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TRICKLE IRRIGATION SALINITY PATTERNS AS INFLUENCED BY IRRIGATION LEVELS AND APPLICATION RATES

Philip David Tscheschke

Utah State University

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UTAH STATE UNIVERSITY
Logan, Utah

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by

Philip David Tscheschke

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Irrigation Engineering

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Philip D. Tscheschke

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ABSTRACT

Trickle Irrigation Salinity Patterns as Influenced

by Irrigation Levels and Application Rates

by

Philip D. Tscheschke, Master of Science

Utah State University, 1973

Thesis Director: Dr. Jose F. Alfaro
Department: Agricultural and Irrigation Engineering

An experiment was conducted in a greenhouse using cherry tomatoes to determine the effect which different irrigation treatments have on the distribution of salts and water within the soil profile under trickle irrigation. The four different treatments were: alternate day irrigations 13 percent under, equal to, and 20 percent over the evapotranspiration and daily irrigation equal to the evapotranspiration. The tomatoes were planted in eight lysimeters, which provided one replication of each irrigation treatment used. Two-dimensional contour patterns are reported for both the saturation extract conductivity and soil water potential of the soil profile between two lines of emitters. Differences between irrigation treatments are noted, and recommendations are made concerning the application of the results to the management of trickle irrigation systems.

(128 pages)

INTRODUCTION

In the last several years the trickle irrigation method has gained considerable momentum in its development and use in irrigated agriculture. One of several advantages cited by its promoters is that because the trickle method maintains high matric potentials, crops may be successfully grown using relatively high saline water, thus allowing lower salinity or osmotic potentials without plant damage. Also trickle irrigation with saline water has a marked advantage over sprinkler irrigation because there is no contact between the irrigation water and the leaves to cause leaf burn to sensitive crops.

In spite of the obvious short term advantage of being able to use saline water with the trickle method, the possible long term effects of salination resulting from the inherent limitations in the leaching patterns of emitters is of some concern, especially in arid zones of light rainfall.

It was the objective of this experiment to study the salt accumulation patterns in the soil profile in relation to different trickle irrigation treatments. A study was made of the relationship between amount of irrigation and the resulting salinity patterns in the soil profile. Three of the treatments were alternate day irrigations: 13 percent under the evapotranspiration (ET), equal to the ET, and 20 percent over the ET. In addition, a fourth treatment consisted of a daily irrigation equal to the

ET at a rate nearly seven times slower than the alternate day irrigation treatments.

REVIEW OF LITERATURE

Some work studying the salinity patterns which develop under a trickle irrigation system has been done in Israel.

Goldberg and Shmueli (1970) examined the salinity profile in a young vineyard growing on a sandy loam soil after two years of irrigation by a trickle system. The irrigation water had an electrical conductivity of 3 mmhos/cm. An irrigation interval of 1 to 3 days was used. No mention was made of how the amount of irrigation was determined. They found that the soil profile could be divided into three main zones: an upper zone where the salinity increases as the distance from the emitter and soil surface decreases, a wide intermediate zone where the salinity values are low, and a lower zone where the salinity level increases with depth and with the distance from the emitter.

Gornat and Goldberg (1970) reported on a salinity study conducted on young avocado trees irrigated at different frequencies: every day, twice a week, and once a week. The irrigation amounts were based on a uniform water loss for the entire field of 2 mm/day. They found that with larger water applications and greater intervals between irrigations, the wetted zone increased, and the salts accumulated at greater distances from the tree. The salts accumulated mainly in the upper soil layer at some distance from the tree.

Goldberg, Rinot, and Karu (1971) reported on the distribution of salt in a soil profile for a seven year old vineyard after a year of trickle irrigation. The irrigation intervals used were 7.5 and 30 days. The irrigation amounts were determined according to a calculated daily consumptive use. They found an isolated zone of accumulated salts adjoining part of the surface and a second deep level of accumulation. An onion-shaped leached zone was situated between these two layers and beneath the row of emitters. The position of the surface zone was related to the radius of the wetted surface strip which ranged from about 40 cm for the 7.5 day interval to 90 cm in the 30 day treatment.

PROCEDURE

For the study eight lysimeters, thereby providing two replications of each irrigation method, were constructed and installed in a greenhouse. With the lysimeters, the evapotranspiration, drainage, and irrigation amounts were closely regulated. Figure 1 shows the general arrangement of the lysimeters in the greenhouse, and Figure 2 shows a lysimeter with the drainage collector at the bottom of it. The lysimeters were designed to simulate the salinity patterns resulting from two rows of trickle lines on a two dimensional scale.

An indirect monitoring of the salinity and soil water content was made approximately every two weeks during the experiment by using the four probe method and the gamma ray attenuation method respectively.

At the termination of the experiment, soil samples were taken on each lysimeter to provide a direct measure of the salinity and soil water content. This data was then compared with the readings from the indirect methods used to measure salinity and soil water content. This provided a check on the accuracy of the indirect methods used.

Figure 1. Lysimeters installed in the greenhouse

Figure 2. Lysimeter drainage collector

Construction of the lysimeter boxes

The lysimeter boxes were constructed of 1.9 cm (3/4 inch) thick exterior plywood. When in an upright normal operating position, the inside dimensions of the boxes were 122 cm (4 feet) high, 122 cm (4 feet) long, and 21 cm (8.25 inches) wide. To add rigidity to the boxes the edges of the plywood sides were ribed with 5 x 5 cm (2 x 2 inch) boards. The bottom planks were 5 cm (2 inch) thick, 157 cm (4.5 feet) long, and 33 cm (13 inches) wide. The inside of the boxes was water proofed with two coats of Urethane Diamond Plastic Boat Varnish manufactured by Fashion Forcast. The outside was painted with one coat of a white exterior house paint.

For use with the four probe conductivity method explained later in this paper, 121 stainless steel bolts were mounted in one side of each of the boxes in a square grid fashion. The 3.3 x 0.47 cm (1-1/4 x 3/16 inch) bolts were placed in 11 rows of 11 bolts each. The spacing between bolts in the rows or columns was 10 cm (3.9 inches), and the grid was placed 11 cm (4.3 inches) from the outer edges of each side. Each bolt was insulated by means of a 2.2 cm (7/8 inch) length of polyethylene tubing capped with two hard fiber washers to prevent any moisture in the wood from affecting the electrical conductivity readings to be taken later. The slotted round heads of the bolts were placed on the inside surface of the box, with the other end protuding 1.3 cm (1/2 inch) through the outer face of the 1.9 cm (3/4 inch) plywood sides.

In order to visually monitor the root growth two of the lysimeters were constructed with one side made of a 122 x 122 cm (4 x 4 foot) sheet of 0.95 cm (3/8 inch) thick clear plexiglass, in place of plywood.

Soil description

The soil used in the lysimeters was obtained along the route of the Bear River near Cornish, Utah. It was a loamy sand textured soil with 80 percent sand, 11 percent silt and 9 percent clay. The soil had a saturation extract conductivity (KSE) equal to 0.5 mmhos/cm.

Filling the lysimeters

Before filling the lysimeters, the soil was sifted through a 0.64 cm (1/4 inch) mesh screen. The lysimeters were filled while in a horizontal position with the plywood side containing the stainless steel bolts removed. In order to achieve a uniform bulk density of 1.44 grams/cc, the soil was compacted in the lysimeters in four 5.1 cm (2-inch) thick layers. After measuring the water content of the soil, the weight of soil required for each 5.1 cm thick layer was determined. The soil was weighed and placed into the lysimeters in nine piles in a square grid pattern. The soil was then leveled to a uniformly thick layer of approximately 6.4 cm (2-1/2 inches). A 20-liter (5-gallon) closed metal can, filled with water for weight, was rolled over the layer in a crisscrossing strip manner till the layers were compacted to a thickness of 5.1 cm (2 inches). The surface was then roughened and lightly wetted to assure a better continuity between layers, after which the next soil layer was applied. After the fourth layer

was placed and compacted, another loose thin layer of soil approximately 1 cm (3/8 inch) thick was applied. This thin layer of soil provided a good contact surface for the upper side of the box that was then put into place.

Six 0.63 cm (1/4 inch) tie rods were then inserted through the sides and intervening soil in order to prevent the sides from bulging when the lysimeters were in an upright position. The tie rods were tightened until the sides had a separation of 21 cm (8-1/4 inches). The sides were then nailed along their edges to the other two bordering sides and bottom of the lysimeter box.

Description of the weighing apparatus

The principle design of the weighing apparatus for the lysimeters was similar to that developed and tested by Hanks and Shawcroft (1965).

A chain hoist was used to upright the approximately 1/2 ton lysimeters onto water-filled, butyl rubber pillows. In order to prevent the pillows from settling into the earth floor of the greenhouse, 5.1 x 30 cm, 2.1 m (2 x 12 inch, 7 feet) long planks were placed underneath the pillows. The bottom surface of the lysimeters rested on 5 x 15 cm, 1.4 meter (2 x 6 inch, 4-1/2 feet) long planks which gave a constant area of contact with the pillows and made the contact area less dependent upon the degree to which the pillows were filled with water. In this manner all lysimeters had a similar calibration, and also if minor leakage occurred during the season the calibration remained constant.

The valve stem of each butyl rubber pillow was connected by means of buried 0.63 cm (1/4 inch) inside diameter polyethylene tubing to a 2.4-meter, 1.1 cm (8-foot, 7/16 inch) inside diameter glass manometer located on the wall of the greenhouse. The resulting calibration of the manometers was that a 2.5 cm (1 inch) drop in water height corresponded to a water use of 7 liters (1.85 gallons) from the lysimeters. A control manometer, one filled with water and sealed at its lower end, was used to correct for the expansion of water due to daily temperature fluctuations.

The eight lysimeters were located in two rows of four each. The lysimeters were held upright by a horizontal wire attached to the top of one end of each lysimeter and stretched between the north and south walls of the greenhouse. The horizontal wire provided a virtually frictionless support for vertical lysimeter movement.

Description of the drainage system

In the bottom of each lysimeters several 0.95 cm (3/8 inch) holes were drilled to allow free drainage from the boxes. In order to collect the drainage water a 6 mil plastic sheet was placed under the box and above the butyl rubber pillow. The plastic was sloped so water would drain into a glass bottle located at each side of the lysimeter as shown in Figure 2. The contents of the bottles were measured and emptied daily.

Description of the irrigation system

The boxes were watered from overhead bottles placed 0.75 meters (2-1/2 feet) above the top of the lysimeters as illustrated in Figure 1. Tubes, open to the atmosphere and running to within 2.5 cm (1 inch) of the bottom, were inserted into the air tight bottles. Through these vent tubes a constant head was maintained, giving a constant flow through the irrigation lines running from the bottles to the emitters at each end of the lysimeter boxes, regardless of the water level in the supply bottles.

Lysimeters 1 and 2 were irrigated daily at an average emitter discharge rate of 0.6 liters/hour (0.16 gallons/hour). Each lysimeter was connected to its own individual glass bottle which could be filled daily to the desired irrigation amount and left to irrigate till the bottle was emptied.

The six remaining lysimeters were irrigated from three 50-liter (13-gallon) plastic bottles, each supplying water to one pair of lysimeters. However, any particular lysimeter could be irrigated as long as needed, and then manually stopped by means of valves in the lines.

The emitters were constructed of various size polyethylene tubing telescoped together. The sizes of the tubing depended on the desired discharge. The total length of the emitter tubes was 67.4 cm (26.5 inches).

The emitters for Lysimeters 3 thru 8 were constructed so that water flowed thru 15.2 cm (6 inches) of 0.475 cm (3/16 inch) tubing, 28.6 cm (11-1/4 inches) of 0.16 cm (1/16 inch) tubing, and 18.5 cm

(7-1/4 inches) of 0.0965 cm (0.038 inch) tubing. All diameters given are inside diameters. These emitters gave an average discharge of 4 liters per hour (1 gallon/hour) at 0.75 meters (2-1/2 feet) of pressure head.

The emitters for Lysimeters 1 and 2 were similiarly constructed, but in order to give an average discharge of 0.6 liter/hour (0.16 gallons/hour) a smaller diameter tubing was added. The water flowed thru 15.2 cm (6 inches) of 0.475 cm (3/16 inch) tubing, 5.6 cm (2-1/4 inches) of 0.16 cm (1/16 inch) tubing, 18.4 cm (7-1/4 inches) of 0.0925 cm (0.038 inch) tubing, and 23 cm (9 inches) of 0.059 cm (0.023 inch) tubing.

In order to avoid as much as possible the formation of air pockets in the thin lines of the emitters, the tubes were mounted at a uniform slope down the legs of an "A" frame support as shown in Figure 1.

Planting of the tomatoes

After all the lysimeters were assembled, three 2-inch high cherry tomato plants of the variety Early Salad were transplanted to each end of each lysimeters on May 30. On June 28, after the plants were about 18 inches high, one plant on each of the ends was thinned out leaving the two strongest plants.

Description of the irrigation treatments

On July 13 all lysimeters were flooded and allowed to drain for three days to allow them to reach a state of hydraulic equilibrium. Then the irrigation with saline water was begun.

In the experiment four different irrigation treatments were tested using eight lysimeters, thus providing two replications of each treatment. In order to build up distinguishable salt concentrations as rapidly as possible, calcium chloride was added to the irrigation water with a resulting electrical conductivity of approximately 5.5 mmhos/cm. Table 1 gives the times when specific conductivities were used.

Table 1. Irrigation water conductivities

Date	Conductivity (mmhos/cm)
July 15 thru August 7	5.0
August 8 thru August 11	3.5
August 12	4.5
August 17 thru termination	5.5

Lysimeters 1 and 2 were irrigated daily at an average rate of 0.6 liters/hour. Each lysimeter received an irrigation equal to its respective evapotranspiration (ET) of the previous day. The soil was initially at hydraulic equilibrium with the lower zones at the saturation point. The soil was essentially maintained at this same moisture content throughout the season, with the soil saturated at the bottom of the soil profile, but with very little drainage occurring.

Lysimeters 3 and 4 were irrigated on an alternate day schedule,

that is every other day, at an average rate of 4.1 liters/hour. Each received a constant irrigation amount for three successive irrigations or six days. At the end of each six-day period, the average ET for the period was determined. The following three irrigations were 20 percent less than the average ET of the previous six-day period. This scheme was followed for 42 days, after which, for the rest of the season in order to further accentuate the under irrigations for these lysimeters, 20 percent less than the previous two days' ET, instead of six-day periods, was used. Therefore, as the season progressed for these two lysimeters, the soil water was depleted from the soil profiles, which were initially at or above field capacity.

Lysimeters 5 and 6 were irrigated on an alternate day irrigation schedule at an average rate of 4.0 liters/hour. The irrigation amount was equal to the ET of the previous two-day period. The soil was initially at hydraulic equilibrium with the bottom zone at the saturation point. The soil was essentially maintained at this same water content throughout the season, with the soil saturated in the bottom zone of the soil profile, but with the little drainage occurring.

Lysimeters 7 and 8 were irrigated on an alternate day irrigation schedule at an average rate of 3.9 liters/hour. The irrigation amount was 20 percent over the ET of the previous two-day period. The soil was initially at hydraulic equilibrium with the bottom zone at the saturation point. The soil was essentially maintained at the same moisture content throughout the season with the excess water draining daily from the lysi-

Table 2 summarizes the evapotranspiration, irrigation, and drainage data for each lysimeter. Appendix C includes the cumulative curves for the ET and irrigation amounts.

Daily experimental routine

Each morning at about 8:30 A.M. the manometer readings were recorded from all lysimeters and the two temperature correction manometers. Also the amount of drainage from each lysimeter was recorded as well as the conductivity of the drainage water.

By knowing the amount of the previous irrigation, the amount of drainage for the period, and the change in manometer readings from one irrigation to the next, the ET from any lysimeter could be calculated. The change in manometer readings was corrected for temperature changes by taking into account the change in height in the control tube. Each lysimeter was then irrigated according to its respective irrigation treatment. Any weight change due to harvesting the tomatoes was also considered in the determination of the ET. The lysimeters were harvested every two days on the day of irrigation of Lysimeters 3 thru 8.

Soil water and salinity monitoring instruments

Two days after the start of the irrigation with saline water and approximately every two weeks thereafter, the water content and the salinity level of the lysimeters were monitored using a gamma probe and a four probe conductivity meter respectively. The soil water was monitored by a Model 2651 Scaler-Ratemeter manufactured by Troxler

Table 2. Irrigation Data

Item	Lysimeter number 1	2	3	4	5	6	7	8
Total days of saline irrigation and ET	57	69	71	73	68	71	73	74
Lengths of irrigation cycles (days)	1	1	2	2	2	2	2	2
Ave. irr. rates (liters/hour)	0.6	0.6	4.0	4.2	4.2	3.9	3.9	3.8
Total ET amount (liters)	266	318	276	290	303	306	369	392
Total irr. amount (liters)	268	320	242	250	303	309	450	467
Total drainage (liters)	6	7	0	0	3	3	80	76
$\frac{\text{Irr. amount}}{\text{ET amount}}$ ratio	1.01	1.01	.88	.86	1.0	1.01	1.22	1.19
Average daily ET (liters)	4.7	4.6	3.9	3.9	4.5	4.3	5.1	5.3
Total salts applied (grams)	699	840	625	648	792	806	1189	1237
Total salts leached (grams)	24	21	0	0	12	16	508	450
Total salts retained (grams)	675	820	625	648	780	790	680	790

Laboratories and a Model 2376 two probe density gage as is shown in Figure 3. The soil conductivity was monitored by a Model R 30 "Michimho Electro-Ground earth resistivity measuring instrument made by Soil Test Inc. as is shown in Figure 4.

Gamma probe method

The principles and theories of the use of the gamma ray attenuation method of measuring soil water content have been discussed by Davidson, Biggar and Nielson (1963), Ferguson and Gardner (1961), Gurr (1961) and others. The theory as given by Troxler Laboratories (1970), and a method of calibration as given by Hanks (1972) is presented in Appendix D.

The method requires two access tubes, one containing a Cesium 137 source, and the other a scintillation probe. When using the gamma ray attenuation method a scaler is used to count the number of gamma photons which pass from the radioactive Cesium source, through the lysimeter box filled with soil, to the detector placed on the opposite side of the box.

The relationship between the volumetric water content and the counts per minute is:

$$\Theta = \frac{\frac{\ln \frac{A}{K}}{x} - B\rho_s - D}{C\rho_w} \quad \ldots\ldots\ldots\ldots \quad (1)$$

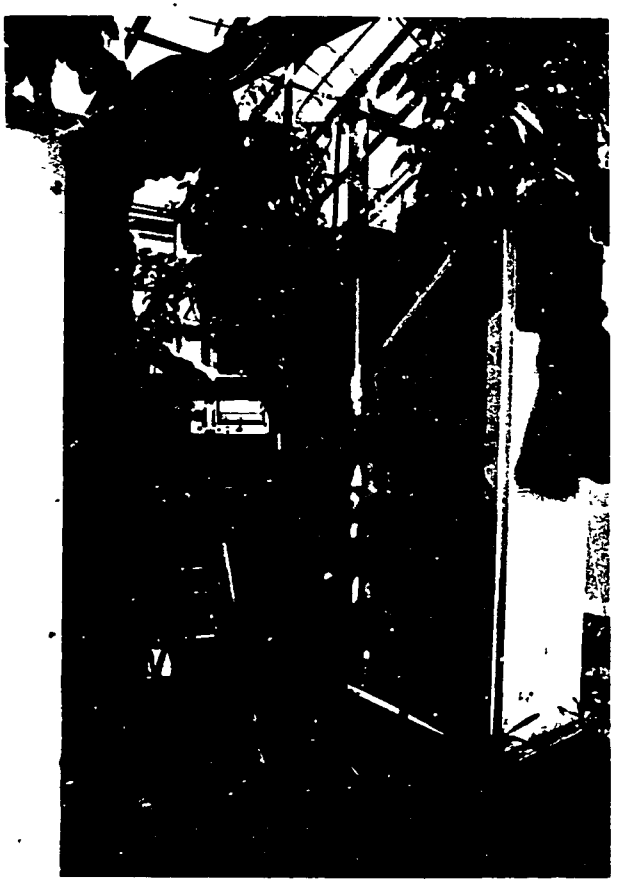


Figure 3. Gamma probe instrument

Figure 4. Four probe instrument

where

Θ = volumetric water content, decimal

K = count rate received through the soil

A = count rate received through the air

B = attenuation coefficient for dry soil, a constant

C = attenuation coefficient for water, a constant

D = attenuation coefficient for the container material

ρ_s = bulk density of the soil, grams/cc

ρ_w = bulk density of water, grams/cc

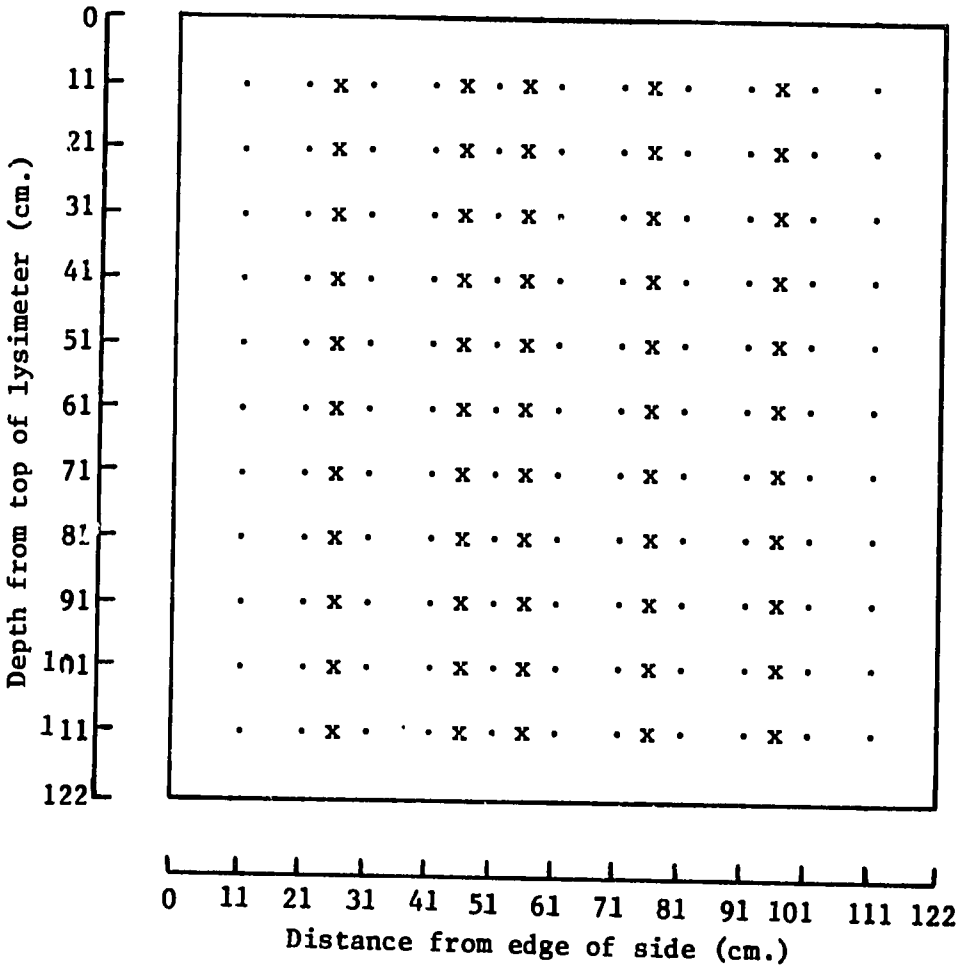
x = distance from the detector to the source, cm

Figure 5 shows the 55 different grid positions where the counts were taken on each lysimeter.

Four probe method

In order to monitor the salinity level in the lysimeters at the same time the soil water was monitored during the experiment, the four probe method of measuring the electrical conductivity of the soil was tried as reported by Gupta and Hanks (1973). In this experiment the Wenner configuration of electrodes was used to measure the soil conductivity. In this arrangement four electrodes are placed in a straight line with equal distances between them (Figure 6).

