FACTORS AFFECTING EFFICIENCIES OF FURROW IRRIGATION

by

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ABSTRACT

Efficiencies of furrow irrigation practices were evaluated. Field observations taken at three different times from eight cotton fields of different length of run, slope and soil texture, provided base for the analysis of irrigation efficiency. Analysis was made for only single furrow using the inflow-outflow method. The measurements included rate of water advance and recession, soil moisture content before and after irrigations, soil density, inflow and outflow rate and the application time. The effect of major causes of water losses was investigated.

INTRODUCTION

Water advancing or receding in a surface irrigation system is a complex, non-uniform, unsteady, open-channel flow phenomenon. Owing to the many variables involved, mathematical approaches are based on simplifying assumptions. Some of the variables are slope, water intake characteristics, stream size, surface roughness, vegetation and effect of channel shape on velocity distribution.

Furrow irrigation is a partial surface flooding method. Water is applied in small channels or furrows between plant rows. The flow regime is both non-uniform and unsteady. Flow in a channel of constant cross section is said to be uniform if the depth is the same at every section of the channel. Since in an irrigation furrow, part of the stream is taken by the soil the depth of the remaining flow along the furrow decreases with distance and the flow is non-uniform. Steady flow occurs if depth at a point does not vary with time. During the advance of the stream, depth of water at a point increases rapidly at first as the water front advances. Following this initial rapid rise, the water intake characteristics of the soil influence depth. Water intake rate usually decreases with time at a decreasing rate, approaching a constant value. As intake rate in the furrow upstream from a given point decreases, depth of water at that point will increase. The result is an unsteady flow condition until the intake rate is nearly constant. The further the point is from the upper end of the run, the greater will be the influence of change of intake rate on changing depth of flow.

In evaluating an irrigation system, methods of measuring water and evaluating irrigation practices are necessary from the time water leaves the point of diversion until it is utilized by the plants. "Irrigation Efficiency" (9,10) terms are used to measure and focus attention upon (1) water conveyance loss, (2) adequacy of the irrigation, (3) uniformity of distribution of water, and (4) ability of plants to utilize the stored water. In evaluating efficiency of furrow irrigation, the term "Water Application Efficiency" and "Water Storage Efficiency" are used in this study to express the efficiency with which irrigation water is being stored in the soil root zone.

Water application efficiency is the ratio of the water stored in the soil root zone during the irrigation to the water delivered, expressed as a percentage. The concept of water application efficiency can be applied to a project, a farm or a field to evaluate irrigation practices. When the delivered water is measured at the farm head gate, it is called farm irrigation efficiency and when measured at the field it is designated as field irrigation efficiency.

Water storage efficiency is the ratio of the water stored in the root zone during the irrigation to the water needed in the root zone prior to the irrigation expressed as a percentage.

Briefly, to determine the water application and water storage efficiencies of a furrow irrigation, it is necessary to know soil moisture deficiency in the root zone before irrigation, the amount of water delivered by the irrigation and the soil moisture content of the root zone after the irrigation. Additional data are required to identify the causes for water losses.

Irrigation efficiencies are a function of intake characteristics, surface roughness, water holding capacity, initial soil moisture content, slope, furrow cross-section, application rate and duration, and crop condition. Use of water for irrigation often is relatively inefficient. Many farm irrigation systems are poorly adapted to the soils and topography on which they have been developed.

Farm management practices may result in farm irrigation efficiency being higher than field irrigation efficiency in a specific field. For example, efficiency may be poor on a given field but the tail water (excess water on lower end of the field) may be reused on a lower field or pumped back into the system so that the overall farm irrigation efficiency may be much better than that on the specific field.

In Central Arizona, the Soil Conservation Service (14) evaluated the irrigation practices of many farms on many separate fields. Field irrigation efficiencies varied from above 70 percent to as low as 25 or 30 percent.

Large losses in deep percolation and excessive runoff contribute to low irrigation efficiency (3,10). Deep percolation losses are caused by irregular land surface, shallow soil underlain by gravels, excessive application times, small streams, and lack of attention to water during long runs. Factors contributing to excessive runoff are large irrigation streams, excessive application times, improper preparation of land, compact impervious soils, steep slopes, and lack of attention during irrigation. Many of the causes of water losses can be controlled by proper irrigation management. However, some physical properties of soils such as texture and depth, can not be controlled by the farmer.

The objective of this study was to determine some ranges of furrow irrigation efficiency under grower's field conditions and to identify the major factor or factors influencing these efficiencies. Observations taken from 8 cotton fields in the Avra Valley, Arizona, provided a basis for the analysis of irrigation efficiency. The inflow-outflow method (4,15) was used to evaluate furrow irrigation practices. Data were collected from fields with two different lengths of run, three types of soil textures and three different ranges of slope. Evaluations were made on the same fields at three different times of cotton irrigation (16).

REVIEW OF LITERATURE

In evaluating irrigation efficiency, it is necessary to know runoff losses and seepage losses. Runoff losses can be determined by inflow-outflow measurement. For seepage losses, both intake characteristics and intake opportunity-time distribution along the runs are required.

Data on intake characteristics are not constant with location or time because of many variables involved. The most important factors related to infiltration rate of water under irrigation are itemized by Erie (6) as soil surface conditions, internal characteristics of the soil mass, soil moisture content, hydrostatic head, season of the year, soil and water temperature, and duration of application.

