aquifer and five tests using the single-part aquifer. The aquifers were charged with salt water having a concentration of 4,000 to 79,770 ppm, which was colored blue for visual identification. Progress of the tests was recorded in both still and timed sequence motion pictures.

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LABORATORY INVESTIGATION OF THE REMOVAL OF
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SUMMARY AND CONCLUSIONS

For the first series of tests a 1:40 scale model of an idealized portion 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, composed of coarse sand and having a permeability about 50 times as great as the fine sand 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 other tests, to the upper aquifer surface and the drain effluent was regularly sampled, analyzed, and used to determine the flow patterns in the model. 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). Five tests were made with the model containing a two-part aquifer. The two-part aquifer was then removed and replaced with a single-part aquifer made from the fine sand only.

Five single-part aquifer tests were made to check a formula developed to determine the position of the salt water-fresh water interface for an aquifer underlying irrigated lands and drained by horizontal tile drains. The formula was based on the Ghyben-Herzberg 1/, 2/, 3/, 4/, 5/ principle discovered during studies of aquifers supplied by rainfall near sea coasts.

1/Numbers refer to references listed at the end of the report.

The statements below are conclusions based on analyses of data from 10 tests made in the Bureau of Reclamation Hydraulics Laboratory. No previous tests of this kind are known and the conclusions must, therefore, be based upon the present test series.

1. A tile drain(s) placed 8 feet below the top surface of a two-member aquifer (top member fine sand 40 feet thick; lower member coarse material 50 times as permeable and 40 feet thick) will not intercept and discharge fresh water if the lower aquifer contains salt water. The drain discharge will have a maximum salt concentration about two-thirds or three-fourths of the salt concentration of the lower part of the 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 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, but it does not appear that a substantial amount of salt storage could be realized unless the drain spacing is made comparable to 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 feet to 315 feet have been investigated in the model.

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 non-irrigated areas, the time necessary to flush the aquifer used in the tests would be of the order of 25 to 35 years. The time scale is one 24-hour model day represents 3.0 prototype years.

6. In two-part aquifer tests the path followed, by 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, 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.

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

7. 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 1 foot the ground-water table is above sea level.

8. 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.

9. 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.

Conclusions 10 and 11 are true for both single-part and two-part aquifers tested in the model.

10. 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.

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

HISTORY

The Wellton-Mohawk area in Arizona is located in the valley of the Gila River near the junction of the Gila and Colorado Rivers. The irrigated lands in this area are located in the river valley which is, on the average, about 4 miles wide and extends for about 40 miles along the valley floor. These relationships are shown on the map of Figure 1.

The river valley occupies a trench eroded in part through lacustrine sediments of an earlier geologic era, and in part passes around and through the boundaries of crystalline rocks. The higher mesa lands which border the river valley along a part of its southern boundary represent the old lake deposits in which the present valley is incised. These beds are also present below the alluvial fill which now exists below the valley floor. The bottom member of this alluvial fill consists generally of coarse sands and gravels; the upper member is generally composed of fine sands and silts. The nature of these deposits is shown in Figure 2.

Beginning about 1915, irrigation of valley lands was started using water obtained from wells. By about 1934, the salinity of the well water had increased to detrimental levels, the water table had sunk alarmingly, and it was apparent that supplemental irrigation water from the Colorado River must be used if irrigation was to continue. By May 1, 1952, water diverted from the Colorado River at Imperial Dam was being delivered and used in the Wellton-Mohawk area. These facilities were constructed by the Bureau of Reclamation.

Continued application of the imported waters caused a rise of the water table, and by about 1959 it was apparent that drainage works would be necessary for control of the water table. To provide the required drainage a concrete-lined channel was constructed traversing the full length of the valley, and 69 wells with pumps were installed to lift the drainage water into the drainage channel. The channel has a maximum capacity of 300 cubic feet per second and discharges into the Colorado River. The effluent had a salt content of about 6,000 parts per million by weight (ppm) when pumping was started for the purpose of controlling the water table.

During the winter months the water delivered via the Colorado River to Mexico at the northern boundary may be as little as 900 cubic feet per second. At such times, the salinity of the delivered water may rise to about 2,700 ppm, making it undesirable for use as irrigation water. The people of Mexico have protested sufficiently against delivery of water having such a high salt content that the President of the United States and the President of Mexico agreed to appoint panels to study the possibilities for reducing the salinity of the waters being delivered to Mexico. The United States panel promptly prepared a report outlining certain measures which could be taken to reduce the salt content of the water being delivered. One suggestion was to install drainage tile or construct open drains at relatively shallow depths to intercept the water being drained from the land before it became salty. It seems to have been supposed that the drains would collect substantially all of their flow from percolations coming from the upper part of the aquifer and leave the lower saline waters in permanent ground-water storage. Investigations described in this report show that this assumption is not confirmed.

The difficulties described here will very likely occur in other places as irrigation develops and the need for drainage arises. Drainage water can be expected to have a salt content higher than the salt content of the irrigation supply. In many cases the only way to dispose of the saline drainage water will be to return it to the

river. Those who divert water lower down on the river must then contend with the difficulties arising from a higher salt content in their irrigation supply, which may, for example, force a more liberal use of water and the provision of more efficient drainage installations. The studies described in this report were initiated to provide information on the pattern of salt removal when drains are installed in a saline area.

PURPOSE OF TESTS

Previous studies of the behavior of fresh water-sea water interfaces in coastal areas, and construction of a classic flow net, indicated that the selective type of drainage operation proposed for the Gila Valley might not be realized. Because of this uncertainty, it was decided to design, build, and test in the laboratory, a model including the aquifer and a drainage system. As far as can be determined there are no previous investigations of this type and consequently there are 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.

THE MODEL

Model Construction

The model was constructed to a linear scale of 1:40 in a glass-walled tank. The primary purpose of the scale was to establish the depth of the model aquifer in terms of the Gila Valley 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. The tank containing the aquifer was 2.5 feet wide and deep and had transparent plastic walls on both long sides. Of the entire length, a portion of 15.71 feet long was isolated and used to represent half the distance between two lines of drains. To scale, this would represent a drain spacing of approximately 1,260 feet. To represent the two-part Wellton-Mohawk aquifer, two laboratory prepared sands were selected having, respectively, the permeability of the coarse sand in the lower member of the Gila Valley aquifer and the permeability of the sand and silt upper member of the Gila aquifer. The sands were selected also on the basis that the coarse sand was 50 times as permeable as the finer 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 3. 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 represented prototype depths of about 40 feet each in a total aquifer depth of 80 feet, and were believed to be an idealized interpretation of the average conditions existing in the Gila Valley, Figure 2.

In establishing these dimensions, it was considered more important to idealize the problem and establish flow and drainage principles, than to represent precisely the aquifer and flow condition at some selected spot in the Wellton-Mohawk area.

In an idealized model using homogeneous aquifers it can be assumed that there is no flow across vertical planes located midway between drains, or through the centerline of the drain line; therefore, at the midpoint between lines of drains an impermeable bulkhead (a plane of symmetry) can be introduced to reduce the model length at one end and a vertical bulkhead through the drain line could be used to terminate the model at the other end without affecting the flow patterns shown by the model. The 2-foot-diameter tile drain itself was represented by a perforated copper tube about 5/8 inch in diameter, wrapped with a single layer of fine brass screen to prevent clogging of the holes. A "T" section 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, the copper drain tube was placed closely against the bulkhead and a small quantity of the intermediate size sand (larger particles than the aquifer sand) was placed around the pipe and against the bulkhead to effectively locate 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, Figure 3. 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 of the pressures on the bottom of the tank. Directly above each of the piezometer taps an observation well was installed consisting of a short, open-end glass tube extending down into the upper aquifer, Figure 3. The position of the water table during a test could be read by a point gage mounted on a traveling carriage and lowered into the tube from above.

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 sand. A valved pipe-distribution-system was also installed along the centerline of the bottom of the flume to introduce salt water into the tank at approximately the one-third points of the model.

Model Operation

Tests 1 through 5 were made using the two-part aquifer described as an idealized representation of the Gila Valley. Tests 6 through 8-3 were made using a single-part aquifer made from the fine sand used in the upper member of the two-part aquifer tests.

In order to verify the behavior of the saline water originally present in the lower member after initiation of drainage, the saline water was introduced only into the lower member for the early tests. To facilitate visual observations of the salt water movements in the lower aquifer the salt water was dyed blue. Sodium chloride (NaCl) was the salt added to provide the proper density; 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. 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 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
Test 8-1	Approximately 250 ppm patent blue dye
8-2	Approximately 75,200 ppm sodium chloride
8-3	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 tapwater) was then added to the surface of the upper aquifer and allowed to permeate the upper sand. The lower salt waterflow 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 4 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 tapwater 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.

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 on 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 an automatically timed toilet flush tank which discharged 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 application arrangement water was applied at three rates: 3 gallons each 2-hour interval, Test 8-1; 3 gallons each 1-hour interval, Test 8-2; and 3 gallons each 1/2-hour interval, Test 8-3.

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 to insure that no free water was ever present in this zone.

Measurements were systematically made 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 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 another drain assembly was placed at the other bulk-head to represent a field problem with 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 5. After a few hours 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 the flushing out of the lower aquifer with fresh water, Figure 6. 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 of this wedge was concave upwards. Two more days of operation failed to dissipate the wedge.

Figure 7 is a record of Test 1 operations and results plotted against the days of the month (which indicate the duration of the testing). The water application curve (which is also the water discharge curve) indicates that water was added during the regular working hours on the 19th, 20th, and 21st of March 1963; 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 8 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 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 8, was a reality and was 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 1/8 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 9 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 needle-valve-control clogging, line pressure variation, etc. 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 these two curves indicates that there is, in general, an increase in salt concentration when there is an increase in fresh water discharge, and that the effect is apparent almost immediately.

Salt concentration in the drain effluent 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 10, 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 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 were placed against the glass wall of the tank by inserting a glass tube through the sand until the bottom was at the desired elevation, dropping the crystals down the tube and pushing them out 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 inspected and traced at regular intervals, indicated flow direction and velocity. Crystals introduced within the boundary of the blue wedge below the drain indicated that the flow direction was toward the drain. Elsewhere, the dye streaks indicated the flow direction to be downward through the upper sand to 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. Figure 11 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

Although the linear scale of the model is 1:40 the time scale is not the same nor is it based on a Froudian or other model relationship. Correlation of model and prototype times must be made on the basis of comparative 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 would replace the original water content in a period of $32/3 = 10\text{-}2/3$ or, say, 11 years. The model is approximately 16 feet long, 2.5 feet wide, and 2 feet deep, making

the volume $(16)(2.5)(2) = 80$ cubic feet. With a total porosity of 40 percent the water content would be $(80)(0.4) = 32$ cubic feet. An inflow of 3 gallons per hour for an 8-hour period would supply $\frac{(3)(8)}{3} = 3$

cubic feet using the approximation that there are 8 gallons in a cubic foot (actually 7.4805 gallons per cubic foot). On this basis, the time required to replace the original water content in the model would be $32/3 = 10\text{-}2/3 = 11$ (approximately) periods of 8 hours each. A comparison of these values will indicate that about 8 hours of model time represents a year of prototype time. It should be noted, however, that this comparison is for a completely irrigated area. Since the entire Wellton-Mohawk Valley is not irrigated, the water replacement process in the Gila area may be expected to take somewhat longer than indicated by the above calculations. It may be reasonable to increase the time by 50 percent (or more) to obtain a realistic prototype time estimate. Thus the 8 days of testing indicated in each of Tests 1 and 2 would probably represent 25 to 35 years of prototype time. However, in the model, the salt was substantially removed in 4 days which could represent perhaps as short a time as 12 years in the prototype.

Results of Test 3

For Test 3 a drain was installed at the bulkheads at each 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 introduced into the lower aquifer was 1 foot.

After the fresh water flow 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 12 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 13 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 14 shows the blue salt water

starting to approach the center drain after only 1 hour and 5 minutes of the test. Figure 15 shows the blue wedges at the drains and a well developed flow pattern 50 minutes later. Figure 16 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 17. 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 also operated 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, applied 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.

As expected, immediately after the start of Test 4 (on May 10), a salt concentration of 7,050 ppm appeared in the drain effluent. As the test progressed it was evident that operation was erratic since the right-hand end of the model (as shown in photographs taken) was cleared of blue salt water long before the left side was cleared. The reason for this, determined after the conclusion of the test, was that inadvertently, (1) the hose was delivering more than half of the water to the right side of the model, and (2) the drains were at slightly different elevations. Figure 18 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, 1963. By May 20, 1963, a well established pattern for Drain A was apparent, and the C drain pattern was no longer visible. By May 28, 1963, 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 19. Testing was then discontinued. The dark lines approaching the drains are, again, lines of least flow and are the last to be flushed clear. Figure 20 shows the salt concentration in the effluent from the three drains plotted against model time. 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 (see Test 4) was plugged for Test 5 leaving the two end drains operative. 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 waterflow rate was maintained at 3.32 gph. Test 5 was started at 8:30 a.m., June 11, 1963. Irrigation water was added to the surface, and the blue salt water began discharging from Drains A and C with a concentration of 6,728 and 6,845 ppm, respectively. Average discharge throughout the test measured from the two drains was 1.87 gph for Drain A and 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 giving a slightly higher distribution of water 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 formation of the stable interface. Figure 21 is 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 concentration in Drain A reduced to 1/10 of the original concentration at 8:30 a.m. on June 14, 1963, after three model days of operation. Discharge from Drain C reduced to 1/10 the original concentration after five model days of operation at 8:30 a.m. on June 16, 1963. This time interval represented, respectively, 13.5 and 22.5 prototype years. Photographs in Figure 22 show the model on June 14 and June 16. Figure 23 shows the position of the interface on July 1, 1963, just before the test was stopped, 20 days and 2 hours (approximately 90 prototype years) after the beginning of the test. The concentration of the effluents just before the test was stopped were 56 ppm and 136 ppm for Drains A and C, respectively, as shown in Figure 21.

TESTS WITH SINGLE-PART UNIFORM AQUIFERS

Results of Test 6

At the conclusion of Test 5, the two-part aquifer was removed and the tank was refilled to a depth of 2 feet to obtain a single-part aquifer consisting of fine sand, the same type of sand previously used in the upper part of the 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 been covered with fine brass screen and a medium sand was placed to a depth of about 1 inch over each pipe inlet to form a reverse filter between the pipe inlets and the fine sand aquifer. Two horizontal drains 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. On August 5, 1963, salt water dyed blue and having a concentration of approximately 4,000 ppm was introduced into the model. Because the results of previous tests had showed that the changes in concentration of sodium chloride in the effluent paralleled very closely the changes in the concentration of the potassium chloride tracer, no potassium chloride tracer was used for Tests 6, 7, and 8.

Specific gravity of the dyed salt water was 1.0034 at 70.5° F and for Denver tapwater 1.0002 at 69° F, measured with precision hydrometers 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 far from the inlet pipes because of the greater resistance to the inflow. To allow the salt water to rise uniformly across the entire fine sand aquifer would take a very long time; therefore, 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 above 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, 1963, 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 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 24 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 (4,000 ppm) to approximately 400 ppm (one-tenth of the original concentration) in 7-1/2 days. Drain C had one-tenth of the original concentration after operating 8-1/2 days, Figure 24.

Ten wells instead of five were used to measure the elevation of the ground-water table in the model to give a closer spacing of points and a better graph of the curved water table as measured with a movable point gage. The positions of the installed wells were as follows:

<u>Well No.</u>	<u>Distance in feet measured from left end of model</u>
1	0.87
2	1.50
3	3.00
4	5.00
5	7.50
6	8.20
7	10.50
8	13.00
9	14.00
10	15.20

Figure 25 shows the interface on August 20 and 21, 1963, when the effluent reached a concentration of one-tenth the original salt concentration in Drains A and C, respectively.

Timed sequence photographs were again taken with a 16-mm motion picture camera. Single frames were exposed at 6-minute intervals and a motion picture of the entire operation of Test 6 (13 days) can be projected normally and viewed on a screen in a period of approximately 5 minutes.

At the conclusion of Test 6 the interface had moved downward so far that it 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 26.

Ghyben-Herzberg Relationship

More than 60 years ago, W. Baydon Ghyben^{1/} and A. Herzberg^{2/} working independently along the European coast, discovered that salt water occurred underground, not at sea level but rather at a depth below sea level of about 40 times the height of the 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 3/, 4/, 5/ have disclosed the reason for this relationship. The equation derived to explain the phenomenon is referred to as the Ghyben-Herzberg relation shown below:

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

where

h_s is the depth to salt water below the sea level (depth to fresh water-saline water interface)
 h_f is 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 $\rho_s = 1.025 \text{ gm/cm}^3$ and $\rho_f = 1.00 \text{ g/cm}^3$ then $h_s = 40 h_f$.

When the Ghyben-Herzberg relationship is applied to the case of drainage by tile drains, saline aquifer water replaces the sea water, irrigation 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. The saline water below the interface is stagnant and the fresh water above the interface moves toward the drain.

Two relationships can be as follows: (1) which expresses the flow of water toward a horizontal agricultural drain in terms of infiltration rate of irrigation water, and (2) which expresses the flow toward a drain in terms of the permeability of the aquifer and the gradient of the water table.

Equating these two relationships and integrating the results gives the following formula with which the depth of the interface below the drain can be computed:

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

in which

h is height of water table above the drain
i is the infiltration rate of irrigation water
L is the distance between drains

m is the ratio
$$\frac{\rho_f}{\rho_s - \rho_f}$$

K is the permeability of the aquifer
X is the distance from one drain toward another drain at the section where h is measured

The development of the above formula by R. E. Glover is given in a memorandum to the Chief Research Scientist and Chief Development Engineer, dated November 26, 1963, a copy of which is included in the appendix to this report. The formula 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 salt water remaining under each drain at the end of Test 6, Figure 26, verify the computation to the extent that the interface did occur far below the bottom of the model floor.

Tests 7 and 8 were then conducted to check the formula 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 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, 1963; and on September 27, 1963, 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 10:00 a.m. on October 2, 1963. 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 in the sand aquifer. As more fresh water became mixed with the highly concentrated salt water, the solution became darker and more blue in color. When this color washed out of the model, the sand cleared to its natural white color. The photograph in Figure 27A 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 27B 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 is compared with the actual interface position in Figure 28 as the interface appeared on October 8, 1963, after 5.9 days of model operation, Figure 29, and on October 15, 1963, after 12.9 days of model operation, Figure 32. The slight displacement of the interface in 7 days of model operation in the interval between the times of 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 30 shows the rate of discharge from the three drains measured at intervals throughout Test 7. Figure 31 shows the rate of change of salinity of effluent from Drains A, B, and C.

The time required for the effluent to be reduced to one-tenth the original concentration was 5-1/4 days for Drain A, 4-3/4 days for Drain B, and 3-1/4 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.

Figure 30 shows that there was some variations in discharge from the drains which was caused by variation in flow from the garden soaker. 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 32 shows the position of the interface on October 15, 1963, 3-1/2 hours before the application of irrigation water was stopped. Following this, no further movement of the interface could be detected except that the curved interface started to flatten as the heavy salt water began to form a level surface. Figure 33 shows the interface on October 18, 1963, 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 rates of water application) for the purpose of checking the formula for predicting the position of the interface between salt and fresh water at equilibrium conditions when the time interval between additions of a given amount of water was varied. The single-part aquifer of fine sand was used.

Salt water, dyed blue 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, 1963, and November 4, 1963, in the filling operation. The average specific gravity of the salt water, measured with a hydrometer, was 1.0550 at 60° F compared to 1.0002 at 60° F for tapwater.

To overcome the difficulties encountered in obtaining uniform discharges from the garden soaker, a flush tank was arranged to supply given quantities of water at any desired time interval. The interval between applications of replacement water is very short compared to the time required for the interface to level out when flow is stopped, Figure 33; therefore, the intermittent applications of replacement water are equivalent to steady flow. The system consisted of a tank and flushing mechanism, an assembly of plastic pipe and 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.

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 so that they could not become clogged with foreign particles. The flush tank and distribution system had previously been calibrated to discharge equal quantities of water to all areas. The time interval between applications could be varied to give different application rates. Figure 34 is a photograph of the automatic distributing system.

The interface between the saline water and fresh water formed soon after water was first applied to the surface, Test 8-1, at 8:30 a.m., November 6, 1963. Figure 35 shows the position of the interface on November 8, 1963, on November 12, 1963, on November 14, 1963, and on November 19, 1963.

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 36. 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 to reach a concentration of one-tenth the original concentration in the aquifer does not vary appreciably whether a two-part aquifer 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 liquids. The time to evacuate the required volume of saline water to form a stable interface is influenced by the depth that the stable interface reaches stability, forms below the level of the drains, and the rate of application of fresh water.

Figure 37 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 37, 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 the variation is so slow 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. Pressure variations in the field, at the depth that an interface would form would be even much slower for transient water applications. (The 79,770 ppm salt solution does not exist in the field, the 6,000 ppm in the field

aquifer would give an interface at a greater depth.) However, the position of the interface is very sensitive to the water table height and consequently to the long-time average irrigation application rate.

Variation in the water table elevation with time, between applications of irrigation water, was measured in the model, and a sample of the changing water table surface is shown in Figure 38. This relationship was developed from data obtained in Test 8-1 by making water table measurements at five points between adjacent drains on the ends of the model and at measured time intervals after an application of water was made through the flush tank and stainless steel trough equipment. Figure 39 shows the variation of water table surface at each observation well plotted against time. Figure 40 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 39 and 40 were used to develop Figure 38.

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. For Test 8-2, the intermittent irrigation application rate was roughly doubled by increasing the rate to 2.89 gallons per hour. For Test 8-3, the rate was again roughly doubled by applying 2.77 gallons of fresh water to the model each 1/2 hour. Figure 41 shows the position of the interfaces that formed at the end of Tests 8-1, 8-2, and 8-3. The interface position was successively lower as the average rate of inflow and head of irrigation water increased in steps.

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 11, shows the model time required for each test to reduce the salinity of the drain effluent to one-tenth that originally placed in the aquifer.

This is based on a rigid water application schedule as described in each test and assumes that water is applied over the entire surface and may not represent the prototype conditions in areas where irrigation does not include the area above the entire aquifer.

The salt concentration in the drain effluent at the time one full water replacement volume and fractions of replacement volumes had been added and drained from an aquifer would be significant information in understanding the process of flushing of saline aquifer water by adding fresh irrigation water. A method of evaluating the

dilution of saline water achieved by recharge would be to compute the percentage of saline water in the drain effluent and to plot the percentage of saline water versus the cumulative quantity of water discharged in relation to the total water stored in the aquifer. Figures 42 through 49 show these plots for Tests 1 through 8-1. When the cumulative discharge of the drain effluent equals one on the abscissa, the recharge added is equal in volume to the total water volume originally stored in the aquifer. The concentration of the effluent indicates the extent that salt water was forced ahead of the fresh water and the amount of the latter that moves 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. There are differences in cumulative discharge from test to test, depending on whether the test included a two-part aquifer (Tests 1 through 5), a single-part aquifer (Tests 6, 7, and 8), whether the saline water was placed to the top of the upper aquifer (Tests 4 to 8) or to the top of the lower aquifer at the beginning of the test (Tests 1, 2, and 3), what the concentration of salt solution in the aquifer was at the beginning of the test, the number of drains operating, and 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 $\frac{P_u}{P_l}$ was $\frac{1}{50}$. Figures 42 and 43 show the relationships

resulting from Tests 1 and 2 in which the lower aquifer was charged with saline water with concentrations of 6,530 and 6,490 ppm, respectively. These, in effect, give the same general curves although they are different in detail. The percent of salt water in the drain effluent reached a maximum for both Tests 1 and 2 of slightly above 70 percent when 0.2 of a model porosity volume had discharged from the drain. When 1.0 model porosity volume of accumulated discharge had discharged from the drain, the effluent contained only about 10 percent of the original aquifer saline water in both tests. The comparison is very good even though the water was applied to the model in two different ways, (1) by intermittent application of irrigation water using a 3-gallon sprinkler can giving an average rate which varied from 2.10 to 3.54 gallons per hour (gph) in Test 1, Figure 42, and (2) the irrigation recharge was applied continuously at an average rate of 2.93 gph using a garden soaker hose, Test 2. In this test the peak concentration of 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 42 and 43, 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 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 gph and 13.35 gph; 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 44 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, and after 1.0 model porosity volume of accumulative discharge had flowed through the model, the concentration of salt in the effluents was only about 3.0 percent.

The rate of removal of salt water from the two-part aquifer model in Tests 4 and 5 are shown in Figures 45 and 46. The initial conditions for these 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 percent 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, there was 65 percent salt water in the effluent and in Test 4 only 38 percent. The differences between the curves plotted for Test 4 and Test 5, Figures 45 and 46, are attributable to the different drain spacing in the two tests.

Test 6 was conducted using a single-part aquifer made from the same material as the upper aquifer for Tests 1 through 5. Salt water with 4,000 ppm concentration was used to completely fill the aquifer. The average discharge for this test through two drains was 2.43 gph. At the beginning of the test the drain effluents contained approximately 100 percent salt water and at the time 1.0 model porosity volume had discharged through the drains, the effluent contained approximately 40 percent of saline water. Figure 47 shows for Test 6 the relationship between percent of saline water in drain effluent and cumulative discharge from drains in terms of total amount of saline water placed in the model (model porosity volume).

Results of Tests 7 and 8-1 are shown on Figures 48 and 49. These two tests were conducted in the same single-part fine sand aquifer, filled with 79,770 and 75,190 ppm salt water, respectively, so that the salt water was to the top of the aquifer at the beginning of both tests. 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 drain effluents 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 48, 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 49, 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 recharge rates used in the tests.

Plots relating the percent of salt water in the drain effluent with accumulative discharges from the drains were not 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.

REFERENCES

1. Badon Ghyben, W., Nota in verband met de voorgenomen put boring nabij Amsterdam (notes on the probable results of the proposed well drilling near Amsterdam) Koninkl Inst Ing Tijdschr, 1888-89, The Hague, pp 8-22, 1889.
2. Herzberg, Alexander, Die Wasserversorgung einiger Nordseebäder (the water supply on parts of the north sea coast) J. Gasbeleucht U. Wasserversorg, Jahrg 44, Munich, 1901.
3. Glover, R. E., "The Pattern of Fresh-Water Flow on a Coastal Aquifer," Journal of Geophysical Research, Volume 64, pp 457-459, April 1959.
4. Cooper, H. H., Jr., "A Hypothesis Concerning the Dynamic Balance of Fresh Water and Salt Water in a Coastal Aquifer," Journal of Geophysical Research, Volume 64, pp 461-467, April 1959.
5. Todd, David K., "Ground Water Hydrology," John Wiley and Sons, Inc., 1959, Third printing, August 1963.