The outer electrodes are connected to the current leads of an earth resistivity meter and the inner two electrodes are connected to the potential leads. The resistance of the soil is the difference in



• Denotes positions of stainless steel bolts
x Denotes positions where gamma and four probe readings were taken

Figure 5. Measurement positions for four probe and gamma probe readings

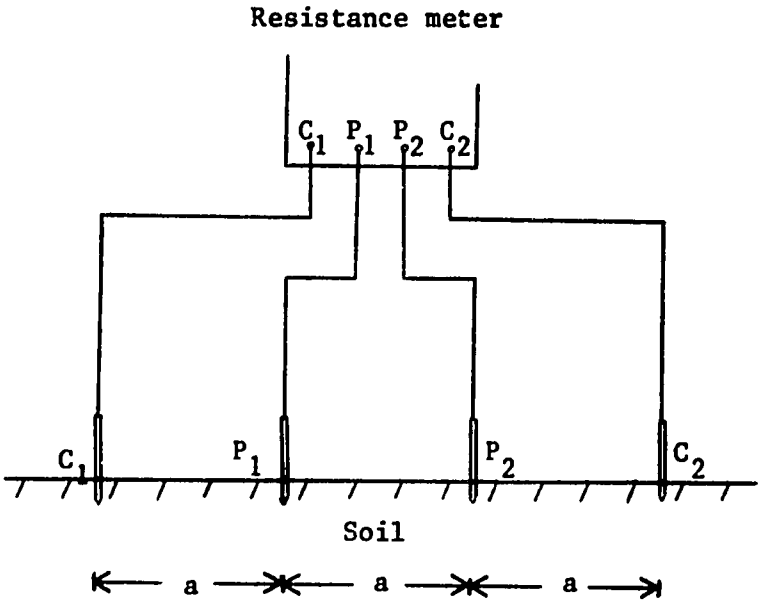


Figure 6. Wenner array of electrodes used in resistance measurements, (a represents the inner-electrode spacing)

potential between the potential electrodes divided by the current entering and leaving through the current terminals. When properly connected to the electrodes, however, the earth resistivity meter gives a direct reading of soil conductivity in mhos.

Gupta and Hanks found that a relationship existed between the four probe conductivity (K4P, mmhos) and the saturation extract conductivity (KSE, mmhos/cm), which is a commonly used measure of soil salinity. The relationship which they found can be represented by:

$$\frac{K4P}{KSE} = N + M(\theta) \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (2)$$

where

M and N = constants which depends on the soil type and probe spacing

In theory, therefore, if θ and K4P are known, the KSE can be estimated by:

$$KSE = \frac{K4P}{N + M(\theta)} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (3)$$

For the loamy sand soil used in this study, the values of N and M were - 0.184 and 42.3 respectively. Appendix E includes a further discussion of the four probe method and the procedure by which the calibration constants N and M were obtained.

In this study K4P and θ were measured five times during the experiment in the 55 different grid positions on each lysimeter as indicated in Figure 5. From these two measurements, K4P and θ, it was

theoretically possible to estimate the KSE of each grid positions.

Final soil sampling procedure

After the experiment the lysimeters were taken apart and the soil samples as shown in Figure 7 were taken from each lysimeter to be later analyzed in the laboratory for water content, bulk density, and saturation extract conductivity. Five surface samples were also analyzed for salinity. Figure 8 shows the 47 grid positions where soil samples were taken from each lysimeter.

The volumetric water percent was calculated by the following relationship:

$$P_v = P_w \times \frac{\rho_s}{\rho_w} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (4)$$

where

P_v = soil water percent expressed on a volumetric basis

P_w = soil water percent expressed on a dry weight basis

ρ_s = soil bulk density, grams/cc

ρ_w = water density, grams/cc

The saturation extracts were obtained by using the standard method as recommended by the U. S. Salinity Laboratory Staff (1954).

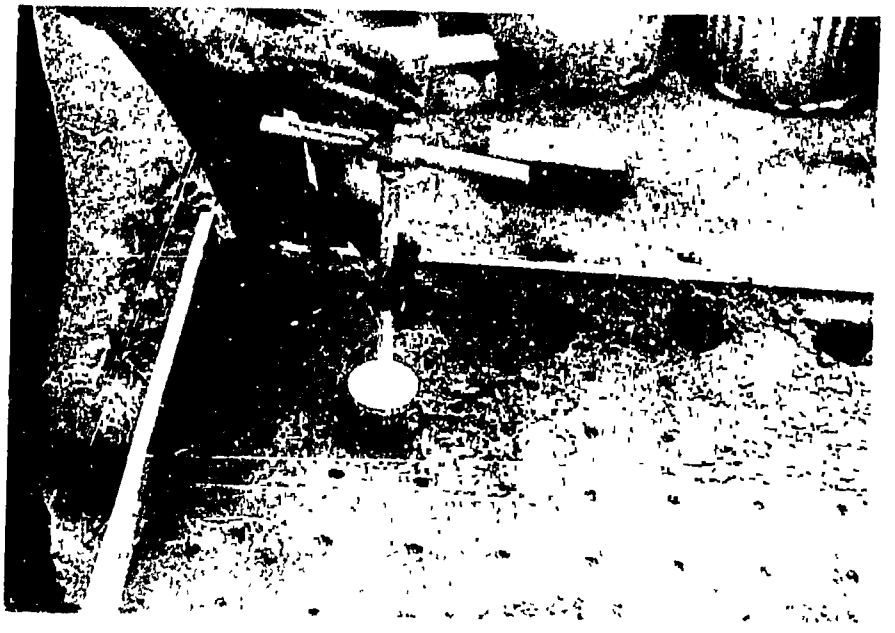
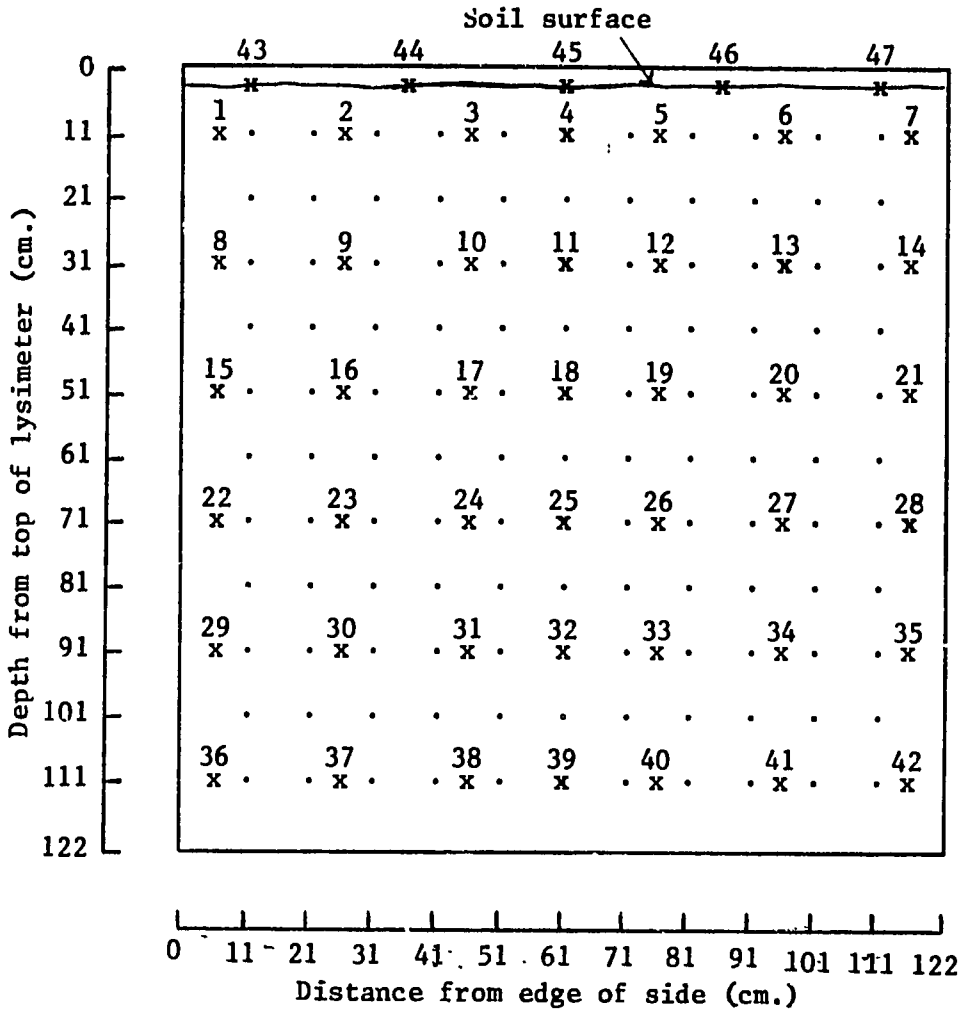


Figure 7. Soil sampling of the lysimeters



. Denotes positions of stainless steel bolts
x Denotes positions where soil samples were taken

Saturation extract samples taken in positions 1 - 47
Soil moisture samples, dry weight basis, taken in positions 1 - 42
Density samples taken in positions 9, 11, 13, 23, 25, 27, 37, 39, 41

Figure 8. Soil sampling positions

RESULTS AND DISCUSSION

The saturation extract conductivity profiles

Figure 9 shows the saturation extract conductivity profile for Lysimeter 1 which resulted after 57 days of irrigation with saline water. Numerical data for this lysimeter is found in Appendix B, Table 5. Each line in the profile represents equal conductivity of the saturation extract measured in mmhos/cm. The total amount of salts applied with the irrigation water and retained in the soil profile was 670 grams of calcium chloride.

Figure 10 shows the saturation extract profiles for Lysimeter 2 which resulted after 69 days of irrigation with saline water. Numerical data for this lysimeter is found in Appendix B, Table 6. The total amount of salts applied with the irrigation water and retained in the soil profile was 820 grams.

Both Lysimeters 1 and 2 were irrigated daily at a rate of 0.6 liters/hour. The amount of water applied daily varied during the experiment, and it was equal to the volume of water evapotranspired from the individual lysimeters the previous day.

The concentration of salts as indicated by the profiles in Figures 9 and 10 shows that in general there is an upper zone where concentrations increase with the horizontal and vertical distance from the emitters. An

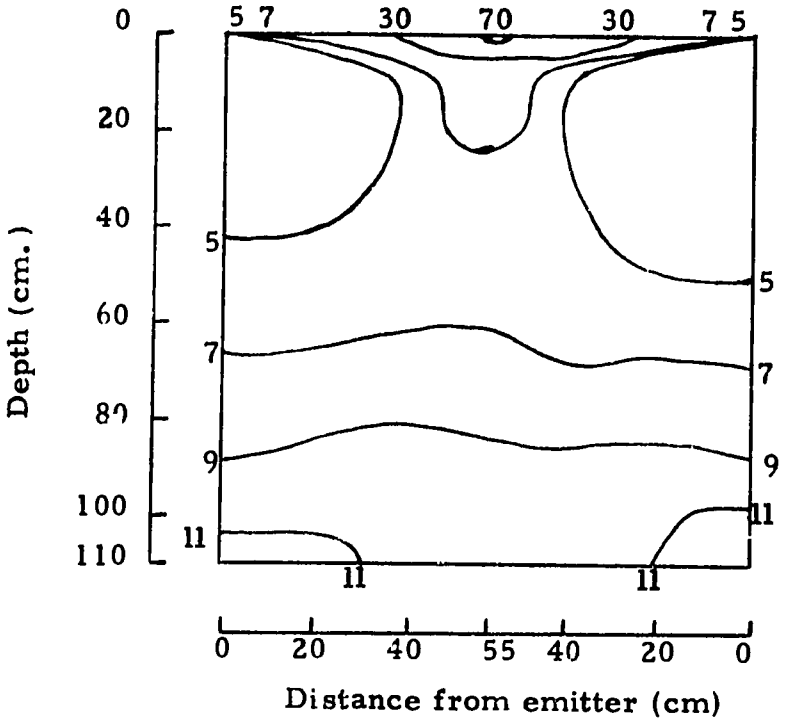


Figure 9. Saturation extract conductivity (mmhos/cm) for Lysimeter 1, which received a daily irrigation equal to the evapotranspiration

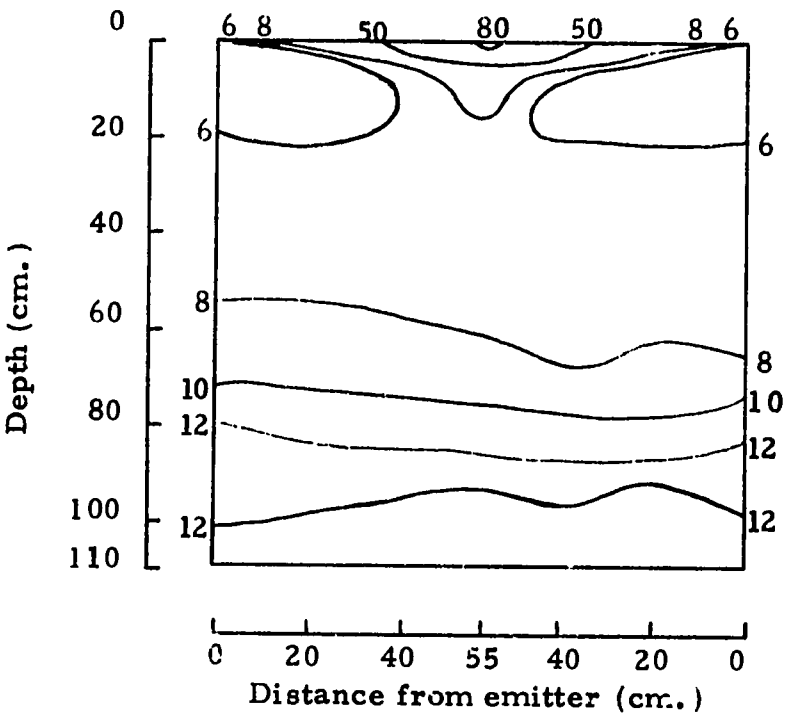


Figure 10. Saturation extract conductivity (mmhos/cm) for Lysimeter 2, which received a daily irrigation equal to the evapotranspiration

intermediate zone is present where the bulb like patterns of the upper zone merge to form horizontal layers of concentrations. In the lower zone the concentrations increase with depth. These profiles resemble those found by Gornat and Goldberg (1970) for young avocado trees, and those of Goldberg, Rinot, and Karu (1971) in a seven year old vineyard.

Figure 11 shows the saturation extract profile for Lysimeter 5 which resulted after 68 days of irrigation with saline water. Numerical data for this lysimeter is found in Appendix B, Table 9. The total amount of salts applied with the irrigation water and retained in the soil profile was 780 grams.

Figure 12 shows the saturation extract profile for Lysimeter 6 which resulted after 71 days of irrigation with saline water. Numerical data for this lysimeter is found in Appendix B, Table 10. The total amount of salts applied with the irrigation water and retained in the soil profile was 790 grams.

Both Lysimeters 5 and 6 received alternate day irrigations with an average application rate of 4.0 liters/hour. The amount of water applied varied with each irrigation and was equal to the volume of water evapotranspired from the individual lysimeters the previous two days.

In general the similarities of the saturation extract profile patterns between Lysimeters 1 and 2 and Lysimeters 5 and 6 are quite close. As with Lysimeters 1 and 2, the profiles show an upper zone where concentrations increase with the horizontal and vertical distances from the

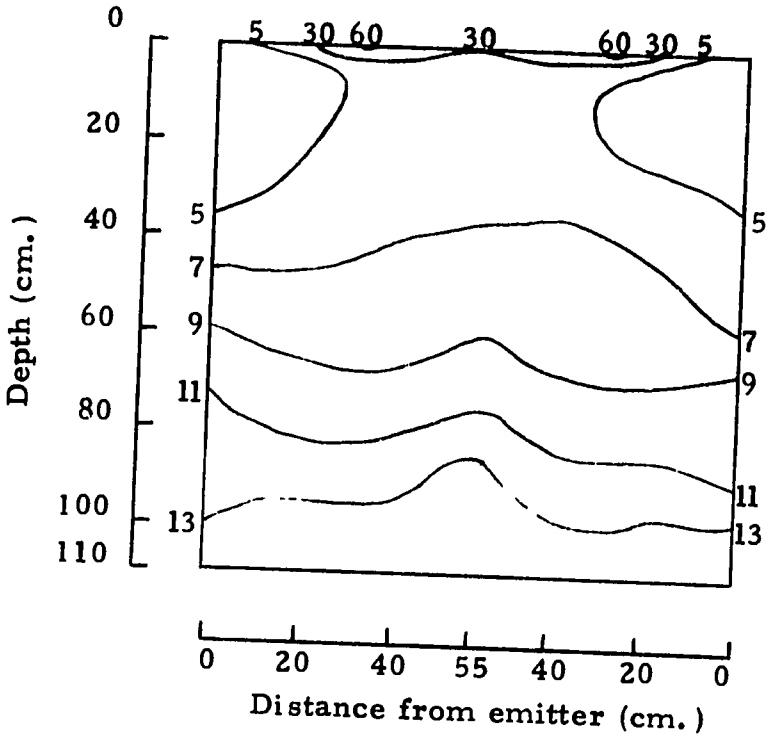


Figure 11. Saturation extract conductivity (mmhos/cm) for Lysimeter 5, which received an alternate day irrigation equal to the evapotranspiration

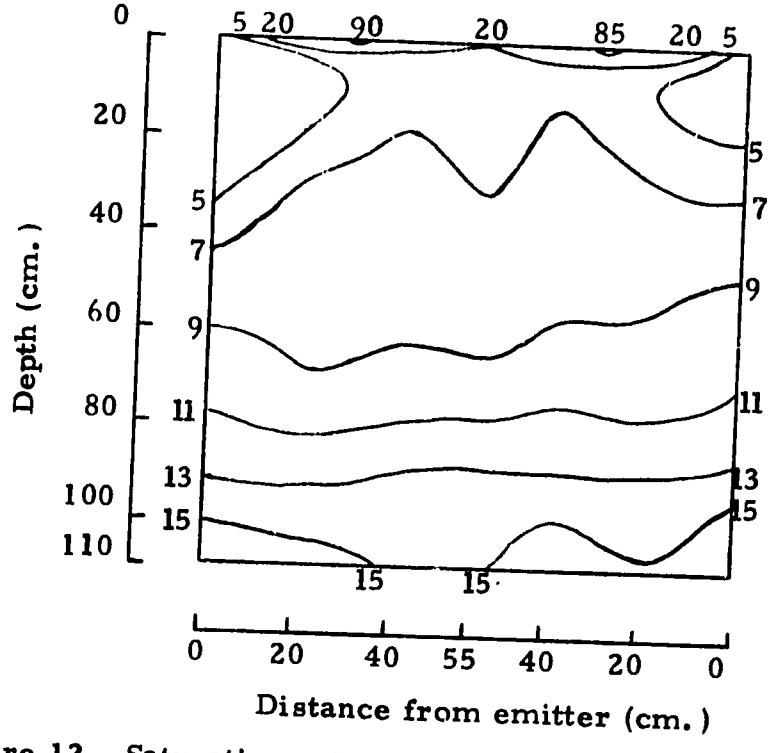


Figure 12. Saturation extract conductivity (mmhos/cm) for Lysimeter 6, which received an alternate day irrigation equal to the evapotranspiration

emitters. An intermediate zone is present where the bulb like patterns of the upper zone merge to form horizontal layers of concentrations. In the lower zones the concentrations of the horizontal layers increase with depth.

Figure 13 shows the saturation extract profiles for Lysimeter 3 which resulted after 71 days of irrigation with saline water. Numerical data for this lysimeter is found in Appendix B, Table 7. The total amount of salts applied with the irrigation water and retained in the soil profile was 630 grams.

Figure 14 shows the saturation extract profile for Lysimeter 4 which resulted after 73 days of irrigation with saline water. Numerical data for this lysimeter is found in Appendix B, Table 8. The total amount of salts applied with the irrigation water and retained in the soil profile was 650 grams.

Both Lysimeters 3 and 4 were irrigated on an alternate day schedule at an average application rate of 4.1 liters per hour. The amount of water applied was less than the volume of water evapotranspired from each lysimeter as was explained in greater detail in the "Description of irrigation treatments" section of this paper.

The concentration of salts as indicated by the profiles in Figures 13 and 14 show that in general they decrease with the horizontal and vertical distances from the emitters. The upper zone midway between the emitters shows lower salt concentrations than near the emitters. This is the exact opposite as was found for Lysimeters 5 and 6. The

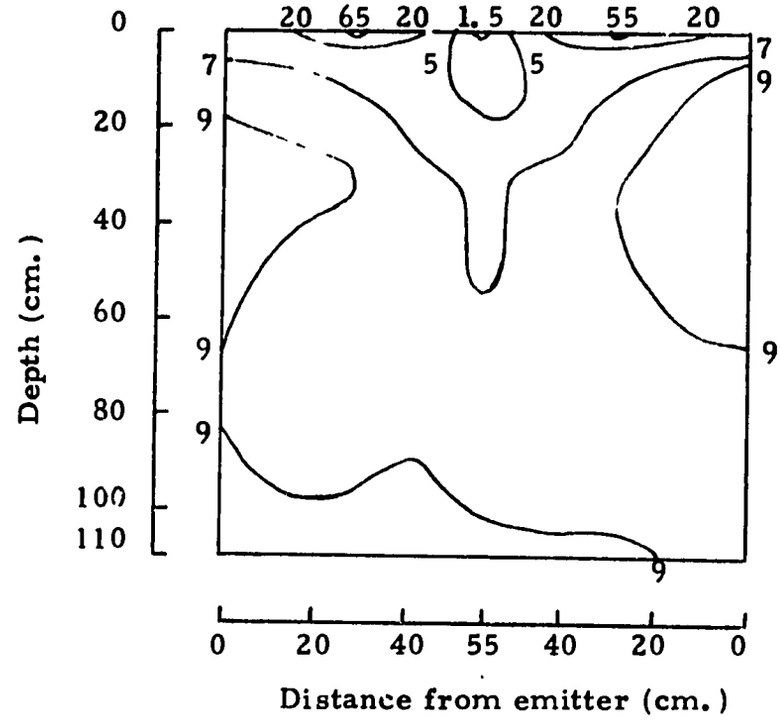


Figure 13. Saturation extract conductivity (mmhos/cm) for Lysimeter 3, which received an alternate day irrigation 13 percent under the evapotranspiration

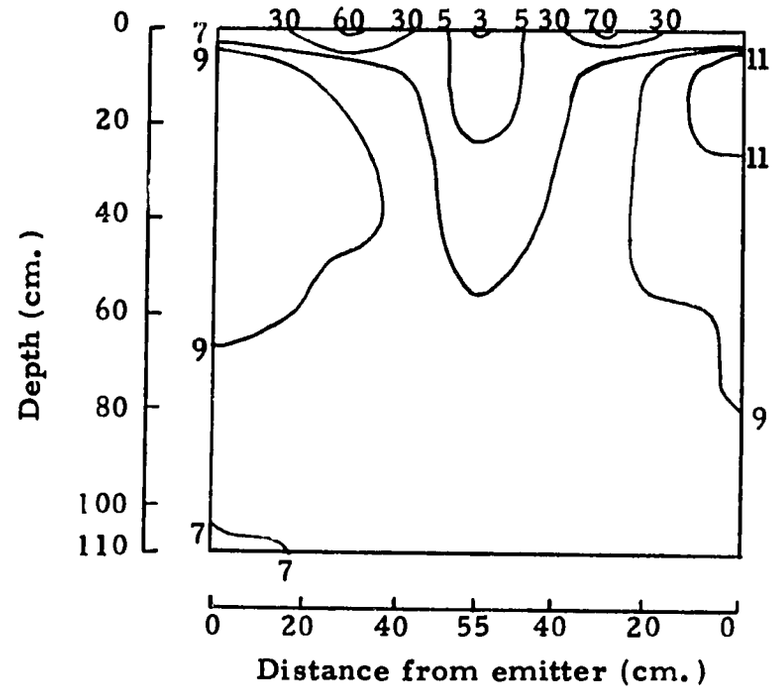


Figure 14. Saturation extract conductivity (mmhos/cm) for Lysimeter 4, which received an alternate day irrigation 13 percent under the evapotranspiration

apparent reason for this can be attributed to the differences in the irrigation treatments. At the beginning of the season both sets of lysimeters received relatively the same volume of irrigation water, and hence the wetting fronts advanced nearly the same distance from the emitters. However, as the season progressed, while Lysimeters 5 and 6 continued to be irrigated according to the volume of water evapotranspired, Lysimeters 3 and 4 were continously being under irrigated in respect to the volume of water which they evapotranspired. As Lysimeters 3 and 4 became drier they progressively evapotranspired less and less than Lysimeters 5 and 6 until at the end of the season Lysimeters 3 and 4 were receiving as little as one-third as much irrigation as Lysimeters 5 and 6. Therefore, the wetting fronts in Lysimeters 3 and 4 did not progress as far at the end of the season as at the beginning. Hence, the salts were successively being pushed less and less distance, and therefore gradually built up near the emitters.

Similiar profiles to those found for Lysimeters 3 and 4 were reported by Goldberg and Shmueli (1970) in a young vineyard, although they made no mention of how their irrigation amounts were determined.