Various methods have been devised to measure infiltration. The intake ring method is widely used and accepted because of its simplicity. Furrow intake characteristics can be determined from inflow-outflow measurements under field conditions (15). Although furrow intake studies can be made on furrow sections of various length, it is desirable to use a section short enough so the rate of advance is essentially uniform.

Variation in physical properties of soil and surface conditions may be great within the field. For this reason intake characteristics as determined from intake rings or furrow infiltrometers (2) are often questioned. Smerdon (13) attempted to evaluate furrow intake characteristics of a soil by measuring the advance of the wetting front during an actual irrigation.

It is necessary to know the rate of water advance and recession to find the intake opportunity-time distribution along the runs. Field observations provide this information, but require considerable time and effort. Therefore, many attempts have been made to predict the rate of advance of the wetting surface from the known average intake characteristics of the soil (5,7,8,11).

Criddle et al. (4), gave a clear indication that application efficiency will be influenced by the length of run, intake rate, and application time. They emphasize the following items in their analysis for evaluating furrow irrigation systems.

1. The amount of water needed to refill the soil moisture reservoir is the difference between the amount of moisture in the root zone before irrigation and the field capacity.

2. Maximum furrow spacing is determined by the type of crop, equipment used, soil texture, and soil profile.

3. Intake characteristics should be determined by measuring the flow into and out of the furrow. When the intake rate is plotted against elapsed time on log paper the resultant curve has a general shape indicated by the formula: $I = Kt^n$, where

I is the intake rate of the soil; t is the time that water is on the surface of the soil; K is the intake-rate intercept at unit time; and n is the slope of the line.

4. Depth of water, D, absorbed by the soil or time, t, required to refill the soil moisture reservoir is determined by integrating the intake equation $I = Kt^n$;

$$D = \frac{K}{(n+1)} t^{n+1} \quad \text{or} \quad t = \left[\frac{D(n+1)}{K}\right]^{\frac{1}{n+1}} \; \ldots\ldots\ldots \; (1)$$

5. The maximum allowable time to get water through the furrow is equal to one-fourth of the total time needed to refill the soil in the root zone.

6. Seepage loss can be calculated as follows, referring to Figure 1;

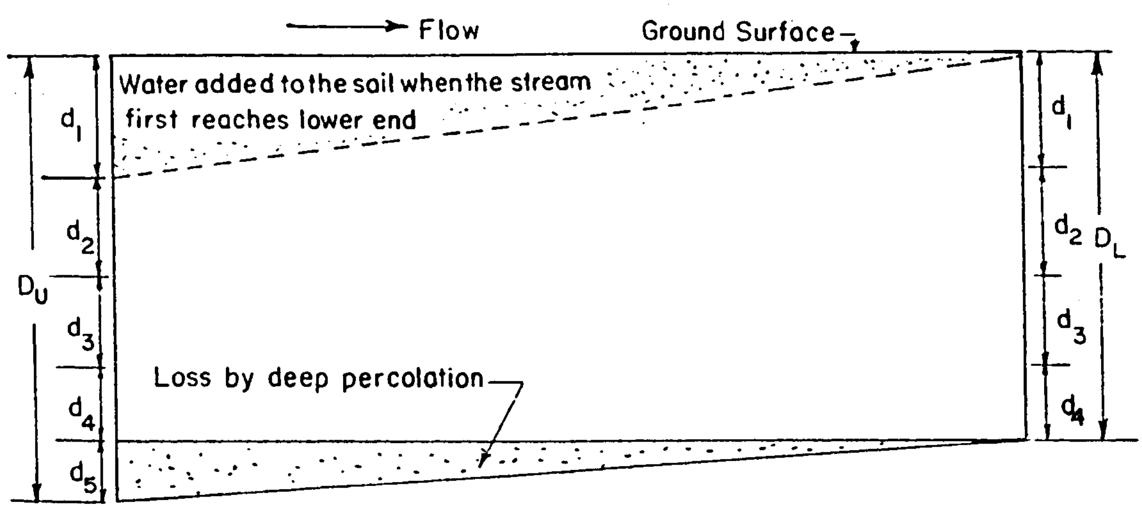


Figure 1. Profile along furrows showing water penetration.

Assume

T = Time required to refill root zone.

$T/4$ = Time required for furrow stream to reach lower end of furrow.

d_1, d_2, d_3, d_4 and d_5 = Depths of water absorbed in equal time increments $T/4$.

$$d_1 = \frac{K(T/4)^{n+1}}{(n+1)}$$

$$d_1 + d_2 = \frac{K\ (2T/4)^{n+1}}{n+1} = 2^{n+1} \cdot d_1$$

$$d_2 = (2^{n+1} - 1)\ d_1$$

$$d_1 + d_2 + d_3 = \frac{K\ (3T/4)^{n+1}}{n+1}$$

$$d_3 = (3^{n+1} - 2^{n+1})\ d_1$$

With intake varying inversely with the square root of time, i,e. $I = Kt^{-0.5}$

Therefore;

$d_2 = (\sqrt{2}-1)d_1$, $d_3 = (\sqrt{3}-\sqrt{2})\ d_1$, $d_4 = (2-\sqrt{3})d_1$ and $d_5 = (\sqrt{5}-2)d_1$

$D_L = d_1(1+\sqrt{2}-1+\sqrt{3}-\sqrt{2}+2-\sqrt{3}) = 2d_1$ = Absorbed at lower end

$D_U = d_1(1+\sqrt{2}-1+\sqrt{3}-\sqrt{2}+2-\sqrt{3}+\sqrt{5}-2) = \sqrt{5}d_2$ = Absorbed at upper end.