Table 1

DRAINING SALINE WATER FROM TWO-PART AND
SINGLE-PART AQUIFERS WITH AGRICULTURAL TILE DRAINS
DATA FROM ALL TESTS
GILA VALLEY GROUND WATER MODEL

Test No.	Start test	Finish test	Drains operating	Average discharge from drains, gph	Single or two-part aquifer	Avg salt concn- tration at start of test, ppm	Top of salt solution at start of test	Model and prototype drain spacing, feet	Model dist. of inter-face below ground at equilibrium, feet	Model days to reduce effluent conc. to 1/10 of original aquifer saline conc., days
1	3-18-63 10:23 a.m.	3-26-63 3:30 p.m.	C	transient 3 p/h	two-part	6,530	Top of lower aquifer	31.42 1,260	Below bottom of model	3.5
2	4-13-63 9:26 a.m.	4-16-63 8:00 a.m.	C	steady 2.93	two-part	6,490	Top of lower aquifer	31.42 1,260	Below bottom of model	3.5
3	4-19-63 1:55 p.m.	4-24-63 10:00 a.m.	A B C	steady 3.42 6.74 2.87 Total 13.03	two-part	6,200	Top of lower aquifer	7.86 315	1.5 lt side 1.5 rt side	0.5 0.4 0.6
4	4-10-63 8:50 a.m.	4-27-63 8:30 a.m.	A B C	steady 0.82 1.75 0.62 Total 3.19	two-part	7,050	Top of upper aquifer	7.86 315	1.35 lt side 1.5 rt side	8.8 3.0 1.8
5	6-11-63 8:30 a.m.	7-1-63 12:30 p.m.	A C	steady 1.87 1.45 Total 3.32	two-part	6,830	Top of upper aquifer	15.71 630	1.7	3 5
6	8-12-63 10:05 a.m.	8-26-63 1:20 p.m.	A C	steady 1.29 1.14 Total 2.43	single	4,000	Top of aquifer	15.71 630	Below bottom of model (80.0 ft by computation)	7.5 8.6
7	10-2-63 10:00 a.m.	10-15-63 11:30 a.m.	A B C	steady 0.53 1.67 0.56 Total 2.76	single	79,770	Top of aquifer	7.86 315	1.4 lt side 1.45 rt side	5.2 4.8 5.3
8-1	11-6-63 8:30 a.m.	11-19-63 9:30 a.m.	A B C	transient 2.77 each 2 hours	single	75,190	Top of aquifer	7.86 315	1.08 rt side 1.00 lt side	5.8 7.0 5.3
8-2	11-19-63 9:30 a.m.	12-2-63 10:30 a.m.	A B C	transient 2.89 each 1 hour	single	75,190	Continued from test 8-1	7.86 315	1.42 rt side 1.25 lt side	
8-3	12-2-63 10:30 a.m.	12-23-63 8:35 a.m.	A B C	transient 2.77 each 1/2 hour	single	75,190	Continued from test 8-2	7.86 315	Below bottom of model	

Figure 1
Report Hyd-541

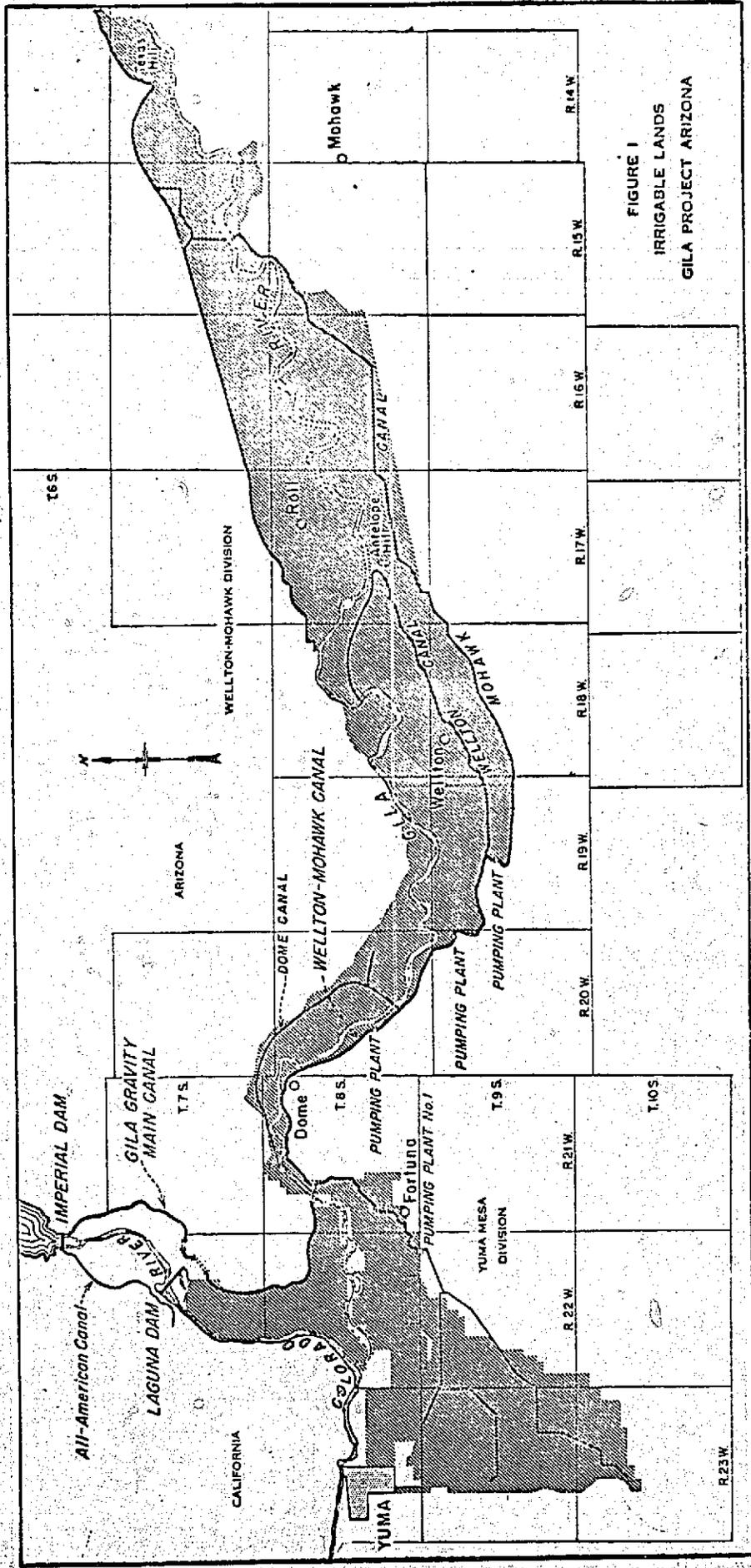
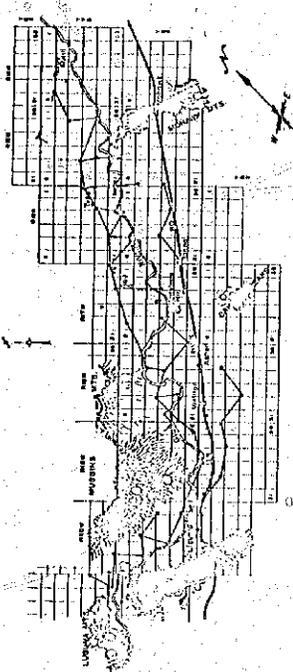
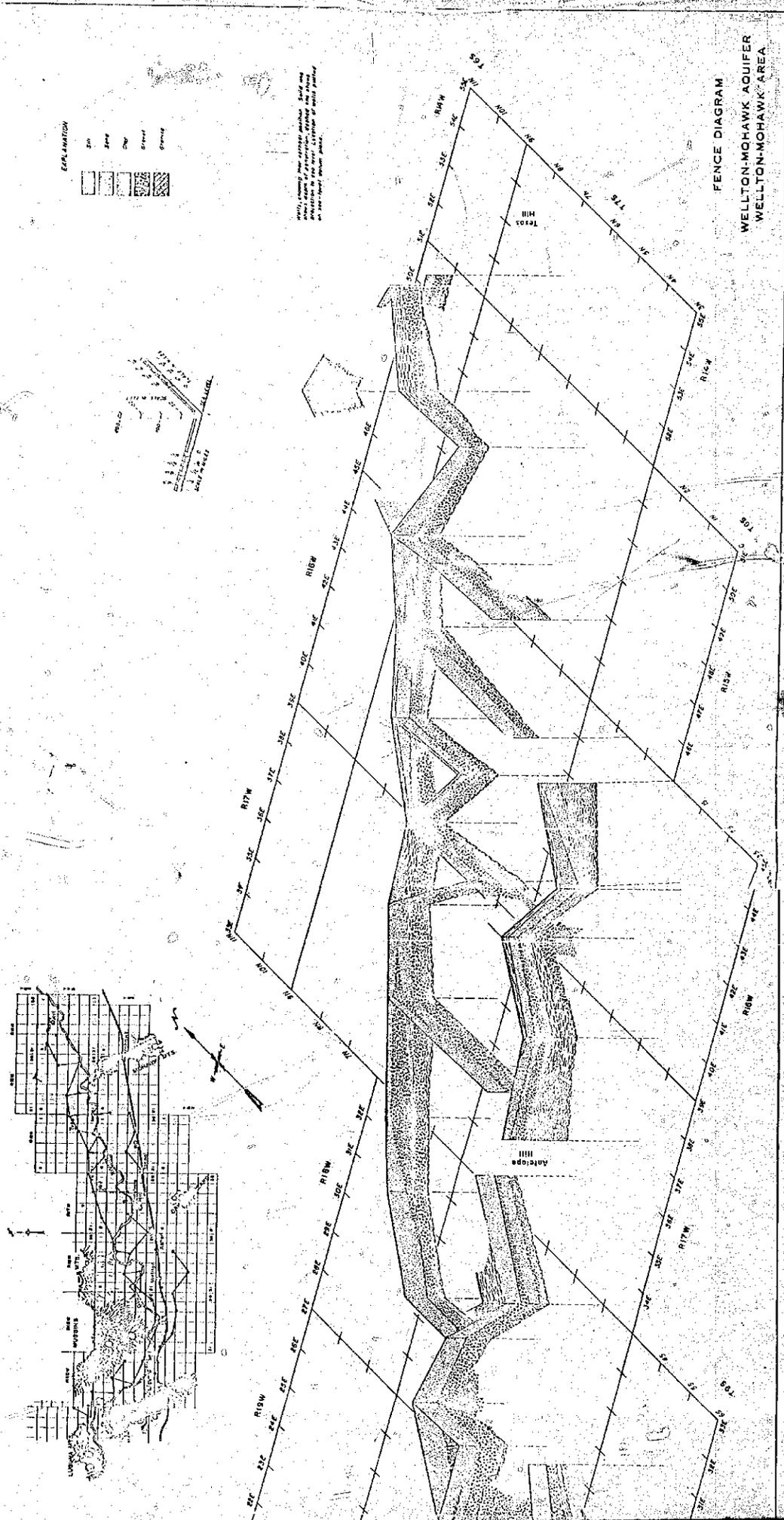
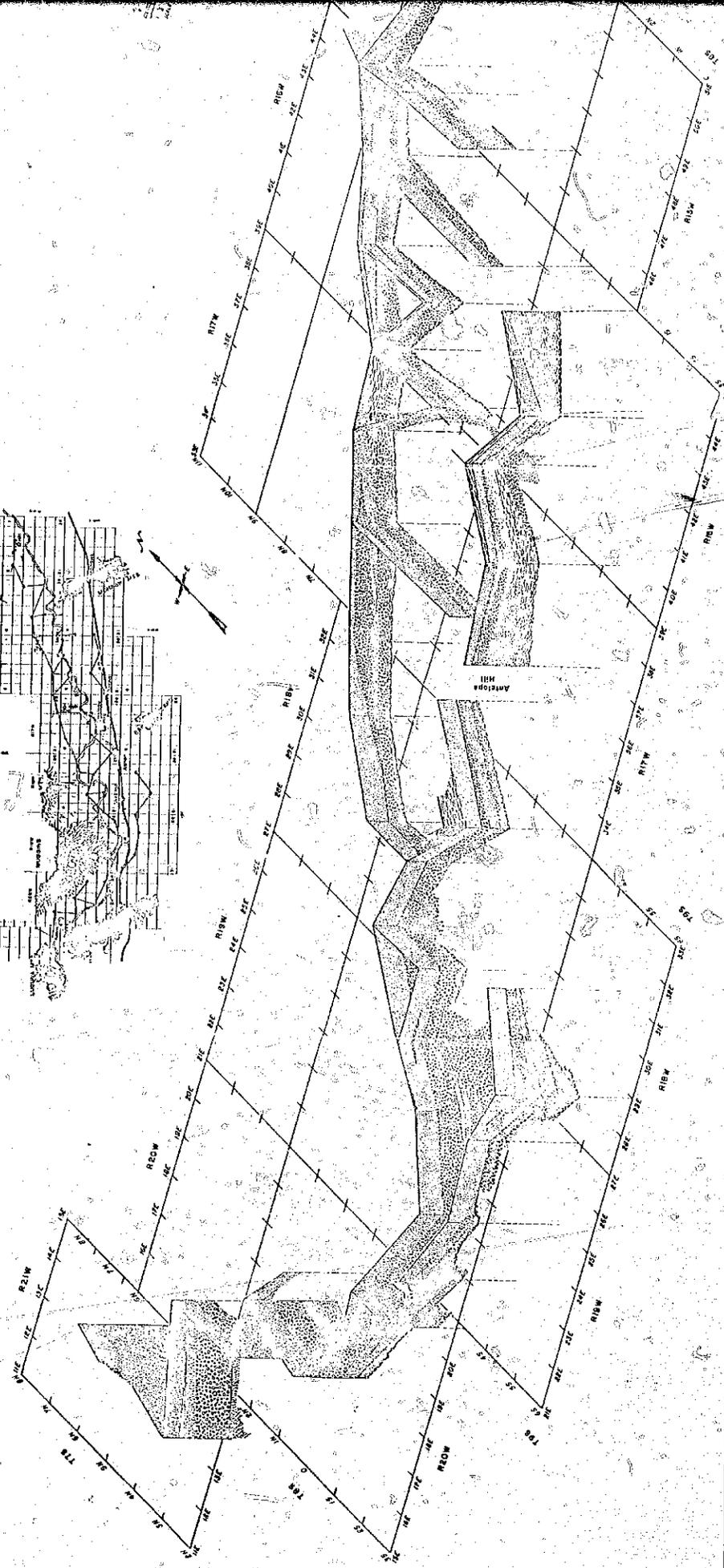
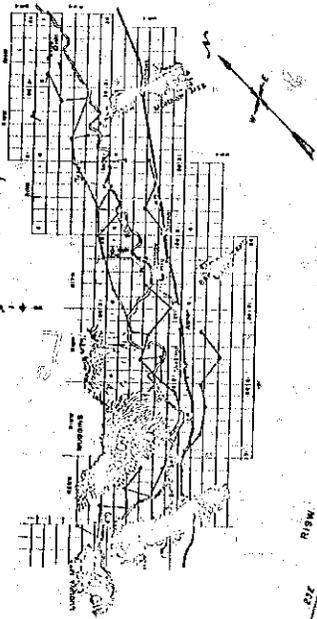


Figure 2
Report Hyd-541





FRAME 2

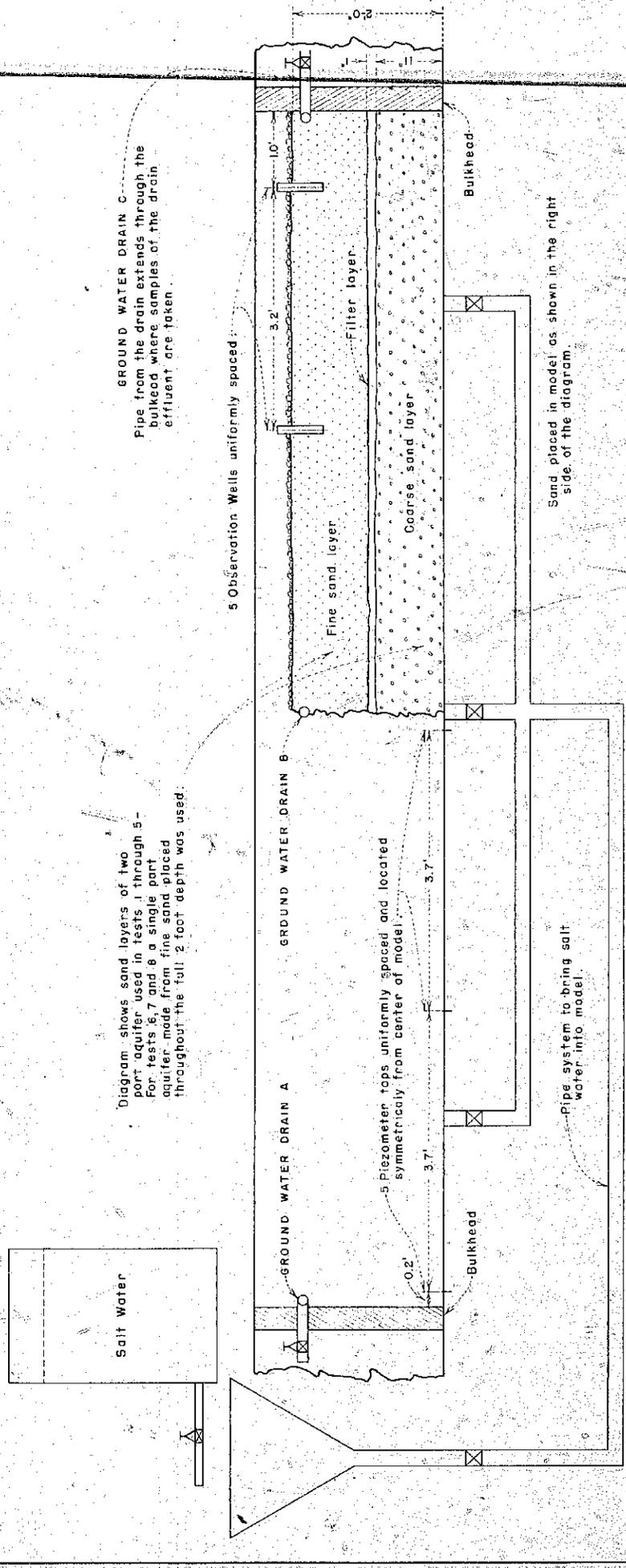


Diagram shows sand layers of two part aquifer used in tests 1 through 5 - For tests 6, 7 and 8 a single part aquifer made from fine sand placed throughout the full 2 foot depth was used.

GROUND WATER DRAIN C
 Pipe from the drain extends through the bulkhead where samples of the drain effluent are taken.

5 Observation Wells uniformly spaced

Fine sand layer

Filter layer

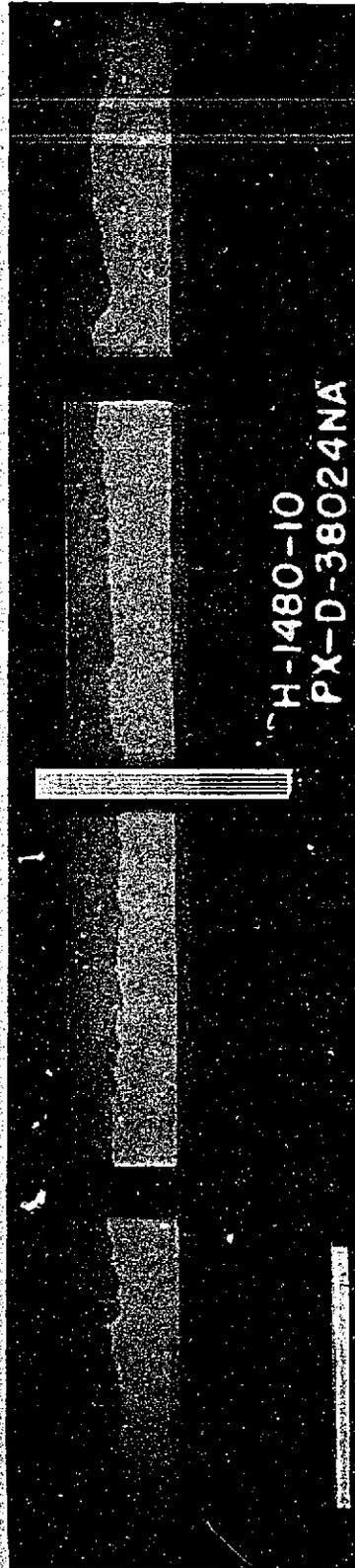
Coarse sand layer

Bulkhead

Sand placed in model as shown in the right side of the diagram.

Pipe system to bring salt water into model.

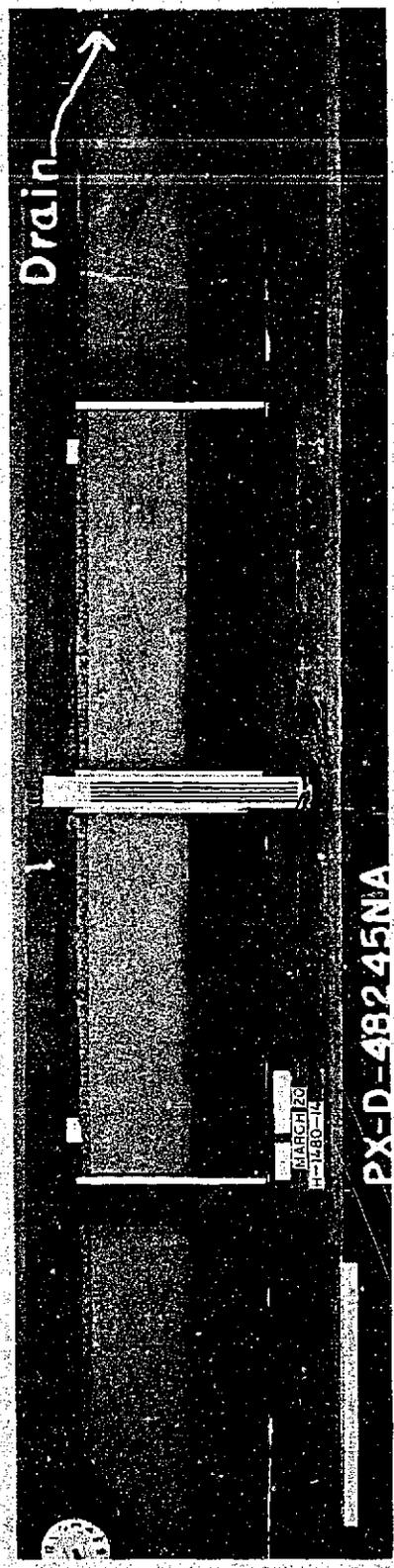
DIAGRAM OF THE
 GILA VALLEY GROUND WATER MODEL



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.

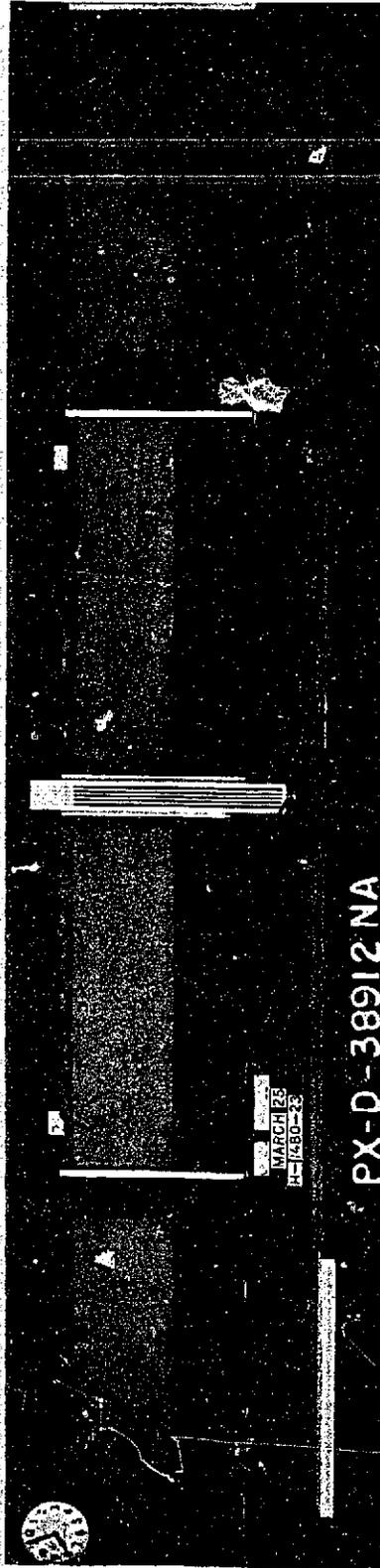
GROUND-WATER MODEL

Figure 5
Report Hyd-541



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.

GROUND-WATER MODEL

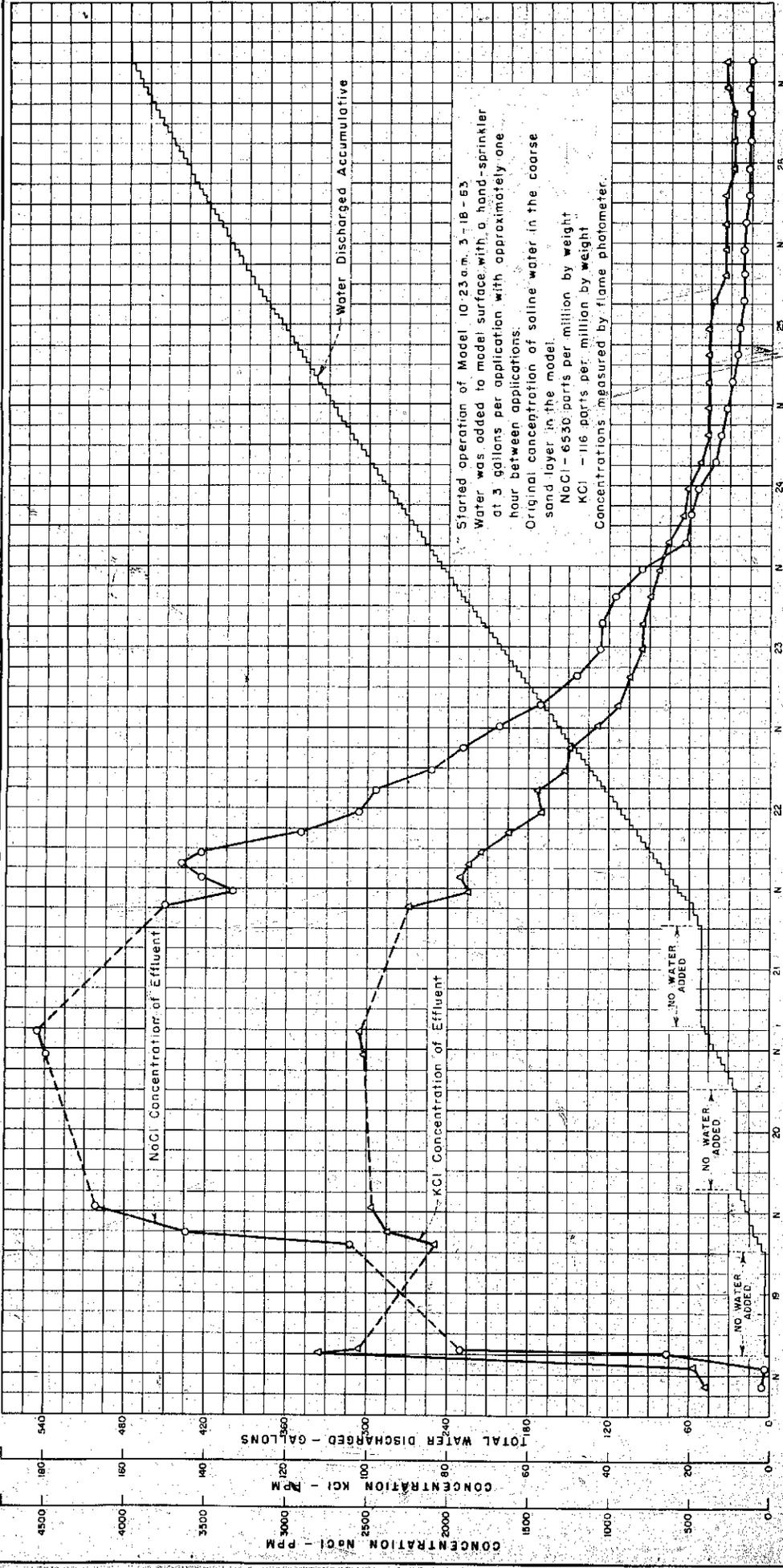


Flow of salt water to the drain continues after 67 hours of operation, Test 1.
Lower part of aquifer is being flushed with fresh water.