Figure 15 shows the saturation extract profile for Lysimeter 7 which resulted after 73 days of irrigation with saline water. Numerical data for this lysimeter is found in Appendix B, Table 11. The total amount of salts applied with the irrigation water was 1190 grams, however, only 680 grams were retained in the profile since salts were carried off in the drainage water from this lysimeter.

Figure 16 shows the saturation extract profile for Lysimeter 8 which resulted after 74 days of irrigation with saline water. Numerical data for this lysimeter is found in Appendix B, Table 12. The total amount of salts applied with the irrigation water was 1240 grams, however, only 790 grams were retained in the profile since salts were carried off in the drainage water from this lysimeter.

Both Lysimeters 7 and 8 received alternate day irrigations with an average application rate of 3.9 liters /hour. The amount of water applied varied with each irrigation and was 20 percent more than the volume of water evapotranspired from the lysimeters the previous two days.

Similar to the profiles for Lysimeters 1 and 2 and Lysimeters 5 and 6, the profiles show an upper zone where concentrations increase with the horizontal and vertical distance from the emitters. An intermediate zone is present where the bulb like patterns of the upper zone merge to form horizontal layers of concentrations. In the lower zone the salt concentrations increase with depth. However, the bulb like patterns of the upper zone in Lysimeter 7 and 8 are much deeper than those found on the other lysimeters, and the horizontal layers do not appear until near the bottom. Even though Lysimeters 7 and 8 received nearly 1.5 times as much salts as Lysimeters 1, 2, 5, and 6, the part of the root zone nearest the emitters and the base of the plants have considerable less salt concentrations. This indicates that emitters

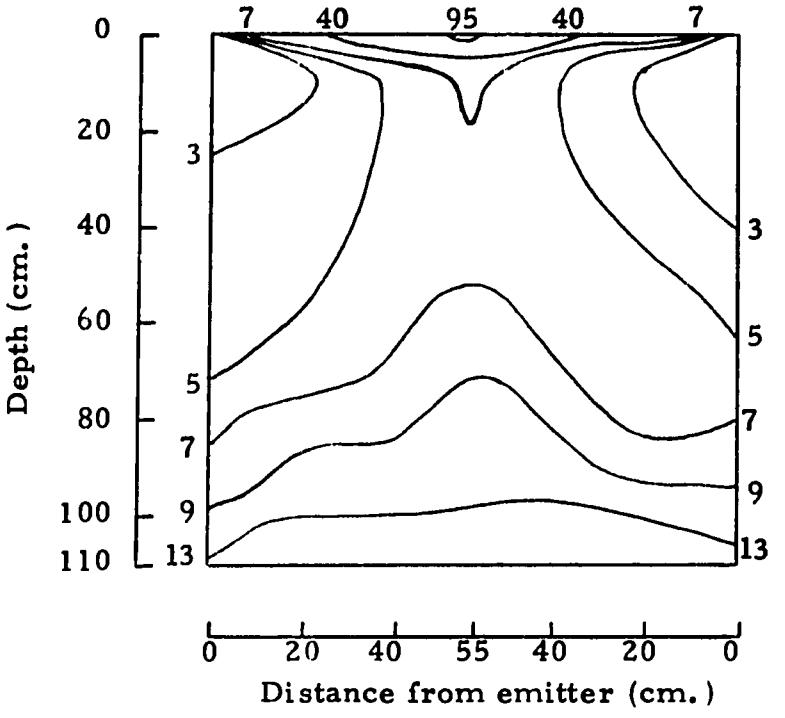


Figure 15. Saturation extract conductivity (mmhos/cm) for Lysimeter 7, which received an alternate day irrigation 20 percent over the evapotranspiration

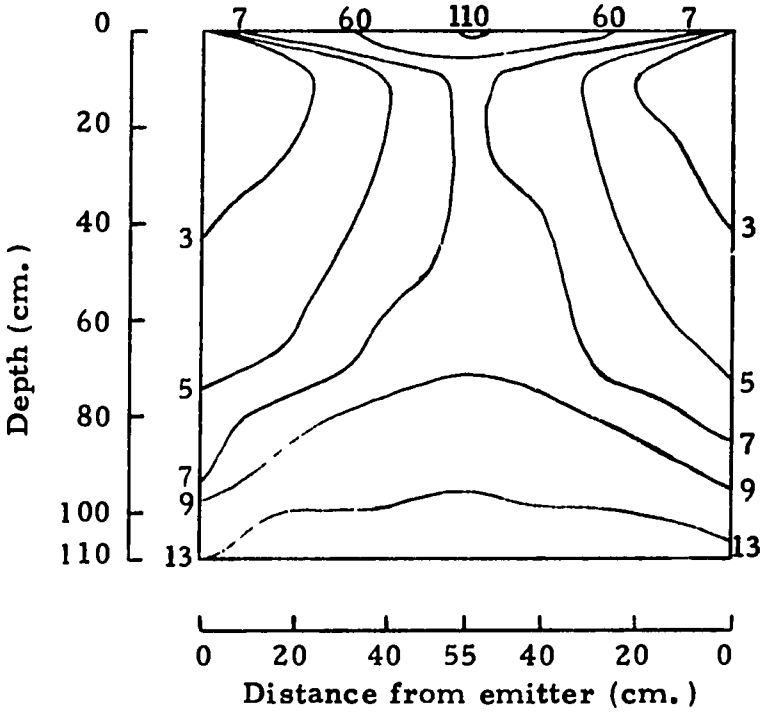


Figure 16. Saturation extract conductivity (mmhos/cm) for Lysimeter 8, which received an alternate day irrigation 20 percent over the evapotranspiration

do have a leaching capacity, at least for the part of the root zone area nearest the emitters.

The saturation extract profiles showed that the four lysimeters that were irrigated at the ET amount had similar salt distributions regardless of whether they received daily or alternate day irrigations. The salt concentrations increased as the distance from the emitters increased.

On the lysimeters which were under irrigated with regard to their consumptive use, the highest concentrations of salts were found nearest the emitters, and decreased as the distance from the emitters increased.

For the lysimeters which were over irrigated, the bulb patterns of salt concentrations were considerably deeper than that found for Lysimeters 1, 2, 5 and 6, but of the same general shape.

Surface saturation extract conductivities

Table 3 shows the surface saturation extract conductivities for all the lysimeters, with samples taken from the top 1.9 cm (3/4 inch) of the soil profile.

Table 3. Surface saturation extract conductivities at various distances from the emitters

Lys. No.	Treatment	Distance from emitter (cm) 5	30	55	30	5
1	daily, 1.0 ET	8.4	21.7	72.0	32.4	8.0
2	daily, 1.0 ET	11.2	50.3	85.1	48.5	7.2
3	alternate day, .87 ET	12.2	66.0	1.3	55.0	18.3
4	alternate day, .87 ET	3.7	63.0	3.0	71.0	6.2
5	alternate day, 1.0 ET	4.6	59.0	28.2	59.6	6.9
6	alternate day, 1.0 ET	14.4	89.0	19.7	84.0	14.6
7	alternate day, 1.2 ET	9.5	65.0	96.9	37.8	13.4
8	alternate day, 1.2 ET	19.0	60.0	112.0	76.0	18.2

Extremely high surface salinity concentrations are present in all lysimeters, especially in the midregions between the emitters. The highest concentration occurred on the fringes of the surface wetting fronts. The wetting fronts on Lysimeters 1 and 2 and Lysimeters 7 and 8 advanced all the way to the center of the boxes due to their longer irrigation periods. On these lysimeters the highest surface concentrations are also in the center of boxes, midway between the emitters.

The normal duration of the irrigations for Lysimeters 5 and 6, and especially for Lysimeters 3 and 4 were shorter than for the other four lysimeters, therefore, their wetting fronts did not reach the center of the boxes. The distance the surface wetting front advanced

is dependent on the length of irrigation time. In Table 3 the highest surface concentrations for Lysimeters 3, 4, 5 and 6 are on either side of the center as were their wetting fronts. In Lysimeters 3 and 4, which received the least water of all the lysimeter sets and hence had the shortest irrigation time, very little salt is found in the center, since only a few of the irrigations in the beginning of the season were long enough to push near the center.

The soil water potential profiles

The next series of figures show the contour profiles of the soil water potentials (SWP) as they existed in the lysimeters at the times of sampling. It will be instructive to examine these profiles because they give an insight of how the osmotic and the matric potential of the soil water combine to stress the growing plants in the lysimeters. A decrease in the osmotic potential or matric potential of the soil solution causes an increase in the soil water stress in relation to the availability of water to plant roots. The effects of the osmotic and matric potentials are additive.

The relationship between electrical conductivity (EC) and osmotic potential (OP) for calcium chloride solutions as given by the U.S. Salinity Laboratory Staff (1954) is:

$$OP = 0.31 \times EC \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (5)$$

where

OP = osmotic potential, atmospheres

EC = electrical conductivity of a calcium chloride solution, mmhos/cm

The values of EC to be used in equation 5 to determine the osmotic potential are those of the soil water electrical conductivity. These values were computed using the relationship:

$$EC_{sw} = EC_{sc} \times \frac{25.8 \times \rho_s}{P_v \times \rho_w} \quad . \; . \; . \; . \; . \; . \; . \; (6)$$

where

EC_{sw} = the electrical conductivity of the soil solution, mmhos/cm

EC_{sc} = the electrical conductivity of the saturation extract, mmhos/cm

25.8 = soil water percent of the saturation paste expressed on a dry weight basis

P_v = soil water percent of the soil sample expressed on a volume-volumetric basis

ρ_s = soil bulk density, grams/cc

ρ_w = water density, 1.0 gram/cc

The saturation extract conductivity, the volumetric water content, and the soil bulk density data needed to calculate the soil water conductivities is given for all lysimeters in Appendix B.

In order to determine the matric potential of the soil water a moisture characteristic curve was determined for the loamy sand soil used in this experiment. This curve is presented in Figure 17.

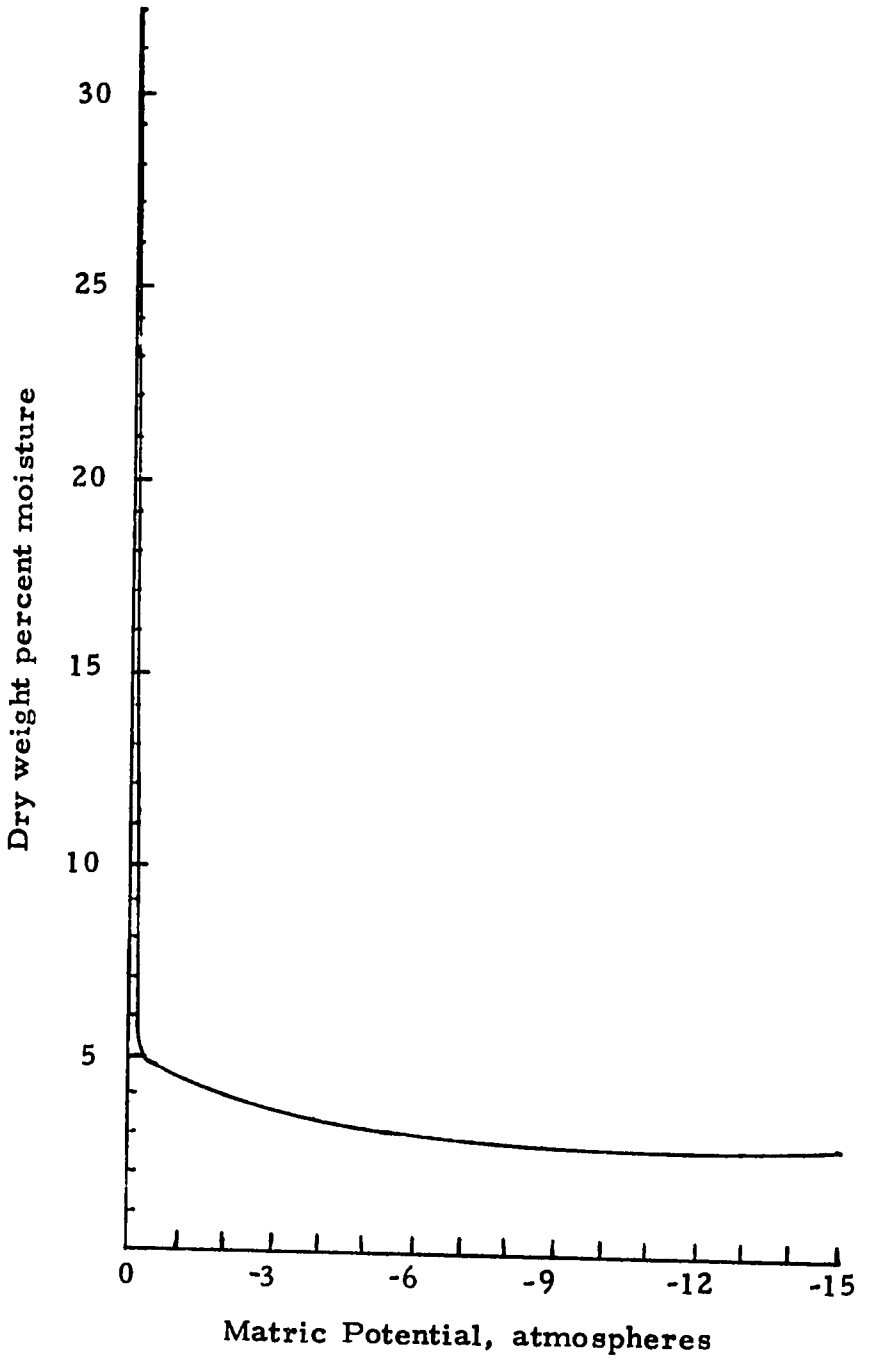


Figure 17. Moisture characteristic curve for the loamy sand soil used in the lysimeters

The soil water potential (SWP) is the sum of the osmotic and matric potential and the values for each lysimeter is given in Appendix B, Table 13 thru 20.

The SWP profiles were drawn using the soil water potential values of Appendix B. These profiles, however, only represent the situation in the lysimeters at the time of sampling. The time of a previous irrigation must be considered in order to give a true picture of any relationship, since both the osmotic and matric potential fluctuates with the state of drying.

Figure 18 shows the soil water potential profile for Lysimeter 1 one day after the last irrigation. Each line in the profile represents equal potential of the soil water at the time of sampling. Figure 19 shows the soil water potential profile for Lysimeter 2, also sampled one day after the last irrigation.

In comparing Figures 18 and 19, it must be recalled that the SWP of Lysimeter 2 must be expected to be lower than that of Lysimeter 1 because Lysimeter 2 had 11 more days of irrigation than Lysimeter 1. The lower potential is due to the higher salt concentrations. Both lysimeters were irrigated every day, and the time of sampling of each was one day after the last irrigation and at the time another irrigation should have been scheduled. Therefore, the profiles represent the time in the irrigation cycle when the osmotic and matric potentials would have been the lowest.

The patterns represented in both profiles are quite similar,

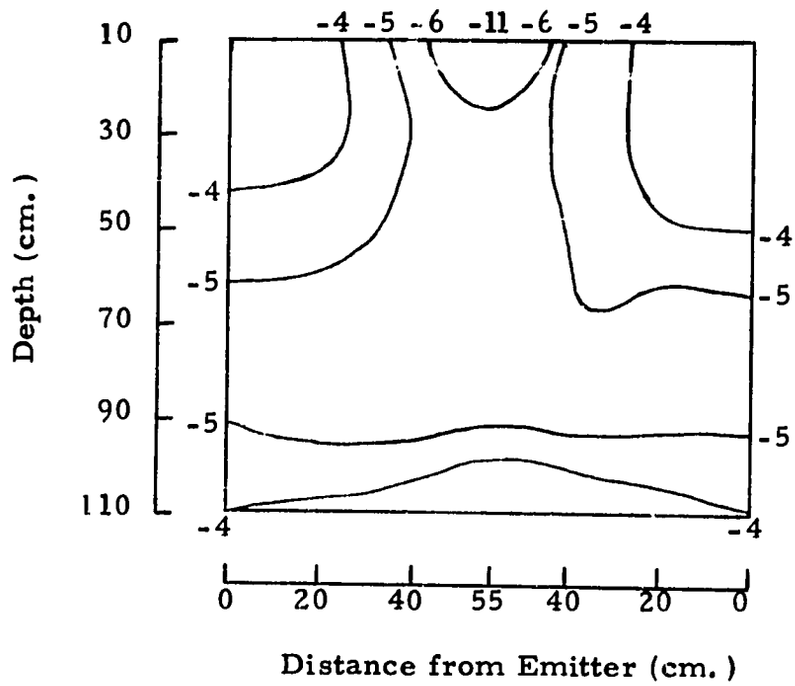


Figure 18. Soil water potential (atm.) for Lysimeter 1 which received a daily irrigation equal to the evapotranspiration. Samples taken one day following last irrigation

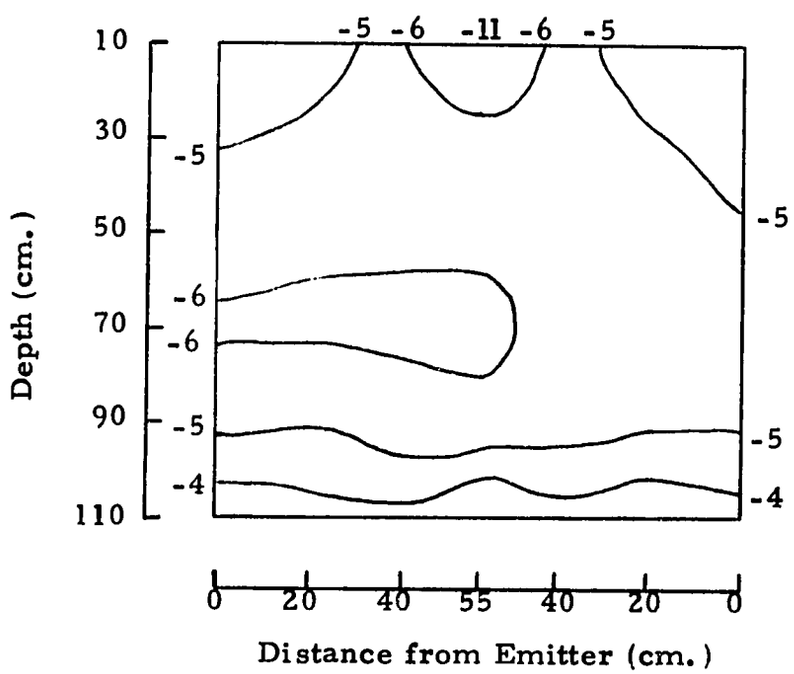


Figure 19. Soil Water potential (atm.) for Lysimeter 2 which received a daily irrigation equal to the evapotranspiration. Samples taken one day following last irrigation

although, as expected the SWP values for Lysimeter 2 are lower negative than those of Lysimeter 1. In the upper zone the SWP decreases with the horizontal and vertical distances from the emitters. In both there is a middle zone of uniform potential and a layer of minimum SWP seems to occur at a depth of 75 cm. Below this layer the potential increases.

Figure 20 shows the soil water potential profile for Lysimeter 5 sampled two days after the last irrigation. Figure 21 shows the soil water potential profile for Lysimeter 6 sampled only one day after the last irrigation. Both lysimeters received alternate-day irrigations at the evapotranspiration rate. Based on the total amounts of salts applied, both should contain the same amount.

Lysimeters 5 and 6 have potential patterns similar to those of Lysimeters 1 and 2. In the upper zone the SWP decreases with the horizontal and vertical distance from the emitters. There is a large middle zone of uniform potential. In the lower zone the potential profiles have horizontal layers of increasing potential as depth increases. In the midsection of Lysimeters 5 and 6 the SWP values, SWP = - 6.3 thru -7.5 atm, are lower than those of Lysimeter 2, SWP = -5.9 thru - 6.2 atm. Lysimeter 2 received an amount of salts comparable to Lysimeters 5 and 6. The lower values of Lysimeter 2 can be explained by the fact that a daily irrigation keeps the soil at a higher moisture content than the alternate day irrigations.

Figure 22 shows the soil water potential profile for Lysimeter 3 one day after the last irrigation. Figure 23 shows the soil water potential

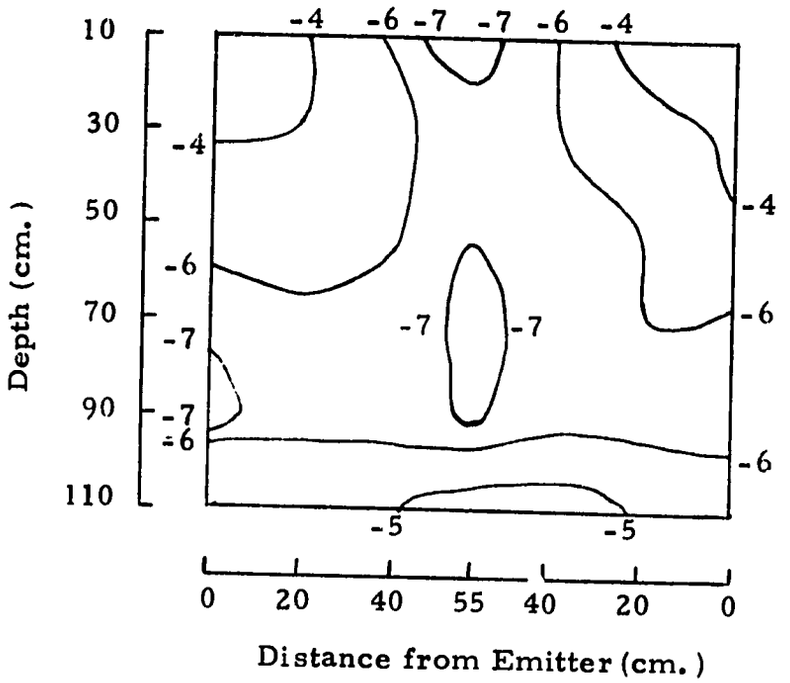


Figure 20. Soil water potential (atm.) for Lysimeter 5 which received an alternate day irrigation equal to the evapotranspiration. Samples taken two days following last irrigation

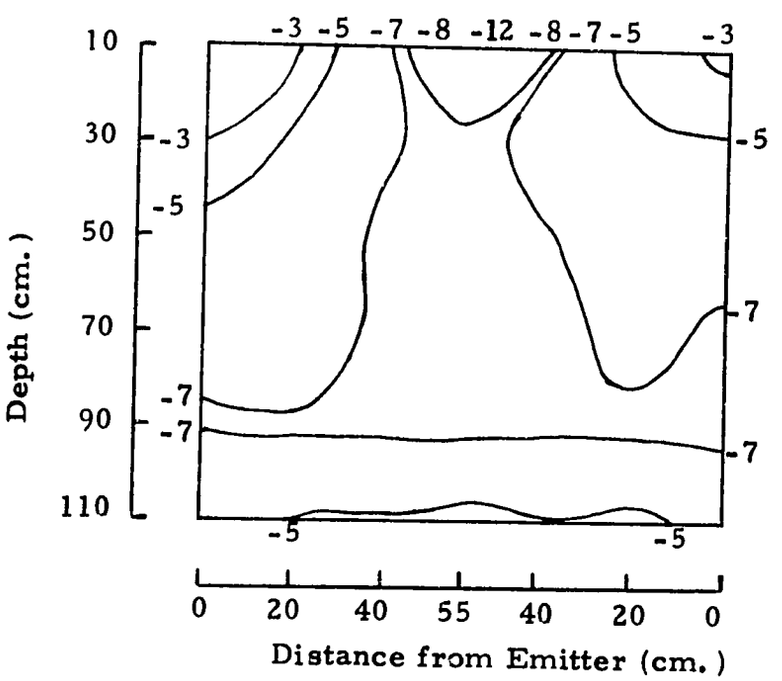


Figure 21. Soil water potential (atm.) for Lysimeter 6 which received an alternate day irrigation equal to the evapotranspiration. Samples taken one day following last irrigation

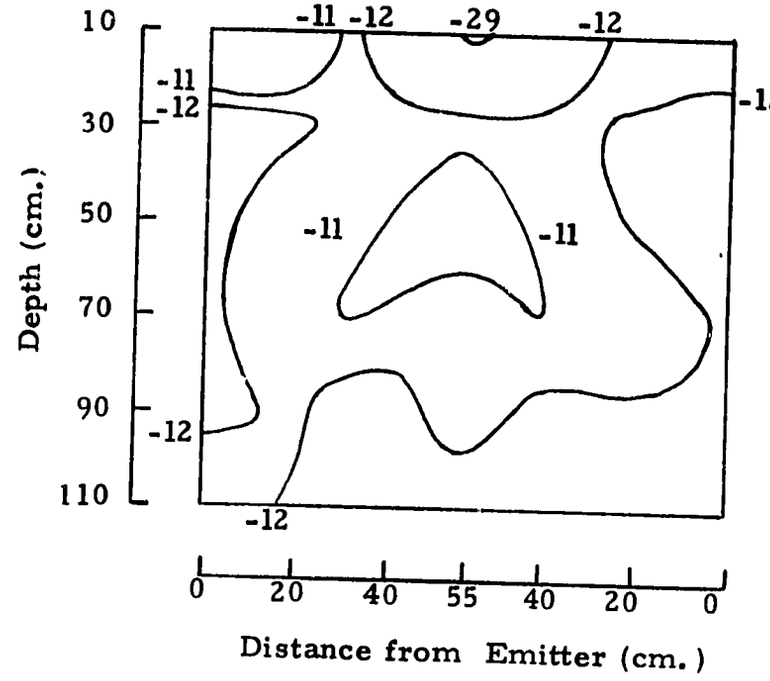


Figure 22. Soil water potential (atm.) for Lysimeter 3 which received an alternate day irrigation 13 percent under the evapotranspiration. Samples taken one day following last irrigation

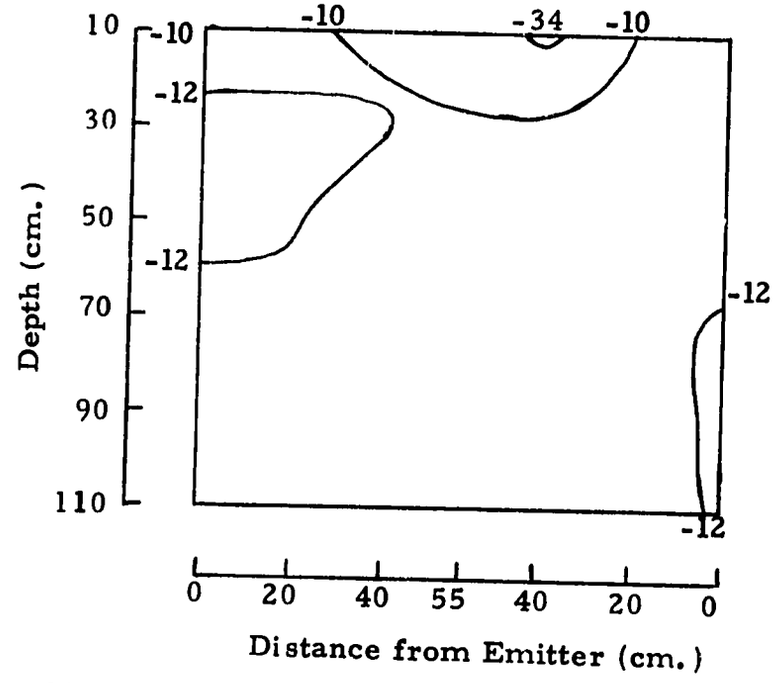


Figure 23. Soil water potential (atm.) for Lysimeter 4 which received an alternate day irrigation 13 percent under the evapotranspiration. Samples taken one day following last irrigation

profile for Lysimeter 4, also sampled one day after the last irrigation.