Then

$$\text{Average deep percolation} = (\sqrt{5}-2)\ \frac{d_1}{2}$$

$$\text{Average depth absorbed} = \frac{2d_1 + \sqrt{5}d_1}{2} = (2+\sqrt{5})\ \frac{d_1}{2}$$

To find the percentage of water absorbed that will be lost to deep percolation in this example:

$$\frac{100(\sqrt{5}-2)\ \frac{d_1}{2}}{(2+\sqrt{5})\ \frac{d_1}{2}} \doteq \frac{100\ (\sqrt{5}-2)}{(2+\sqrt{5})} = 5.3 \text{ percent}$$

7. A first approximation of design stream size may be estimated from the formula $Q = 10/S$ where Q is the stream size in gal/min. and S is the slope of the furrow in percent.

8. The maximum allowable furrow stream is determined by the capacity of the furrow and the amount of erosion permissible on the soils.

9. The maximum allowable length of run is a compromise between the maximum non-erosive stream and maximum time that can be allowed for the stream to advance down the furrow.

An analysis of deep percolation loss similar to the method discussed by Criddle et al. has been followed by Bishop (1). He assumed that as the time increased, the intake rate approached a constant value and that the wetting pattern in the soil profile parallel to the run below the root zone is triangular. The deep percolation loss is given by the equation;

$$P = \frac{(R + 1)^{n+1} - R^{n+1}}{(R + 1)^{n+1} + R^{n+1}} (100) \text{.................} (2)$$

where

P = deep percolation loss expressed as a percentage;

R = the ratio of the time required to refill the root zone to the time required for the water to reach the end of the run;

n = exponent of t in the intake equation $I = Kt^n$

Equation (2) is based on the assumption of constant rate of advance. Bishop showed that no appreciable error was introduced by asuming that:

$$P = \frac{1+n}{2R+1} (100) \text{..............................} (3)$$

when $o > n > -1$.

Equation (3) is applicable for various lengths of runs and soil intake characteristics. It allows the design engineer to evaluate the losses caused by deep percolation.

Bishop's assumption of a constant rate of advance prompted Willardson (1) to suggest modification for a rate of advance varying with time. His refinement resulted in somewhat greater calculated deep percolation losses.

PROCEDURE

Area of Study

The area studied is a portion of the Avra Valley, west of the town of Marana, located about 20 miles northwest of Tucson. Surface irrigation with both border and furrow methods is used in this area. Ground-water is the only source of irrigation supply. Average annual precipitation is about 10 inches (17). Evaporation averages between 6 and 7 feet per year. The overdraft over the last 10 years has resulted in an increase in the average depth to the water table of 50 feet for this portion of the ground-water basin(18). The long growing season and freedom from killing frosts has led to development of large agricultural acreage. Cotton is the dominant crop in the area. Crop surveys prepared by the University of Arizona (18) estimated that 64 percent of the growing area is in cotton. Cotton may be planted from March 15 to April 15, usually the first two weeks of April. It needs at least 190 rather warm, frost-free days to produce a high yield(16).

Experimental Fields

Data were collected on cotton fields of various lengths of run, slopes and soil texture. The experimental fields were selected with assistance from the Tucson Office of the Soil Conservation Service. Fields used in this study are shown in Table 1.

Table 1 Experimental Fields

Field No.	Farm Owner	Length of Run (Mile)	Approx. slope (percent)	Soil Texture
1	John Kai	$\frac{1}{2}$	0.4	Fine
2	Louis Anway	$\frac{1}{2}$	0.1	Fine
3	Jimmie Wong	$\frac{1}{4}$	0.1	Coarse
4	Jimmie Wong	$\frac{1}{4}$	0.1	Medium
5	Buck White	$\frac{1}{4}$	0.4	Medium
6	Buck White	$\frac{1}{4}$	0.4	Fine
7	John Kai	$\frac{1}{4}$	0.1	Fine
8	Lee Hurst	$\frac{1}{4}$	Flat	Fine

Site Selection

Field test locations were selected with the aid of S.C.S..soil maps. Furrow tests to evaluate irrigation efficiency must be made on carefully selected sites that are representative of the conditions to be evaluated. Only furrows of uniform cross section and uniform grade along the slope were used.

Timing of Irrigation Evaluations

Irrigation evaluations were made at three different times in the growing season. The first set of measurements were made in the early to mid-season of cotton growing in

1964. At this stage of growth, the cotton height varied from 6 inches in early June to 2 to 4 feet in late July. The soil surface before irrigation was dry and well cultivated. Top soil was directly exposed to the sun with very little plant shading except in late July. The furrows were recently cultivated, and the effect of tractor wheels was easy to identify.