GROUND-WATER MODEL



FIGURE 7
REPORT HYD-541



GILA VALLEY
GROUND WATER MODEL
TEST NO. 1

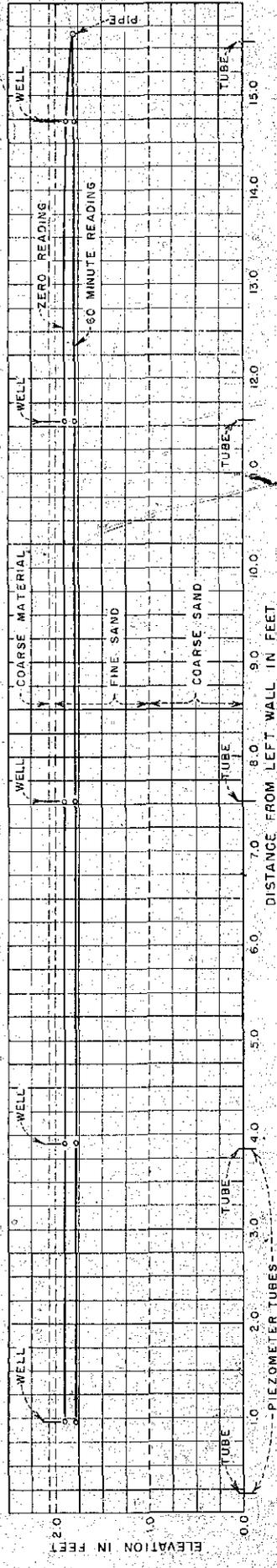
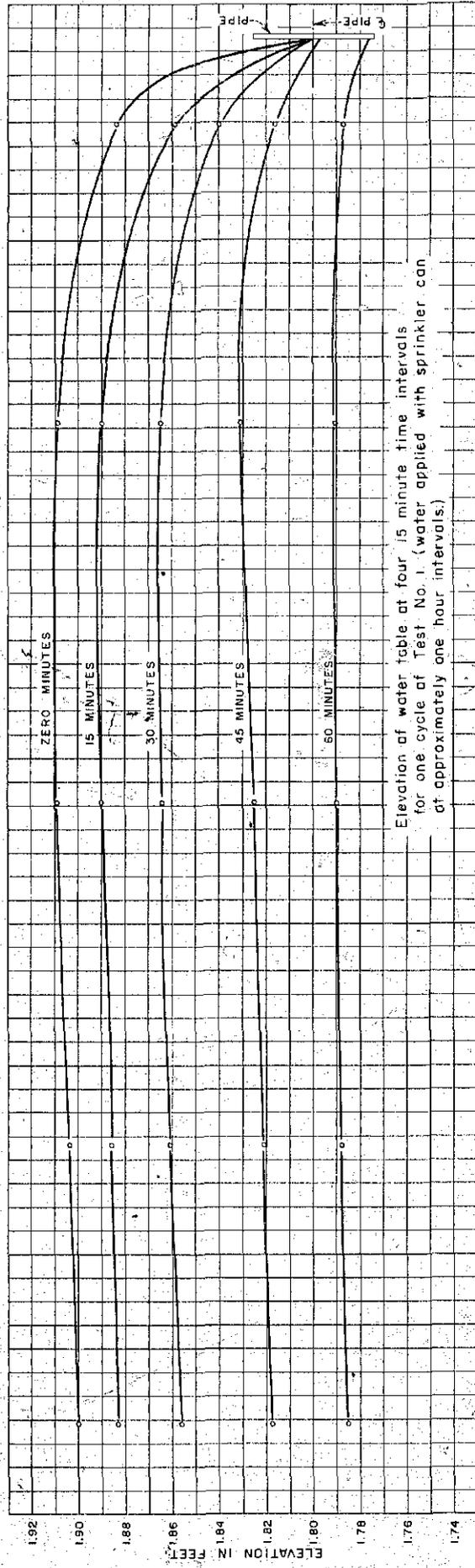
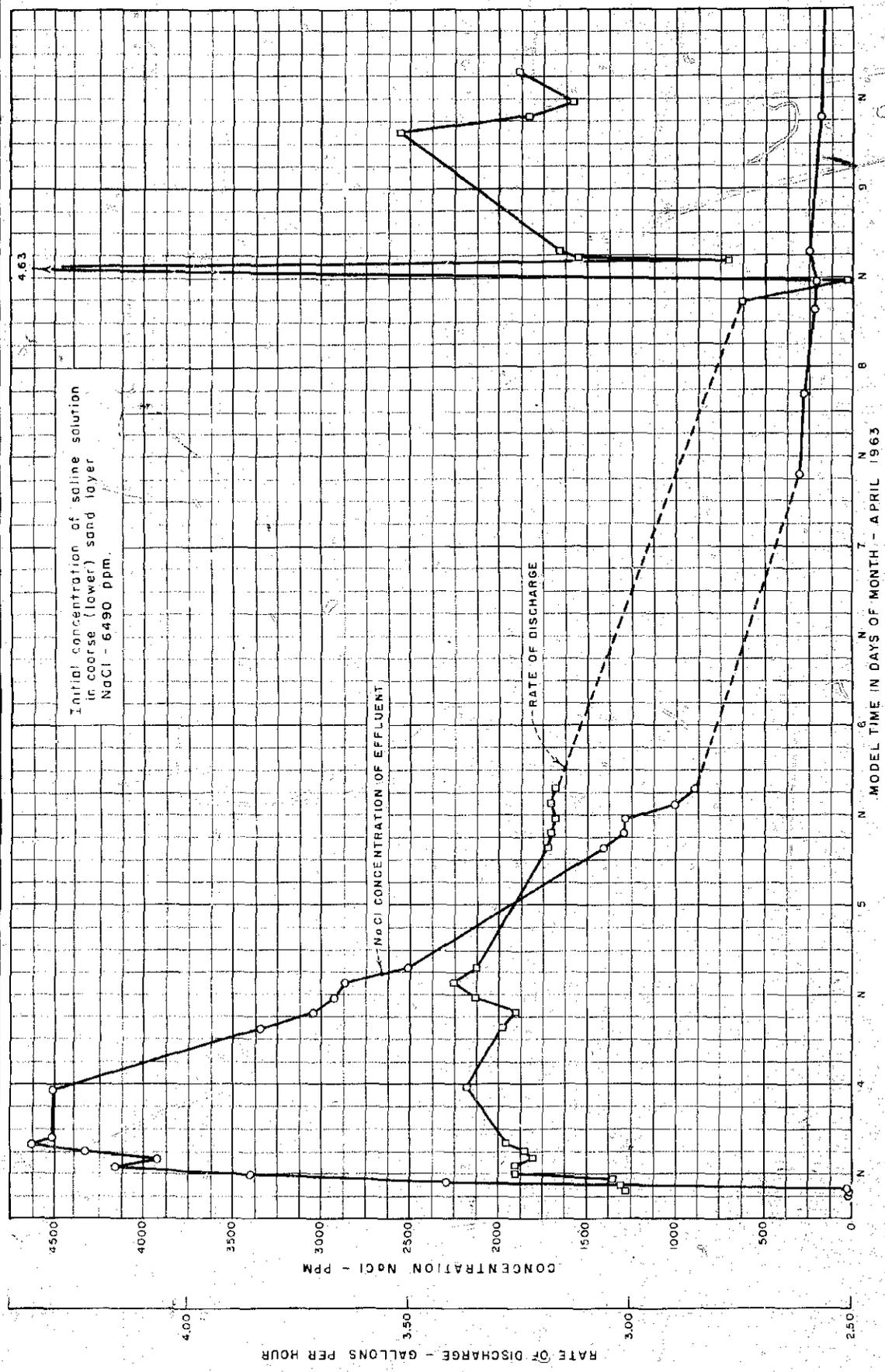
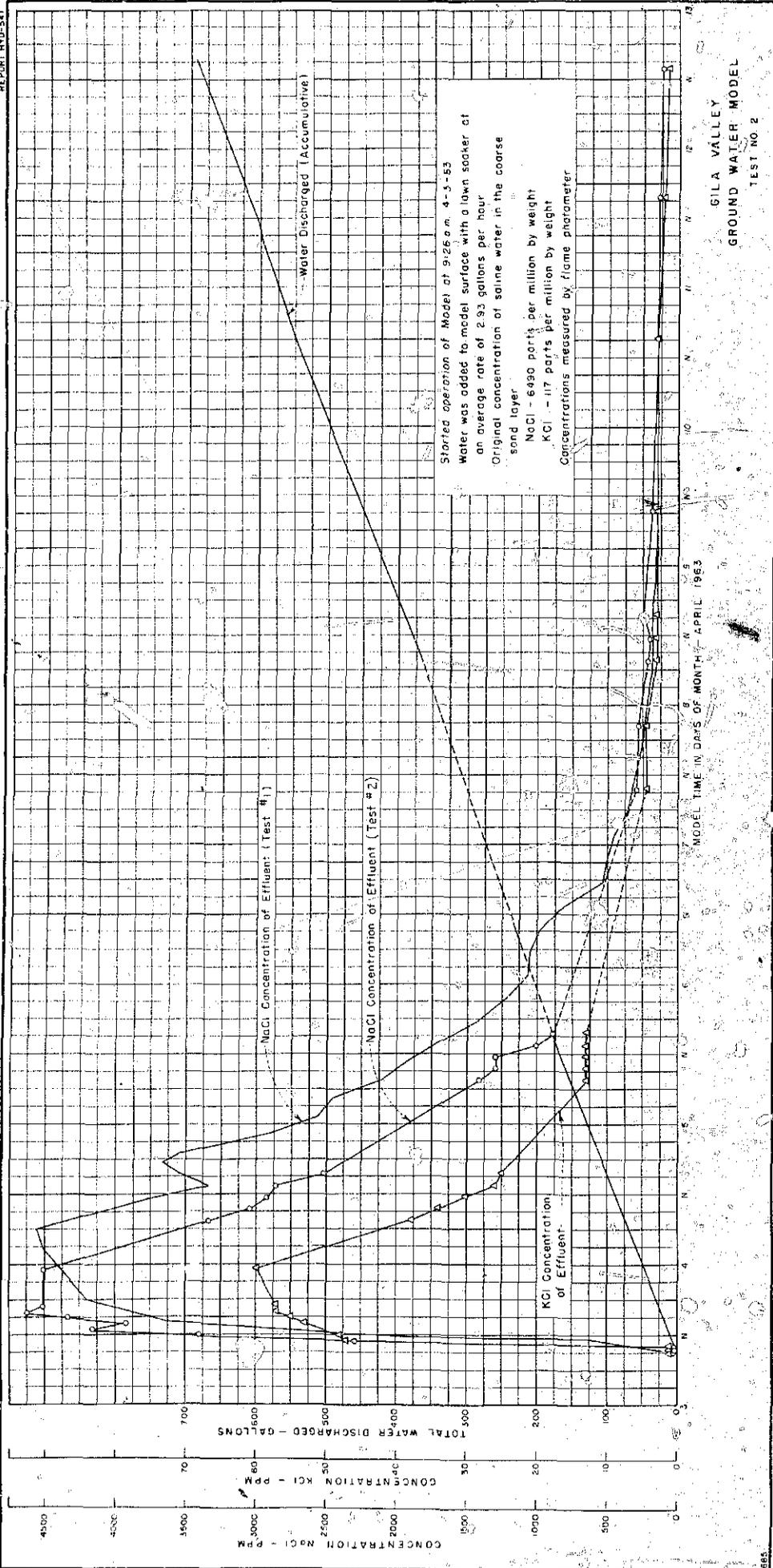
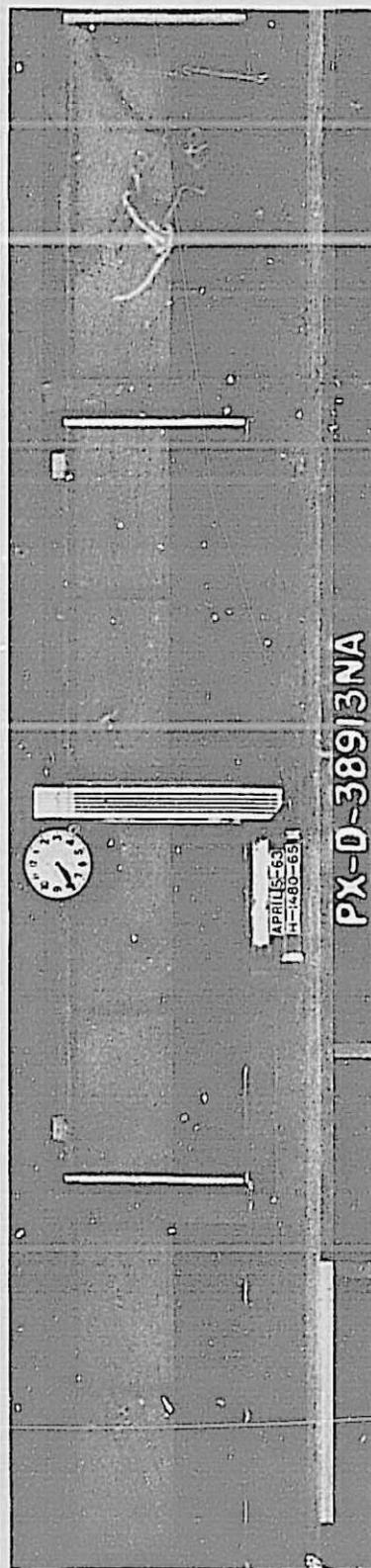


FIGURE 9
REPORT HYD-541



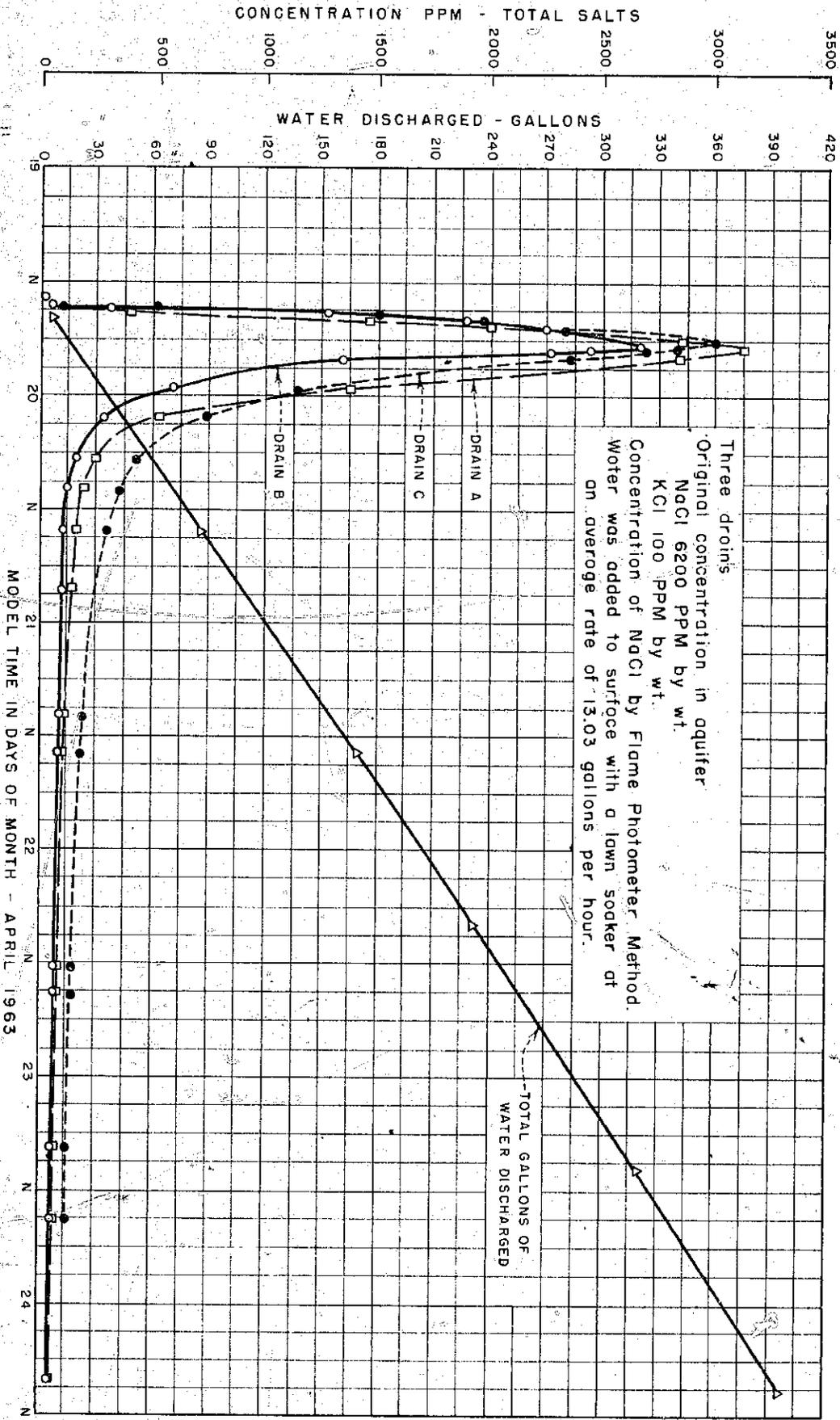
GILA VALLEY
GROUND WATER MODEL
TEST NO. 2





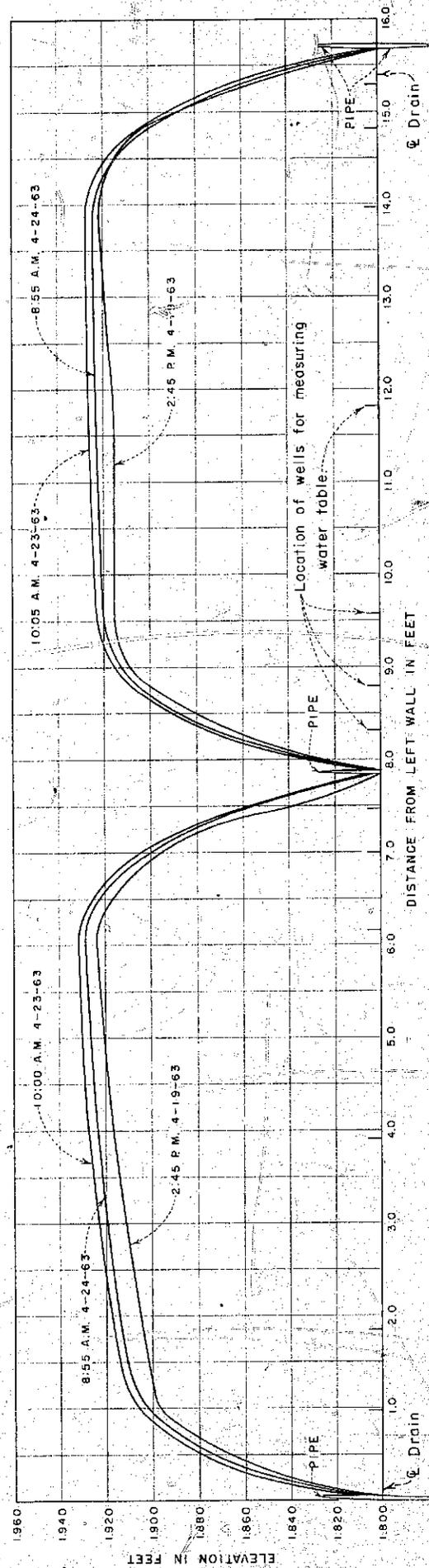
Dye paths in center of panels show that path of fresh water is vertically downward from surface to lower aquifer, horizontally to vicinity of drain, then vertically into drain. Two dye traces at extreme right show flow from upper aquifer is directly into drain on a curved path, Test 2.

GROUND-WATER MODEL

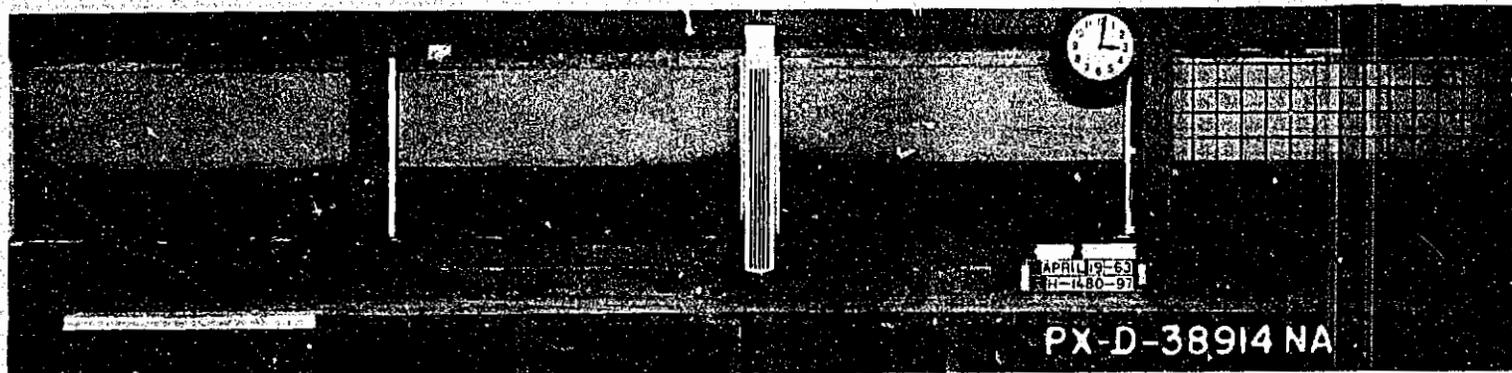


GILA VALLEY
 GROUND WATER MODEL
 TEST NO. 3

Water table elevations at three different times for Test No. 3
(Water applied continuously at an approximate rate of
13.03 gallons per hour.)

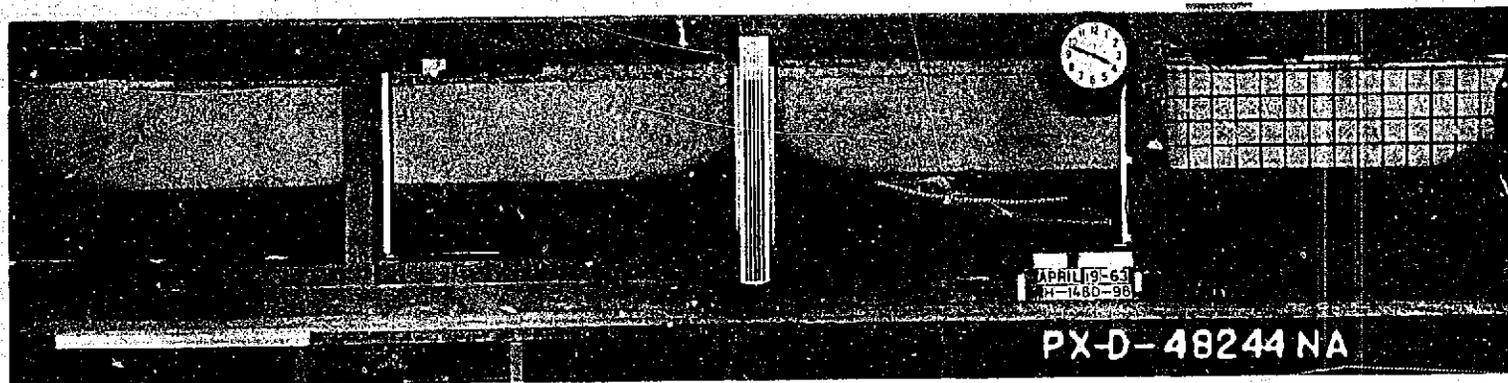


GILA VALLEY
GROUND WATER MODEL
TEST NO. 3



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.

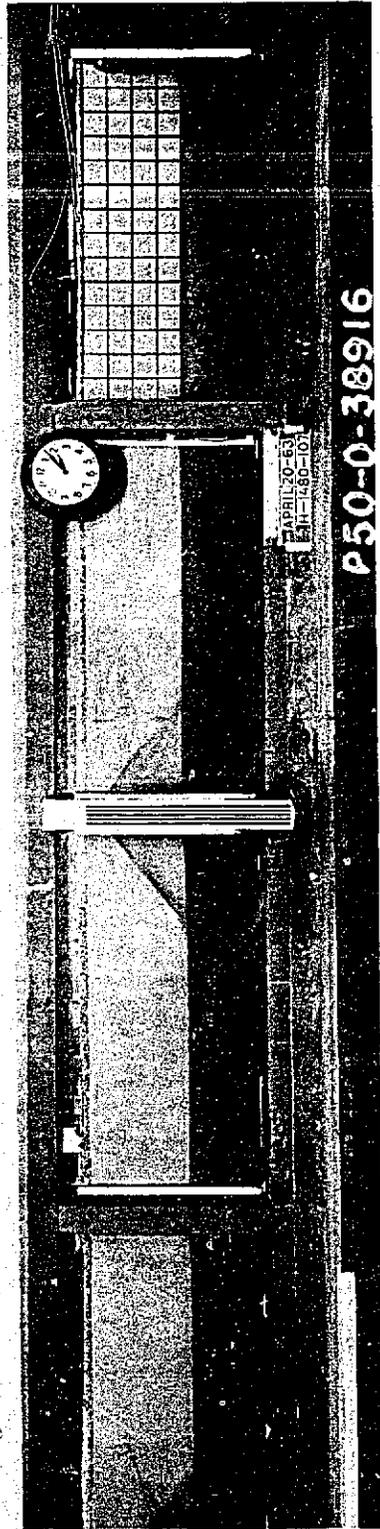
GROUND-WATER MODEL



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.

GROUND-WATER MODEL

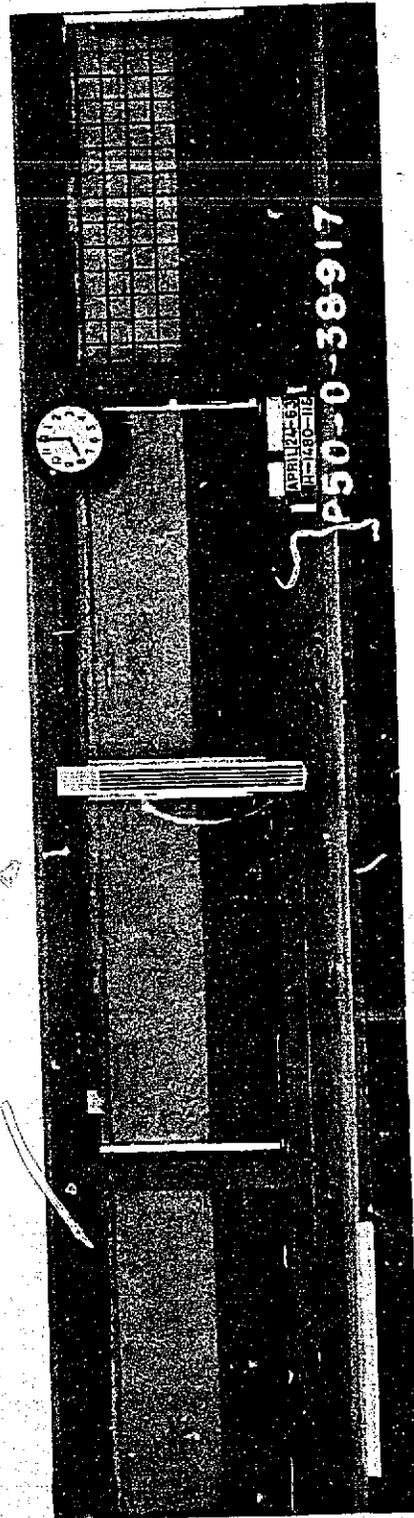
Figure 16
Report Hyd-541



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.