Because both Lysimeters 3 and 4 were sampled one day after an irrigation of a two day irrigation cycle, neither Figure 22 nor 23 represents a condition of maximum stress for the plants. In both profiles a fairly uniform low potential which encompasses most of the entire box is present, unlike the patterns of Lysimeters 5 and 6. The SWP of Lysimeters 3 and 4 also appear to be approximately twice as low as those of Lysimeters 5 and 6 even though the first contain less than 80 percent as much of the total salts applied. The low potential is due to the lower water content of Lysimeters 3 and 4, because they were the under irrigated lysimeters in the experiment.

Figure 24 shows the soil water potential profile for Lysimeter 7 one day after the last irrigation. Figure 25 shows the soil water potential profiles for Lysimeter 8 two days after the last irrigation. Both lysimeters received alternate day irrigations at 1.2 times the ET amount and received relatively the same amount of total salts applied.

Both lysimeters have potential patterns similar to those of Lysimeters 1, 2, 5 and 6, however, they are much deeper and elongated. The SWP decreases with the horizontal and vertical distance from the emitters. Although Lysimeters 7 and 8 received roughly 1.5 times the total amount of salts received by the lysimeters which were irrigated at the ET amount, the SWP values for Lysimeters 7 and 8 are in general considerably higher. This illustrates the effect of leaching.

Because the conductivity of the irrigation water was 5.5 mmhos/cm

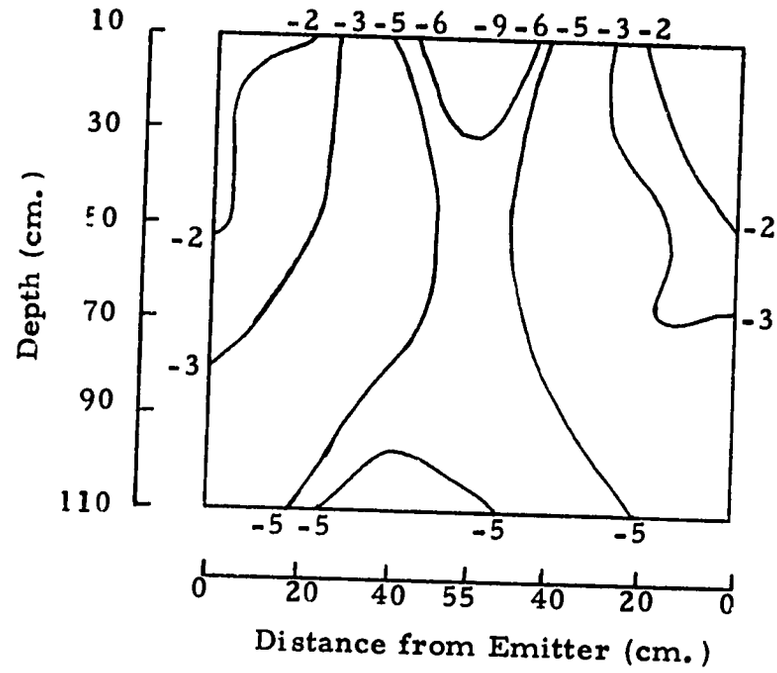


Figure 24. Soil water potential (atm.) for Lysimeter 7 which received an alternate day irrigation 20 percent over the evapotranspiration. Samples taken one day following last irrigation

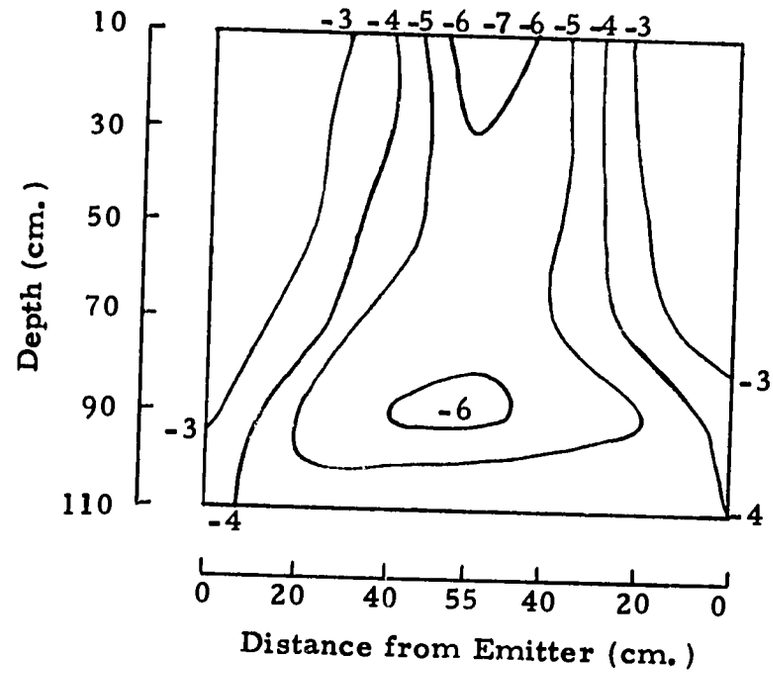


Figure 25. Soil water potential (atm.) for Lysimeter 8 which received an alternate day irrigation 20 percent over the evapotranspiration. Samples taken two days following last irrigation

or OP equal -1.6 atm., this is likewise the least possible osmotic potential of the soil water. If OP is -1.6 atm, it would represent the case where a dry soil free of salts was brought up to the moisture percentage desired by merely adding water with EC of 5.5 mmhos/cm. Table 11, Appendix B, shows that in the area of the emitter Lysimeter 7, which was sampled one day following an irrigation, was nearly "perfectly" leached in a zone near each emitter. In none of the other lysimeters which were sampled one day following an irrigation was there such a zone of leaching. In all areas of the profiles for the lysimeters which were irrigated at the ET amount or lower, there was an accumulation of salts.

The SWP Tables, Appendix B, for all lysimeters indicate that unless the lysimeters were over irrigated with respect to the ET there is no zone of leaching which has an $OP = OP_{irrigation\ water}$. Even if the emitters were supplying the evapotranspiration demand, the OP everywhere in the soil profile is lower than that of the irrigation water and if the crop is consistently under irrigated the OP may be lower than that of the irrigation water by several times. A daily irrigation may hold some advantages over an alternate day irrigation in that the soil has a higher moisture percentage, and hence for the same total amount of applied salts, the SWP is increased.

An interesting observation was that little difference in the size and yield was noted between the tomato plants of Lysimeters 3 and 4 and the other lysimeters irrigated at the ET amount as is shown in Table 4.

Table 4. Yields and weights of the tomato plants

Lys. No.	No. days of test	Plant weight at termination (grams)	Total tomatoes harvested (grams)
1	57	1900	3200
2	69	2000	3600
3	71	2200	5000
4	73	2500	4300
5	68	2700	5400
6	71	2100	4200
7	73	2800	5300
8	74	3200	5000

The little difference in yields can probably be attributed to the fact that even though Lysimeters 3 and 4 had almost twice as low SWP values as the other lysimeters, the SWP values had not yet reached the permanent wilting point potential, - 15.0 atm., and hence though the plants of Lysimeters 3 and 4 evapotranspired less than the other lysimeters, the tomato production was not yet appreciably affected.

It was also noted that the general growth and yields of Lysimeters 7 and 8 were higher than from the other six lysimeters. This probably reflects the fact that these lysimeters also had the highest SWP of all lysimeters, and hence had the least soil water stress.

The four probe conductivity method

The relationship between the conductivity of the saturation extract (KSE) and the conductance of the four probe (K4P) is given by:

$$KSE = \frac{K4P}{N + M(\Theta)} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (3)$$

By equation 3 the KSE of the soil can be obtained when the volumetric moisture content Θ, and the value of K4P are known.

The constants N and M were found as described in Appendix E. However, these constants were determined for a soil with uniform water and salt content throughout the soil volume within the electrical field of the instrument. For the probe separation used of 10 cm (4 inches), the volume sampled was approximately 10 cm deep, the spacing between the electrodes (Rhoades and Ingvalson, 1971), and 60 cm (24 inches) wide as described in Appendix E.

Because of the nature of the experiment, the volume of soil sampled in any lysimeter by the four probe method was neither uniform in water nor salt content.

In order to verify the reliability of the four probe method in estimating the conductivity of the saturation extract for the lysimeters, the four probe conductivity was measured and immediately after soil samples were carefully taken to determine the actual conductance of the saturation extract, density, and water content. This test was performed for every lysimeter at the end of the experiment.

Figure 26 shows the relationship between the measured and the estimated saturation extract conductivities for Lysimeters 1 and 2. The

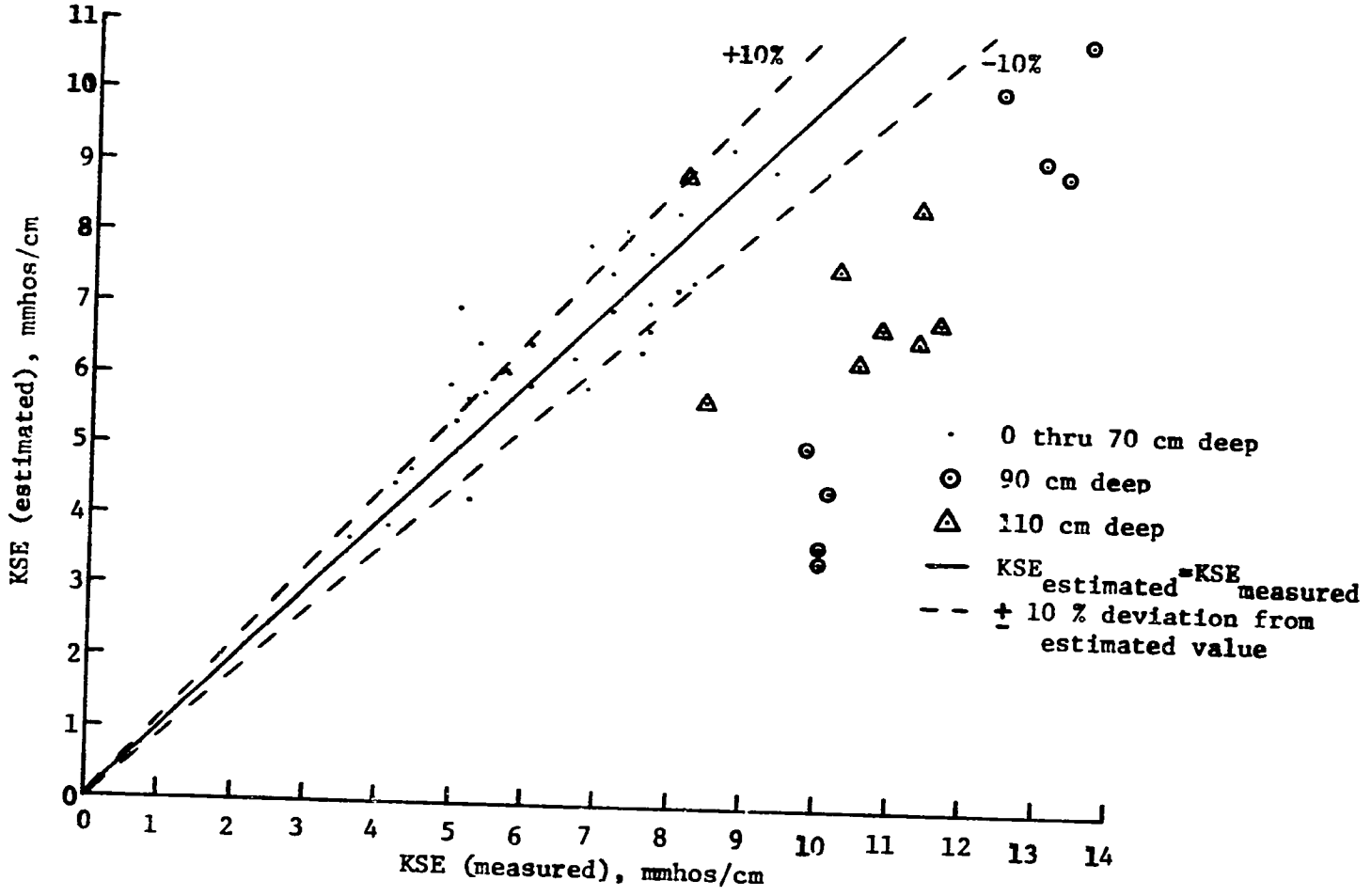


Figure 26. Measured versus estimated saturation extract conductivity for Lysimeters 1 and 2

estimated saturation extract conductivity was found by using Equation 3 with the calibration constants found for the uniform water and salinity contents. The dry weight water contents were obtained by oven drying the soil samples. Using an average density for each row of samples, the volumetric water content was calculated as the product of the dry weight water content and the density. Figure 26 indicates that there is considerable deviation of the estimated and the measured saturation extract conductivities. Many points fall outside the $\pm$ 10 percent deviation lines of the estimated and measured KSE values. This is especially true for the sample points 90 and 120 cm below the surface. These sample points had high volumetric water contents, 20 thru 40 percent as is shown in Appendix B, Tables 21 and 22.

Figure 27 shows the relationship between the measured and estimated saturation extract conductivities for Lysimeters 3 and 4. The poor relationship can be partially attributed to the fact that roughly 80 to 85 percent of the volumetric water contents found in these lysimeters as given in Appendix B, Tables 23 and 24, are 9 percent or below. Gupta and Hanks (1972) also found that the relationship of Equation 3 does not hold for low water contents in the soil.

Figure 28 shows the relationship between the measured and estimated saturation extract conductivities for Lysimeters 5 and 6. The figure indicates that the KSE is consistently under estimated, and that the relationship is especially poor for the sample points 90 and 120 cm below the surface. These lower sample points had high volumetric

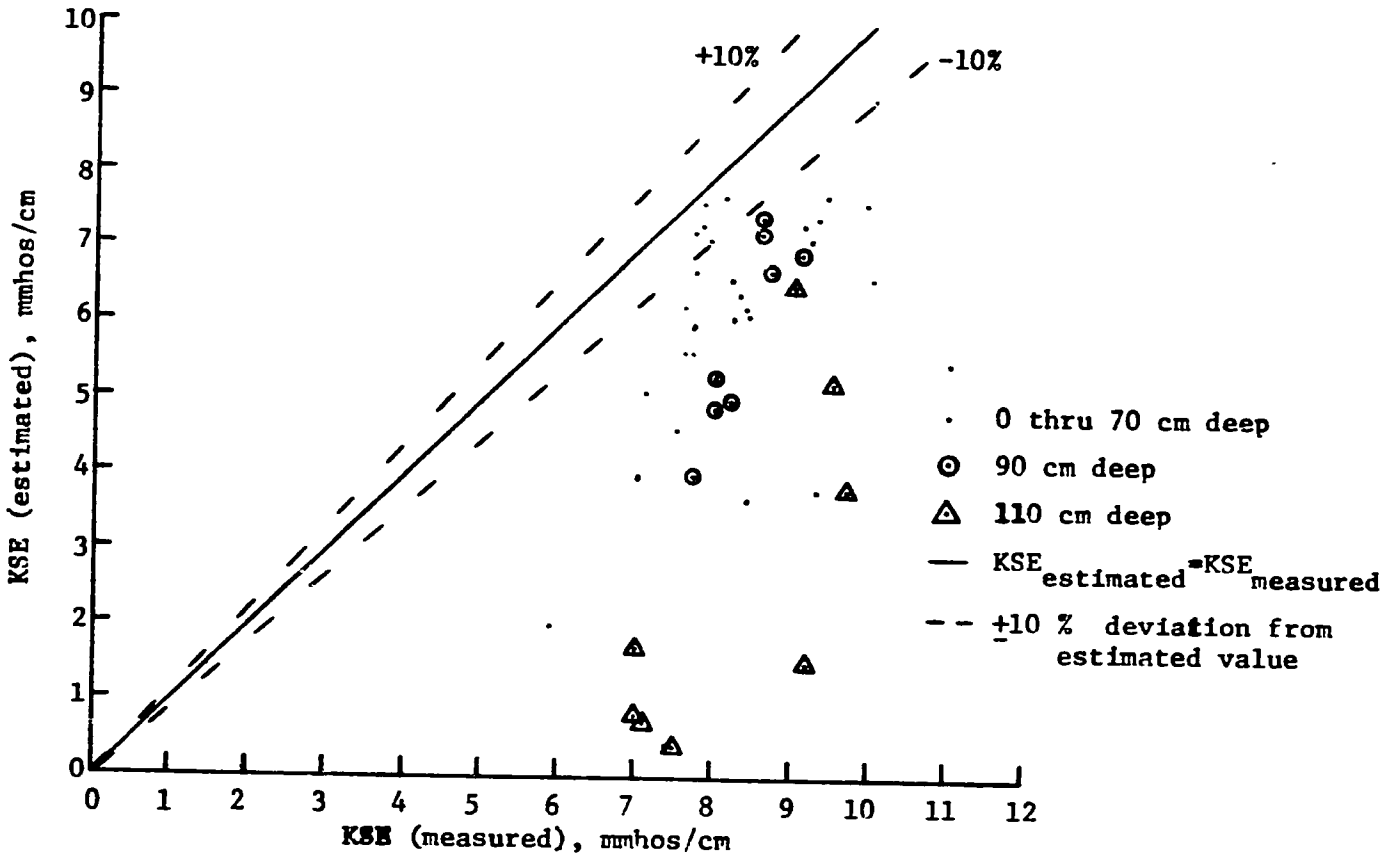


Figure 27. Measured versus estimated saturation extract conductivity for Lysimeters 3 and 4

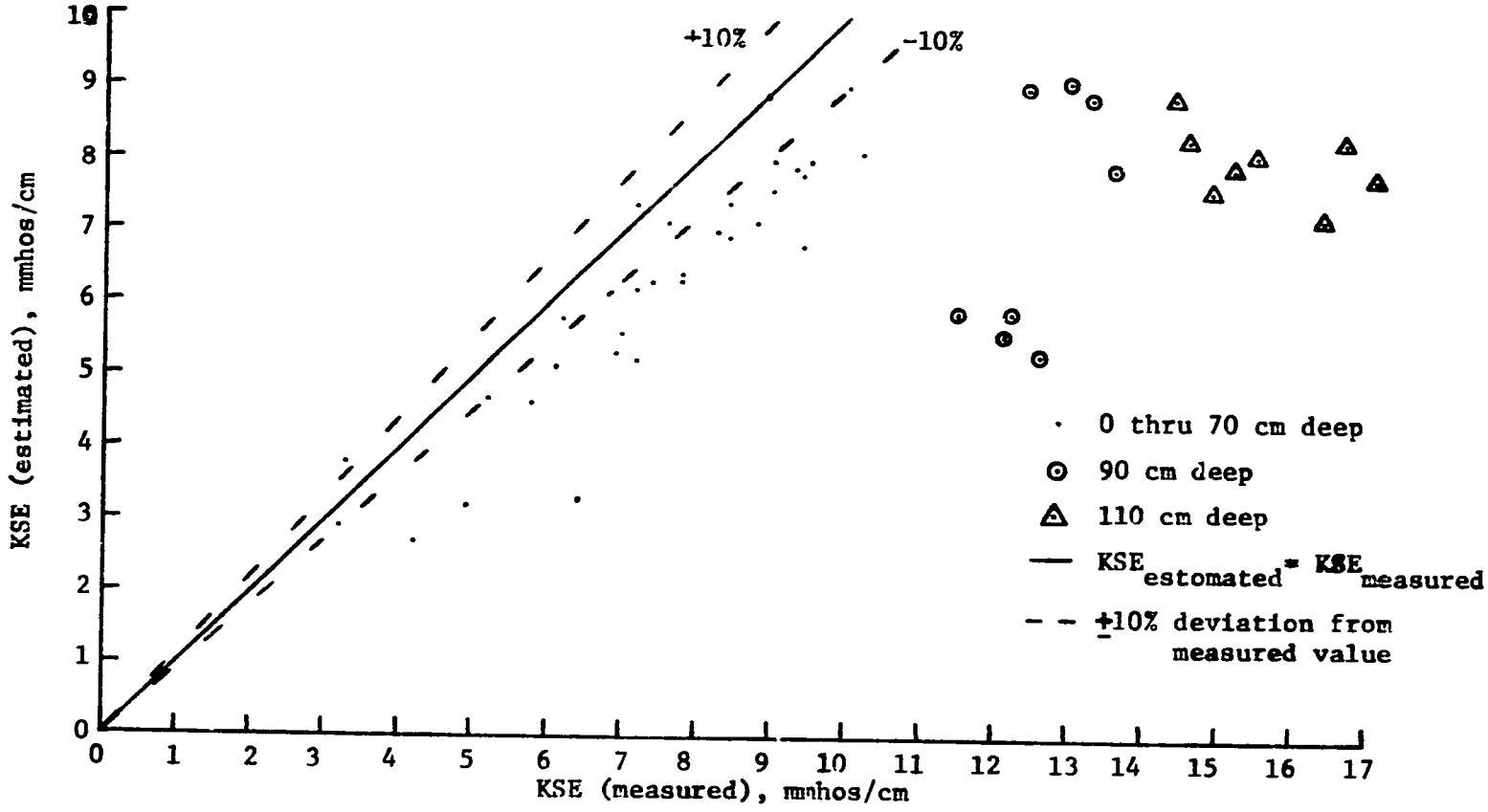


Figure 28. Measured versus estimated saturation extract conductivity for Lysimeters 5 and 6

water contents, 20 thru 40 percent as is given in Appendix B, Tables 25 and 26.