The second series of measurements was made during the last cotton irrigations of 1964. The surface was generally moist because of extensive shading by plants. The furrow surface remained smooth from the previous irrigation through the absence of cultivation. Cracking was observed along the furrow in the fine textured soils. Furrows were frequently blocked with trash and vegetation. The test furrows were chosen close to the location of the first group of observations to minimize variations in soil texture and slope. Reference marks gave positive identification for the locations. Two types of marks were used, either red paint on the lined head ditch or a stake painted red and driven in the ground near the head ditch.

Pre-planting irrigation usually starts before the growing season. Data were collected in early March 1965. Observations were made in the same manner and on the same fields used during the 1964 season. The rough, plowed land permitted more rapid intake for replenishment of water in root zone reservoir, leaching of excessive soluble salts and storage at lower depths for late-season use.

Field Equipment used for Furrow Irrigation Evaluations

The equipment required for tests of furrow irrigation need not be complex. The items below are generally used for these tests:

1. Engineer's level and rod.
2. Steel tape.
3. Stakes.
4. Stop watch and regular watch.
5. Shovel.
6. Orifice plates.
7. Soil auger and soil tube.
8. Plastic bags.
9. Forms for recording field data.

Flow Measurement

Flow of water in a furrow can be measured in several different ways. The measuring device should be easy to build, simple to install and move, and light enough to carry in the field. Accuracy must be within a range of ± 5 percent. Among the several devices available, orifice plates were chosen for this study. They have been calibrated in hydraulics laboratories and proved acceptable(12).

Various orifice diameters are available to provide a range of flow rates. To minimize head loss a correct hole diameter is required for a particular stream size. The head difference should range from 1 inch to 3 inches for an accurate measurement. Plates with hole diameters of $3\frac{1}{2}$, 3, $2\frac{1}{2}$ and 2 inches were used.

The orifice plate is installed across the furrow as nearly perpendicular to the direction of flow as can be done by eye. The orifice opening should be at least one inch from the furrow boundary (bottom and sides). If the furrow silts up near the bottom of the opening during operation, it should be cleaned out and the flow allowed to restabilize before measurement. The downstream water surface should be above the top of the opening to insure submerged flow conditions. The plates were installed at the inflow and outflow stations and, in some cases, a middle station was added.

Flow rates were recorded as inches of head difference, and then converted to gallons per minute using calibration tables. The head measurements were made with care and precision and read to the nearest 0.05 inch. A hook gage and engineer's scale were used in measuring the head of water.

Soil Moisture Measurement

Soil moisture content was determined by driving a soil tube to a depth of four feet. The sample of moist soil was then removed and placed in a plastic bag. The soil samples were taken to a laboratory for weighing and drying. Samples of 100 grams or more were kept in an oven having a temperature of 110 C for a minimum of 15 hours. Soil moisture content was then calculated as the percentage of the water loss based on the oven-dry sample weight.

Soil moisture content can also be expressed as a depth of water by the equation $d = \frac{P_w}{100} A_s \cdot D$ where d is the depth of water in inches, D is the depth of soil in inches, A_s is the apparent specific gravity or bulk density and P_w is the percentage of soil moisture content on a dry weight basis(10).

The apparent specific gravity is the ratio of the weight of a given volume of dry soil, air space included, to the weight of an equal volume of water. It is obtained by taking a soil sample of known volume. Data on apparent specific gravity were collected by using a King soil sampling tube. The tube was driven into the soil and samples were removed in one foot increments to a depth of four feet. The soil samples were placed in plastic bags and taken to the laboratory for weighing and drying.

Operating Procedure

The following fifteen points describe in chronological order, the sequence of operations for a furrow irrigation evaluation.

1. Select the furrows to be tested. Describe the condition of the furrows, soil surface and stage of plant growth.

2. Set stakes at 100 ft. spacing from head of furrow down the field.

3. Check individual furrows for evidence of tailwater back-up from the previous irrigations. Locate the outflow measuring station above the back-up area. Whenever it is feasible, locate another measuring station in the middle of the furrow.

4. Install orifice plates at the selected locations.

5. Take soil samples before irrigation in the vicinity of the measuring stations on the center line of the furrow.

6. Apply water and record time when the water passes the inflow station.

7. Record the first inflow reading after the water level in the farm ditch has stabilized to almost constant inflow. Usually it takes about 10 to 15 minutes to stabilize the flow. Make additional measurements periodically or at any time when the flow is changing. Record the time when each flow measurement is made.

8. Record the time when each furrow stream reaches intermediate stations and the time when each furrow stream reaches the outflow station.

9. Measure the flow at the intermediate measuring station and outflow station periodically and record the time of measurement. When each furrow stream reaches the stations, measurement is made after the orifice becomes fully submerged.

10. Check to prevent break-over to adjoining furrows. Remove trash in front of the orifice plates periodically.

11. Turn off the water and record the time water recedes at each station.

12. Remove and clean equipment.

13. Take soil samples 2 days after irrigation at the same location as the pre-irrigation samples.

14. Run levels to each station to determine the soil surface profile.

15. Take soil samples for apparent specific gravity when the soil is again firm.

ANALYSIS

Evaluation of irrigation requires:

(1) Examination of the physical characteristics of the fields including soil texture, soil profile, slope, and length of run, and

(2) Measurements or computation of:

a. Soil moisture content and apparent specific gravity.

b. Depth of water required to refill the root zone.

c. Intake opportunity time.

d. Intake characteristics.

e. Irrigation efficiencies.