GROUND-WATER MODEL

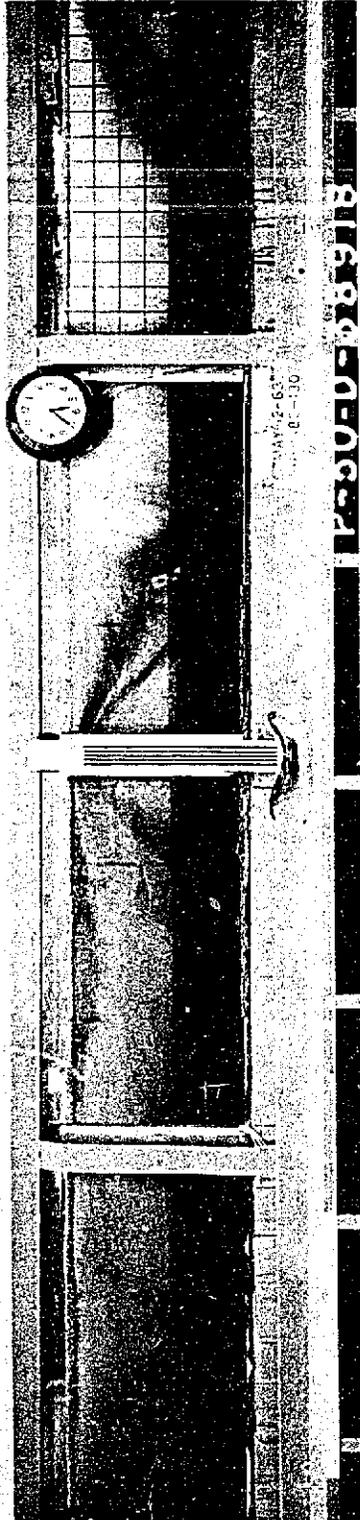
Figure 17
Report Hyd-541



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.

GROUND-WATER MODEL

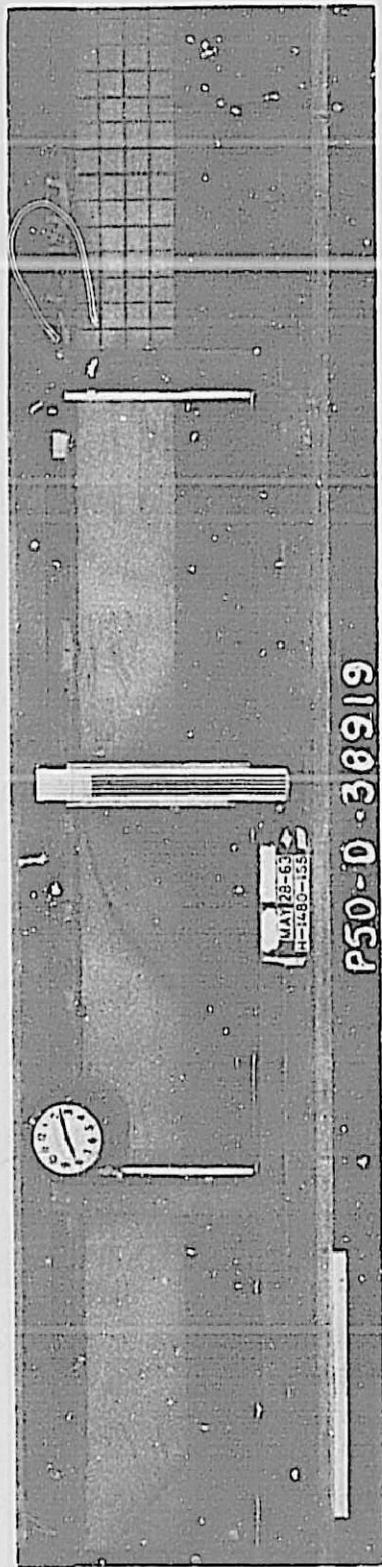
Figure 18
Report Hyd-541



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 is evident.

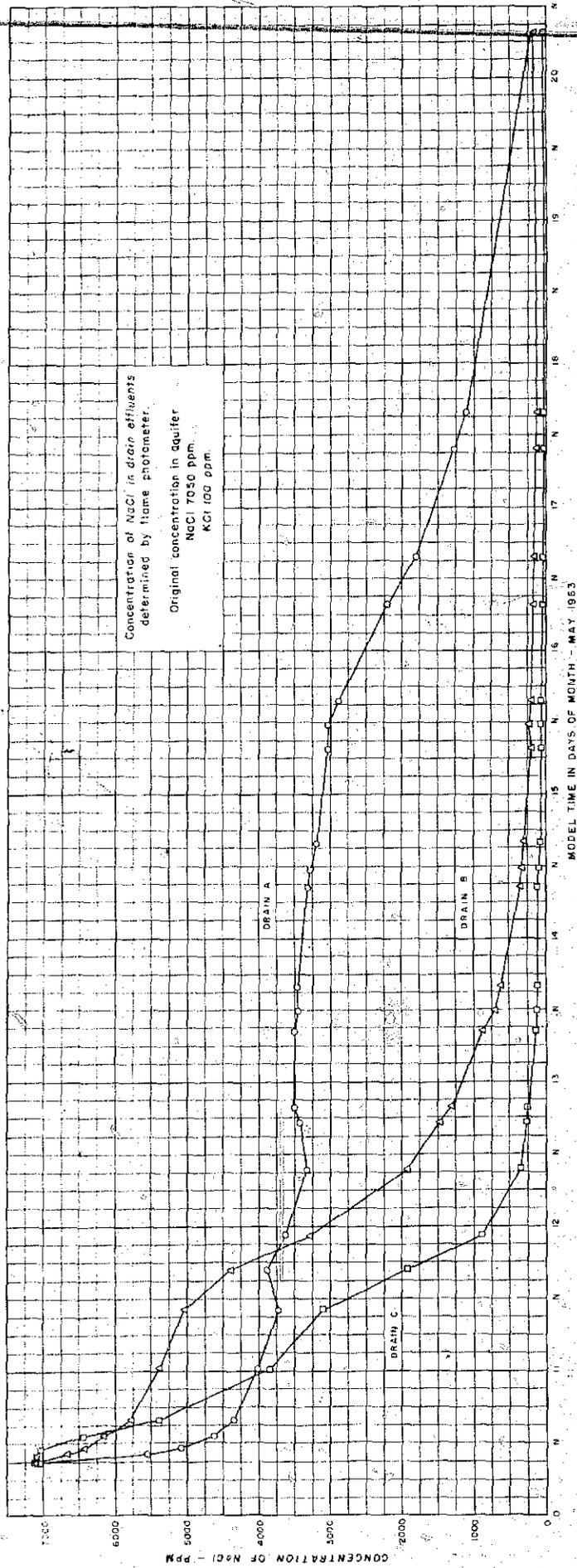
GROUND-WATER MODEL

Figure 19
Report Hyd-541

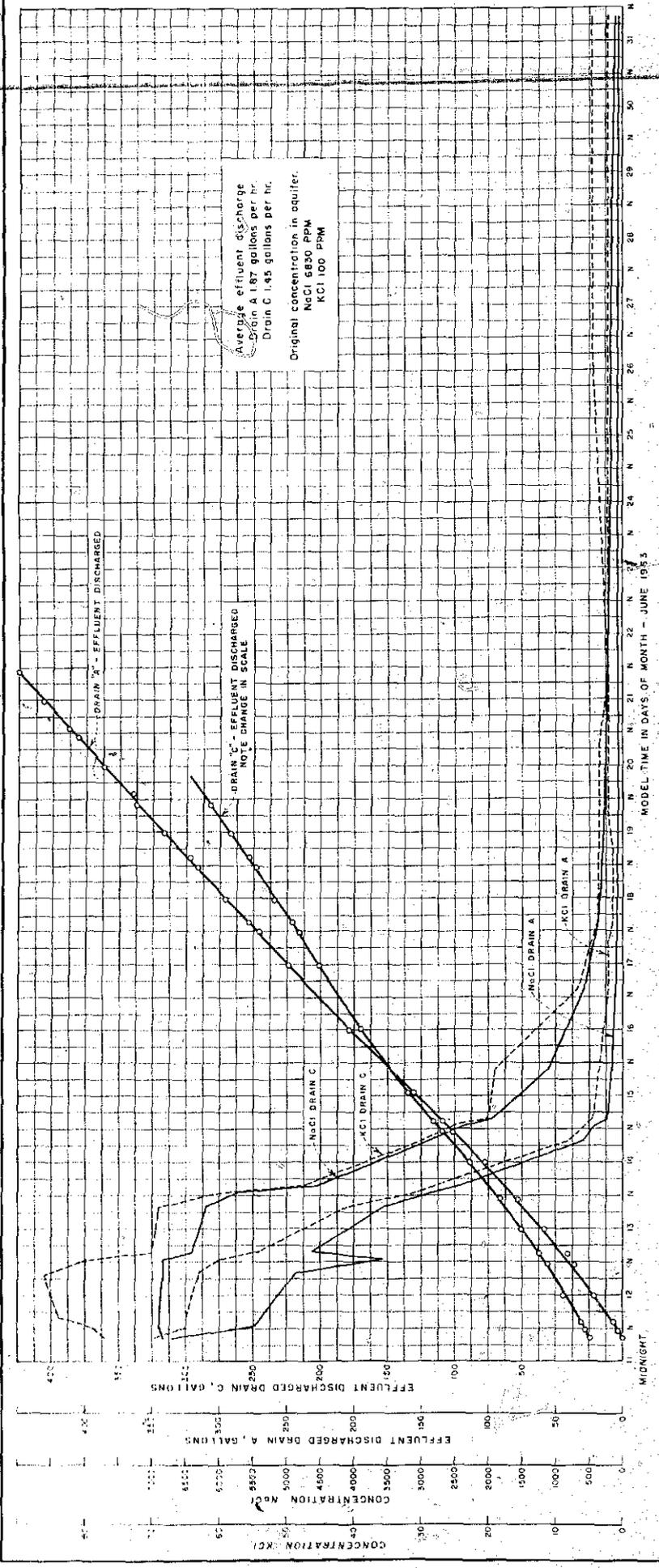


End of Test 4. Permanent storage of salt water in lower part of the aquifer is indicated. Storage pattern in lower part is not symmetrical about center-line of model because water was inadvertently applied more rapidly to right-hand side (in photograph).

GROUND-WATER MODEL



GILA VALLEY
GROUND WATER MODEL
TEST NO. 4

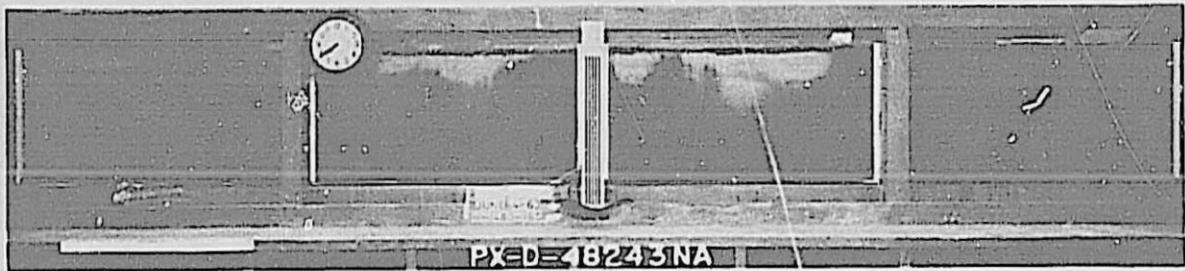


Average effluent discharge
Drain A 1.87 gallons per hr.
Drain C 1.45 gallons per hr.
Original concentration in aquifer:
NaCl 6830 PPM
KCl 100 PPM

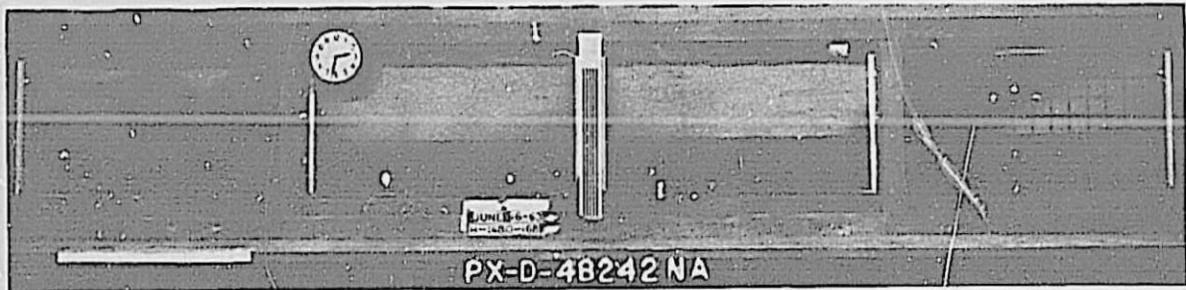
GILA VALLEY
GROUND WATER MODEL
TEST NO. 5

MODEL TIME IN DAYS OF MONTH - JUNE 1983

MIDNIGHT



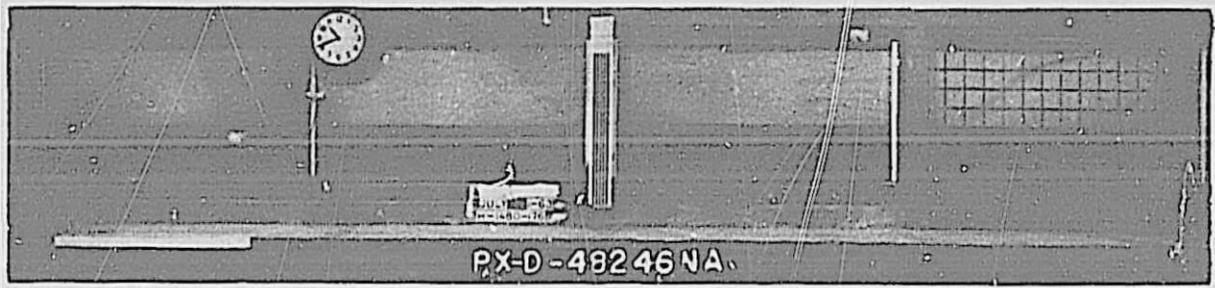
- A. Position of interface on June 14, 1963, when concentration in effluent from Drain A was 1/10 (683 ppm) of that initially placed in the aquifer (6,830 ppm).



- B. Position of interface on June 16, 1963, when concentration in effluent from Drain C was 1/10 (683 ppm) of that initially placed in the aquifer (6,830 ppm).

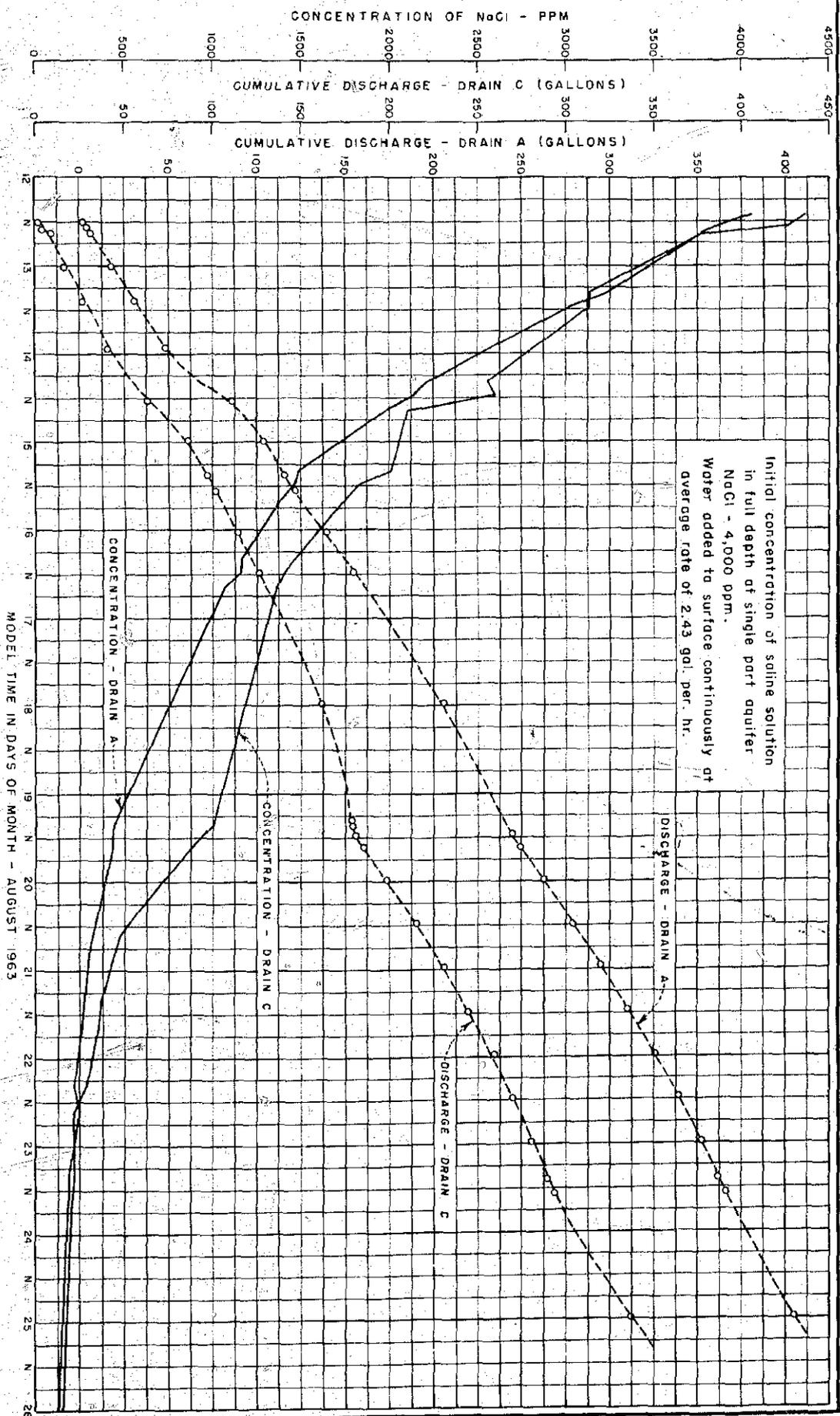
Appearance of Model Interface during Test 5
when Drain Effluent Contain 1/10 of Initial Salt
Concentration

GROUND-WATER MODEL



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.

GROUND-WATER MODEL

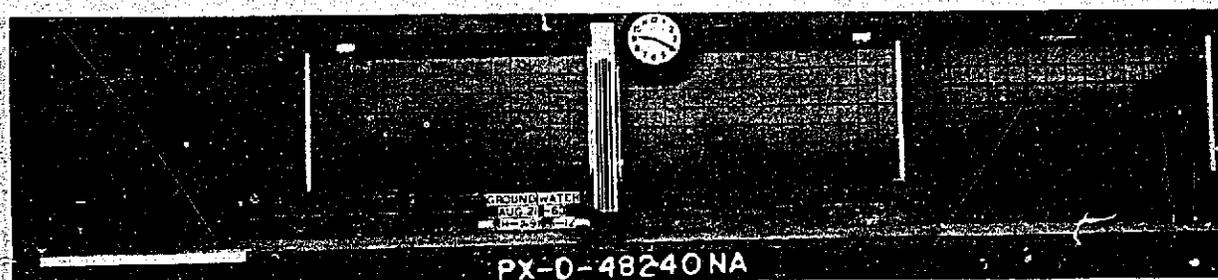


GILA VALLEY
GROUND WATER MODEL
TEST NO. 6

FIGURE 24
REPORT HVD-541



- A. Interface when Drain A, left, effluent had a salt concentration $1/10$ (400 ppm) of original concentration 7-1/2 days after beginning of test.

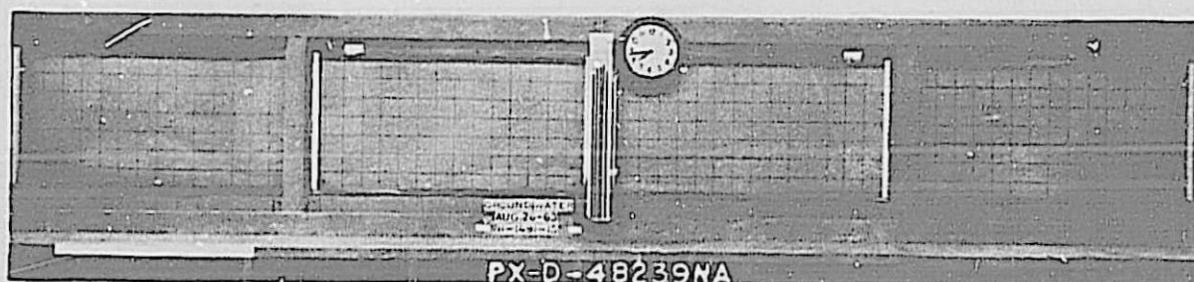


- B. Interface when Drain C, right, effluent had a salt concentration $1/10$ (400 ppm) of original concentration 8-1/2 days after beginning of test.

Appearance of fresh water-salt water interface in Test 6 when drain effluents contain $1/10$ of original aquifer salt concentration.

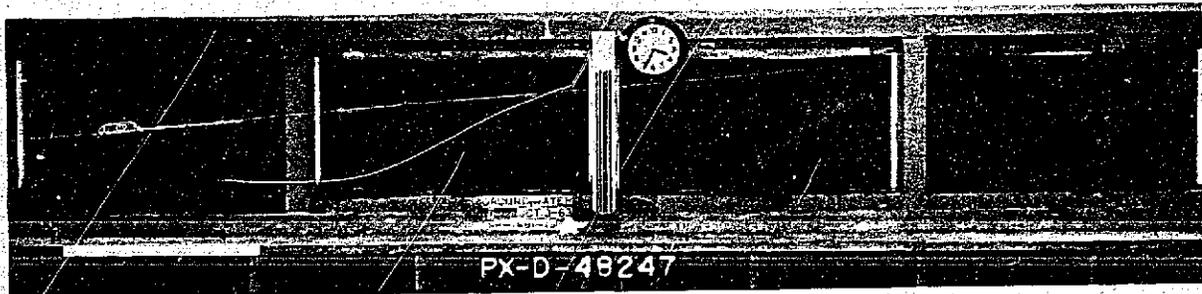
GROUND-WATER MODEL

Figure 26
Report Hyd-541

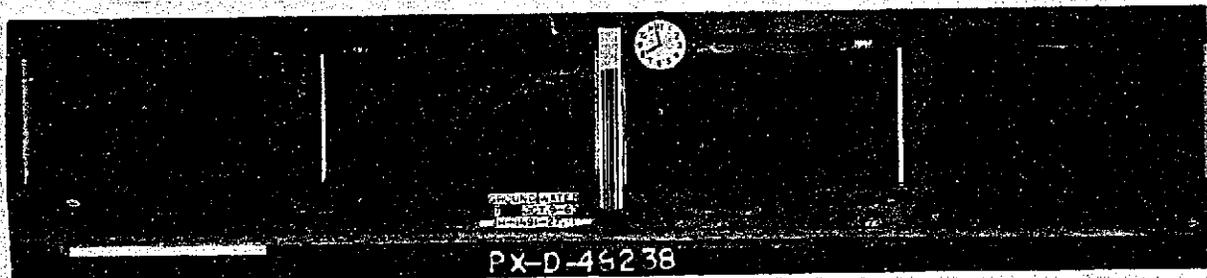


Only small wedges of salt water in the lower corners beneath the drains remain in the aquifer of Test 6 on August 26, 1963, after 13 days (50-1/2 prototype years) of model operation.

GROUND-WATER MODEL



- 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.

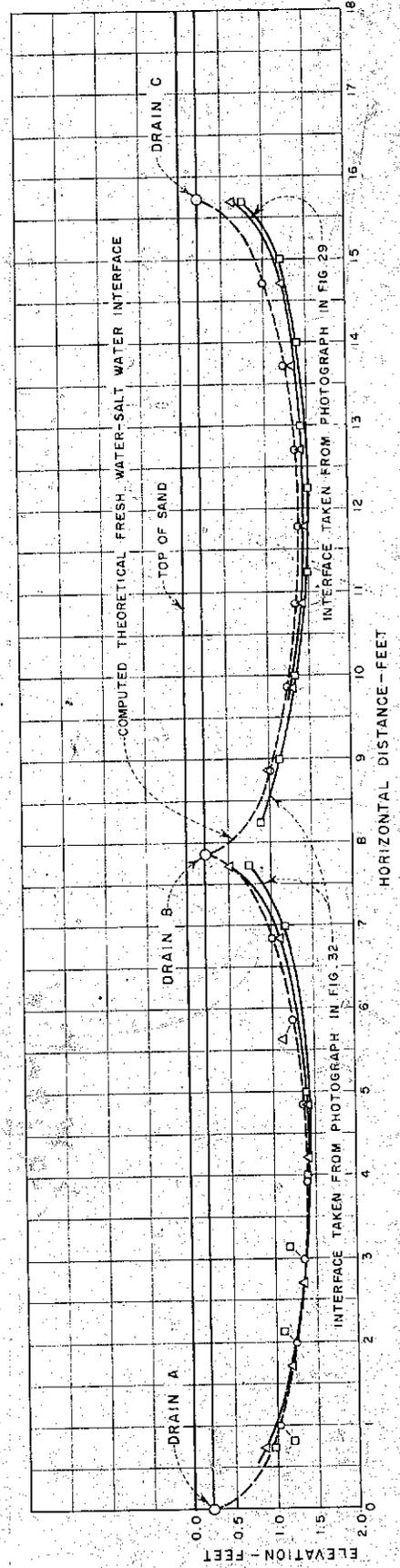


- B. The dark-blue band (interface) separates the fresh water above and the saline water below after 7 days of operation of Test 7. Original concentration of salt was approximately 79,770 ppm.

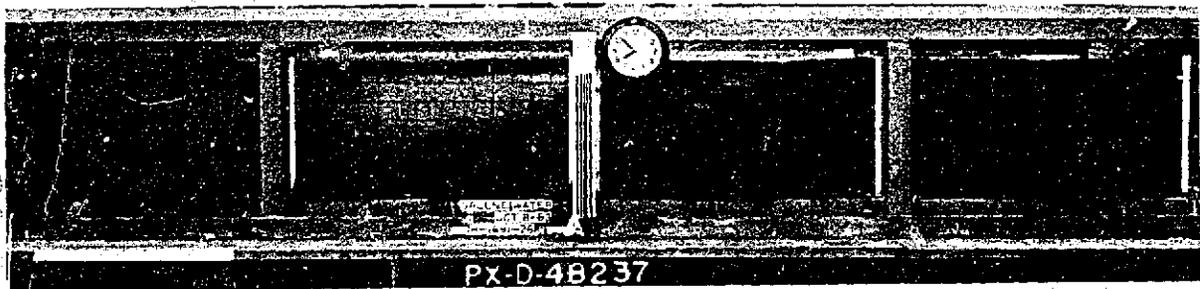
Test 7 at the beginning and
after 7 days operation

GROUND-WATER MODEL

- Initial salt concentration = 79,270 PPM
- One part aquifer - 3 drains.
- Q = 2.76 Gallons per hour
- o - Theoretical fresh water-salt water interface.
- Δ - Interface taken from photograph of 10-8-63, 7:52 A.M. (5.9 days of model operation - Figure 29.)
- - Interface taken from photograph of 10-15-63, 6:00 A.M. (12.9 days of model operation - Figure 32.)