Figure 29 shows the relationship between the measured and estimated saturation extract conductivities for Lysimeters 7 and 8. The figure indicates that the KSE is again generally under estimated, and that the relationship is especially poor for the sample points 90 and 120 cm below the surface. These lower sample points had high volumetric water contents, 20 thru 45 percent, as is given in Appendix B, Tables 27 and 28.

Figure 30, which is a plot of $\frac{K4P}{KSE}$ versus Θ, gives an indication as to which points are deviating from the expected readings. The solid line is the calibration line, and if there was a perfect linear relationship between $\frac{K4P}{KSE}$ and Θ, as described by Equation 3, then all points would fall on this line. The figure indicates that for water contents less than 11 percent and greater than 20 percent, the correlation of $\frac{K4P}{KSE}$ and Θ is very poor. Even within the zone of water contents from 11 percent to 20 percent, there is considerable scatter about the calibration line.

The points which fall within the 11 to 20 percent water content range are those of Lysimeters 1, 2, 5, 6, 7 and 8 less than 90 cm deep. Figure 26, 28, and 29 indicate that even for these best fit points there is considerable variation of KSE measured and KSE estimated with many points falling outside the $\pm$ 10 percent error lines.

It may be stated, therefore, that for this experiment, the four probe method is unreliable in estimating the saturation extract

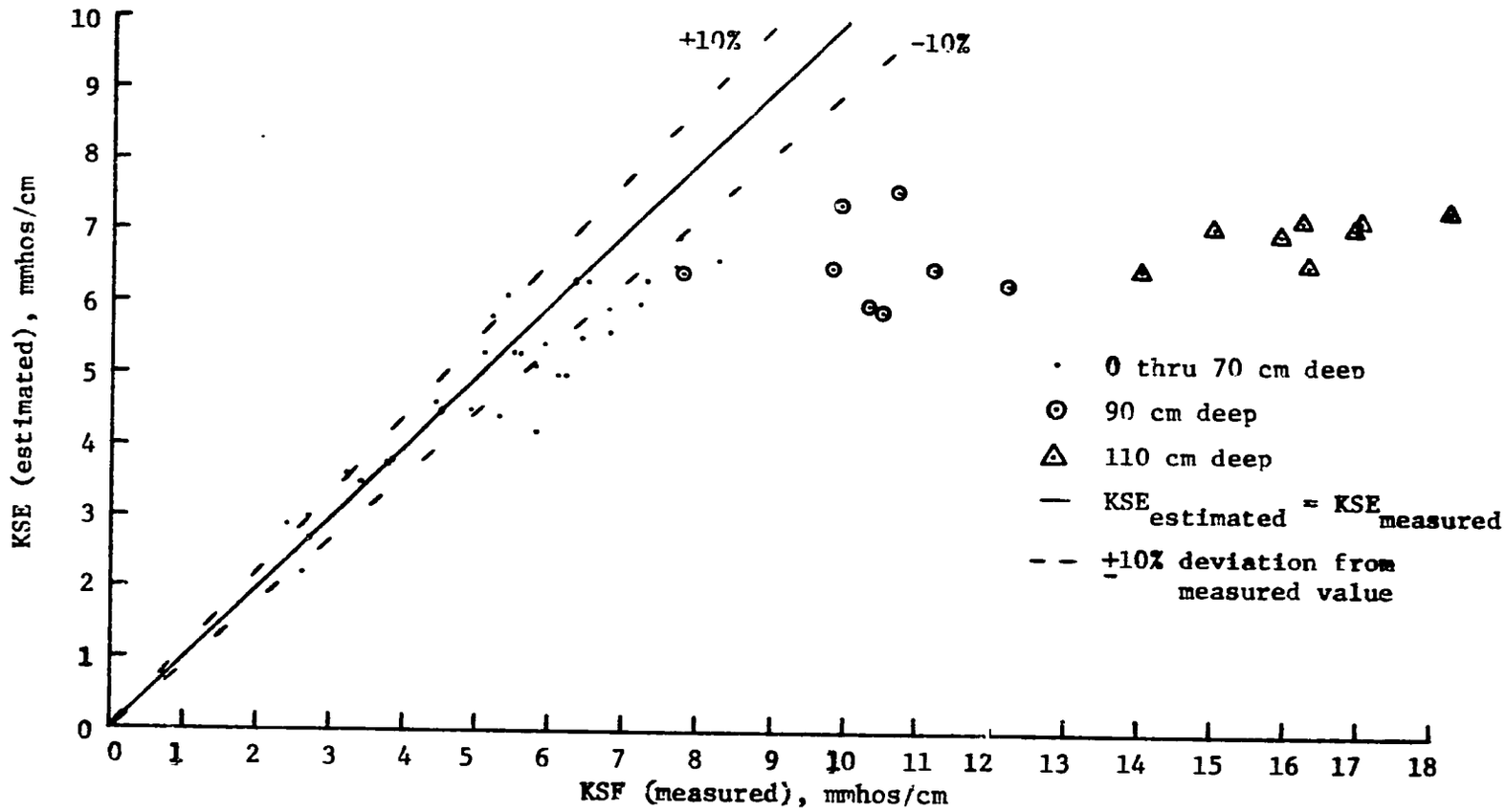


Figure 29. Measured versus estimated saturation extract conductivity for Lysimeters 7 and 8

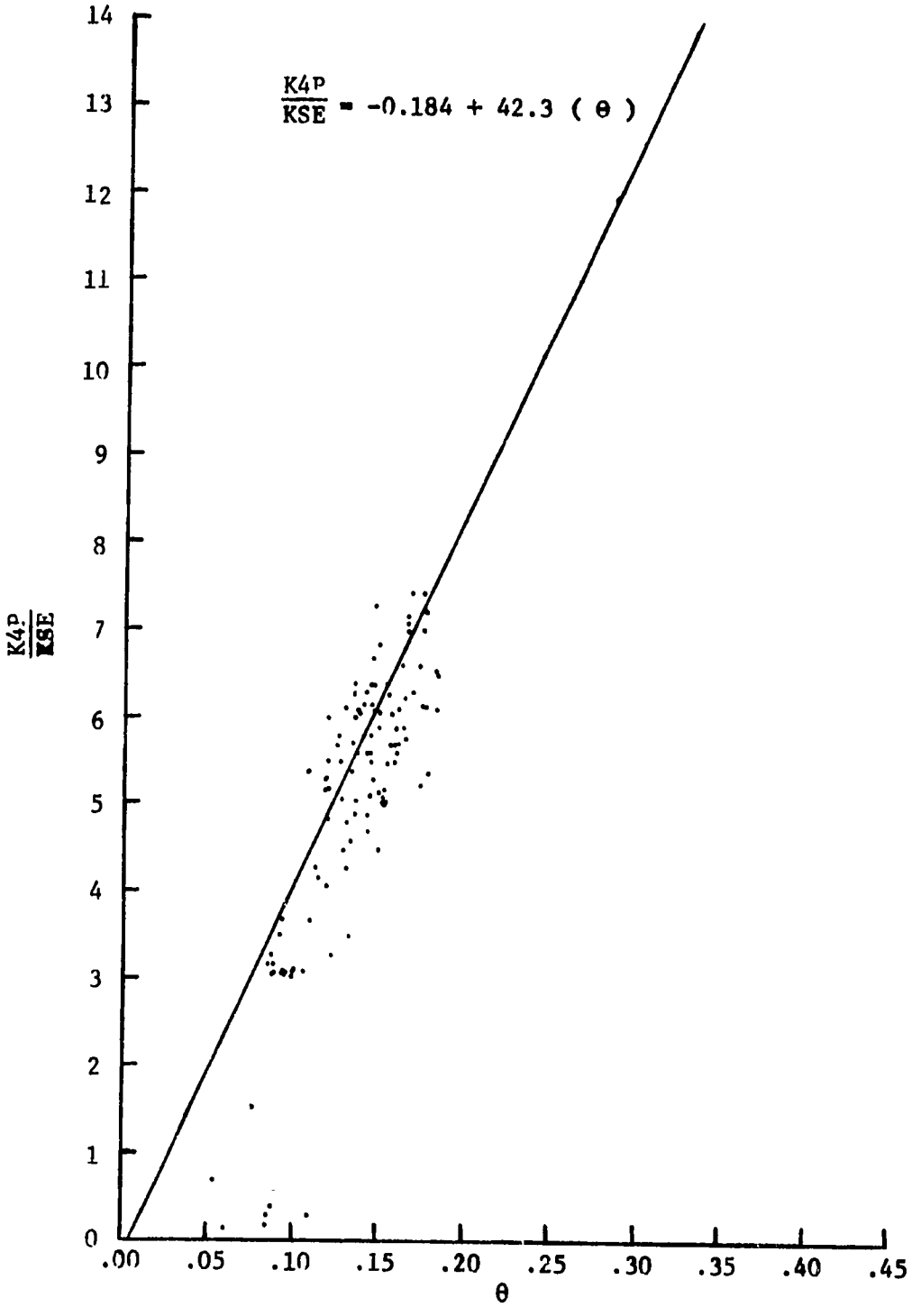


Figure 30. Four probe saturation extract conductivity versus volumetric water content

conductivity. In many cases, even within the most favorable moisture range, Θ greater than 9 percent and less than 20 percent, the deviation between estimates was greater than 20 percent of the measured value. In this experiment, which had many points less than 9 percent and greater than 20 percent water content, estimates of KSE were needed which were valid over a wider range of water contents than was found.

Even though an excellent correlation was found between $\frac{K4P}{KSE}$ and Θ for samples with a uniform water and salinity contents, Appendix E, a poor relationship was found when the method was used with the lysimeters which had variable water and salinity contents. Therefore, additional data involving the estimation of KSE from the K4P readings which were taken five times during the duration of the experiment are not presented in this paper.

SUMMARY

The objectives of this experiment were to study the salt accumulation patterns associated with trickle irrigation with regard to various irrigation treatments.

Eight lysimeters were installed in a greenhouse in order to monitor the evapotranspiration, irrigation and drainage occurrring from tomato plants. Four different trickle irrigation treatments were followed: alternate day irrigations 13 percent under, equal to, and 20 percent over the ET use, and a daily irrigation equal to the ET use. With all irrigation treatments saline water with a conductivity of 5.5 mmhos/cm for a period of 70 days was applied. At the termination of the two and a half month experiment, extensive soil samples were taken and analyzed for salinity and water content.

In the lysimeters which were consistently under irrigated with regard to their consumptive use, it was found that the highest concentrations of salt in the soil were found in the bulb like zones nearest the emitters, and that the lowest concentrations were found midway between them.

In the lysimeters which were irrigated at their ET amount or above, however, the reverse was found. That is, the zones of lowest concentrations were nearest the emitters, and the highest concentrations were found midway between the emitters and in the deepest areas of the

lysimeters. In the lysimeters which were over irrigated, the zones of least salinity tended to reach deeper into the profile than those of the lysimeters irrigated at the ET.

Little difference in overall salinity patterns were noted between the corresponding lysimeters which were irrigated daily and those that had alternate day irrigations at ET, except in the case of surface concentrations.

The lysimeters which received the daily irrigations at ET had higher surface concentrations than the corresponding lysimeters with alternate day irrigations at ET. All lysimeters, however, had very high surface concentrations of salt which were many times the concentrations 10 cm below the surface. The highest surface concentrations were on the fringes of the surface wetting fronts.

Of interest equal to the profiles of the conductivities of the saturation extract were the profiles of the soil water potential. These profiles indicated the zones where the osmotic and matric potentials were apt to be most inhibitive to water uptake by the plants.

On the lysimeters that were irrigated at or above their consumptive use, the soil water potential decreased with the horizontal and vertical distance from the emitters. In only the lysimeters which were irrigated at 1.2 ET, however, were there appreciable zones where the osmotic potential of the soil water was nearly equal to that of the irrigation water. Furthermore, in the lysimeters irrigated at 1.2 ET the zones of higher potentials tended to reach deeper into the profile than

those of the other lysimeters.

In the lysimeters which were under irrigated, a large zone of nearly uniform low soil water potential was found. This zone was nearly twice as low as the average potential found in the other lysimeters, even though less total grams of salt was applied.

In comparing the lysimeters which were irrigated daily at ET versus the ones with alternate day irrigations at ET, it was found that the former have generally higher soil water potentials.

CONCLUSIONS AND RECOMMENDATIONS

Practical applications

In applying the results of this experiment, the author feels several recommendations can be made concerning the management of trickle systems.

If saline irrigation water is used, it is desirable to over irrigate with regard to the consumptive use in order to leach salts from the portion of the root zone nearest the emitters. In the experiment the lysimeters which were irrigated 20 percent above the consumptive use had roughly one-fourth of the root zone maintained at a soil water potential of greater than -3 atm. On the other lysimeters, which were irrigated equal to or less than the consumptive use, few points of the soil profile were greater than -3 atm. An over irrigation thus maintains the most desirable root zone potential for the four irrigation treatments tested, especially if salt sensitive crops are to be grown with trickle irrigation.

On the lysimeters which received a 20 percent over irrigation on alternate days, approximately one-fourth of the root zone nearest the emitter was maintained at a soil water potential not less than 1.8 times the osmotic potential of the irrigation water (-1.6 atm). It is felt that one-fourth of the root zone is sufficient to adequately supply most of the water needs of a plant. A rough "rule of thumb" guide, therefore, might

be that for a 20 percent over irrigation on alternate days, only crops which are sensitive to a soil water potential less than 1.6 times the osmotic potential of the irrigation water should be grown.

In areas where there is good quality irrigation water, but it is in short supply during the growing season, it is recommended that the soil profile be at field capacity at the beginning of the season and that the crop may be under irrigated throughout the season. In this experiment little difference in the yield of tomatoes was noted between the lysimeters which were under irrigated 13 percent and those that were irrigated at their consumptive use amount or above. However, this practice is not recommended for use in areas where the irrigation water is saline. because the salinity stress builds up rapidly as the soil dries. In this experiment the salinity stress was nearly twice as great, after only 70 days of irrigation, in the under irrigated lysimeters as in the other lysimeters.

If all other factors are equal, a daily irrigation is to be preferred over an alternate day irrigation. In comparing Lysimeter 2 and Lysimeter 6, both sampled one day following an irrigation, it is seen that the greater part of Lysimeter 6 has 25 percent higher soil water potentials than Lysimeter 2.

In any situation where saline water is used, high surface concentrations of salts will build up. If there are light rains during the growing season these salts might be displaced into the root zone and cause serious damage to the roots. The trickle system should be started immediately

after such a rain in order to increase the water content of the soil and to flush the salts as rapidly as possible through the root zone. If possible, these surface concentrations should be leached yearly after the end of each growing season to prevent dangerous accumulations over several seasons. A method of leaching might be by sprinkling.

Suggestion for further research

Further research is needed in the area of plant response to trickle irrigation. The U. S. Salinity Laboratory Staff (1954) has prepared a table showing the relative tolerance of crops to salt. However, this table is applicable only under normal irrigation conditions, while trickle irrigation presents a very unique soil water condition where the water content can be constantly near or above field capacity. Under trickle irrigation, therefore, the salinity limits established by the U. S. Salinity Laboratory Staff need to be revised upward.

A further understanding is also needed concerning the percent of volume of the root zone that is needed to maintain a satisfactory water supply for the plants irrigated with a trickle system. Such a study would provide insight as to the percent of the root zone which can be permitted to contain high salt concentrations.

Study also needs to be done concerning leaching techniques to be used with trickle irrigation. Various amounts of over irrigation might be tried. The economics of having dual systems, sprinkler and trickle, might be investigated. Another possible method of leaching might be to

move the trickle lines periodically between rows and leaching in this position.

In further experiments of this type, which require a close monitoring of the salinity status of a soil profile which has a rapidly changing salinity and soil moisture content, it is recommended that the four probe method of measuring soil conductivity not be used to estimate the saturation extract conductivity unless further study shows that another correlation other than the one used in this study exists.

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APPENDIXES

Appendix A.

Symbols and abbreviations

A count rate measured across air by the gamma probe scaler

B attenuation coefficient for dry soil, used in gamma probe equation

C attenuation coefficient for water, used in gamma probe equation

D attenuation coefficient for the container material, used in gamma probe equation

EC electrical conductivity of a saline solution, mmhos/cm

EC_{se} electrical conductivity of a saturation extract solution, mmhos/cm

EC_{sw} electrical conductivity of the soil water solution, mmhos/cm

ET evapotranspiration

K count rate measured by the gamma probe scaler

KSE saturation extract conductivity, mmhos/cm

K4P four probe conductivity, mmhos

M constant used in the four probe equation which depends on the soil type and probe spacing

N constant used in the four probe equation which depends on the soil type and probe spacing

OP osmotic pressure, atmoshperes

P_v soil water percent expressed on a volumetric basis

P_w soil water percent expressed on a dry-weight basis

SWP soil water potential, sum of the osmotic and matric potentials, atm.

x distance from the detector to the source used in the gamma probe equation

θ	volumetric water content, fraction
ρ_s	soil bulk density, grams/cc
ρ_w	water density, grams/cc

Appendix B.

Tables

TABLE 5. SATURATION EXTRACT CONDUCTIVITY (MMHOS/CM) FOR LYSIMETER 1 WHICH RECEIVED A DAILY IRRIGATION EQUAL TO THE EVAPOTRANSPIRATION

DEPTH (CM.)	DISTANCE FROM EMITTER (CM.) 0	20	40	55	40	20	0
0	8.40		21.70	72.00	32.40		8.00
10	4.2	3.6	5.3	9.2	4.9	4.1	4.1
30	4.3	4.4	5.4	5.6	5.1	4.2	4.4
50	5.5	5.6	6.0	6.5	5.7	5.0	5.0
70	7.3	7.6	8.0	7.5	7.1	7.5	7.2
90	9.2	10.0	10.0	9.6	10.1	9.8	9.3
110	12.2	11.6	10.5	9.4	8.4	11.3	13.7

TABLE 6. SATURATION EXTRACT CONDUCTIVITY (MMHOS/CM) FOR LYSIMETER 2 WHICH RECEIVED A DAILY IRRIGATION EQUAL TO THE EVAPOTRANSPIRATION

DEPTH (CM.)	DISTANCE FROM EMITTER (CM.) 0	20	40	55	40	20	0
0	11.20		50.30	85.10	48.50		7.20
10	5.2	5.0	6.0	8.9	5.7	5.2	5.7
30	6.5	6.6	6.8	6.4	6.3	6.8	6.3
50	7.5	7.6	7.3	6.9	7.1	7.6	7.1
70	9.5	9.3	8.7	8.9	8.0	8.2	8.3
90	14.8	13.3	13.6	12.9	13.0	12.4	13.9
110	9.6	10.2	11.3	7.3	10.8	8.1	9.5

TABLE 7. SATURATION EXTRACT CONDUCTIVITY (MMHOS/CM) FOR LYSIMETER 3 WHICH RECEIVED AN ALTERNATE DAY IRRIGATION 13 PERCENT UNDER THE EVAPOTRANSPIRATION

DEPTH (CM.)	DISTANCE FROM EMITTER (CM.) 0	20	40	55	40	20	0
0	12.20		66.00	1.30	55.00		18.30
10	7.4	7.1	6.1	4.1	5.9	7.7	10.2
30	11.3	10.0	7.6	6.8	7.6	9.9	10.7
50	9.7	7.8	7.7	6.8	8.3	9.1	10.2
70	8.9	7.9	7.8	8.3	8.4	8.2	8.6
90	9.1	8.7	9.1	8.5	8.6	8.6	9.1
110	9.1	9.5	9.7	9.4	9.2	9.0	8.9

TABLE 8. SATURATION EXTRACT CONDUCTIVITY (MMHOS/CM) FOR LYSIMETER 4 WHICH RECEIVED AN ALTERNATE DAY IRRIGATION 13 PERCENT UNDER THE EVAPOTRANSPIRATION

DEPTH (CM.)	DISTANCE FROM EMITTER (CM.) 0	20	40	55	40	20	0
0	3.70		63.00	3.00	71.00		6.20
10	10.2	9.3	7.5	3.2	6.3	9.3	12.8
30	10.9	11.0	8.4	5.6	7.0	9.4	10.6
50	10.4	9.3	8.1	6.6	7.5	9.2	9.2
70	8.4	8.4	7.7	8.0	7.7	8.2	9.2
90	7.8	8.2	7.7	7.8	8.0	8.0	8.7
110	6.7	7.0	7.1	8.0	7.5	7.0	8.3

TABLE 9. SATURATION EXTRACT CONDUCTIVITY (MMHOS/CM) FOR LYSIMETER 5 WHICH RECEIVED AN ALTERNATE DAY IRRIGATION EQUAL TO THE EVAPOTRANSPIRATION

DEPTH (CM.)	DISTANCE FROM EMITTER (CM.) 0	20	40	55	40	20	0
0	4.60		59.00	28.20	29.60		6.90
10	3.2	4.2	6.2	6.3	6.1	3.2	3.2
30	4.3	5.2	6.8	6.5	6.8	5.8	4.7
50	7.4	7.2	7.2	7.9	7.6	7.8	5.9
70	10.8	9.4	9.3	10.3	9.0	8.9	9.7
90	12.4	12.2	12.6	13.9	12.1	11.5	11.0
110	13.7	16.7	14.4	15.0	14.6	15.5	17.2

TABLE 10. SATURATION EXTRACT CONDUCTIVITY (MMHOS/CM) FOR LYSIMETER 6 WHICH RECEIVED AN ALTERNATE DAY IRRIGATION EQUAL TO THE EVAPOTRANSPIRATION

DEPTH (CM.)	DISTANCE FROM EMITTER (CM.) 0	20	40	55	40	20	0
0	14.40		89.00	19.70	84.00		14.60
10	2.9	3.3	6.4	6.4	6.9	4.9	3.3
30	3.8	7.0	7.8	6.9	7.4	7.2	6.9
50	8.3	8.4	8.3	7.5	8.4	8.8	9.3
70	9.7	9.0	9.4	9.6	10.2	9.5	11.1
90	12.6	12.4	13.0	13.2	13.3	13.0	13.5
110	16.9	16.4	14.9	14.1	17.1	15.2	19.0

TABLE 11. SATURATION EXTRACT CONDUCTIVITY (MMHOS/CM) FOR LYSIMETER 7 WHICH RECEIVED AN ALTERNATE DAY IRRIGATION 20 PERCENT OVER THE EVAPOTRANSPIRATION

DEPTH (CM.)	DISTANCE FROM EMITTER (CM.) 0	20	40	55	40	20	0
0	9.50		65.00	96.90	37.80		13.40
10	2.4	2.4	5.4	7.2	5.2	2.7	2.4
30	3.1	3.8	5.6	6.8	5.8	3.4	2.5
50	3.2	4.5	6.2	7.0	6.4	5.8	3.4
70	5.0	6.2	7.3	9.1	7.2	5.3	6.0
90	7.4	9.8	9.9	10.6	10.7	7.8	8.2
110	13.7	16.9	16.2	17.0	18.2	17.0	14.8

TABLE 12. SATURATION EXTRACT CONDUCTIVITY (MMHOS/CM) FOR LYSIMETER 8 WHICH RECEIVED AN ALTERNATE DAY IRRIGATION 20 PERCENT OVER THE EVAPOTRANSPIRATION

DEPTH (CM.)	DISTANCE FROM EMITTER (CM.) 0	20	40	55	40	20	0
0	19.00		60.00	112.00	76.00		18.20
10	2.4	2.2	5.1	7.4	6.3	2.7	2.4
30	2.4	3.2	5.5	7.2	6.8	3.8	2.5
50	3.3	4.4	6.5	7.5	7.7	4.9	3.3
70	4.6	5.9	8.0	8.9	8.3	6.1	4.8
90	6.3	10.3	12.2	12.4	11.2	10.5	8.1
110	13.2	16.3	14.0	14.9	15.0	15.9	15.5

TABLE 13. OSMOTIC, MATRIC AND WATER POTENTIAL (ATM. X -1.) FOR LYSIMETER 1 WHICH RECEIVED A DAILY IRRIGATION EQUAL TO THE EVAPOTRANSPIRATION. SAMPLES TAKEN ONE DAY FOLLOWING LAST IRRIGATION