The result of field evaluations provides a basis for the study of the major factors affecting the efficiency of furrow irrigation.

Physical Characteristics of the Fields

a. Soil Texture and Soil Profile.

Data on soil texture and soil profile were provided by the Tucson Office of the Soil Conservation Service. Field observations indicated some additional variation in soil texture with depth and distance in the furrow. General pictures of soil texture and soil profile taken from the same field provide the most appropriate descriptions. The soil columns are presented in Figure 2 and 2a.

b. Slope of the Field.

The longitudinal profiles of the test furrows are presented in Figure 3 through 3b. The slope variation ranged from dead level (0.00 percent) to 0.43 percent. For the most part land slope was constant over the length of the field.

c. Length of Run.

The lengths of run are also shown in Figure 3 through 3b. The total length of run as bounded by the end of the cotton row ranged from 1000 feet to 2,400 feet.

<u>Furrow Irrigation System Performance</u>

a. Soil Moisture Content and Apparent Specific Gravity.

The soil moisture content prior to the evaluated irrigation is presented in Table 2. The average soil moisture contents before irrigation are expressed in terms of the average moisture for the 4-foot depth of samples from the upper and lower end of the fields (in some cases, samples from the middle of the field were added).

The field capacity was determined from the moisture content two days after each irrigation. The samples were taken from the upper and lower ends of the field. The arithmetic means and standard errors of the field capacity and apparent specific gravity of the samples at 1-foot depth increments to 4-foot depth of sampling are

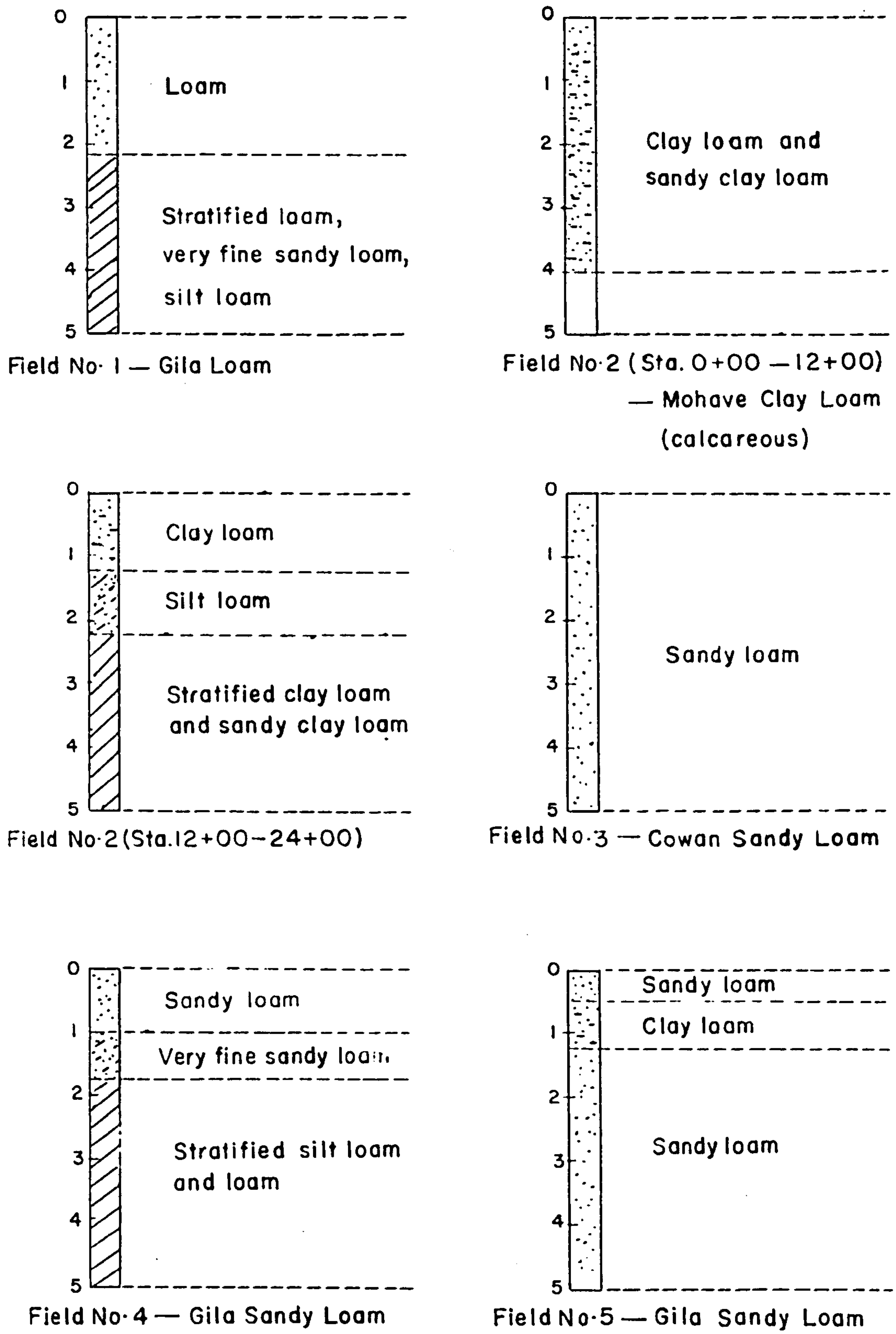
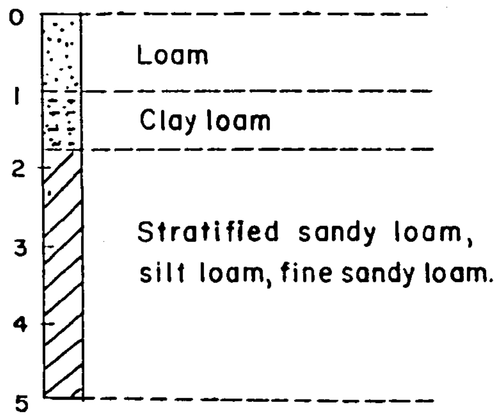
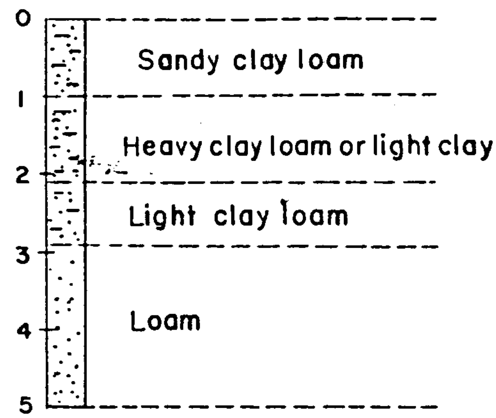