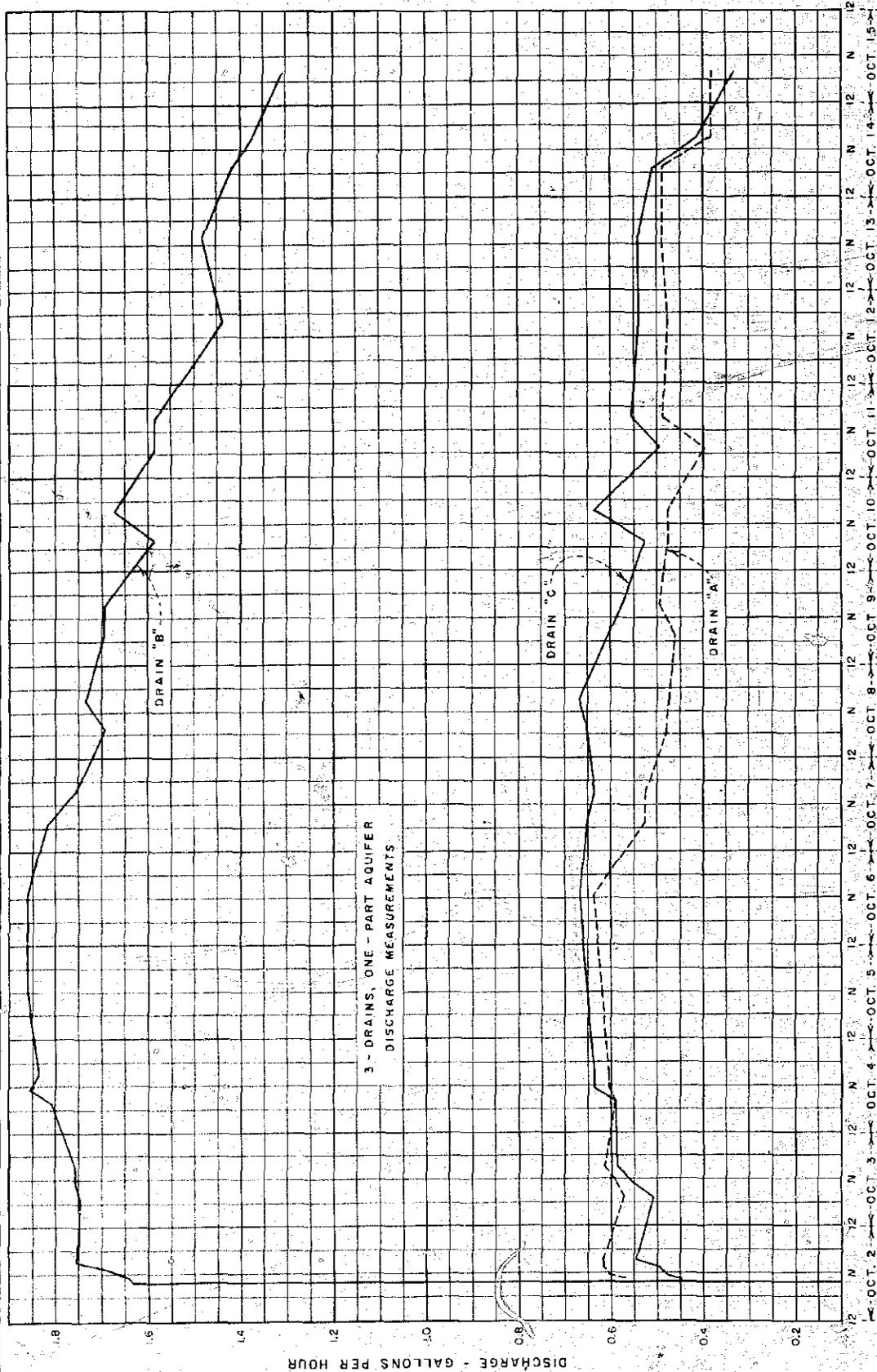


GILA VALLEY
GROUND WATER MODEL
TEST NO. 7



Test 7, with single-part aquifer, showing saline water-fresh water interface on October 8, 1963. Interface is in same general position as computed using the Ghyben-Herzberg principle shown on Figure 28. Salt concentration in the aquifer at the beginning of the test was approximately 79,770 ppm.

GROUND-WATER MODEL



DISCHARGE - GALLONS PER HOUR

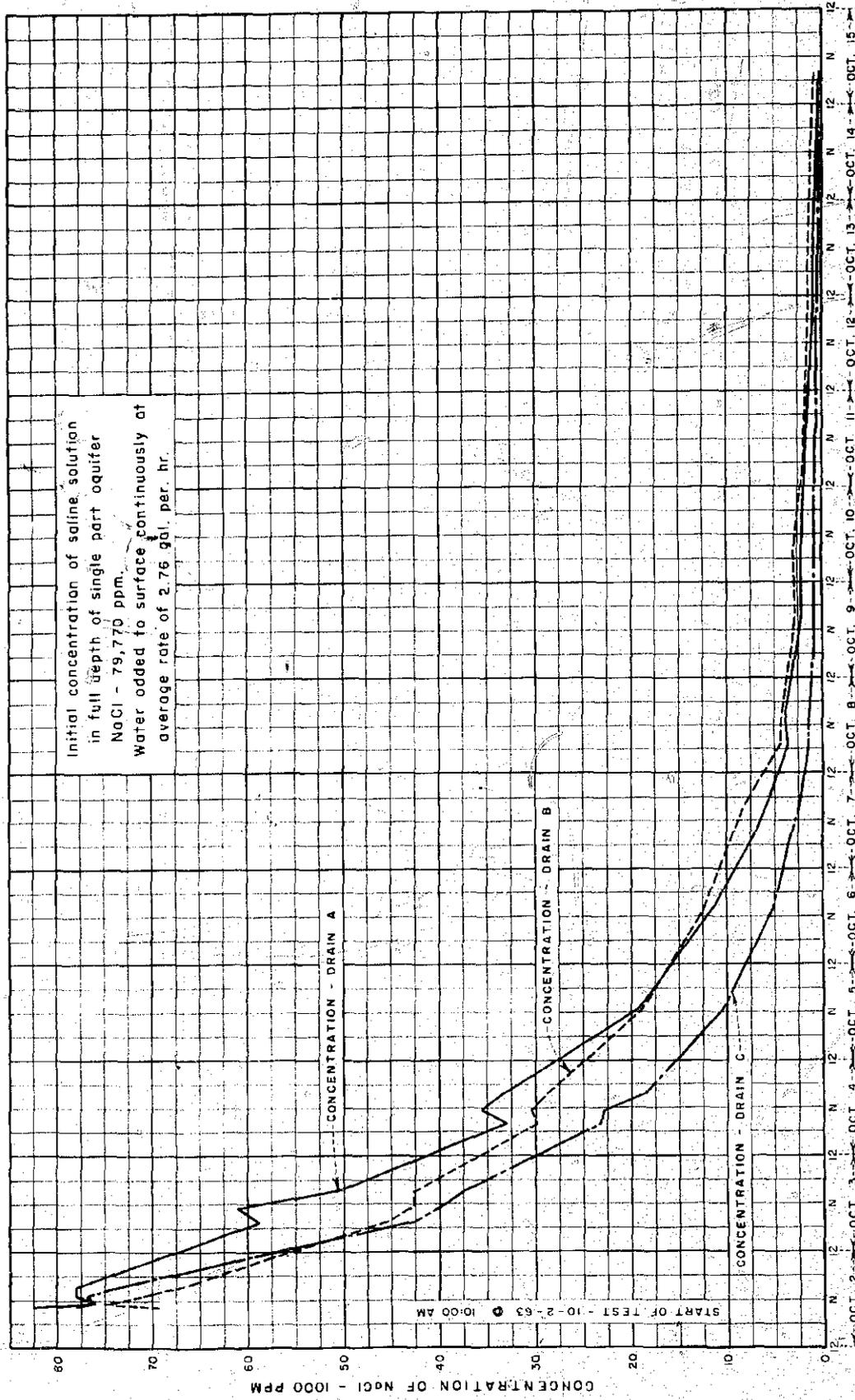
3 - DRAINS, ONE - PART AQUIFER
DISCHARGE MEASUREMENTS

DRAIN "B"

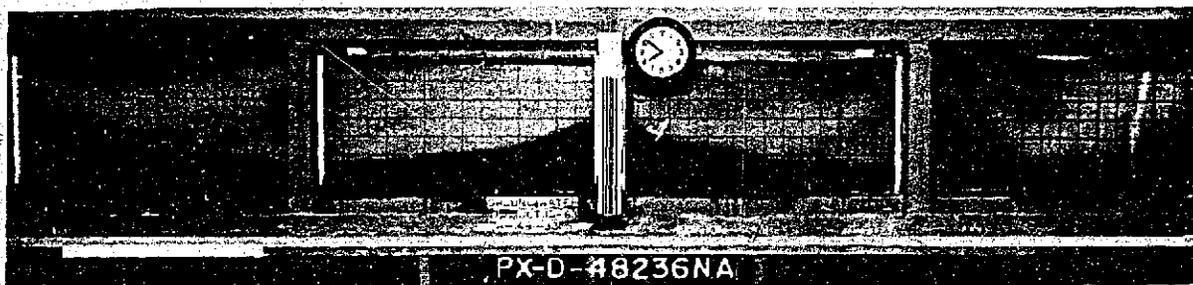
DRAIN "C"

DRAIN "A"

GILA VALLEY
GROUND WATER MODEL
TEST NO. 7



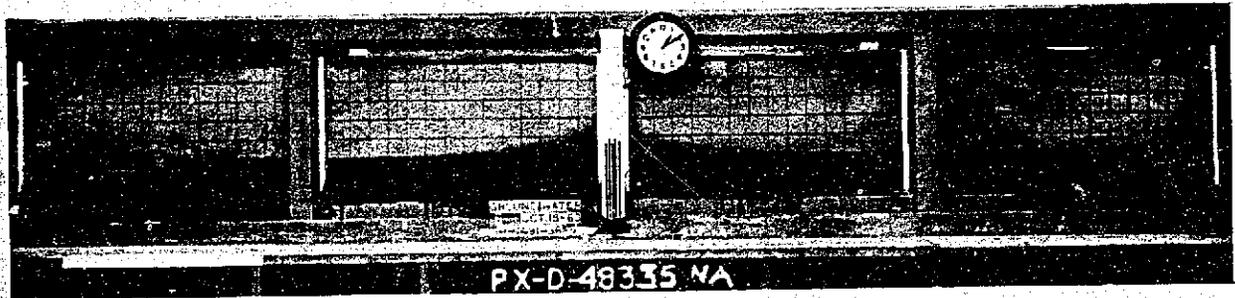
GILA VALLEY
GROUND WATER MODEL
TEST NO. 7



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

GROUND-WATER MODEL

Figure 33
Report Hyd-541



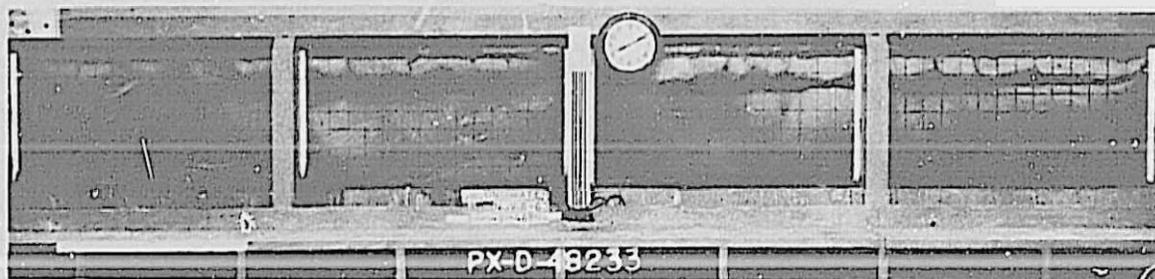
Saline water-fresh water interface of Test 7, 3 days (13.8 prototype years) after the application of irrigation water was stopped. Comparison with Figure 32 shows that the interface has not leveled completely.

GROUND-WATER MODEL

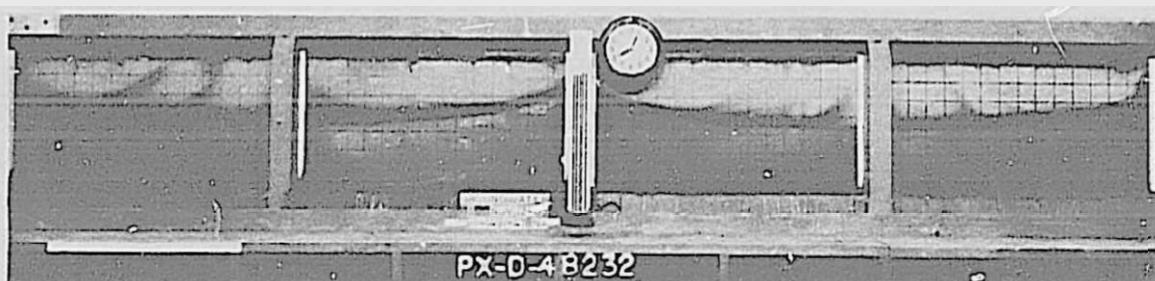


Sand tank model with automatically operated flush tank and stainless steel troughs installed for Test 8, to apply irrigation water at regular intervals and distribute it uniformly over the aquifer surface.

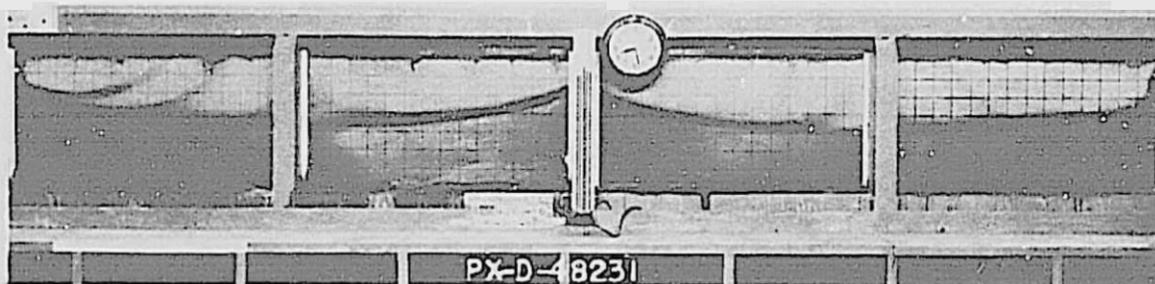
GROUND-WATER MODEL



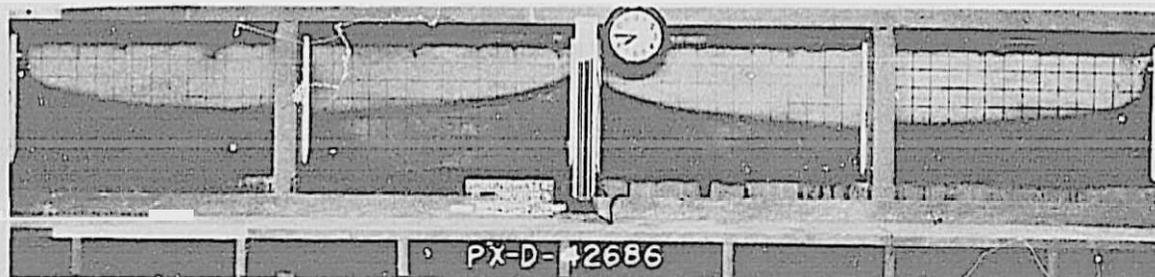
November 8, 1963



November 12, 1963



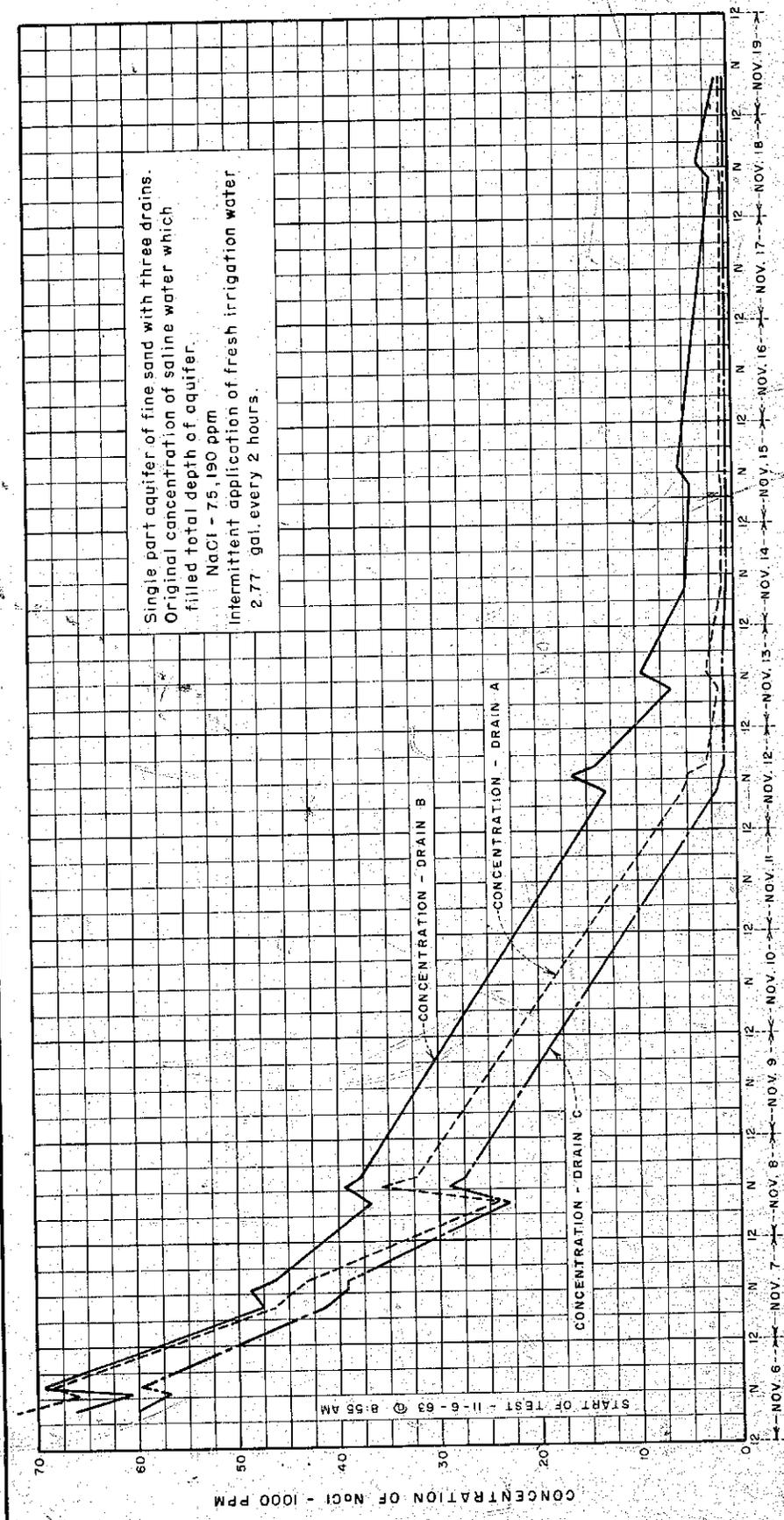
November 14, 1963

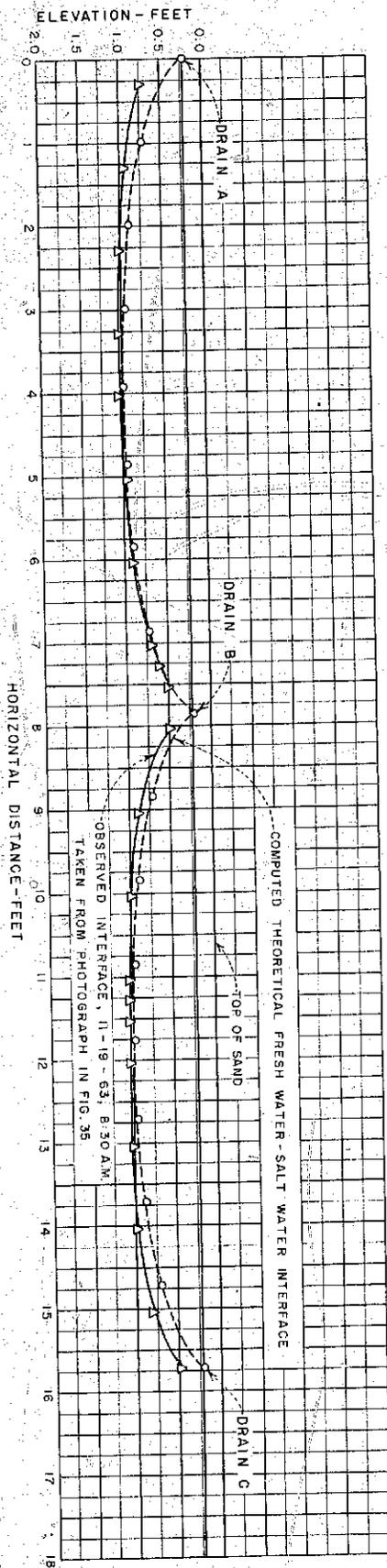


November 19, 1963

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, 1963, to November 19, 1963.

GROUND-WATER MODEL



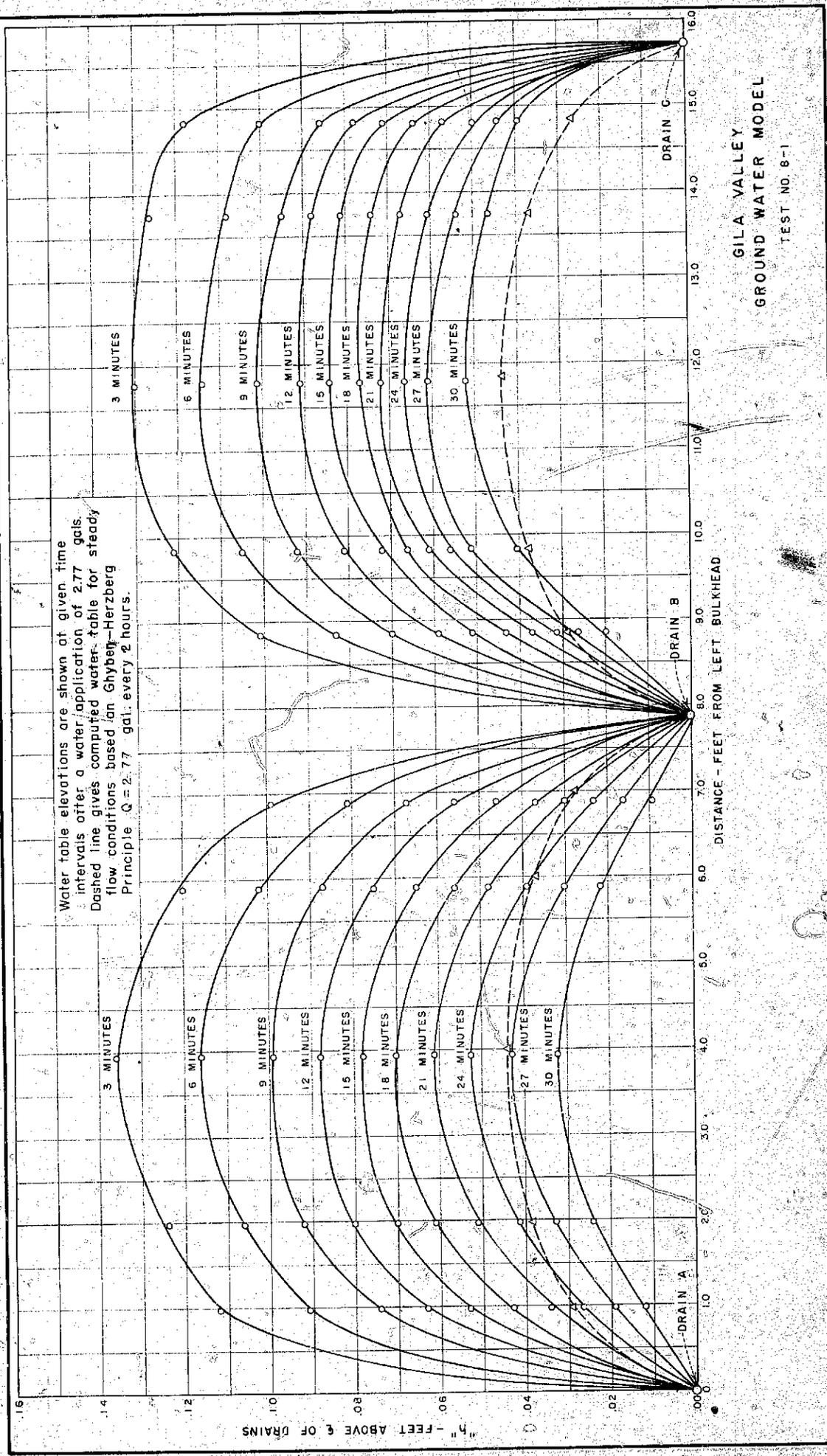


One part aquifer
 3 - Drains
 $Q = 2.77$ gal in 2 hours

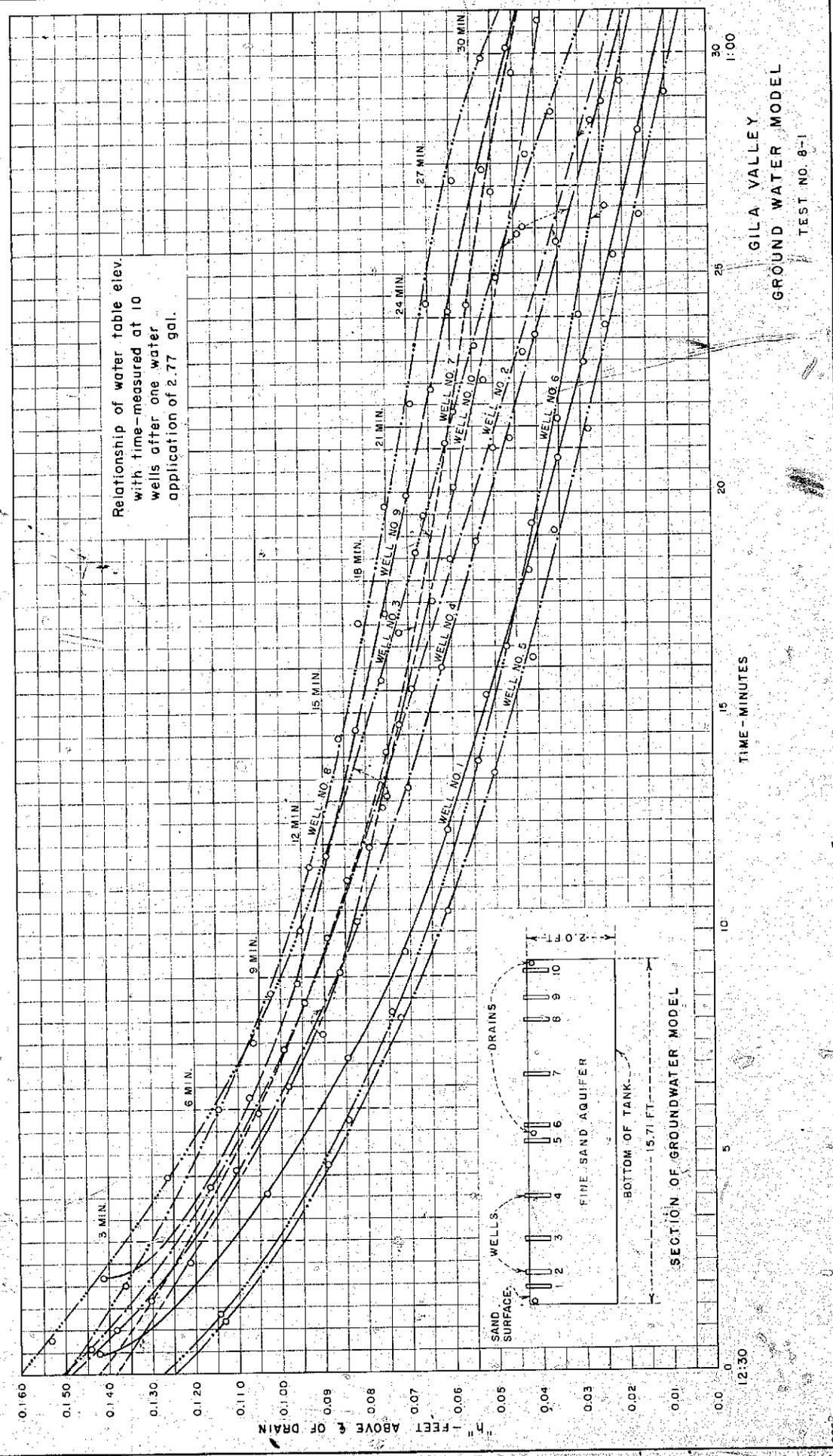
GILA VALLEY
 GROUND WATER MODEL
 TEST NO. 8-1