DEPTH (CM.)	DISTANCE FROM EMITTER (CM.) 0	20	40	55	40	20	0	
10	3.22	3.20	5.59	10.62	4.65	3.45	2.74	O
	0.15	0.20	0.24	0.25	0.20	0.18	0.10	M
	3.37	3.41	5.83	10.88	4.86	3.64	2.84	T
30	3.33	3.45	4.95	5.28	4.69	3.28	3.33	O
	0.15	0.16	0.19	0.20	0.19	0.16	0.14	M
	3.49	3.61	5.14	5.48	4.89	3.44	3.47	T
50	4.21	4.33	5.11	5.47	4.83	3.98	3.89	O
	0.15	0.15	0.16	0.16	0.16	0.16	0.16	M
	4.36	4.48	5.27	5.63	5.00	4.14	4.05	T
70	5.26	5.38	5.76	5.40	5.12	5.45	5.28	O
	0.10	0.10	0.10	0.10	0.10	0.10	0.11	M
	5.36	5.48	5.87	5.51	5.22	5.56	5.39	T
90	5.15	5.48	5.52	5.26	5.61	5.30	5.35	O
	0.09	0.08	0.09	0.08	0.09	0.08	0.09	M
	5.23	5.56	5.60	5.34	5.70	5.38	5.44	T
110	3.97	3.81	3.43	2.76	2.47	3.51	3.91	O
	0.04	0.04	0.04	0.03	0.03	0.04	0.03	M
	4.01	3.85	3.47	2.79	2.51	3.55	3.94	T

TABLE 14. OSMOTIC, MATRIC AND WATER POTENTIAL (ATM. X -1.) FOR LYSIMETER 2 WHICH RECEIVED A DAILY IRRIGATION EQUAL TO THE EVAPOTRANSPIRATION. SAMPLES TAKEN ONE DAY FOLLOWING LAST IRRIGATION

DEPTH (CM.)	DISTANCE FROM EMITTER (CM.) 0	20	40	55	40	20	0	
10	3.77	3.98	5.75	10.65	5.52	3.91	4.09	O
	0.13	0.16	0.21	0.26	0.21	0.14	0.12	M
	3.90	4.14	5.95	10.91	5.73	4.05	4.21	T
30	4.77	5.07	5.77	5.64	5.25	5.07	4.31	O
	0.11	0.13	0.16	0.18	0.16	0.11	0.10	M
	4.88	5.20	5.94	5.81	5.41	5.19	4.41	T
50	5.38	5.68	5.78	5.68	5.59	5.58	5.11	O
	0.10	0.11	0.14	0.15	0.14	0.11	0.10	M
	5.48	5.79	5.91	5.84	5.73	5.68	5.21	T
70	6.08	6.12	5.97	6.16	5.54	5.55	5.51	O
	0.09	0.10	0.10	0.10	0.10	0.10	0.10	M
	6.17	6.22	6.07	6.26	5.64	5.65	5.61	T
90	5.25	4.92	5.75	5.64	5.33	5.11	5.03	O
	0.05	0.05	0.06	0.07	0.06	0.06	0.05	M
	5.29	4.97	5.81	5.71	5.39	5.18	5.08	T
110	3.46	3.59	3.90	2.56	3.60	2.97	3.57	O
	0.05	0.05	0.05	0.05	0.05	0.06	0.06	M
	3.52	3.65	3.95	2.61	3.65	3.03	3.63	T

TABLE 15. OSMOTIC, MATRIC AND WATER POTENTIAL (ATM. X -1.) FOR LYSIMETER 3 WHICH RECEIVED AN ALTERNATE DAY IRRIGATION 13 PERCENT UNDER THE EVAPOTRANSPIRATION. SAMPLES TAKEN ONE DAY FOLLOWING LAST IRRIGATION

DEPTH (CM.)	DISTANCE FROM EMITTER (CM.) 0	20	40	55	40	20	0	
10	7.44	7.73	12.22	13.17	13.47	9.52	10.61	O
	0.22	0.24	2.27	16.43	3.80	0.27	0.22	M
	7.67	7.97	14.49	29.61	17.27	9.79	10.83	T
30	12.33	12.18	10.55	10.86	10.39	12.20	12.71	O
	0.23	0.26	0.30	0.33	0.30	0.26	0.25	M
	12.56	12.44	10.84	11.19	10.68	12.46	12.96	T
50	12.80	9.97	10.74	10.06	10.88	11.85	12.79	O
	0.28	0.28	0.30	0.31	0.29	0.28	0.27	M
	13.08	10.25	11.04	10.37	11.16	12.12	13.06	T
70	12.01	10.62	10.79	11.20	10.74	10.42	11.91	O
	0.28	0.29	0.30	0.29	0.28	0.28	0.29	M
	12.29	10.91	11.08	11.49	11.01	10.69	12.20	T
90	11.92	11.59	12.44	11.12	12.08	11.96	13.07	O
	0.28	0.28	0.29	0.28	0.29	0.29	0.30	M
	12.20	11.87	12.72	11.41	12.38	12.26	13.37	T
110	11.00	11.84	12.34	12.56	12.63	12.44	12.30	O
	0.26	0.26	0.27	0.28	0.29	0.29	0.29	M
	11.26	12.11	12.61	12.85	12.92	12.73	12.59	T

TABLE 16. OSMOTIC, MATRIC AND WATER POTENTIAL (ATM. X -1.) FOR LYSIMETER 4 WHICH RECEIVED AN ALTERNATE DAY IRRIGATION 13 PERCENT UNDER THE EVAPOTRANSPIRATION. SAMPLES TAKEN ONE DAY FOLLOWING LAST IRRIGATION

DEPTH (CM.)	DISTANCE FROM EMITTER (CM.) 0	20	40	55	40	20	0	
10	9.35	9.65	18.67	13.29	18.50	10.13	11.67	O
	0.18	0.22	7.59	18.95	15.38	0.24	0.17	M
	9.53	9.87	26.26	32.24	33.88	10.36	11.83	T
30	12.57	12.64	11.78	9.71	9.88	10.20	10.99	O
	0.24	0.24	0.29	0.91	0.30	0.23	0.22	M
	12.82	12.88	12.08	10.62	10.18	10.43	11.21	T
50	12.83	12.00	10.45	10.34	9.84	11.04	10.68	O
	0.26	0.27	0.28	0.33	0.29	0.26	0.25	M
	13.09	12.27	10.73	10.67	10.13	11.30	10.94	T
70	11.06	10.97	10.56	11.14	10.49	10.24	11.85	O
	0.29	0.28	0.30	0.30	0.29	0.27	0.27	M
	11.35	11.26	10.86	11.44	10.78	10.52	12.12	T
90	10.93	10.87	10.37	10.75	11.04	10.47	12.02	O
	0.30	0.29	0.29	0.30	0.30	0.28	0.29	M
	11.23	11.15	10.66	11.05	11.34	10.75	12.32	T
110	9.98	9.85	10.09	11.12	10.46	9.47	11.80	O
	0.31	0.30	0.30	0.30	0.30	0.29	0.30	M
	10.30	10.15	10.39	11.42	10.76	9.77	12.09	T

TABLE 17. OSMOTIC, MATRIC AND WATER POTENTIAL (ATM. X -1.) FOR LYSIMETER 5 WHICH RECEIVED AN ALTERNATE DAY IRRIGATION EQUAL TO THE EVAPOTRANSPIRATION. SAMPLES TAKEN TWO DAYS FOLLOWING LAST IRRIGATION

DEPTH (CM.)	DISTANCE FROM EMITTER (CM.) 0	20	40	55	40	20	0	
10	3.37	3.75	6.38	7.45	5.89	3.05	3.35	O
	0.25	0.20	0.23	0.27	0.21	0.22	0.25	M
	3.63	3.95	6.61	7.72	6.09	3.27	3.60	T
30	3.46	3.87	5.76	6.10	6.00	4.67	3.61	O
	0.17	0.14	0.16	0.20	0.18	0.14	0.15	M
	3.62	4.01	5.92	6.30	6.18	4.81	3.77	T
50	5.35	5.24	5.75	6.76	6.05	5.87	4.01	O
	0.10	0.10	0.14	0.17	0.14	0.12	0.10	M
	5.45	5.34	5.89	6.92	6.19	5.99	4.12	T
70	6.82	6.24	6.13	7.29	6.28	5.88	6.45	O
	0.09	0.10	0.10	0.10	0.10	0.10	0.10	M
	6.92	6.34	6.22	7.39	6.38	5.98	6.55	T
90	7.11	6.60	6.49	7.06	6.17	6.32	6.12	O
	0.09	0.08	0.08	0.08	0.08	0.08	0.09	M
	7.20	6.68	6.57	7.14	6.25	6.41	6.21	T
110	4.07	5.36	4.99	4.16	4.34	5.03	5.64	O
	0.03	0.03	0.04	0.02	0.03	0.04	0.04	M
	4.10	5.40	5.03	4.19	4.37	5.07	5.67	T

TABLE 18. OSMOTIC, MATRIC AND WATER POTENTIAL (ATM. X -1.) FOR LYSIMETER 6 WHICH RECEIVED AN ALTERNATE DAY IRRIGATION EQUAL TO THE EVAPOTRANSPIRATION. SAMPLES TAKEN ONE DAY FOLLOWING LAST IRRIGATION

DEPTH (CM.)	DISTANCE FROM EMITTER (CM.) 0	20	40	55	40	20	0	
10	2.23	2.57	6.81	10.96	8.23	3.89	2.53	O
	0.15	0.16	0.24	0.77	0.26	0.16	0.15	M
	2.38	2.73	7.04	11.73	8.49	4.05	2.68	T
30	2.45	5.17	6.69	7.13	6.45	5.43	4.97	O
	0.10	0.11	0.17	0.23	0.17	0.12	0.10	M
	2.55	5.28	6.86	7.36	6.63	5.54	5.07	T
50	5.68	6.24	7.00	7.23	6.96	6.49	6.46	O
	0.10	0.11	0.16	0.21	0.15	0.11	0.10	M
	5.78	6.35	7.16	7.43	7.12	6.60	6.56	T
70	6.51	6.39	7.06	7.40	7.54	6.51	7.25	O
	0.10	0.10	0.12	0.13	0.11	0.10	0.10	M
	6.61	6.49	7.17	7.52	7.65	6.60	7.34	T
90	7.09	6.95	7.19	7.19	7.26	7.25	7.33	O
	0.09	0.09	0.09	0.08	0.08	0.09	0.08	M
	7.17	7.04	7.28	7.27	7.34	7.34	7.41	T
110	5.69	5.00	4.75	4.19	5.23	4.34	5.75	O
	0.04	0.03	0.03	0.03	0.03	0.03	0.03	M
	5.73	5.03	4.79	4.23	5.26	4.37	5.78	T

TABLE 19. OSMOTIC, MATRIC AND WATER POTENTIAL (ATM. X -1.) FOR LYSIMETER 7 WHICH RECEIVED AN ALTERNATE DAY IRRIGATION 20 PERCENT OVER THE EVAPOTRANSPIRATION. SAMPLES TAKEN ONE DAY FOLLOWING LAST IRRIGATION

DEPTH (CM.)	DISTANCE FROM EMITTER (CM.) 0	20	40	55	40	20	0	
10	1.66	1.74	5.13	8.42	4.76	1.93	1.40	O
	0.11	0.13	0.20	0.26	0.19	0.12	0.09	M
	1.77	1.87	5.33	8.68	4.95	2.05	1.50	T
30	1.80	2.43	4.16	5.90	4.26	2.18	1.50	O
	0.09	0.10	0.14	0.17	0.13	0.10	0.09	M
	1.90	2.53	4.30	6.07	4.39	2.28	1.59	T
50	1.70	2.72	4.13	5.33	4.29	3.46	1.88	O
	0.09	0.10	0.10	0.12	0.10	0.09	0.09	M
	1.78	2.81	4.24	5.45	4.39	3.55	1.97	T
70	2.48	3.31	4.26	5.93	4.65	2.91	2.99	O
	0.08	0.09	0.09	0.10	0.10	0.09	0.08	M
	2.56	3.39	4.35	6.03	4.75	3.00	3.07	T
90	3.30	4.87	5.06	5.34	5.45	3.75	3.84	O
	0.07	0.08	0.08	0.08	0.08	0.08	0.08	M
	3.37	4.95	5.14	5.42	5.53	3.83	3.92	T
110	3.90	5.10	4.74	4.91	5.12	4.98	4.12	O
	0.03	0.03	0.02	0.02	0.02	0.02	0.02	M
	3.92	5.12	4.77	4.93	5.14	5.00	4.15	T

TABLE 20. OSMOTIC, MATRIC AND WATER POTENTIAL (ATM. X -1.) FOR LYSIMETER 8 WHICH RECEIVED AN ALTERNATE DAY IRRIGATION 20 PERCENT OVER THE EVAPOTRANSPIRATION. SAMPLES TAKEN TWO DAYS FOLLOWING LAST IRRIGATION

DEPTH (CM.)	DISTANCE FROM EMITTER (CM.) 0	20	40	55	40	20	0	
10	1.95	1.79	4.02	6.80	5.35	2.39	2.27	O
	0.17	0.17	0.16	0.19	0.16	0.20	0.22	M
	2.12	1.96	4.18	6.99	5.51	2.60	2.49	T
30	1.74	2.25	3.99	5.90	5.34	2.73	1.92	O
	0.13	0.12	0.13	0.15	0.13	0.13	0.15	M
	1.87	2.37	4.12	6.05	5.48	2.86	2.07	T
50	2.02	2.69	4.68	5.37	5.45	2.99	2.02	O
	0.10	0.10	0.10	0.10	0.10	0.10	0.10	M
	2.12	2.78	4.79	5.47	5.55	3.08	2.11	T
70	2.38	3.18	4.93	5.50	5.12	3.18	2.46	O
	0.09	0.09	0.09	0.09	0.09	0.09	0.08	M
	2.47	3.27	5.03	5.59	5.21	3.27	2.54	T
90	2.74	5.02	6.01	6.29	5.57	5.05	3.49	O
	0.07	0.08	0.08	0.08	0.08	0.07	0.07	M
	2.81	5.09	6.08	6.37	5.65	5.12	3.56	T
110	3.55	4.83	3.64	4.03	3.96	4.32	3.98	O
	0.02	0.02	0.02	0.02	0.02	0.02	0.01	M
	3.57	4.86	3.65	4.05	3.98	4.34	3.99	T

TABLE 21. VOLUMETRIC WATER CONTENTS (PERCENT) FOR LYSIMETER 1 WHICH RECEIVED A DAILY IRRIGATION EQUAL TO THE EVAPOTRANSPIRATION. SAMPLES TAKEN ONE DAY FOLLOWING LAST IRRIGATION

	DISTANCE FROM EMITTER (CM.)						
DEPTH (CM.)	0	20	40	55	40	20	0
10	14.0	12.0	10.8	10.2	12.0	12.7	16.0
30	14.1	13.9	12.7	12.4	12.7	14.0	14.5
50	14.2	14.0	13.6	13.8	13.7	13.6	13.9
70	16.2	16.5	16.2	16.2	16.2	16.1	15.9
90	21.2	21.6	21.5	21.6	21.3	21.9	20.6
110	35.9	35.6	35.7	39.8	39.6	37.6	40.9

TABLE 22. VOLUMETRIC WATER CONTENTS (PERCENT) FOR LYSIMETER 2 WHICH RECEIVED A DAILY IRRIGATION EQUAL TO THE EVAPOTRANSPIRATION. SAMPLES TAKEN ONE DAY FOLLOWING LAST IRRIGATION

	DISTANCE FROM EMITTER (CM.)						
DEPTH (CM.)	0	20	40	55	40	20	0
10	14.9	13.5	12.0	9.9	11.9	14.3	15.0
30	15.7	15.0	13.6	13.1	13.8	15.4	15.8
50	16.1	15.4	14.6	14.0	14.6	15.7	16.0
70	18.0	17.5	16.8	16.6	16.6	17.0	17.3
90	32.9	31.6	27.6	26.7	28.5	28.3	32.3
110	31.1	31.8	32.6	32.0	33.6	30.6	29.9

TABLE 23. VOLUMETRIC WATER CONTENTS (PERCENT) FOR LYSIMETER 3 WHICH RECEIVED AN ALTERNATE DAY IRRIGATION 13 PERCENT UNDER THE EVAPOTRANSPIRATION. SAMPLES TAKEN ONE DAY FOLLOWING LAST IRRIGATION

	DISTANCE FROM EMITTER (CM.)						
DEPTH (CM.)	0	20	40	55	40	20	0
10	11.4	10.6	6.1	3.8	5.4	9.6	11.4
30	11.2	10.1	8.6	7.4	8.7	10.0	10.3
50	9.3	9.3	8.5	8.0	9.1	9.4	9.8
70	9.1	8.8	8.6	8.8	9.3	9.4	8.9
90	9.4	9.2	9.0	9.1	8.7	8.8	8.5
110	9.9	9.9	9.7	9.2	9.0	8.9	8.9

TABLE 24. VOLUMETRIC WATER CONTENTS (PERCENT) FOR LYSIMETER 4 WHICH RECEIVED AN ALTERNATE DAY IRRIGATION 13 PERCENT UNDER THE EVAPOTRANSPIRATION. SAMPLES TAKEN ONE DAY FOLLOWING LAST IRRIGATION

	DISTANCE FROM EMITTER (CM.)						
DEPTH (CM.)	0	20	40	55	40	20	0
10	13.0	11.5	4.9	3.0	4.2	10.9	13.4
30	10.6	10.7	8.7	6.9	8.4	11.0	11.5
50	9.9	9.5	9.2	7.6	9.1	9.9	10.2
70	9.0	9.1	8.7	8.5	8.7	9.5	9.5
90	8.5	9.0	8.8	8.6	8.6	9.1	8.9
110	8.0	8.5	8.4	8.6	8.5	8.8	8.6

TABLE 25. VOLUMETRIC WATER CONTENTS (PERCENT) FOR LYSIMETER 5 WHICH RECEIVED AN ALTERNATE DAY IRRIGATION EQUAL TO THE EVAPOTRANSPIRATION. SAMPLES TAKEN TWO DAYS FOLLOWING LAST IRRIGATION

	DISTANCE FROM EMITTER (CM.)						
DEPTH (CM.)	0	20	40	55	40	20	0
10	10.3	12.2	11.3	9.8	12.0	11.4	10.4
30	13.5	14.6	13.7	12.4	13.1	14.4	14.1
50	16.1	15.9	14.5	13.6	14.6	15.4	16.0
70	18.4	17.5	17.6	16.4	16.6	17.5	17.4
90	20.6	21.9	23.0	23.3	23.2	21.5	21.3
110	38.3	37.8	35.1	41.0	38.2	37.5	37.1

TABLE 26. VOLUMETRIC WATER CONTENTS (PERCENT) FOR LYSIMETER 6 WHICH RECEIVED AN ALTERNATE DAY IRRIGATION EQUAL TO THE EVAPOTRANSPIRATION. SAMPLES TAKEN ONE DAY FOLLOWING LAST IRRIGATION

	DISTANCE FROM EMITTER (CM.)						
DEPTH (CM.)	0	20	40	55	40	20	0
10	13.7	13.5	10.6	6.8	9.8	13.3	13.8
30	16.3	15.3	13.1	10.9	12.9	15.0	15.7
50	16.5	15.2	13.4	11.7	13.6	15.3	16.2
70	16.8	15.9	15.0	14.6	15.3	16.5	17.3
90	20.5	20.5	20.8	21.2	21.1	20.6	21.2
110	36.3	40.1	38.4	38.5	40.0	40.1	40.4

TABLE 27. VOLUMETRIC WATER CONTENTS (PERCENT) FOR LYSIMETER 7 WHICH RECEIVED AN ALTERNATE DAY IRRIGATION 20 PERCENT OVER THE EVAPOTRANSPIRATION. SAMPLES TAKEN ONE DAY FOLLOWING LAST IRRIGATION

	DISTANCE FROM EMITTER (CM.)						
DEPTH (CM.)	0	20	40	55	40	20	0
10	15.5	14.7	12.0	10.1	12.5	15.0	18.3
30	18.4	16.7	14.4	13.2	14.6	16.7	17.8
50	20.2	17.7	16.0	15.0	16.0	17.9	19.4
70	21.6	20.1	18.3	17.5	17.7	19.5	21.5
90	24.3	23.3	22.7	23.0	22.8	22.5	23.2
110	39.5	39.8	41.0	41.5	42.6	41.0	40.3

TABLE 28. VOLUMETRIC WATER CONTENTS (PERCENT) FOR LYSIMETER 8 WHICH RECEIVED AN ALTERNATE DAY IRRIGATION 20 PERCENT OVER THE EVAPOTRANSPIRATION. SAMPLES TAKEN TWO DAYS FOLLOWING LAST IRRIGATION

	DISTANCE FROM EMITTER (CM.)						
DEPTH (CM.)	0	20	40	55	40	20	0
10	13.0	13.0	13.4	12.3	13.3	11.9	11.2
30	14.6	15.0	14.5	13.8	14.4	14.7	13.7
50	17.2	17.3	15.7	15.7	15.9	17.3	17.3
70	20.4	19.6	18.3	18.3	18.3	20.2	20.6
90	24.8	23.6	23.4	22.7	23.1	23.9	25.0
110	42.3	41.0	43.8	42.0	43.1	41.9	44.3

Table 29. Density data for all lysimeters

Depth from surface	Lysimeter number 1	2	3	4	5	6	7	8
10	1.43	1.44	1.44	1.44	1.45	1.41	1.43	1.41
30	1.46	1.44	1.44	1.44	1.45	1.41	1.43	1.41
50	1.45	1.44	1.44	1.44	1.45	1.41	1.43	1.41
70	1.46	1.44	1.44	1.44	1.45	1.41	1.43	1.41
90	1.48	1.46	1.44	1.44	1.48	1.44	1.45	1.44
110	1.56	1.50	1.45	1.44	1.52	1.53	1.50	1.52

Appendix C.