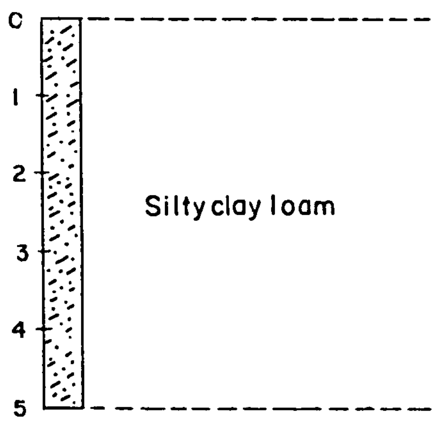
Figure 2. Soil Texture and Soil Profile (Fields No. 1-5)



Field No. 6 — Gila Sandy Clay Loam



Field No. 7 — Continental Sandy Clay Loam



Field No. 8 — Glendale Silty Clay Loam

Figure 2a. Soil Texture and Soil Profile (Fields No. 6-8)

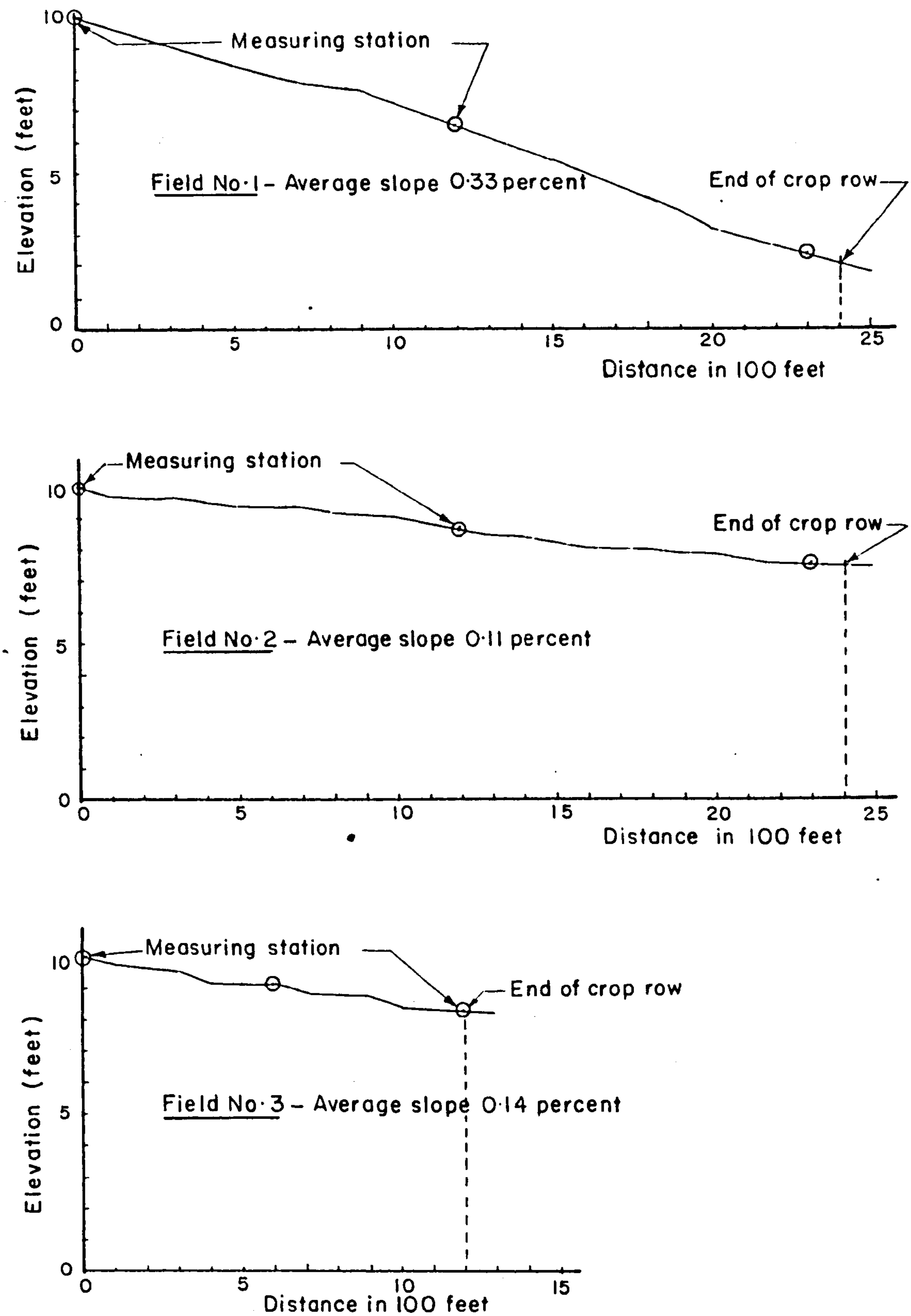


Figure 3. Soil Slope Profile (Fields No. 1-3)

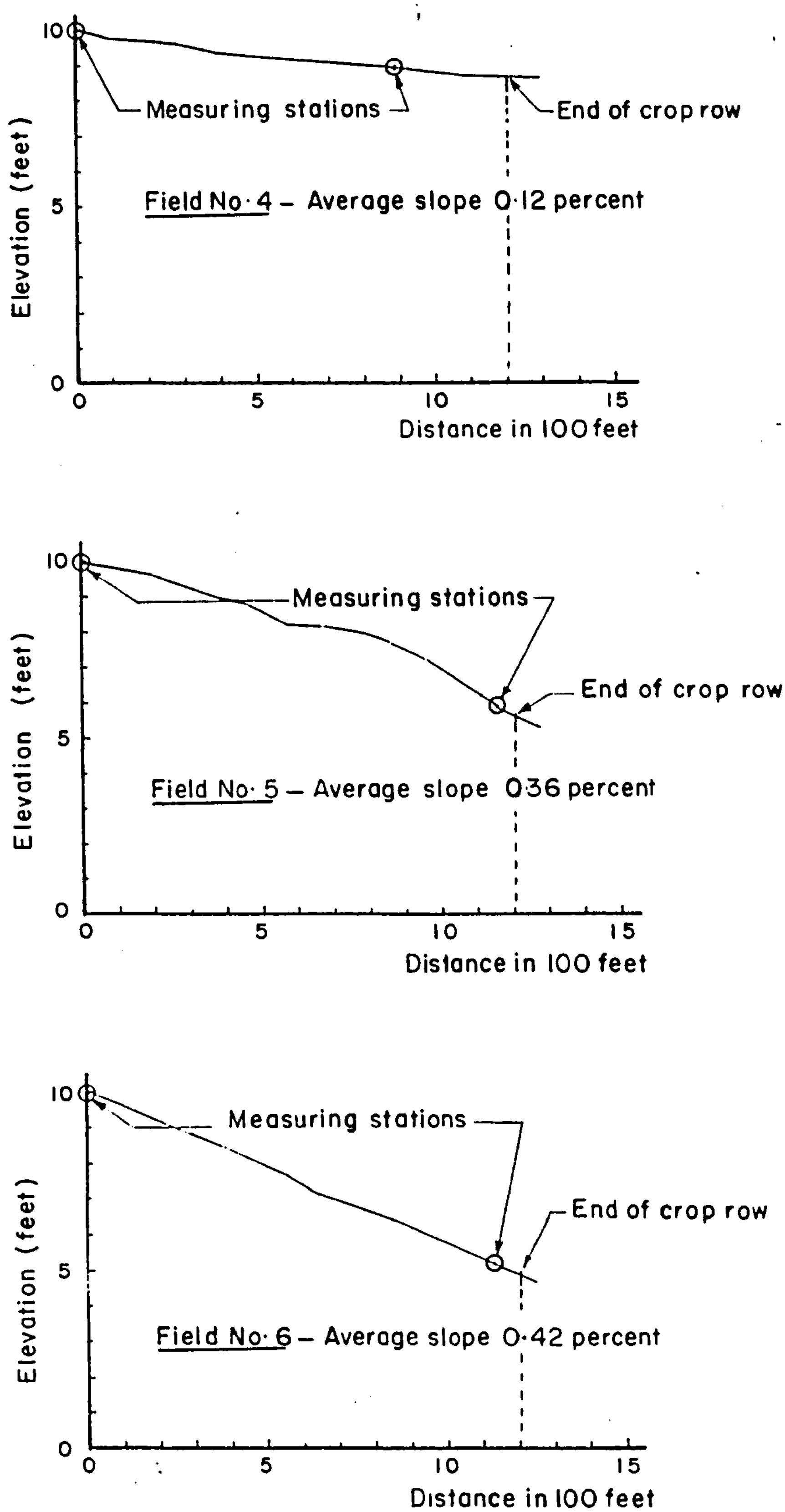
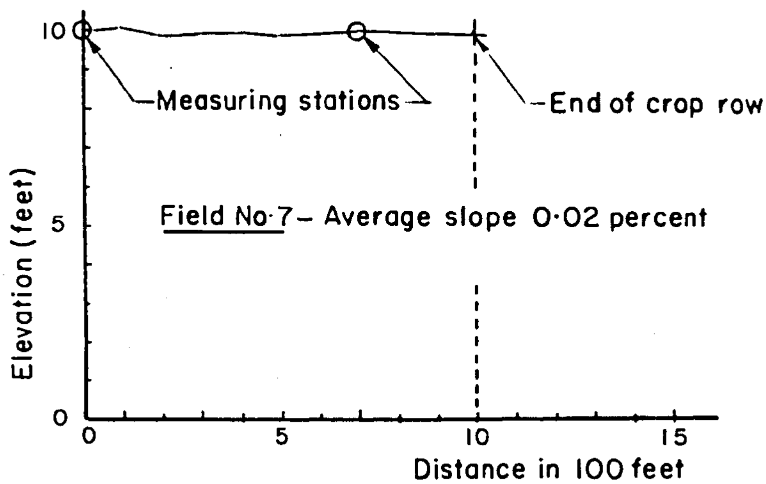