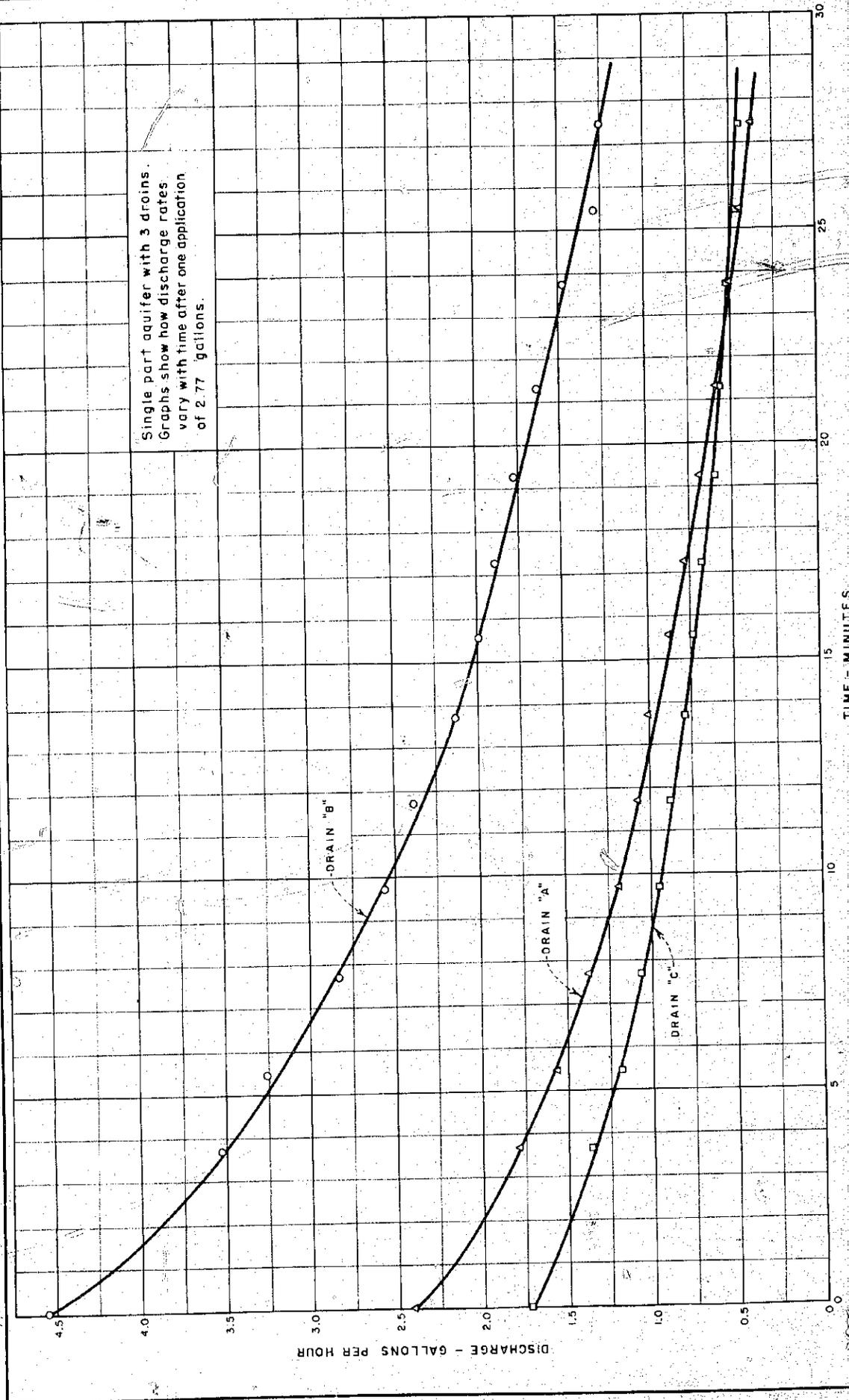
FIGURE 37
 REPORT HD-541

FIGURE 3B
REPORT HYD-541

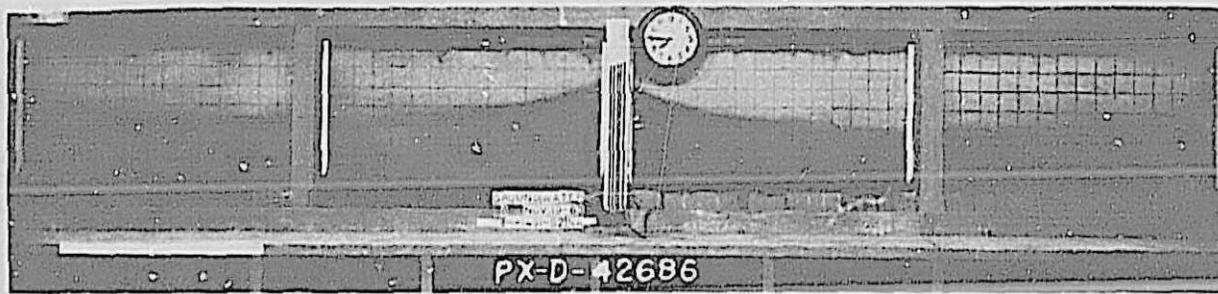


GILA VALLEY
GROUND WATER MODEL
TEST NO. 8-1

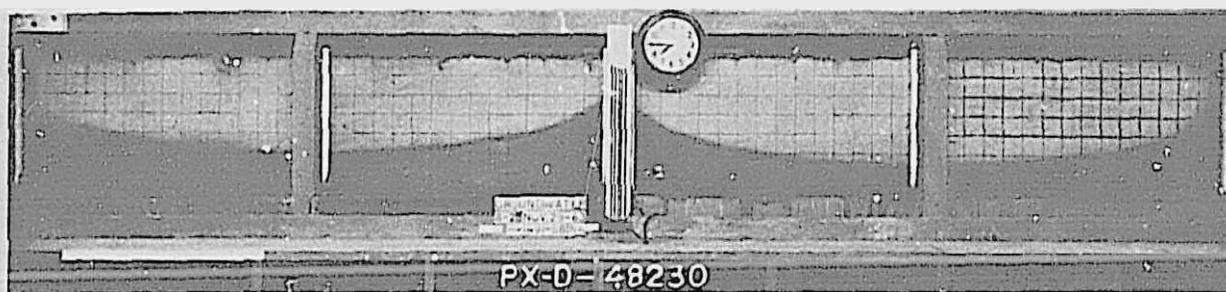




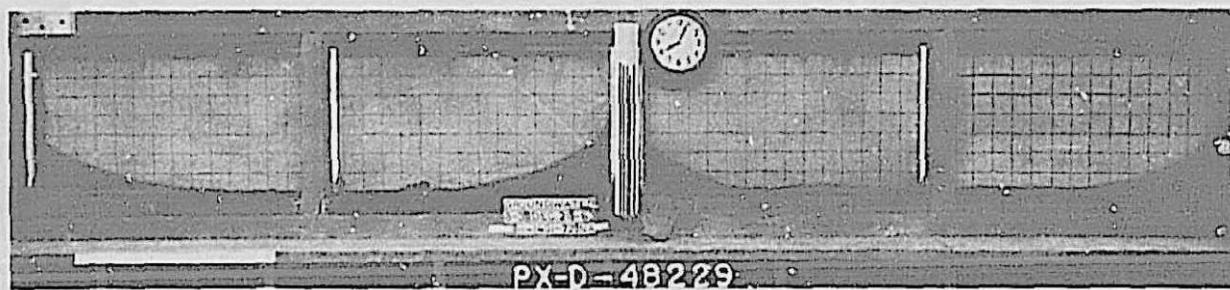
GILA VALLEY
GROUND WATER MODEL
TEST NO. B-1



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.



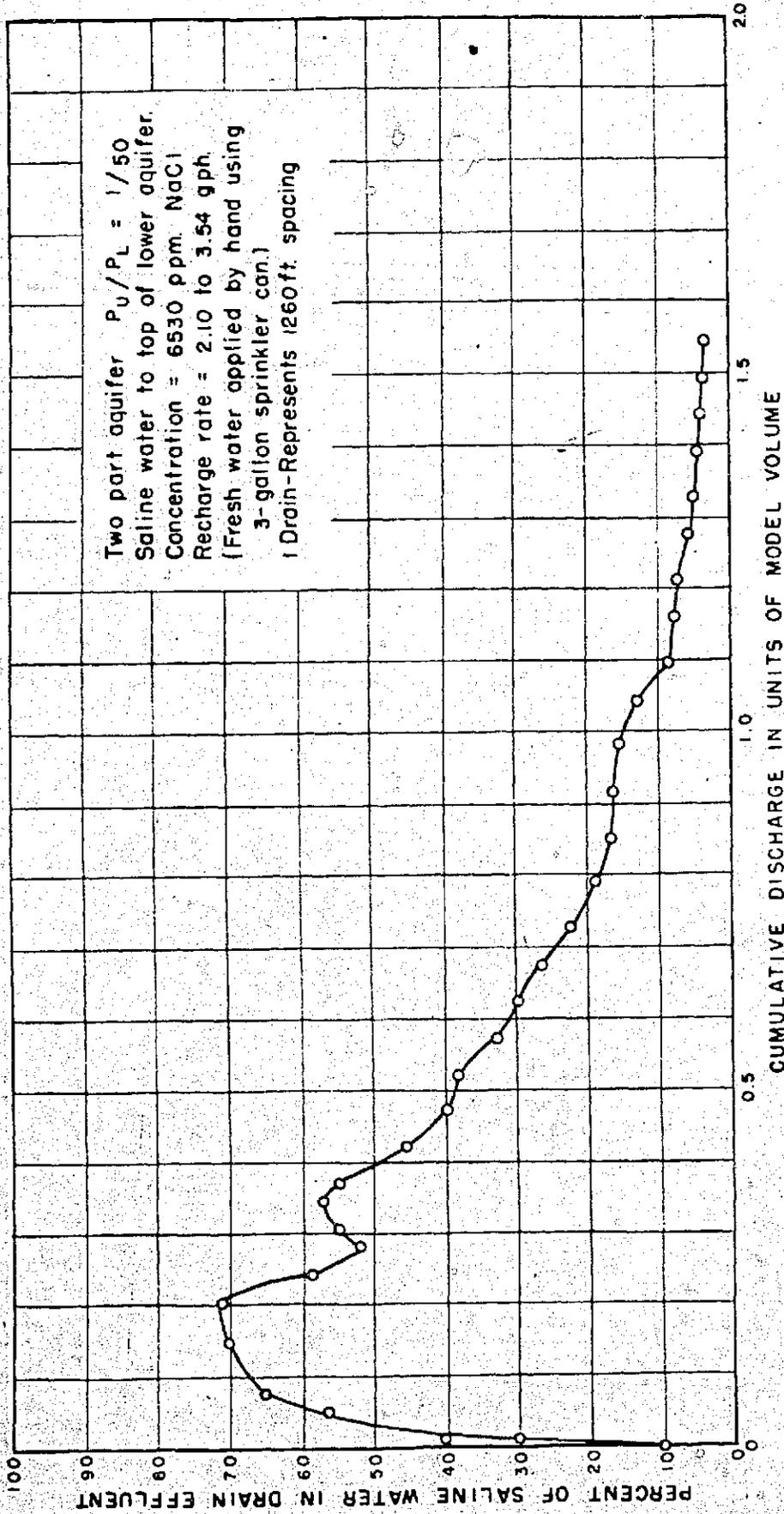
B. The stable interface at the end of Test 8-2 is lower than in A above. Fresh recharge water had been applied at the rate of 2.89 gallons every hour.



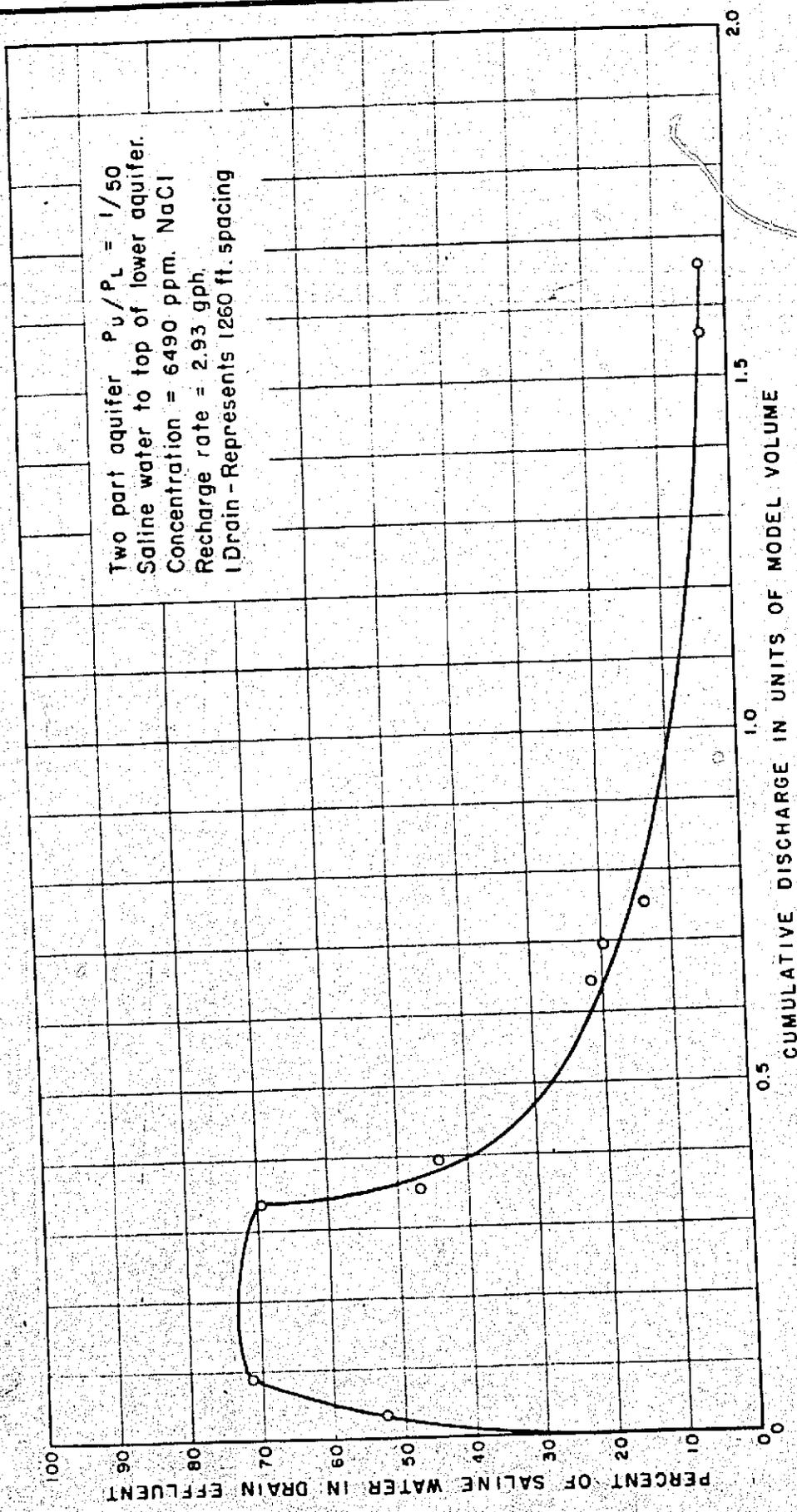
C. The stable interface at the end of Test 8-3 is lower than in A and B above. Fresh recharge water had been applied at the rate of 2.77 gallons every one-half hour.

Photographs of stable interface positions at end of Tests 8-1, 8-2, and 8-3.

GROUND-WATER MODEL

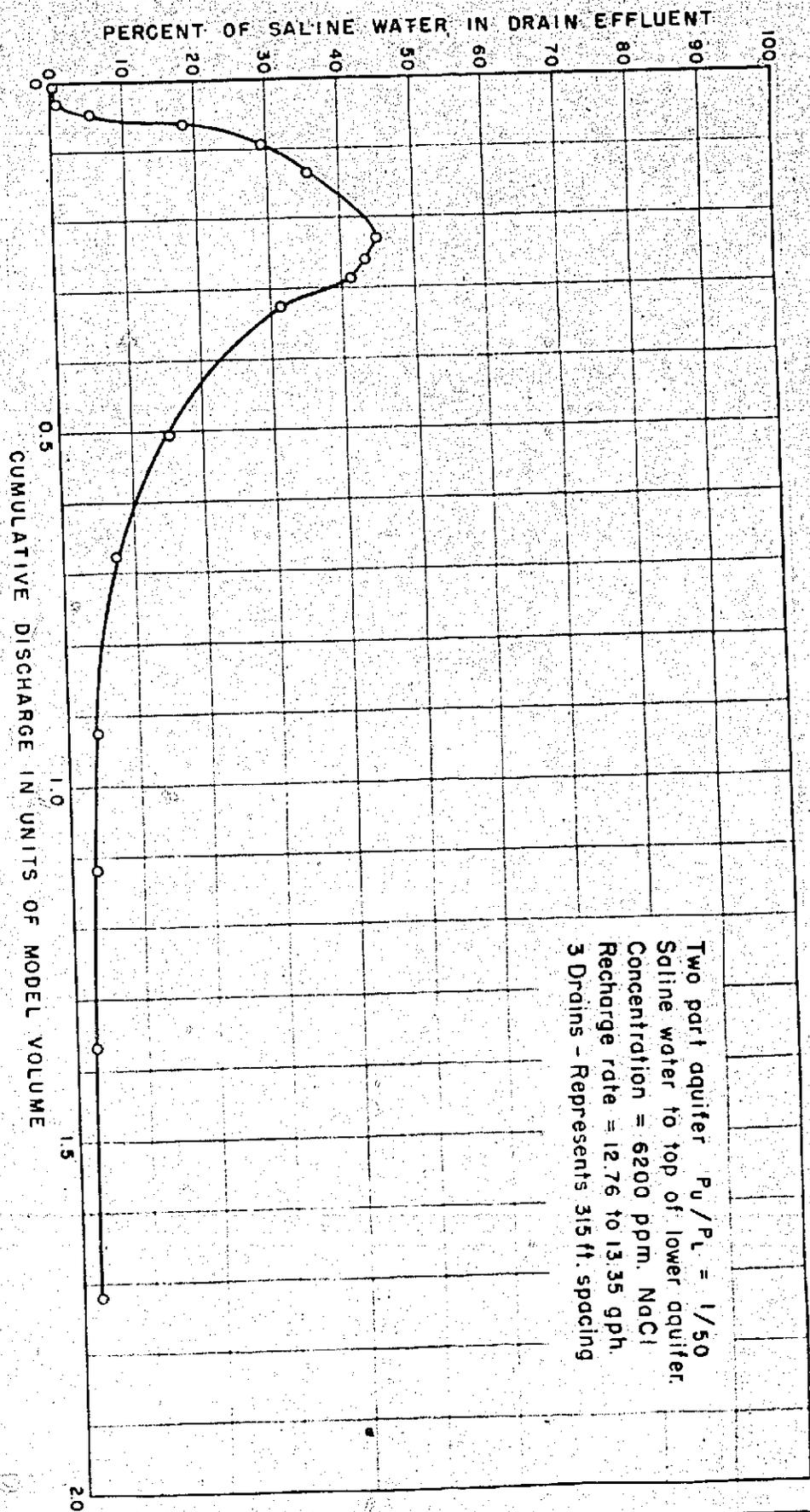


GILA VALLEY
GROUND WATER MODEL
TEST NO. 1



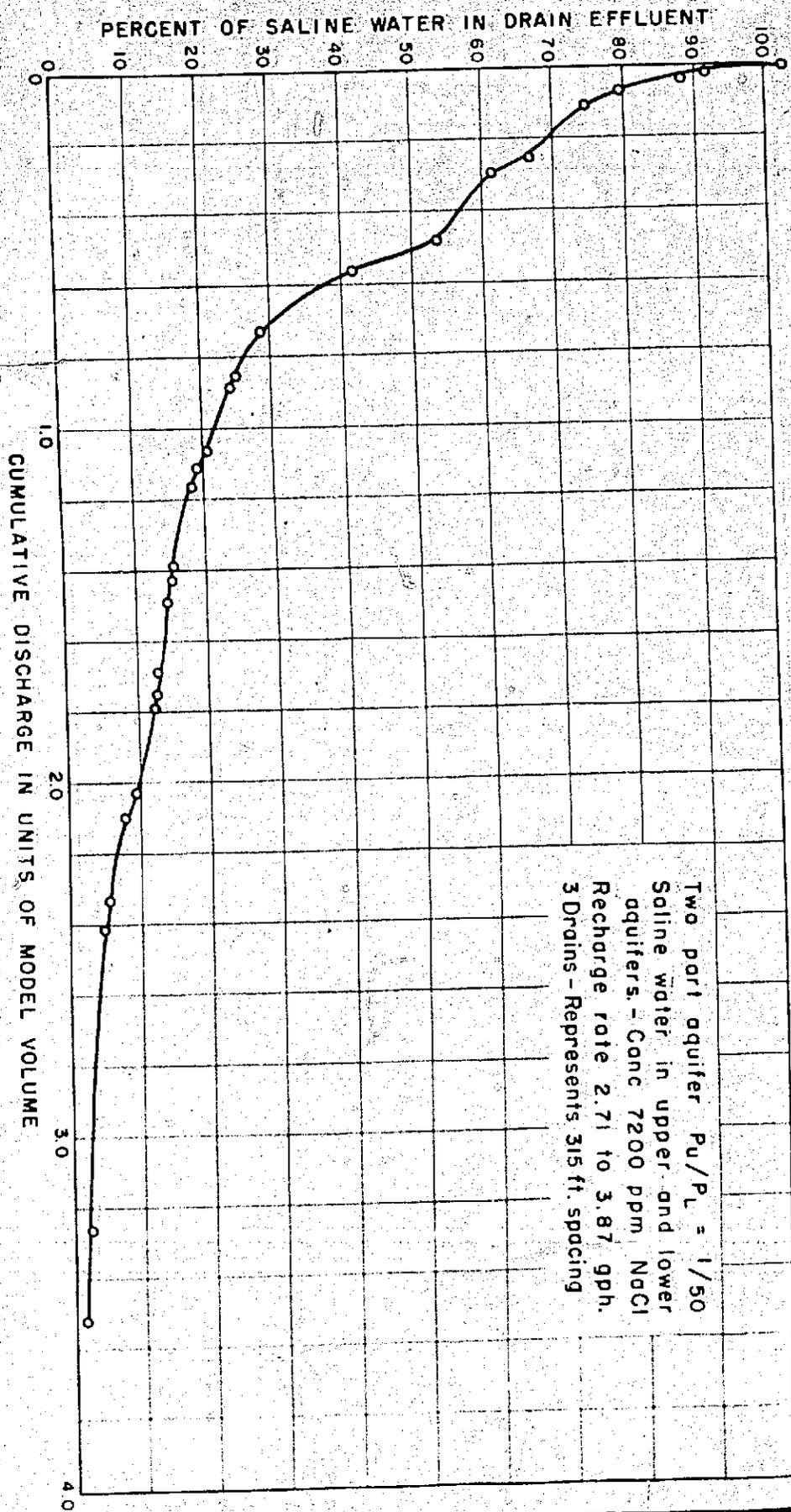
Two part aquifer $P_u/P_L = 1/50$
Saline water to top of lower aquifer.
Concentration = 6490 ppm. NaCl
Recharge rate = 2.93 gph.
| Drain - Represents 1260 ft. spacing

GILA VALLEY
GROUND WATER MODEL
TEST NO. 2



Two part aquifer $P_u/P_L = 1/50$
Saline water to top of lower aquifer.
Concentration = 6200 ppm. NaCl
Recharge rate = 12.76 to 13.35 gph.
3 Drains - Represents 315 ft. spacing