Figures

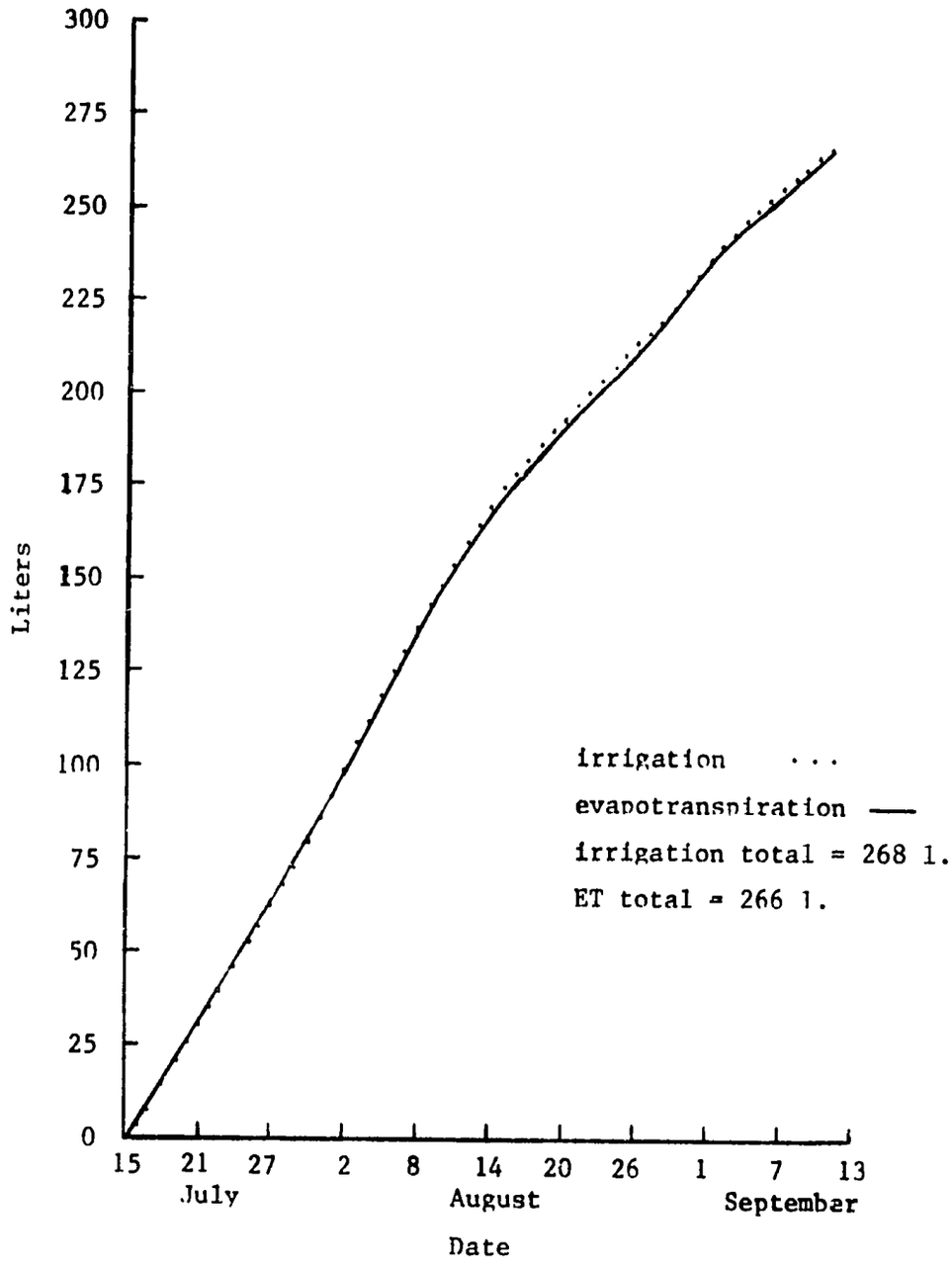


Figure 31. Cummulative irrigation and evapotranspiration amounts for Lysimeter 1

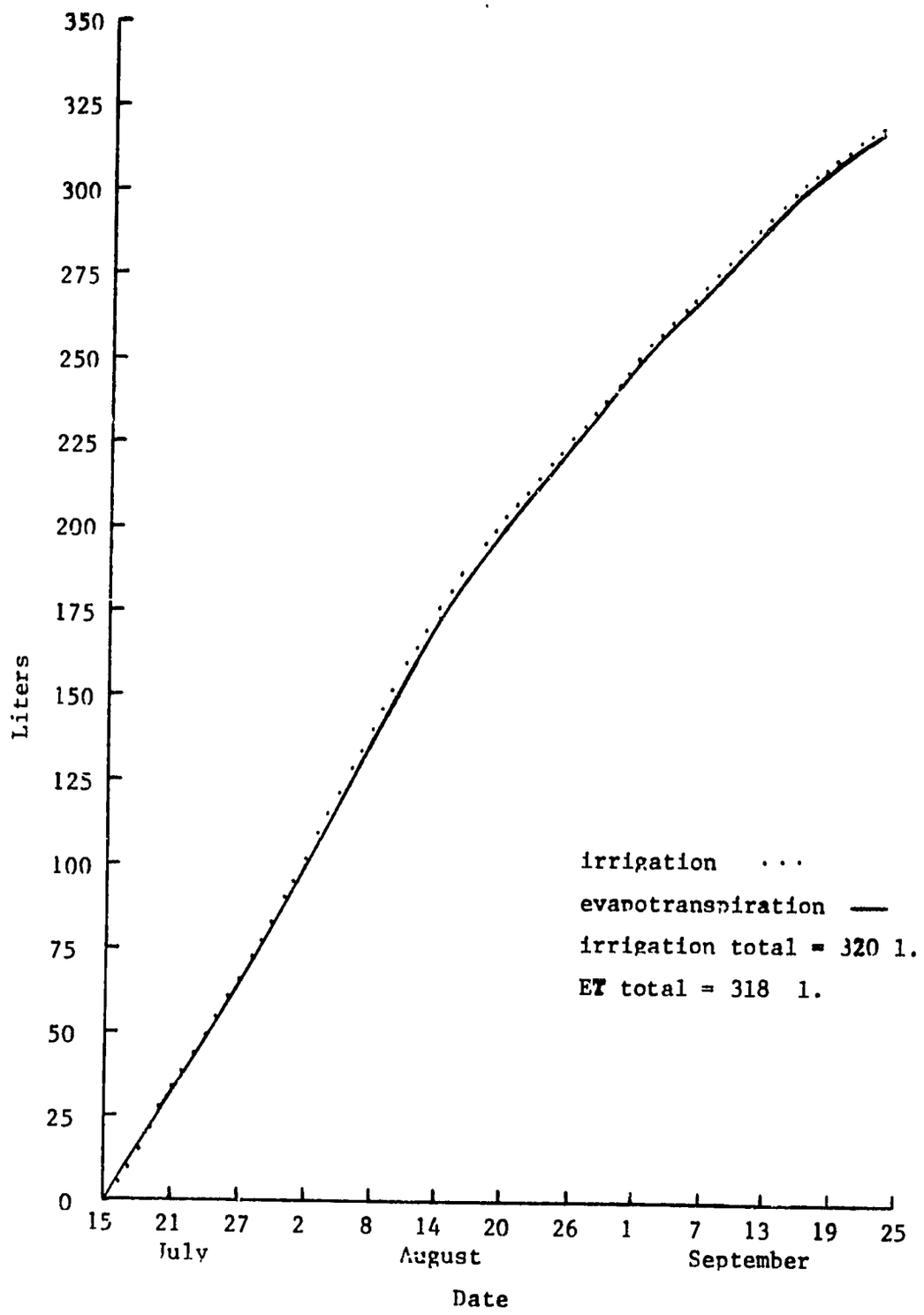


Figure 32. Cummulative irrigation and evapotranspiration amounts for Lysimeter 2

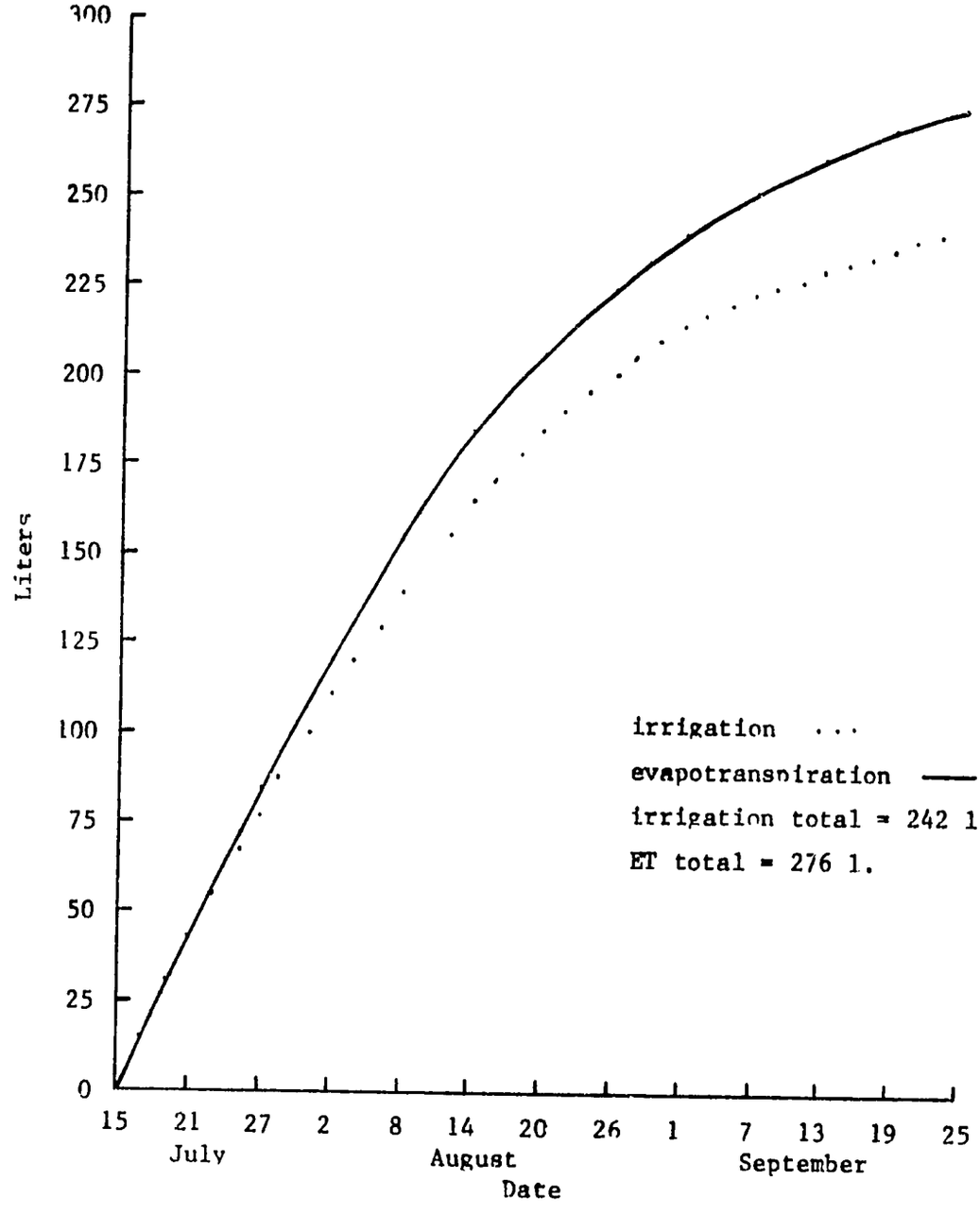


Figure 33. Cummulative irrigation and evapotranspiration amounts for Lysimeter 3

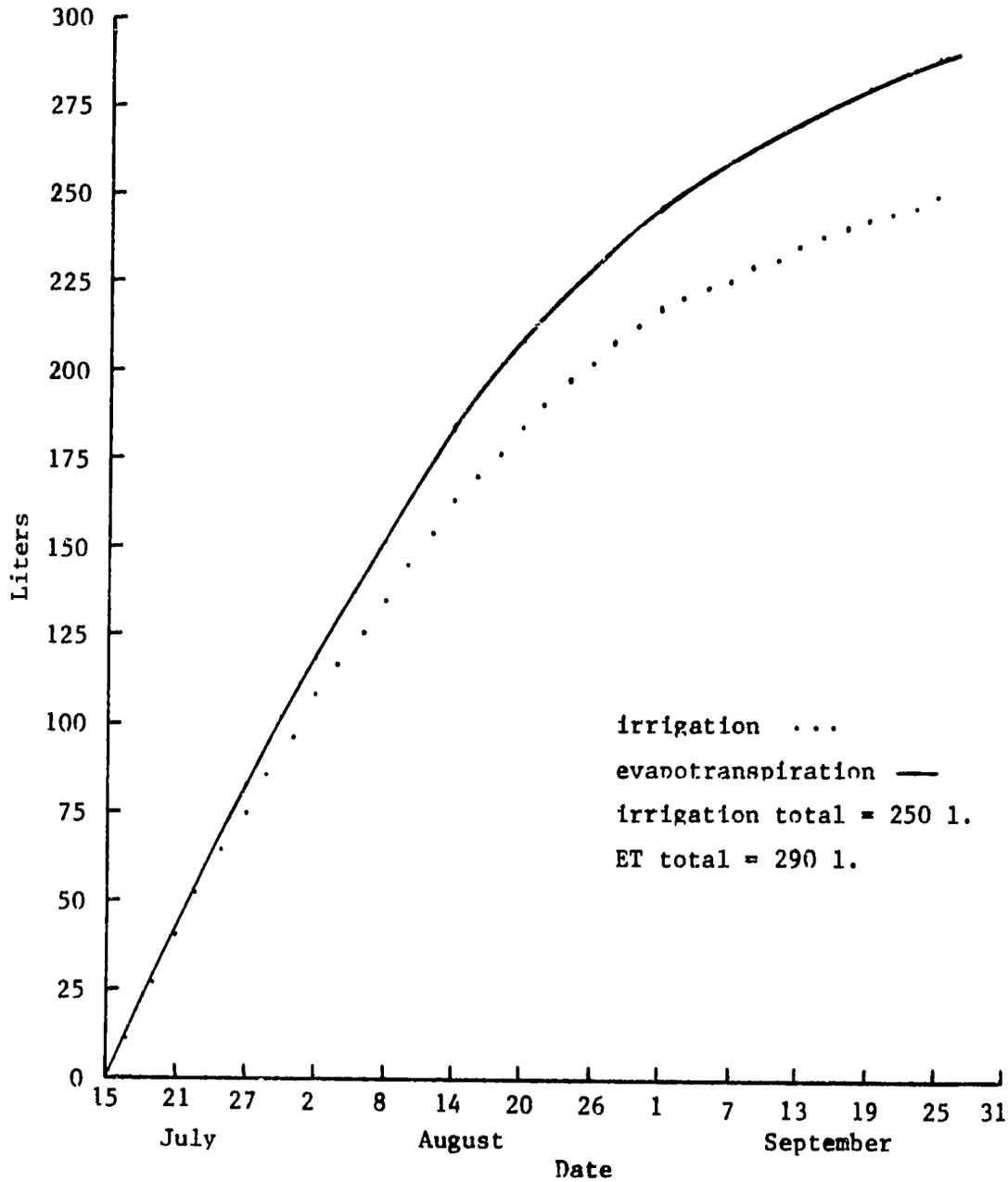


Figure 34. Cummulative irrigation and evapotranspiration amounts for Lysimeter 4

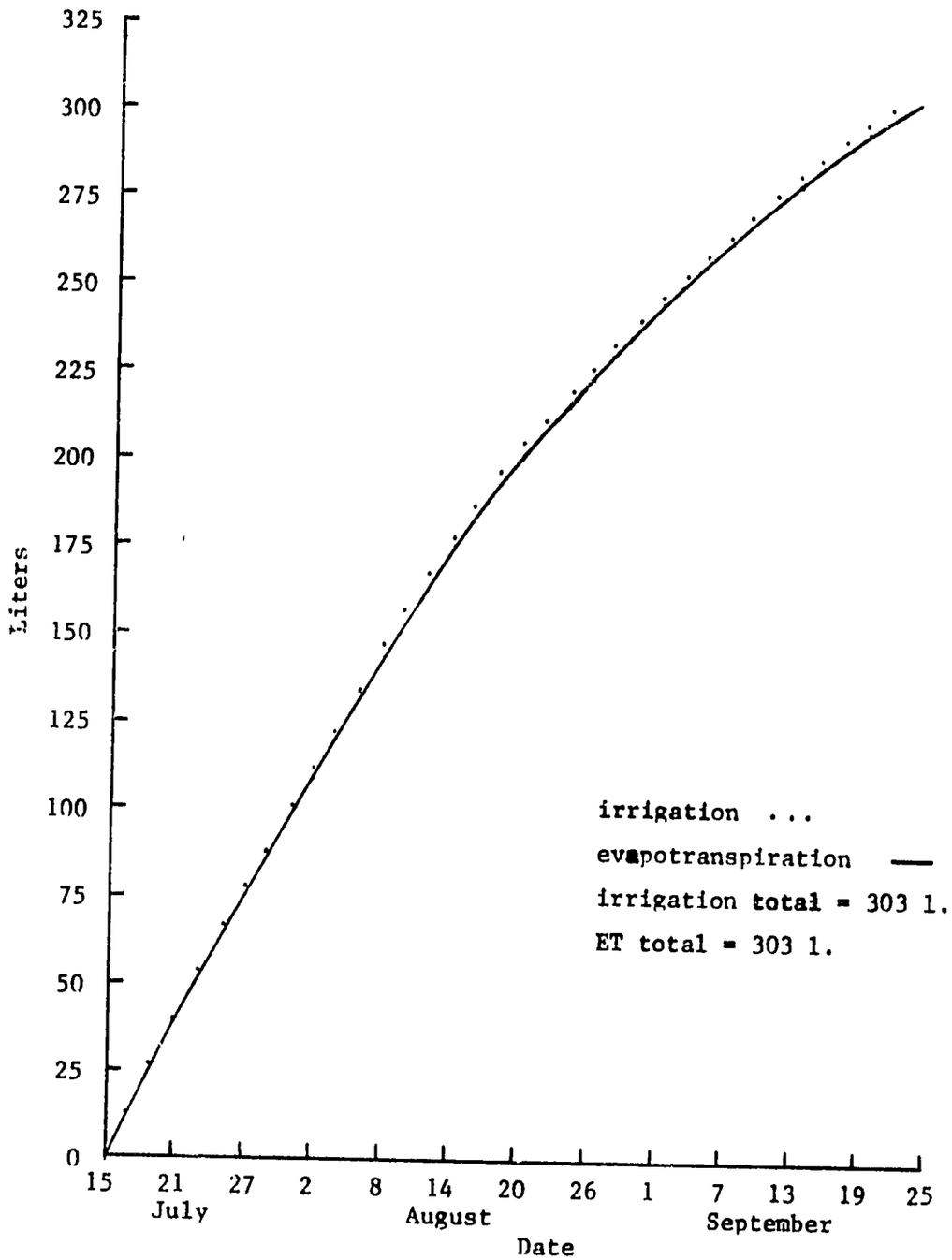


Figure 35. Cummulative irrigation and evapotranspiration amounts for Lysimeter 5

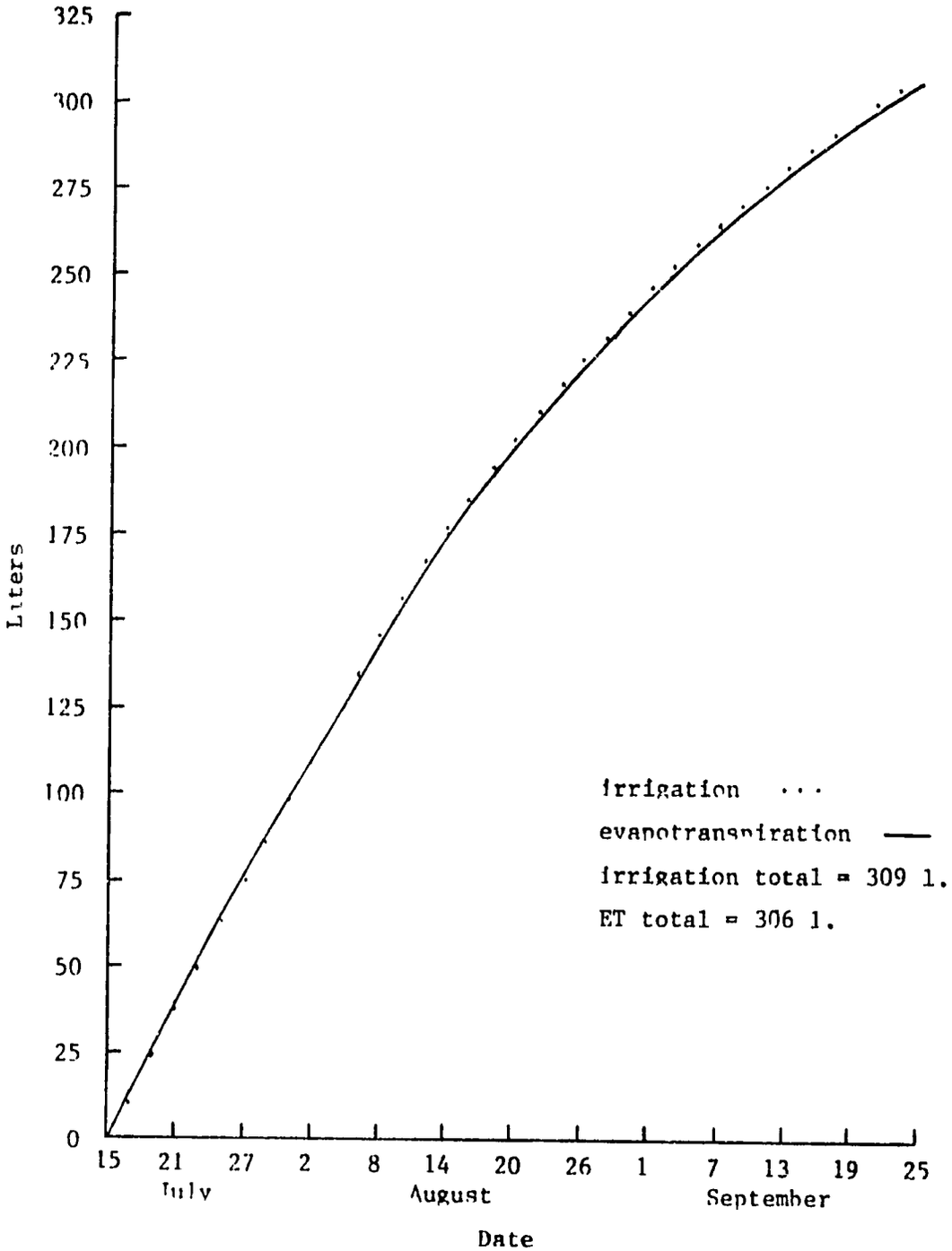


Figure 36. Cummulative irrigation and evapotranspiration amounts for Lysimeter 6

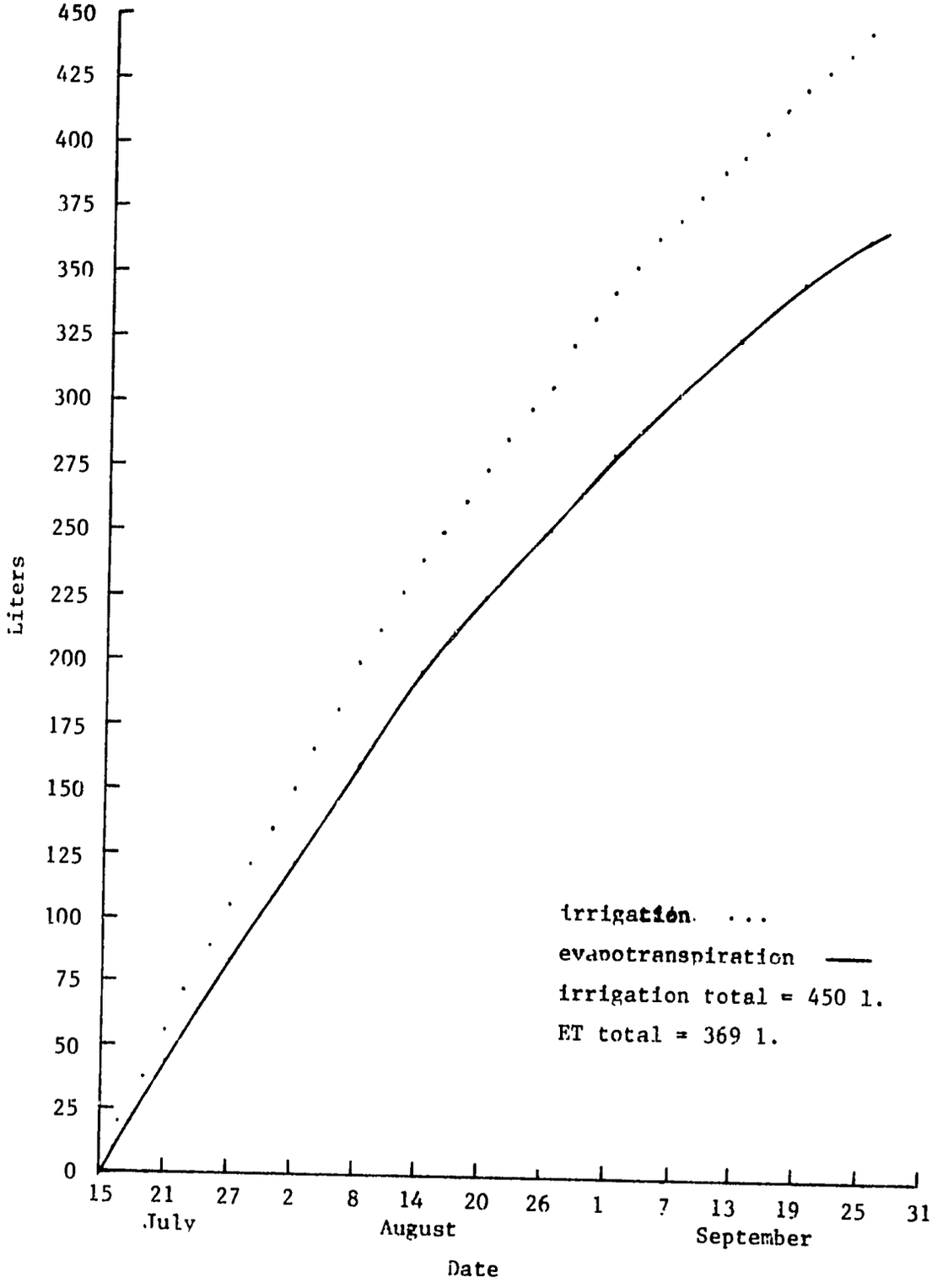


Figure 37. Cummulative irrigation and evapotranspiration amounts for Lysimeter 7

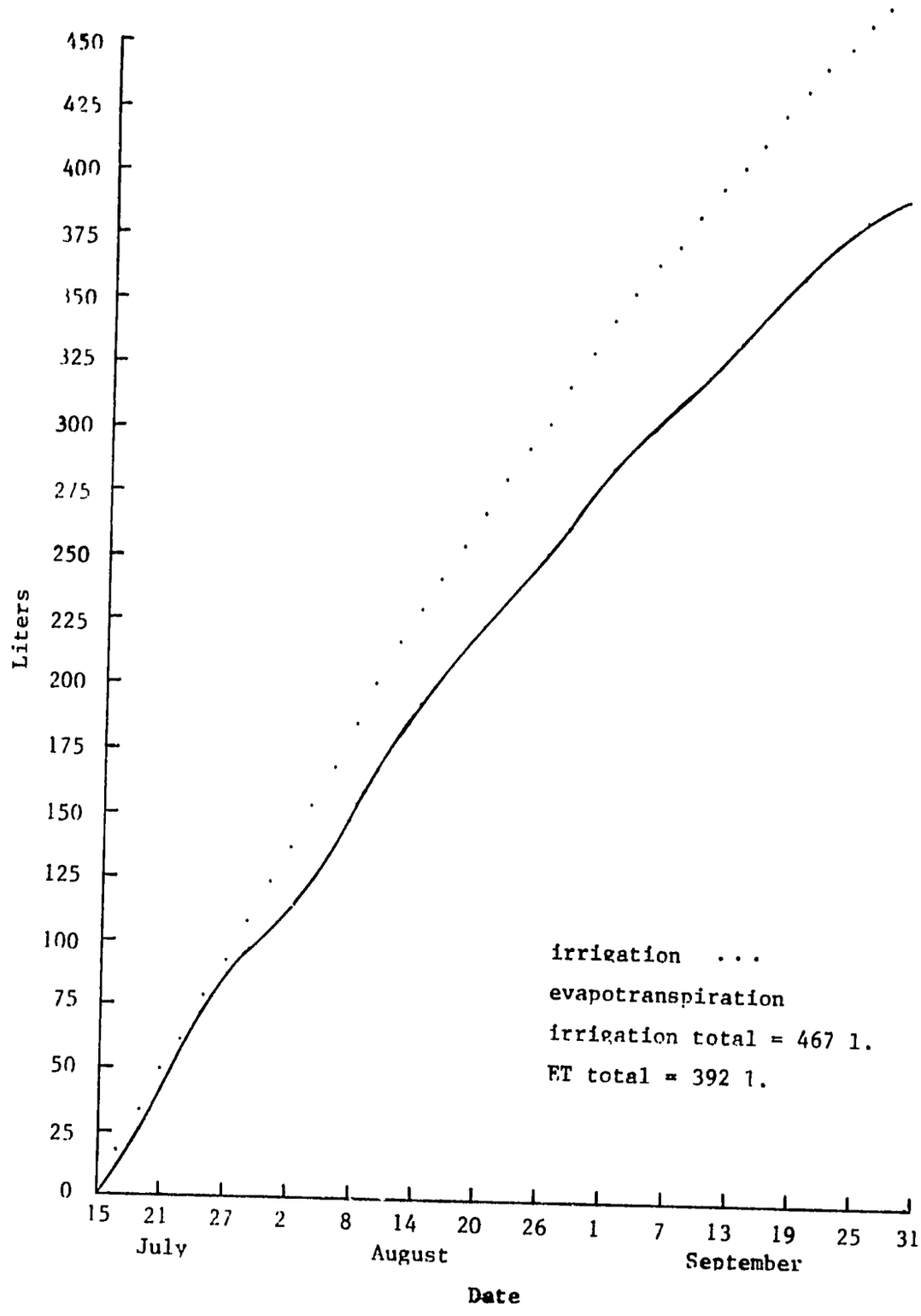


Figure 38. Cummulative irrigation and evapotranspiration amounts for Lysimeter 8

Appendix D.

Theory and method of calibration of the gamma probe

The theory of the operation of the gamma probe as adopted from Troxler Laboratories (1970) is given below.

The gamma probe method requires two access tubes, one containing a Cesium 137 source, and the other a scintilation probe. The probe acts as a detector, which by electronic discrimination within it, can be made to sense photons of any energy level. The Cesium 137 source produces by radioactive decay, gamma photons of 661 KeV energy. The photons are emitted uniformly in all directions, and travel in a straight line until they collide with an orbital electron of an atom, upon which occurance they may be either scattered in another direction or absorbed. The radiation received at the detector, therefore, may have a whole spectrum of energy depending on the number of collisions an individual particle may have had before arriving at the detector. However, the particles which experience no collisions will still have the source energy of 661 KeV. Therefore, if the detector is set so that it senses only those photons of 661 KeV, the density of the material between the source and detector can be measured. A large count of photons of 661 KeV indicates a material of low density, and visa-versa. The intensity of radiation is directly proportional to the source activity and to the solid angle formed by the source and detector. It is an inverse log function of the number of electrons in the space between the source and detector. By discriminating against energies other than

661 KeV, the intensity becomes an inverse log function of the number of electrons in the solid angle. And assuming, furthermore, that most of the chemical elements in the soil have an electron mass ratio of 0.5, the intensity becomes an inverse log function of the unit weight of the material in the solid angle.

Specifically, the solid angle in the system used is a pyramid with a rectangular base of 1/2 x 1-1/2 inches and a height of 12 inches as shown in Figure 39.

The system uses a photomultiplier tube to produce pulses proportional to the energy of the gamma radiation striking the detector. When the pulses corresponding to the 661 KeV are electronically counted, the relationship between the count rate and a chemically uniform material within the solid angle is defined by:

$$K = A e^{-B \rho x} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

where

K = count rate

A = constant, count when $\rho = 0.0$, or $x = 0.0$

B = constant, attenuation coefficient for the material

ρ = density of the material

x = distance between the source and detector, 26.83 cm

A better equation, however, for real soils contained by a box is given by the following equation which accounts for a different attentuation for water, soil and the container material.

$$K = A\, e^{-(B \rho_s + C \Theta \rho_w + D)\, x} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \qquad (8)$$

where

K = count rate

A = constant, count rate when ρ_s and ρ_w are 0.0. or x is 0.0

B = attenuation coefficient of the dry soil

C = attenuation coefficient of water

D = attenuation coefficient for the container material

Θ = water content by volume, decimal

ρ_w = density of water, 1.0 grams/cc

ρ_s = density of the soil, grams/cc

x = distance from the detector to the source, 26.83 cm

The soil, water and container attenuation coefficients may be obtained by the following procedure used by Hanks (1972).

The procedure used to find the water attenuation coefficient C entailed the use of five galvanized soil containers 5 cm wide, 7.7 cm long and 5.2 cm deep. These containers were placed between the source and detector as shown in Figure 40.

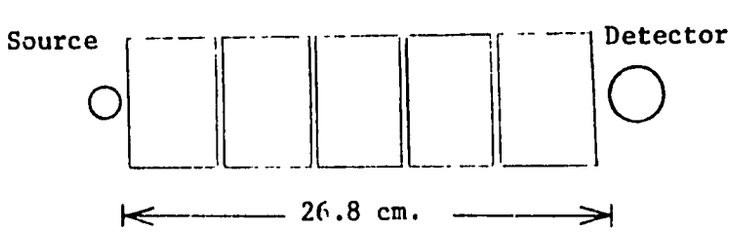


Figure 40. Positions of the calibration boxes used with the gamma probe

A one minute count was then taken with all cans empty. Then successively the cans were filled with water, with a count taken each time until all five cans were filled. The cans were then emptied one by one with a count taken each time until the cans were again all empty. Therefore two readings were obtained for each number of cans filled, for example, two readings with no cans filled, two readings with one can filled, two readings with two cans filled, etc. Because the total distance between the source and detector was 26.83 cm, and the width of each can was 5 cm, the percent of distance occupied by any one can is: 5.0/ 26.83 x 100 or 0.184. Therefore, the percent of the volume occupied by one, two, three, four, and five cans filled are: 0.184, 0.368, 0.554, 0.738, and 0.924, respectively.

Equation 8 when applied to the case where the containers are filled only with water reduces to:

$$K = A\, e^{-(C\,\Theta\,\rho_w)\,x} \quad \ldots\ldots\ldots\ldots \quad (9)$$

where

A = average of the two readings with all cans empty.

Upon rearrangement and simplification this reduces to:

$$\frac{\ln \frac{A}{K}}{26.83} = C\,\Theta \quad \ldots\ldots\ldots\ldots \quad (10)$$

when

ρ_w = 1.0 grams/cc

x = 26.83 cm

When $\ln \frac{A}{K}$ versus θ are plotted on a linear scale, the slope of the resulting line is equal to C / 26.83. Referring to Figure 41, we see that C = 0.0704.

By a similar method as was used to find C, the soil coefficient B may be found by filling the five cans with dry soil packed to a uniform density. The density, ρ_s , which is sensed by the gamma probe is merely that fraction of volume occupied by the cans, as was previously determined for the water coefficient, multiplied by the density to which each can is packed.

Equation 8, when applied to the case where the cans are filled only with soil reduces to:

$$K = A\, e^{-B\, \rho_s\, x} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \qquad (11)$$

Upon simplification and rearrangement this reduces to:

$$\frac{\ln \frac{A}{K}}{26.83} = B\ \rho_s \qquad (12)$$

When $\ln \frac{A}{K}$ versus ρ_s are plotted on a linear scale, the slope of the resulting line is equal to B / 26.83. Referring to Figure 42, it is seen that B equals 0.062.

In order to find the attenuation coefficient D for the plywood and/or plexiglass material, readings were taken in air with nothing between the source and detector, and then readings were taken with the empty lysimeter box between them.

Equation 8, when applied to this case reduces to:

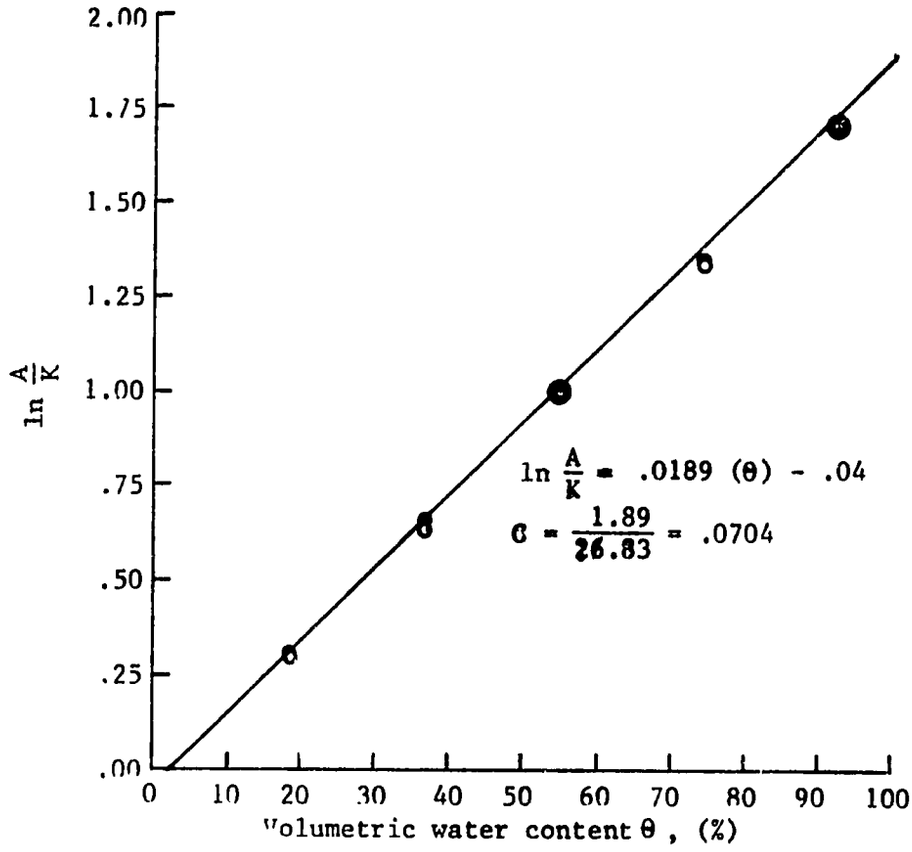


Figure 41. Gamma probe calibration - attenuation coefficient for water

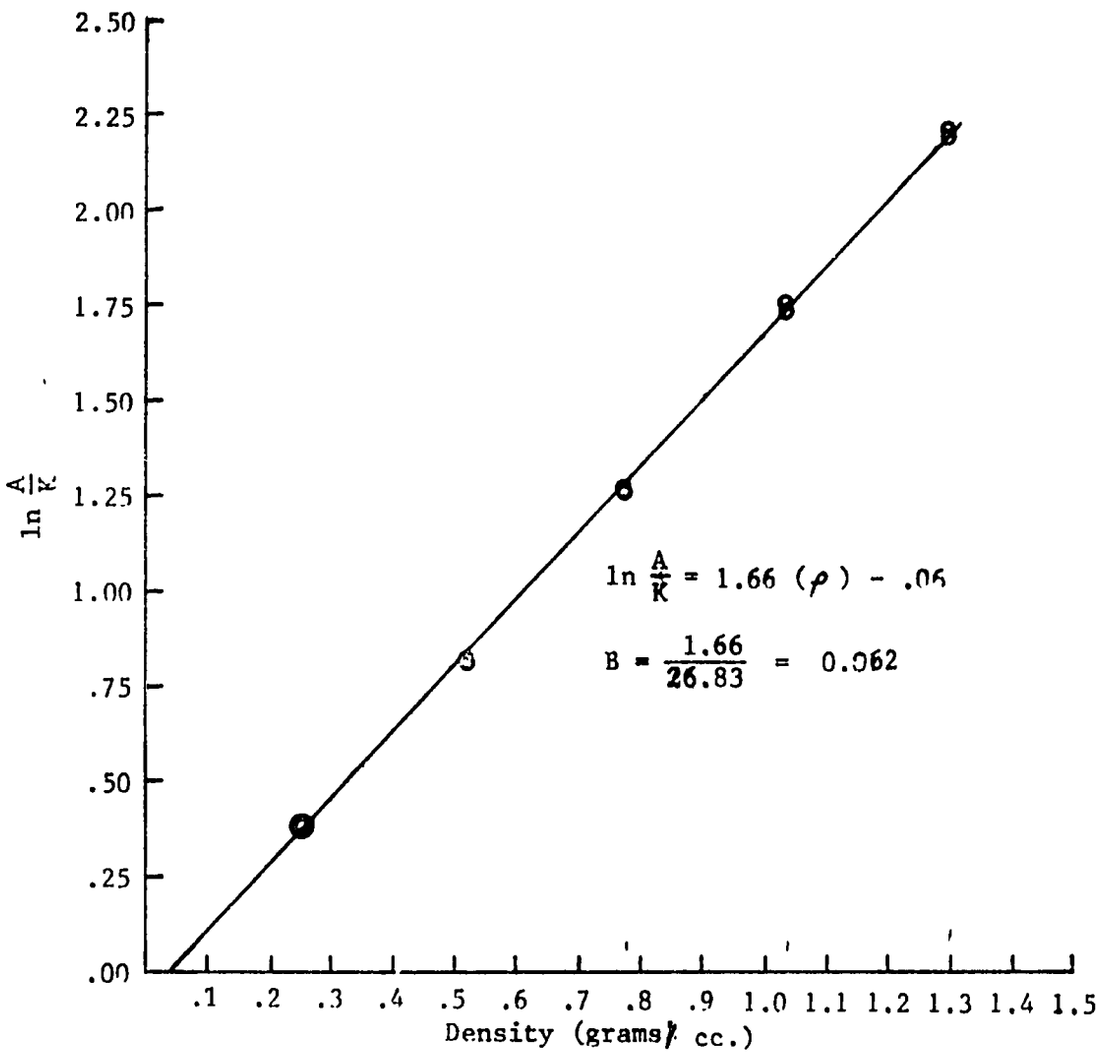


Figure 42. Gamma probe calibration - attenuation coefficient for soil

$$K = A\,e^{-Dx} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \qquad (13)$$

which after simplification reduces to:

$$D = \frac{\ln \frac{A}{K}}{26.83} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \qquad (14)$$

where

A = the average of ten 2-minute counts with no box between the source and detector

K = the average of ten counts when the box material is between the source and detector

For the lysimeters constructed of all 3/4 inch plywood, D equals 0.005, and when one side is plexiglass, D equals 0.0065.

The values found above for B and C apply if the soil and soil water completely fill the space between the source and detector of 26.83 cm. However, since the inside dimension of the lysimeters were about 21 cm, then the coefficients B and C must be reduced by a factor 21 / 26.83. Therefore, the new values for C and B are 0.055 and 0.485, respectively.

The final equation used for the gamma probe, therefore, is:

$$K = A\,e^{-(0.0485\,\rho_s + 0.055\,\Theta + D)\,26.83} \quad . \; . \; . \; . \; . \; . \qquad (15)$$

or

$$\theta = \frac{\ln \frac{A}{K} - 0.0485\,\rho_s - D}{26.83} \Big/ 0.055 \quad . \; . \; . \; . \; . \; . \; . \; . \; . \qquad (16)$$

By substituting in the appropriate values for the density to which

each lysimeter was packed, approximately 1.44 grams/cc, and the appropriate value of D, depending on whether the lysimeter had a plexiglass side or not, the volumetric water content could be found for each point desired.

Appendix E.

Four probe conductivity method and procedure for calibration

The four probe method of measuring the salinity of soils has been reported on by several investigators. Shea and Luthin (1961) examined the possibility of installing permanently buried sets of electrode probes at several depths in a soil profile to monitor salt movement and assess salinity changes. Rhoades and Invalson (1971) used the four probe method to determine the bulk soil salinity of field plots. They found high correlation between the saturation extract (KSE) and the four probe conductivity, K4P. However, their studies were conducted at a near constant water content. Gupta and Hanks (1973) reported on laboratory tests using the four probe method of measuring soil water conductivity when the soil water content is not constant. They reported a correlation of $r = 0.88$, for a sandy loam soil when relating the four probe and saturation extract ratio (K4P/KSE) and the volumetric water content (Θ). However, their data was collected by analyzing samples of constant salinity and water content, and by only varying these parameters between samples.

This experiment also used the four probe method of measuring the salinity of the soil as reported by Gupta and Hanks (1973) to estimate the saturation extract conductivity. It was hoped that the limitations of the validity of their relationship, which was that the volume of the soil sampled be of a uniform moisture content and salinity content, would not prove too limiting if the soil sample was not at these conditions.

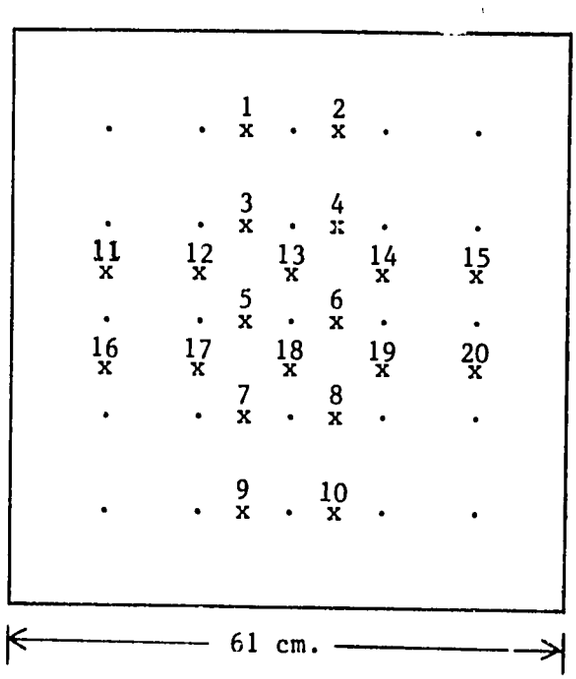
The relationship which Gupta and Hanks (1973) found was of the form:

$$\frac{K4P}{KSE} = N + M(\Theta) \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \qquad (17)$$

where the constants N and M vary with the soil type and probe configuration used.

In order to determine the constants N and M for the soil type and probe configuration used in the lysimeters, a small calibration box was constructed with the same width as the lysimeters, 21 cm, but only 61 cm long and high. In one side was mounted a 5 x 5 grid of stainless steel bolts of the same spacing, 10 cm, as was used in the lysimeters. Four probe readings were then taken in 20 different positions for each trial ran. Using sets of four electrodes, ten readings were taken on both horizontal and vertical lines as is indicated in Figure 43.

A soil sample of uniform salinity and moisture content was mixed and placed in the box at nearly the same density as was used in the lysimeters. Four probe readings were then taken from the box at the 20 positions indicated. Five samples from the box were then taken to obtain the saturation extract conductivity, and five were taken to obtain a volumetric water content. The average of these sets of five samples were then used as the representative saturation extract and water content for the trial and in all further calculations. Four trials of samples were mixed at varying water contents, but essentially the same average salinity as is shown in Table 30.



. Denotes position of stainless steel bolts
x Denotes sampling positions

Figure 43. Measurement positions of the four probe calibration box

Table 30. Salinity and moisture contents of the four probe calibration tests

Trail	Volumetric moisture	KSE (mmhos/cm)
1	0.0881	1.92
2	0.154	2.04
3	0.233	2.16
4	0.313	2.23

After computing the $K4P/KSE_{ave}$ ratio for the 20 positions of each of the four trails, it was noted that all readings for positions nearest the side, top, or bottom of the box were consistently lower than the others in the midsection. This indicates an edge effect due to the outer boundaries of the box. Therefore, for calibration purposes it was decided to use only the four readings taken nearest to the center of the box, reading numbers 5, 6, 13, and 18. On the trail with $\Theta = 0.313$, however, the edge effects were not noticeable on the readings of positions 3, 4, 7, 8, 12, 14, 17, and 19 also, so these were also used in the calibration equation. Figure 44 presents the resulting plot of K4P/KSE versus Θ. A linear regression analysis gave the following relationships:

$$\frac{K4P}{KSE} = 42.3\,(\Theta) - 0.184 \quad . \; . \; . \; . \; . \; . \; . \; . \; . \quad (18)$$

with a correlation coefficient $r = 0.99$.

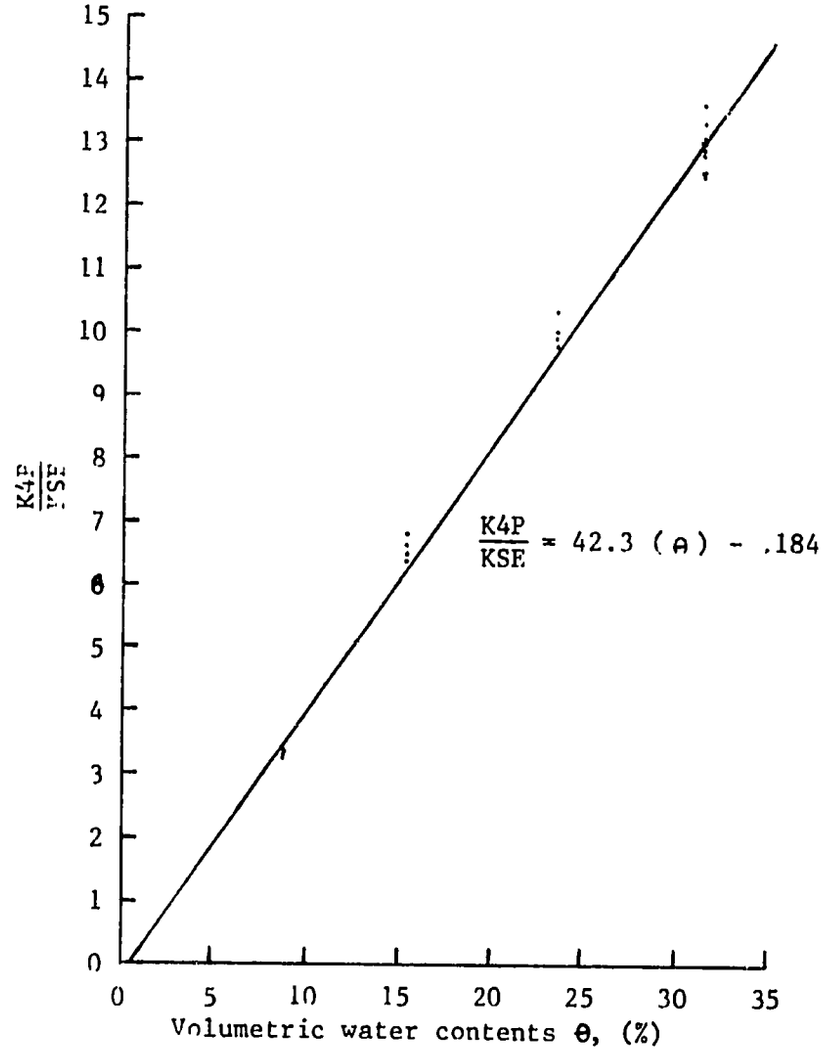


Figure 44. Four probe calibration

The results of the calibration test, therefore, confirmed Gupta and Hanks (1973) findings and gave a calibration for the loamy sand soil and the four probe configuration used in the lysimeters. The tests also showed that boundary effects were present, especially with Θ less than 0.15, if the distance from the line of electrodes were closer than 30 cm from the boundary. This indicates that there is considerable lateral volume sampled by the four probe method. The standardly accepted depth from the surface sampled by the method is given as equal to the spacing of the electrodes (Rhoades and Ingvalson, 1971). In this experiment the probe spacing is 10 cm, therefore the depth would also be 10 cm.

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