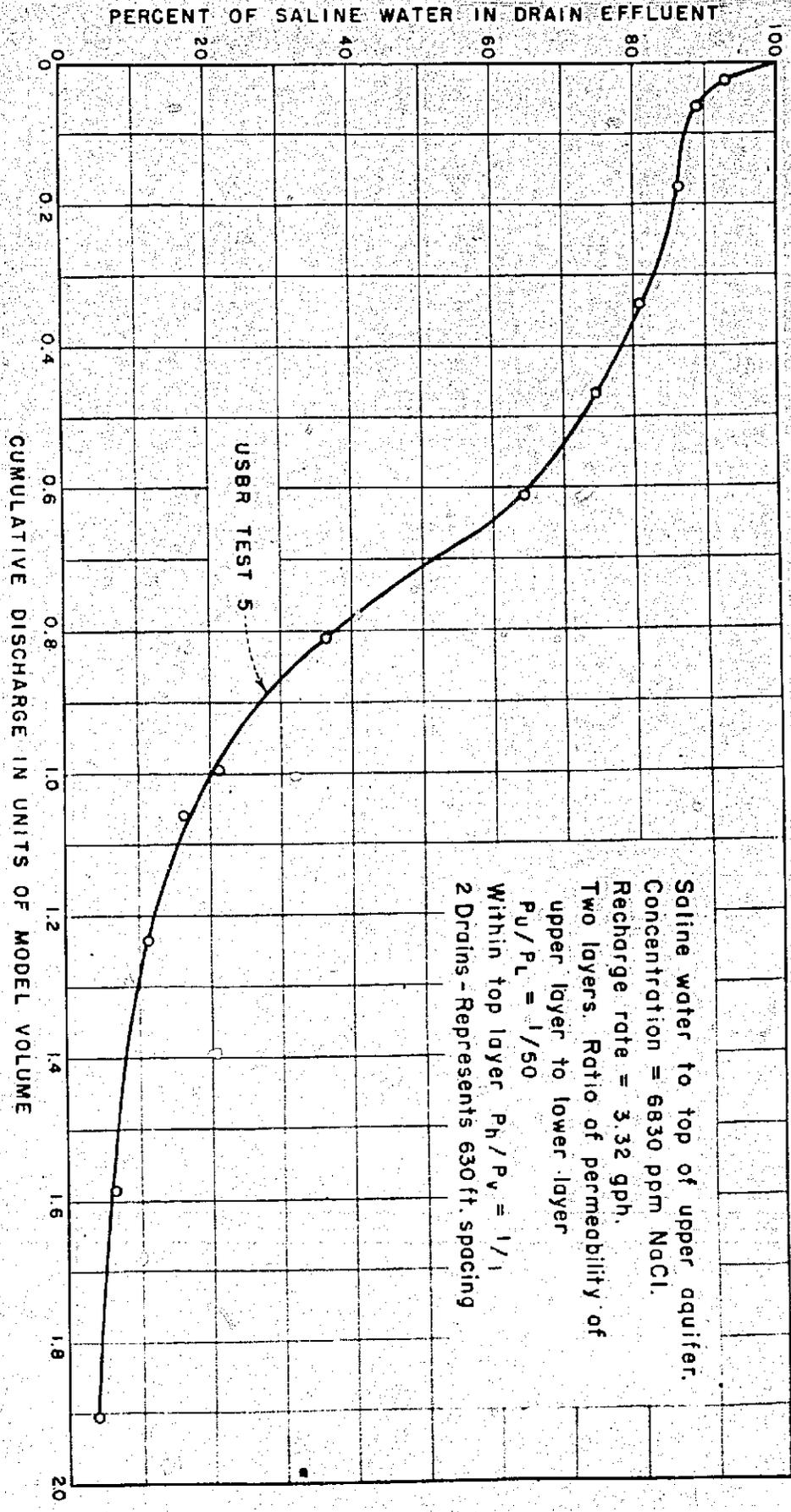
GILA VALLEY
GROUND WATER MODEL
TEST NO 3



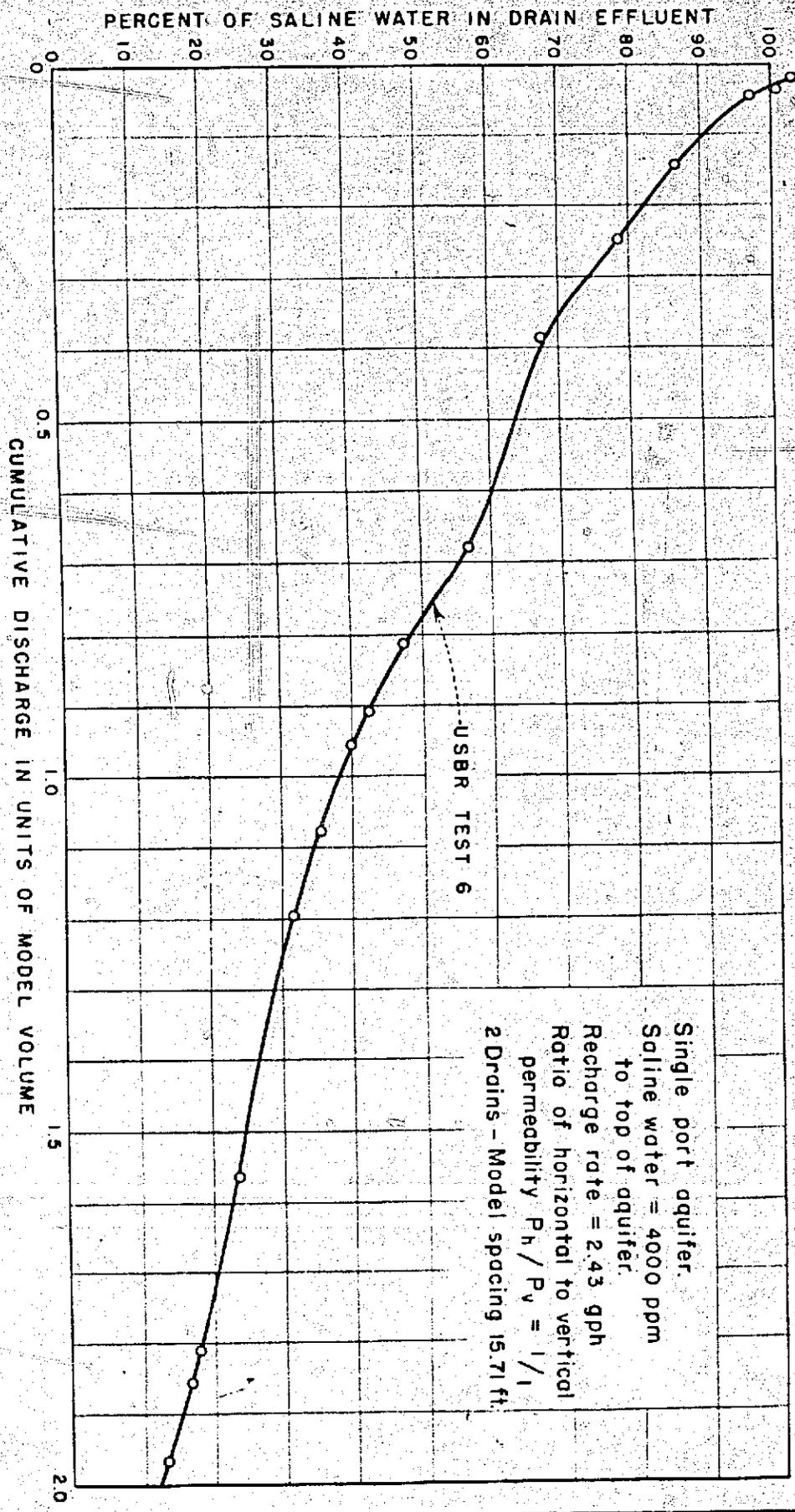
Two part aquifer $P_u/P_L = 1/50$
 Saline water in upper and lower
 aquifers. - Conc 7200 ppm NaCl
 Recharge rate 2.71 to 3.87 gph.
 3 Drains - Represents 315 ft. spacing

GILA VALLEY
 GROUND WATER MODEL
 TEST NO. 4

GILA VALLEY
GROUND WATER MODEL
TEST NO. 5

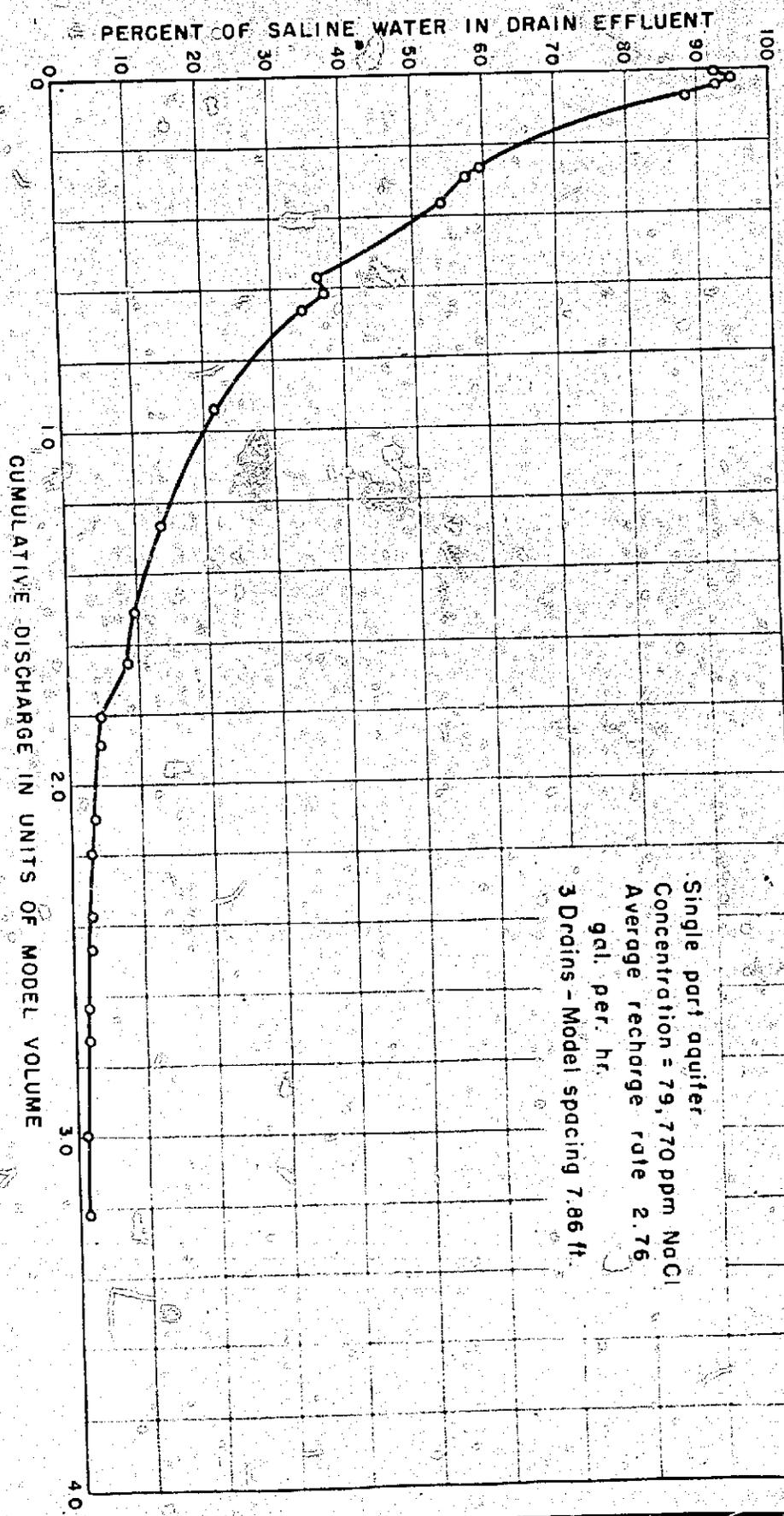


Saline water to top of upper aquifer.
 Concentration = 6830 ppm NaCl.
 Recharge rate = 3.32 gph.
 Two layers. Ratio of permeability of
 upper layer to lower layer
 $P_u/P_L = 1/50$
 Within top layer $P_h/P_v = 1/1$
 2 Drains - Represents 630 ft. spacing



Single port aquifer.
Saline water = 4000 ppm
to top of aquifer.
Recharge rate = 2.43 gph
Ratio of horizontal to vertical
permeability $P_h / P_v = 1/1$
2 Drains - Model spacing 15.71 ft.

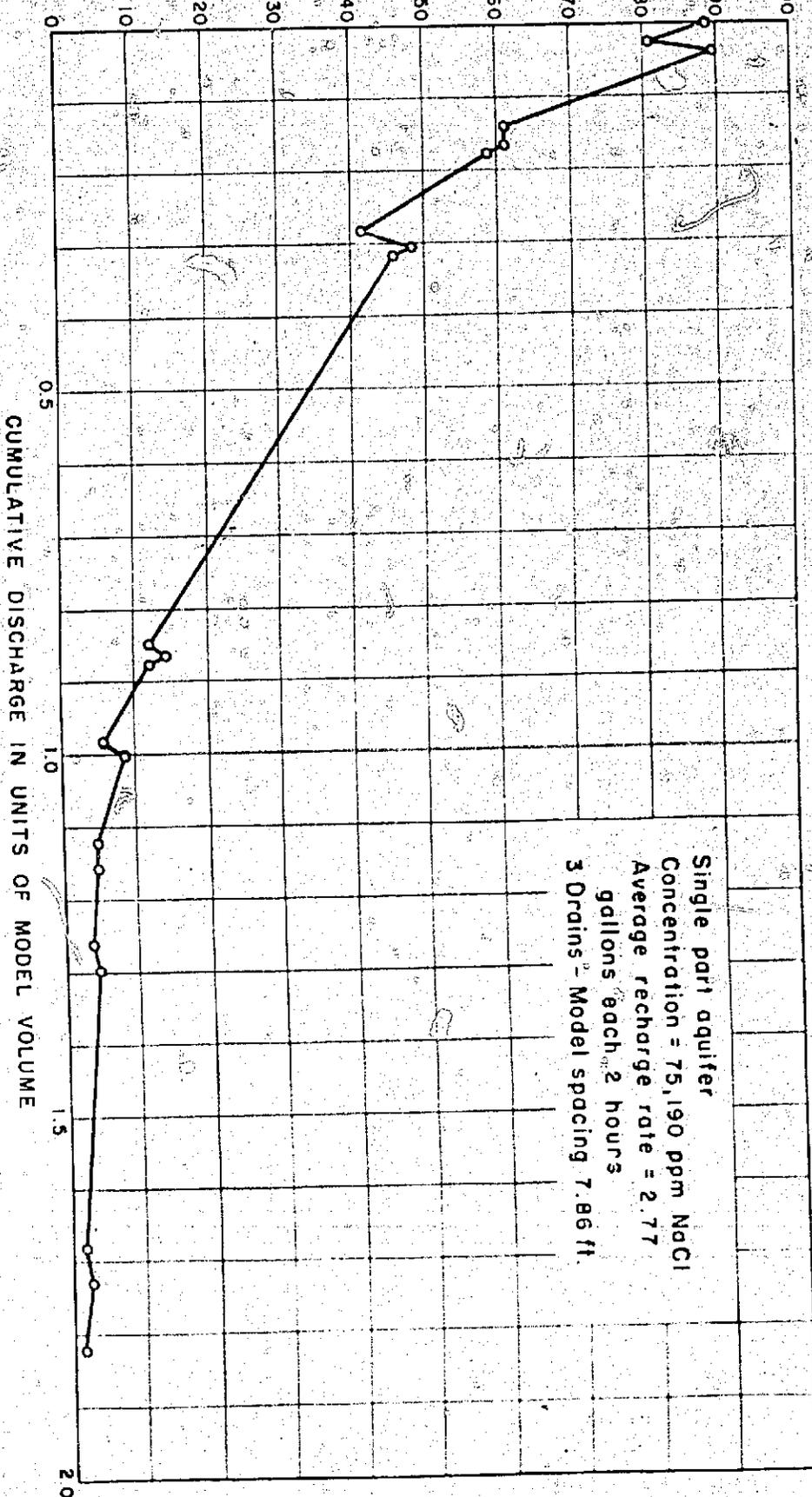
GILA VALLEY
GROUND WATER MODEL
TEST NO. 6



Single part aquifer
 Concentration = 79,770 ppm NaCl
 Average recharge rate 2.76
 gal. per hr.
 3 Drains - Model spacing 7.86 ft.

GILA VALLEY
 GROUND WATER MODEL
 TEST NO. 7

PERCENT OF SALINE WATER IN DRAIN EFFLUENT



Single part aquifer
 Concentration = 75,190 ppm NaCl
 Average recharge rate = 2.77
 gallons each 2 hours
 3 Drains - Model spacing 7.86 ft

GILA VALLEY
 GROUND WATER MODEL
 TEST NO. 8-1

APPENDIX

Memorandum to Chief Development Engineer and Chief Research Scientist from R. E. Glover, dated November 26, 1963, subject: "A formula for estimating the ultimate position of the interface separating an initially present salt water from a freshening replacement water in a drained aquifer."

Memorandum to Chief, Hydrology Branch, from R. E. Glover, dated April 17, 1964, subject: "Pattern of aquifer sweetening where tile drains are installed."

Memorandum

Denver, Colorado

To: Chief Development Engineer
Chief Research Scientist

Date: November 26, 1963

From: R. E. Glover

Subject: A formula for estimating the ultimate position of the interface separating an initially present salt water from a freshening replacement water in a drained aquifer

Purposes

A study of the mechanics of aquifer sweetening has been initiated to provide information on the changes which follow the installation of drains in an originally salinized area. Of particular concern is the quality of the drain effluent and its changes with time and the part of the original saline water which may be left in storage. Experiments are being conducted in a glass-walled tank, and the experimental work is being supplemented by analyses which will permit a correlation of the laboratory data and an extension to other conditions. The development described here relates to the terminal state reached when the movement of the saline water has ceased below an interface separating the saline and fresh waters. The saline waters below the interface may remain in storage for long periods of time.

Definition of Salt Storage

It will be well to clarify here what will be intended by the statement that salt will be left in storage. In any given case, a number of mechanisms will contribute to removal of the salt originally present in an aquifer prior to the installation of drains. Some of these mechanisms will be very slow compared to others. Among these slow mechanisms may be listed molecular diffusion, diffusion of salt water across an interface due to a bodily movement of the interface and the like. In the early phases of the salt removal an interface develops between the original saline waters and the incoming replacement waters, and the replacement waters push the saline waters ahead of them to the drain. This is a relatively fast mechanism and comes to the end of its activity when the interface reaches a stable configuration in which the saline water below the interface becomes stagnant. The saline water below the stable position of the interface is assumed to be retained in storage because the mechanisms which then come into play act very slowly. Actually, all of the salt will ultimately be removed from the aquifer; but, after the first phase comes to an end, the sweetening process is complete for practical purposes.

The Ghyben-Herzberg Principle

It has been known since the time of W. Badon-Ghyben and A. Herzberg who published the results of their discoveries in the years 1889 and 1901, respectively, that lenses of fresh water are present in many coastal areas which exhibit the property that for each foot of elevation maintained above sea level in a water table receiving infiltrating rain waters there will be 40 feet of fresh water below sea level. Recent analytical studies have disclosed the reason for this important relationship [1]. The sea water below the interface is stagnant and the fresh water above it is flowing. The difference in static pressures due to the difference in densities must be made up by the head sustaining the flow on the fresh water side of the interface. Sea water has a salinity of about 35,000 parts per million and a density of about 1.025. The difference in density is 0.025, and this will require 1 foot of water table elevation above sea level for each 40 feet of fresh water below sea level to maintain equilibrium.

Salt Storage

It must be expected that the Ghyben-Herzberg principle will operate also in the case of drainage by tile. Here the infiltration from irrigation replaces the rainfall infiltration and the drain replaces the coastline. The ultimate position of the interface will be determined by the drain spacing, the infiltration rate, the permeability, and the density difference between the saline and replacement waters. The relations will be as shown on Figure 1. The quantity m has the value

$$m = \left(\frac{1}{\gamma_s - \gamma_r} \right) \dots \dots \dots (1)$$

where

γ_s represents the density of the saline water

γ_r represents the density of the replacement water.

Development of Formulas

Where the flow to unit length of drain q is sustained by an infiltration rate i ,

$$q = i \left(\frac{L}{2} - x \right) . \quad \dots \dots \dots (2)$$

Where L represents the drain spacing, in terms of the permeability K and the gradient $\frac{dh}{dx}$ the flow is also expressed by.

$$q = K(1 + m) h \frac{dh}{dx} . \quad \dots \dots \dots (3)$$

When q is eliminated from these expressions, the following differential equation is obtained:

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

By integration, with $h = h_0$ when $x = 0$

$$\frac{h^2}{2} = \frac{-i \left(\frac{L}{2} - x \right)^2}{2(1 + m) K} + \frac{iL^2}{8(1 + m) K} + \frac{h_0^2}{2} \quad \dots \dots \dots (5)$$

or

$$h = \sqrt{\frac{iL^2}{4(1 + m) K} - \frac{i \left(\frac{L}{2} - x \right)^2}{(1 + m) K} + h_0^2} . \quad \dots \dots \dots (6)$$

In most cost cases h_0 will be zero. This is the formula defining the ultimate position of the interface between the saline and replacement waters. Consistent units are used throughout.

Example

Use of the formulas described above will be illustrated by applying them to a laboratory test arrangement.

Consider the laboratory test conditions provided by a glass-walled tank 15.72 feet long and 2.5 feet wide filled to a depth of 2 feet with sand having a permeability of 0.000533 ft/sec. An essentially pure water is supplied at a rate of 2 gallons per hour. The saline water originally in the sand has a salinity of 71,500 ppm.

A drain is placed at each end of the tank at a depth of 0.2 foot below the upper surface of the sand, and an additional drain is placed at the center. Computation of the position of the interface is made in the manner shown below.

Table 1

Computation of the Ultimate Position
of the Interface between Saline and Fresh
Water in a Sand Model

$$L = 7.86 \text{ ft} \quad K = 0.000533 \text{ ft/sec} \quad m = 20.0 \quad i = 1.89 \times 10^{-6} \text{ ft/sec}$$

$\left(\frac{x}{L}\right)$	$\sqrt{1 - \left(1 - \frac{2x}{L}\right)^2}$	$\frac{h}{\text{(feet)}}$	$\frac{mh}{\text{}}}$
0.0	0.000	0.0000	0.000
0.1	0.600	0.0307	0.614
0.2	0.800	0.0408	0.816
0.3	0.917	0.0468	0.936
0.4	0.980	0.0500	1.000
0.5	1.000	0.0511	1.020

$$\sqrt{\frac{iL^2}{4(1+m)K}} = \sqrt{\frac{(1.89)(10)^{-6}(7.86)^2}{(4)(21.0)(0.000533)}} = \sqrt{\frac{(116.8)(10)^{-6}}{0.0448}} = 0.0511$$

The position of the interface is shown graphically on Figure 2.

Comments

The present status of the analytical work is that a formula for estimating the ultimate position of the interface separating the saline and replacement waters has been developed and subjected to an analytical check. A laboratory test has been initiated to test this formula. Before using the formula for design purposes, it would be very desirable to check it against field observations, but this may be difficult due to lack of available data.

These developments have had the benefit of a check by Messrs. W. T. Moody and E. J. Carlson.

/s/ Robert E. Glover

References

- [1] "The Pattern of Fresh Water Flow in a Coastal Aquifer," by R. E. Glover, Journal of Geophysical Research, Vol. 64, No. 4, April 1959.

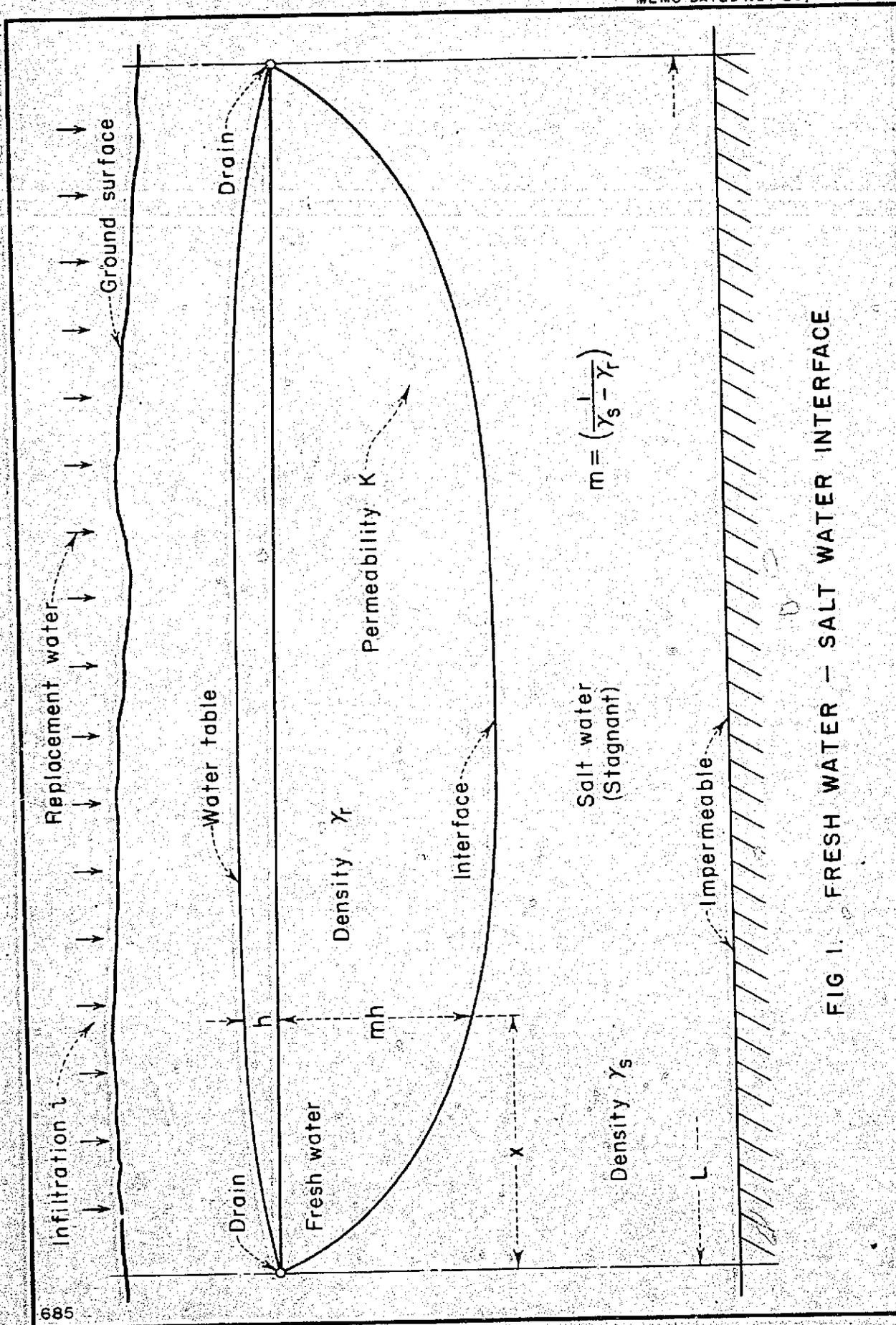


FIG 1. FRESH WATER - SALT WATER INTERFACE

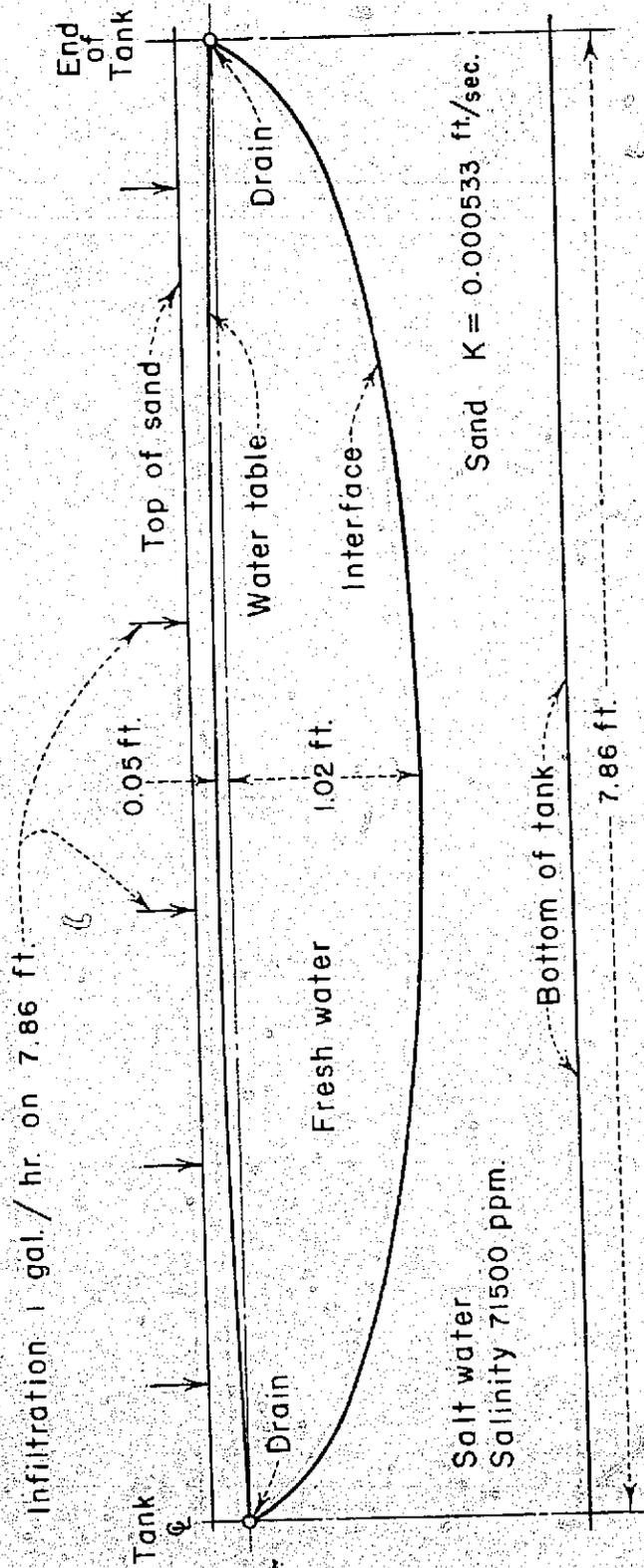


FIG 2. ESTIMATED POSITION OF INTERFACE FOR SAND MODEL EXPERIMENT.

Memorandum

To: Chief, Hydrology Branch

Denver, Colorado

Date: April 17, 1964

From: R. E. Glover

Subject: Pattern of aquifer sweetening where tile drains are installed

Purposes

When tile drains are installed to provide drainage of an aquifer which contains saline waters, it becomes important to evaluate the quality of the drain effluent because it may contribute to the flow of a stream whose salt content is already high. The mechanics of aquifer sweetening has been made the subject of a laboratory investigation. An analytical investigation has also been made to determine the ultimate position of the interface separating the replacement water from the residual saline water, and this determination has been correlated with the laboratory findings. It remains to evaluate the pattern of effluent salinity as a function of time after drainage begins.

It is the purpose of the developments described herein to evaluate the changes of salinity of the drainage water with time.

References

Reference is made to the following:

Hydraulic Laboratory Report No. 520--Progress Report No. 1--
Laboratory investigation of the removal of salt water from
a two-part aquifer using tile drains installed in the upper
member, June 27, 1963

Memorandum to Chief, Hydrology Branch, from R. E. Glover on
the subject "A formula for estimating the ultimate position
of the interface separating an initially present salt water
from a freshening replacement water in a drained aquifer,"
dated September 19, 1963

Rate of Aquifer Sweetening--One-Part Aquifer

The laboratory and analytical investigations described in the above references disclose that a stable interface ultimately forms between the freshening replacement waters and a remnant of the originally present saline waters. Below this interface the remaining salt water is stagnant while the replacement waters above the interface are flowing to the drain. All of the saline waters

originally present in the aquifer above the position of this final stable interface are removed. The removal occurs over an extended period of time during which the quality of the drain effluent gradually improves.

As a first step toward an evaluation of the sweetening process it is necessary to estimate the amount of saline water to be removed. On page 4 of the memorandum of September 19, 1963, the height of the water table mound is given by the expression:

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

where

h represents the height of the water table above the level of the drains (feet)

i the infiltration rate of the replacement waters (ft/sec)

K the permeability of the aquifer, supposed to be uniform and homogeneous (ft/sec)

$$m = \left(\frac{1}{\gamma_s - \gamma_r}\right) \dots \dots (2)$$

where γ_s and γ_r are the densities of the saline and replacement waters, expressed as a ratio to the density of pure water taken as unity (dimensionless)

L the distance between drains (feet)

x a distance measured from one drain toward the other (feet)

In addition, let

$q = \frac{1L}{2}$ represents the flow of drainage water per foot of drain from one side (ft²/sec)

- s the salinity of the drain effluent in excess of that of the replacement water expressed as a ratio of the weight of the solute to the weight of the solution (dimensionless)
- s₀ an initial salinity concentration (dimensionless)
- t time (seconds)
- V the ratio of the voids to the gross volume in any portion of the aquifer (dimensionless)
- W the volume between the plane of the drains and the ultimate position of the interface per unit length of drain (ft²)
- Ww the volume of water in the volume W (ft²)
- u a variable of integration (dimensionless)

Notes:

Gallons per cubic foot 7.4805

Pounds of water per gallon 8.341

1 cubic foot per second is equivalent to 448.8 gallons per minute or 7.480 gallons per second

By the Ghyben-Herzberg principle, the depth of replacement water below the level of the drains when the interface has reached its ultimate stable position is mh .

Then

$$W = \int_0^L mh \, dx \dots \dots \dots (3)$$

or

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

By introducing the change of variable

$$u = \left(1 - \frac{2x}{L}\right) \quad du = -\frac{2}{L} dx \quad \dots \dots (5)$$

The above expression takes the form

$$W = \frac{mL^2}{4} \sqrt{\frac{1}{(1+m)K}} \int_{-1}^{+1} \sqrt{1-u^2} du \quad \dots \dots (6)$$

Since

$$\int_{-1}^{+1} \sqrt{1-u^2} du = \frac{1}{2} \left[u \sqrt{1-u^2} + \sin^{-1} u \right]_{-1}^{+1} = \frac{\pi}{2}, \dots \dots (7)$$

it follows that

$$W = \frac{mL^2}{8} \sqrt{\frac{1}{(1+m)K}} \quad \dots \dots (8)$$

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

$$\frac{ds}{dt} + \frac{2qs}{VW} = 0 \quad \dots \dots (9)$$

This is a differential equation whose solution is

$$s = s_0 e^{-\frac{2qt}{VW}} \quad \dots \dots (10)$$

where s_0 represents the salinity at the time $t = 0$. The factor 2 appears in this expression because of the assumption that the drainage flow passes to two drains.

Rate of Aquifer Sweetening--Two-Part Aquifer

In the case of a two-part aquifer where the lower member has a much higher permeability than the upper member, some modification of the procedures outlined above must be made. These will be best illustrated by examples based upon the performance of the laboratory model.

Correlation with Laboratory Test Data

Laboratory Test No. 7 was performed with a one-part aquifer, that is, with an aquifer of one material from top to bottom. The expressions (1) to (10) apply without modification to this condition. The tank used for this test was 15.72 feet long and 2.5 feet wide. It was filled to a depth of 2.0 feet with a sand having a permeability $K = 0.000533$ ft/sec. There was a drain at each end of the tank and one in the middle. These were placed 0.2 foot below the top of the sand. With this arrangement the drain spacing was $L = 7.86$ feet. The effective voids ratio was taken as 0.35. Water was supplied at the rate of 2.76 gallons per hour. This is equivalent to 0.3689 cubic feet per hour. Then

$$i = \frac{0.3689}{(3,600)(2.5)(15.72)} = (2.6078)(10)^{-6} \text{ ft/sec.}$$

Before the test began the sand was filled to the top with a solution containing 78,000 parts per million of salt by weight based upon the solution. The density of such a solution is 1.055. The replacement water had a salt (sodium chloride) content of only about 6 parts per million. Then, from expression (2)

$$m = \frac{1}{(1.055 - 1.000)} = 18.182$$

and

$$\sqrt{\frac{i}{(1+m)K}} = \sqrt{\frac{(2.6078)(10)^{-6}}{(19.182)(0.000533)}} = 0.01643 \text{ (dimensionless)}$$

From formula (8)

$$W = \frac{mrL^2}{8} \sqrt{\frac{1}{(1+m)K}} = \frac{(18.182)(3.1416)(7.86)^2(0.01643)}{8} = 7.247$$

and the volume of saline water to be removed over the 7.86-foot spacing is

$$VW = (0.35)(7.247) = 2.536 \text{ ft}^2 .$$

The flow to each drain from one side is

$$q = \frac{0.3689}{(4)(2.5)(3,600)} = 10.248(10)^{-6} \text{ ft}^2/\text{sec}$$

and

$$\frac{2q}{VW_1} = \frac{2(10.248)(10)^{-6}}{3.086} = (6.642)(10)^{-6} .$$

Here the saline water above the drains in amount

$(7.86)(0.2)(0.35) = 0.550 \text{ ft}^2$ has been included in the amount of saline water to be removed. The total is

$2.536 + 0.550 = 3.086 \text{ ft}^2$. The computation of the drain salinity as a function of time is shown in Table 1 below.

Table 1

Computation of Saline Content
of Drainage Water for Laboratory Test No. 7

<u>Time</u> <u>hours</u>	<u>Time</u> <u>days</u>	<u>Time</u> <u>seconds</u>	$\frac{2ct}{VW}$	$e - \frac{2ct}{VW}$	<u>s</u> <u>(ppm)</u>
0		0	0	1.0000	78,000
1		3,600	0.024	0.9763	76,200
2		7,200	0.048	0.9531	74,300
6		21,600	0.143	0.8668	67,600
12		43,200	0.287	0.7505	58,500
24	1	86,400	0.574	0.5633	43,900
48	2	172,800	1.148	0.3173	24,700
72	3	259,200	1.722	0.1787	15,900
144	6	518,400	3.443	0.0304	2,400

These values are compared to the test values by plotting them on Figure 1. The correlation of observed and computed values is considered good.

Test No. 5 was made with a two-part aquifer. The upper member was of fine sand, was 1.0 foot in depth, and had a permeability of 0.000533 ft/sec. The lower member composed of a coarse sand or fine gravel was also 1.0 foot thick and had a permeability of about 0.0294 ft/sec. To prepare for the test, water having 6,835 parts per million of sodium chloride and 100 ppm of potassium chloride was used to saturate the model sands up to the top of the upper sand. Fresh water was then applied at the rate of 3.32 gallons per hour, of which 1.87 gallons per hour passed out of Drain A and 1.45 gallons per hour passed out of Drain B. These two drains were in the ends of the tank. There was no central drain so that the distance between drains was, in this case, 15.72 feet. A blue dye was placed in the saline water so that its behavior could be observed through the glass walls of the tank.

Observations made during the progress of this and of previous tests indicate that, for the most part, the applied water moves directly downward to the lower gravel bed, moves horizontally along it, and then moves upward to the drain through a narrow zone of the upper bed. This zone is contained approximately within a quadrant of a circle having its center at the top of the gravel layer directly below the drain. The circle passes through the drain location. Waters applied directly above these quadrants flow to the drain through the upper layer. The remaining waters go downward to the gravel layer and flow to the drain within the quadrant.

Under these conditions it may be expected that saline water of the original concentration will flow to the drains until the interface between the saline and replacement water reaches the upper surface of the gravel layer. After this happens fresh water will begin to move to the drain and an improvement in the quality of the effluent can be expected.

The application rate of 3.32 gallons per hour or 0.444 cubic feet per hour will maintain an infiltration rate of

$$i = \frac{(0.444)}{(3,600)(15.72)(2.5)} = \frac{0.444}{141,480} = (3.140)(10)^{-6} \text{ ft/sec .}$$

The time required for the interface to traverse the 1.0-foot thickness of the upper bed is

$$\frac{(1.0)(0.35)}{(3.140)(10)^{-6}} = 111,500 \text{ seconds}$$

or

31 hours

or

1.29 days .

With salinity of this concentration and a drain spacing long compared to the depth of the aquifer, it is to be expected that substantially all of the saline water will be removed. However, after the interface reaches the top of the lower bed, only about half of the original salinity remains since, in this model, the upper and lower members are of equal thickness. Then it will be reasonable to take

$$W = (1.0)(15.72) = 15.72 \text{ ft}^2$$

and

$$W = (0.35)(15.72) = 5.502 \text{ ft}^2$$

with a corresponding average drain flow of

$$q = \frac{3.32}{2.50} = 1.328 \text{ gallons per hour per foot}$$

or

$$(49.31)(10)^{-6} \text{ ft}^2/\text{sec} .$$

Then

$$\frac{2q}{W} = \frac{(49.31)(10)^{-6}}{5.502} = (8.962)(10)^{-6} \text{ 1/sec} .$$

The following computation is based upon times beginning when the interface reaches the lower bed.

Table 2

Computation of the Salinity
of Drainage Water for Test No. 5

<u>Time</u> <u>hours</u>	<u>Time</u> <u>days</u>	<u>Time</u> <u>seconds</u>	$\frac{2qt}{W}$	$e - \frac{2qt}{W}$	S (ppm)
0		0	0	1.0000	6,835
1		3,600	0.032	0.9685	6,620
2		7,200	0.064	0.9380	6,410
6		21,600	0.194	0.8236	5,629
12		43,200	0.387	0.6791	4,642
24	1	86,400	0.774	0.4612	3,152
48	2	172,800	1.549	0.2125	1,452
72	3	259,200	2.323	0.0980	670
144	6	518,400	4.646	0.0097	66

and

$$VW = (0.35)(15.72) = 5.502 \text{ ft}^2$$

with a corresponding average drain flow of

$$q = \frac{3.32}{2.50} = 1.328 \text{ gallons per hour per foot}$$

or

$$(49.31)(10)^{-8} \text{ ft}^2/\text{sec} .$$

Then

$$\frac{2q}{VW} = \frac{(49.31)(10)^{-8}}{5.502} = (8.962)(10)^{-8} \text{ 1/sec} .$$

The following computation is based upon times beginning when the interface reaches the lower bed.

Table 2

Computation of the Salinity
of Drainage Water for Test No. 5

<u>Time</u> <u>hours</u>	<u>Time</u> <u>days</u>	<u>Time</u> <u>seconds</u>	$\frac{2qt}{VW}$	$e^{-\frac{2qt}{VW}}$	<u>S</u> <u>(ppm)</u>
0		0	0	1.0000	6,835
1		3,600	0.032	0.9685	6,620
2		7,200	0.064	0.9380	6,410
6		21,600	0.194	0.8236	5,629
12		43,200	0.387	0.6791	4,642
24	1	86,400	0.774	0.4612	3,152
48	2	172,800	1.549	0.2125	1,452
72	3	259,200	2.323	0.0980	670
144	6	518,400	4.646	0.0097	66

The results of these computations are compared with the test results on Figure 2.

Test No. 2 was performed on a two-part aquifer. The upper member consisted of fine sand having a permeability of 0.000533 ft/sec. The lower member was composed of a fine gravel with a permeability of 0.0294 ft/sec. Both members had a thickness of 1.00 foot. The salt solution containing 6,497 ppm of sodium chloride and 112 ppm of potassium chloride was originally present only in the lower member. There was only one drain at the end of the tank so that the equivalent drain spacing was $(2)(15.72) = 31.44$ feet.

The supply of replacement water averaged 3.171 gal/hr for the first 4 days. Details of the observations are shown on Figure 3.

For a tank width of 2.5 feet and a supply rate of 3.171 gallons per hour or 0.000178 cubic foot per second,

$$q = \frac{0.000178}{2.5} = (47.1)(10)^{-6} \text{ ft}^2/\text{sec}$$

$$\frac{2q}{VW} = \frac{(2)(47.1)(10)^{-6}}{(0.35)(15.72)(2)} = \frac{(94.2)(10)^{-6}}{11.004} = (8.560)(10)^{-6}$$

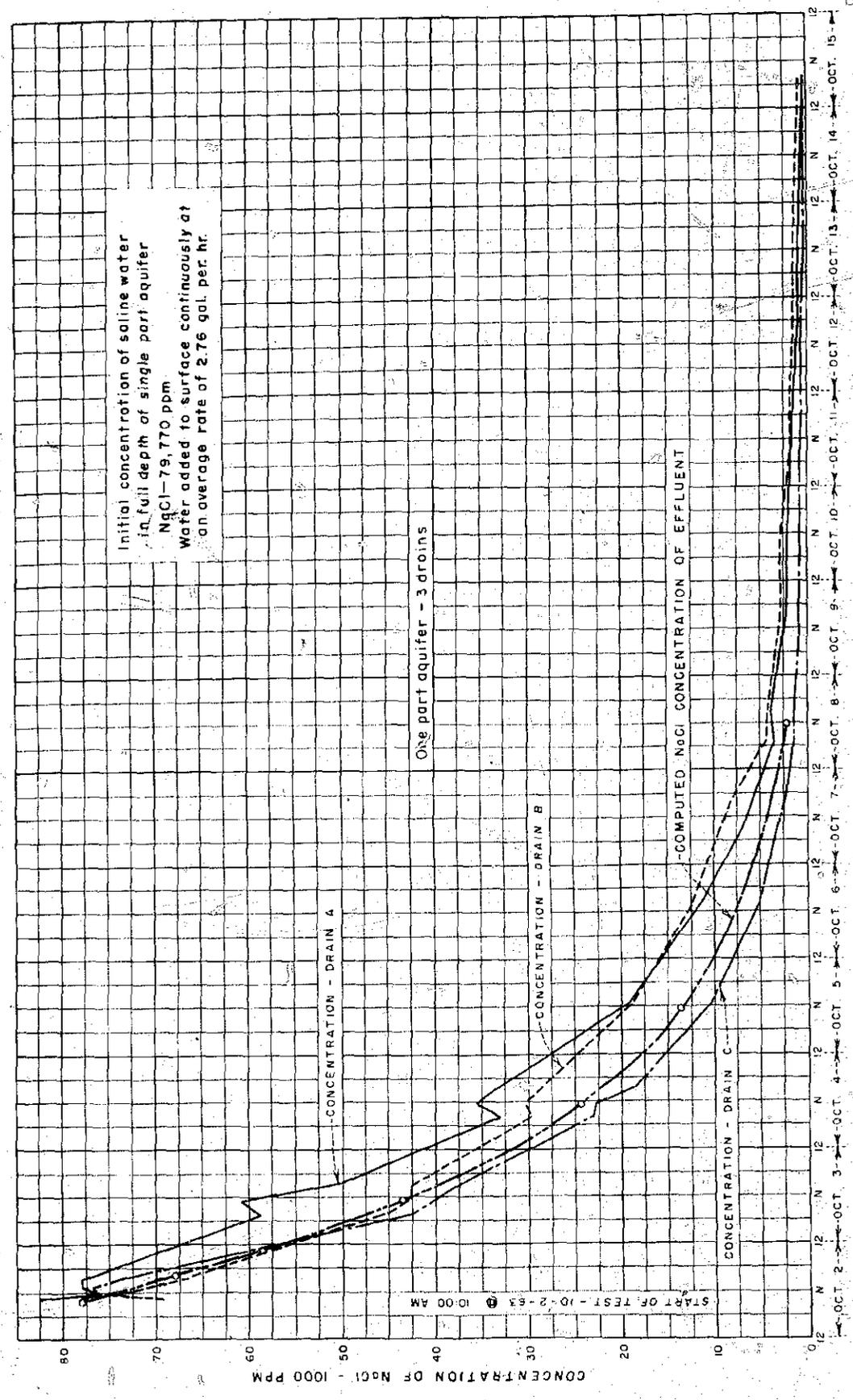
The computation of the salinity of the drain effluent is shown in Table 3.

Table 3

Computation of Saline Content
of Drainage Water for Laboratory Test No. 2

<u>Time</u> <u>hours</u>	<u>Time</u> <u>days</u>	<u>Time</u> <u>seconds</u>	$\frac{2qt}{VW}$	$\frac{e - \frac{2qt}{VW}}{e}$	<u>s</u> <u>(ppm)</u>
0		0	0	1.0000	6,497
1		3,600	0.0308	0.9697	6,300
2		7,200	0.0616	0.9402	6,108
6		21,600	0.185	0.8311	5,400
12		43,200	0.370	0.6907	4,487
24	1	86,400	0.740	0.4771	3,100
48	2	172,800	1.479	0.2278	1,480
72	3	259,200	2.219	0.1087	706
96	4	345,600	2.958	0.0519	337

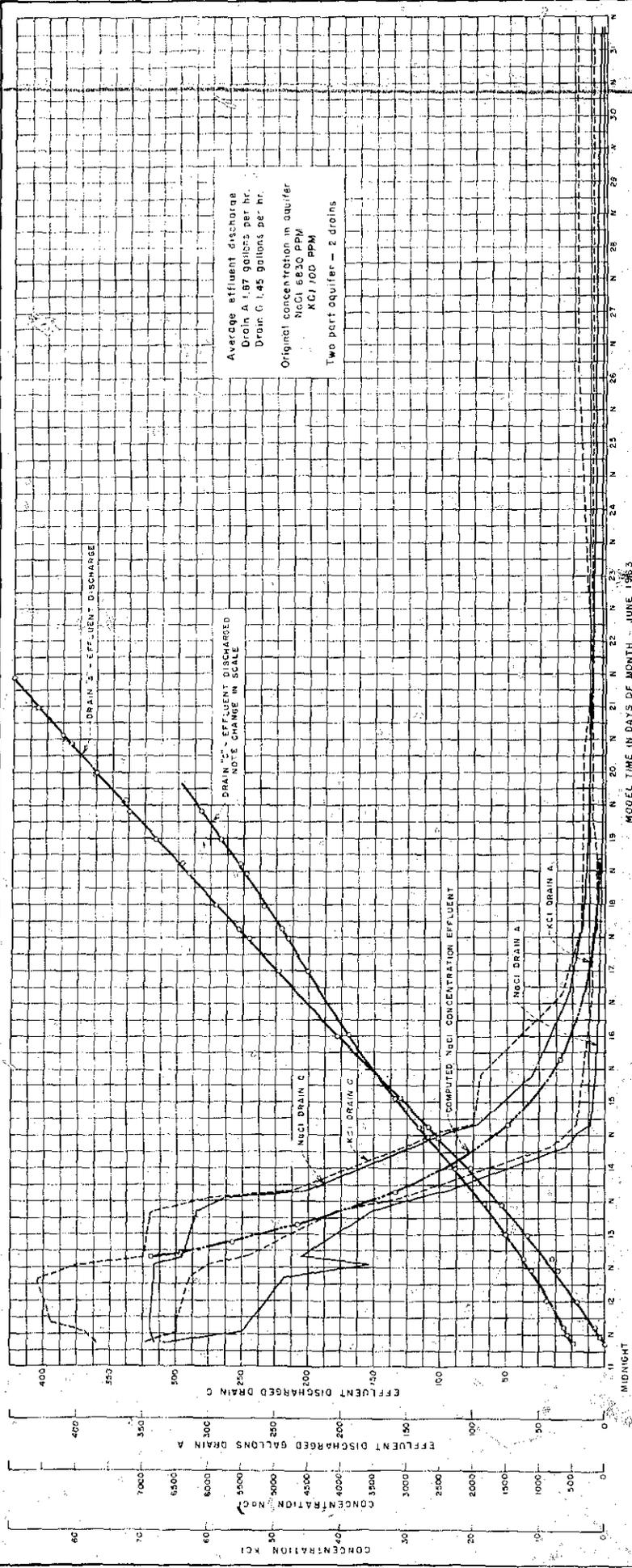
/s/ Robert E. Glover



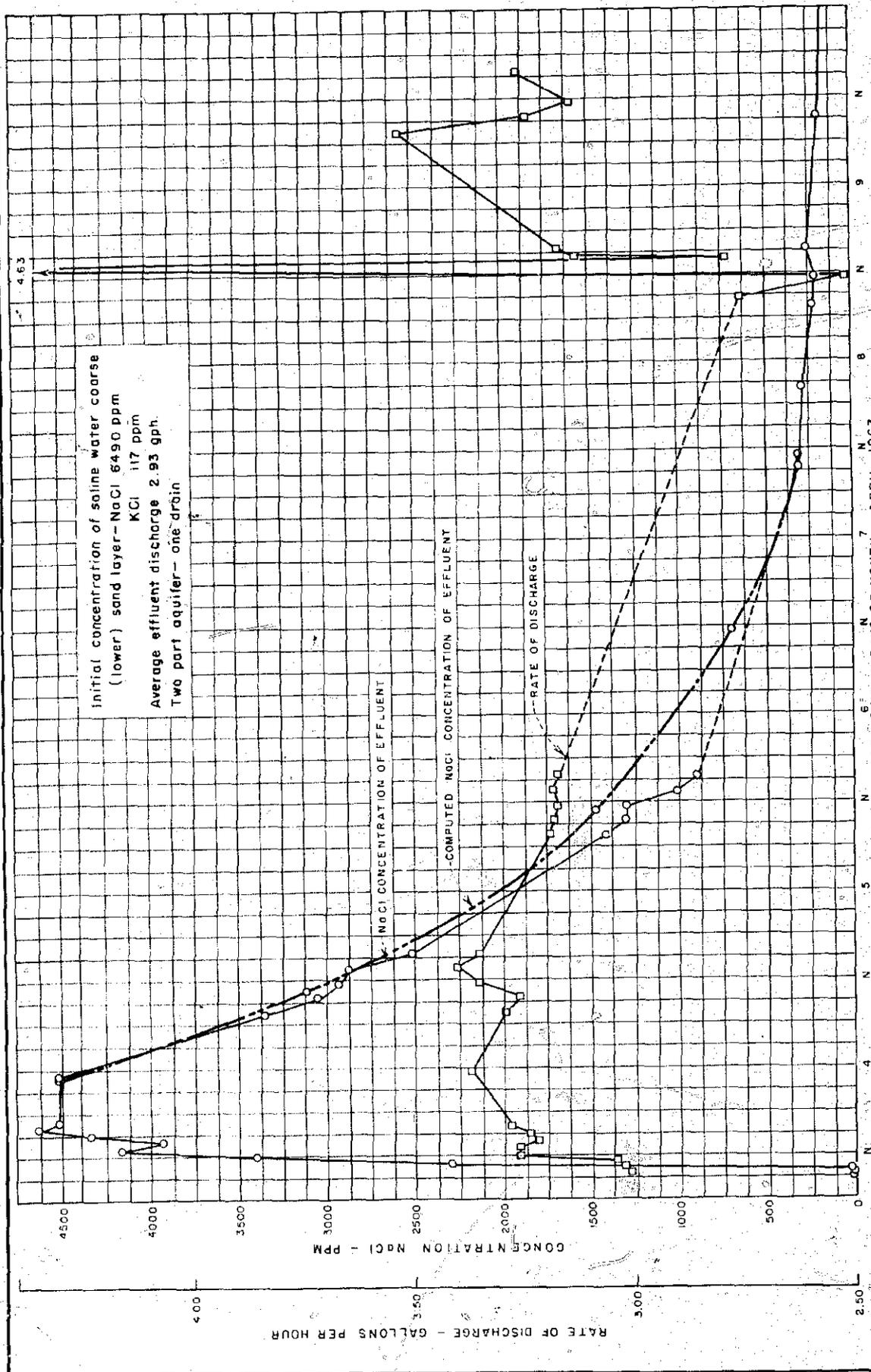
GILA VALLEY
GROUND WATER MODEL
TEST NO 7

FIGURE 2

APPENDIX REPORT NO. 14-1
GROUNDWATER MODEL



GILA VALLEY
GROUND WATER MODEL
TEST NO. 5



GILA VALLEY
GROUND WATER MODEL
TEST NO. 2