Figure 3a. Soil Slope Profile (Fields No. 4-6)



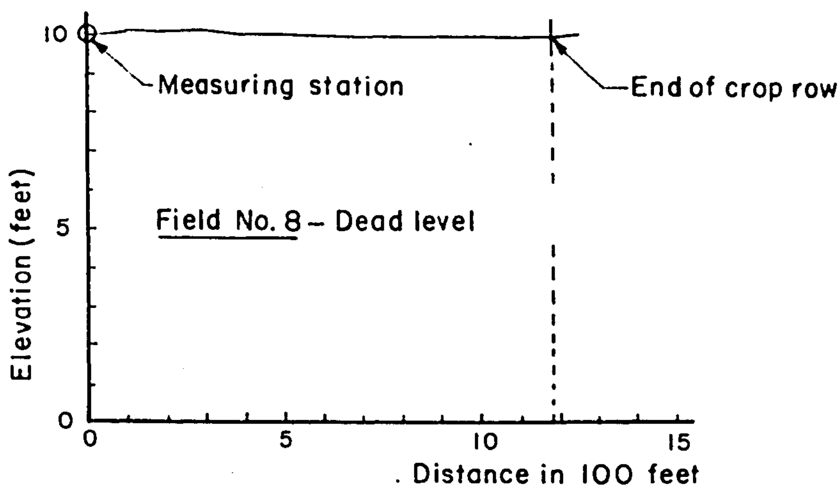


Figure 3b. Soil Slope Profile (Fields No. 7-8)

Table 2. Average Soil Moisture Content Before Irrigation, Field Capacity, and Apparent Specific Gravity[a].

Field No.	Moisture content before irrigation (percent)			Field capacity (percent)	Apparent Specific gravity
	Pre-Planting	Early/Mid-Season	Late-Season		
1	10.0	9.8	10.3	17.2 (2.3)	1.41 (0.06)
2	10.0	11.0	11.8	16.6 (2.4)	1.54 (0.10)
3	8.0	5.6	7.4	13.5 (2.0)	1.53 (0.03)
4	7.6	5.3	6.8	12.6 (0.7)	1.50 (0.07)
5	6.4	9.0	9.4	16.3 (1.6)	1.51 (0.07)
6	5.9	6.1	8.1	17.7 (2.2)	1.37 (0.05)
7	-	11.0	-	18.0 (2.0)	1.54 (0.07)
8	-	12.5	13.0	19.8 (2.5)	1.49 (0.05)

[a]Figures in parentheses are standard errors.

presented in Table 2. Average field capacity ranged from 12.6 percent for coarse textured soil to 19.8 percent for fine textured soil. For apparent specific gravity, three replications for the 1-foot increments from 0 to a 4-foot depth were made at each location.

b. Depth of Water Required to Refill the Root Zone (W_n).

The depth of water required to refill the root zone is the difference between the amount of moisture in the root zone just before irrigation and the field capacity. Values of field capacity and moisture content from Table 2 were used to estimate the amount of water required in the root zone. Depth of root zone was estimated from the age of the cotton and cotton height. The depths of water required to refill the root zone are presented in Table 3. Where the root zone extended below the 4-foot depth of soil probing it was assumed that soil moisture deficit and field capacity in the lower part of the root zone were the same as in the upper 4-feet.

c. Intake Opportunity Time.

The intake opportunity time represents the time that water is in the furrow at any point in the field. It is calculated from the measurement of water advance and recession. A typical plot of advance, recession and intake opportunity time is shown in Figure 4. The results of the field study are presented as the Intake Opportunity Time Curves in Figure 5 through 5c.

Table 3. Depth of Water Required to Refill the Root Zone[b] (W_n).

Field No.	Average depth of water (inches)		
	Pre-Planting	Early/Mid-Season	Late-Season
1	7.32 (6.00)	5.01 (4.00)	7.00 (6.00)
2	7.32 (6.00)	4.14 (4.00)	5.32 (6.00)
3	6.06 (6.00)	5.80 (4.00)	6.72 (6.00)
4	5.40 (6.00)	6.57 (5.00)	6.27 (6.00)
5	10.75 (6.00)	7.94 (6.00)	7.50 (6.00)
6	11.64 (6.00)	9.54 (5.00)	9.46 (6.00)
7	-	5.17 (4.00)	-
8	-	5.22 (4.00)	7.30 (6.00)

[b] Figures in parentheses are estimated depth of root zone in feet.

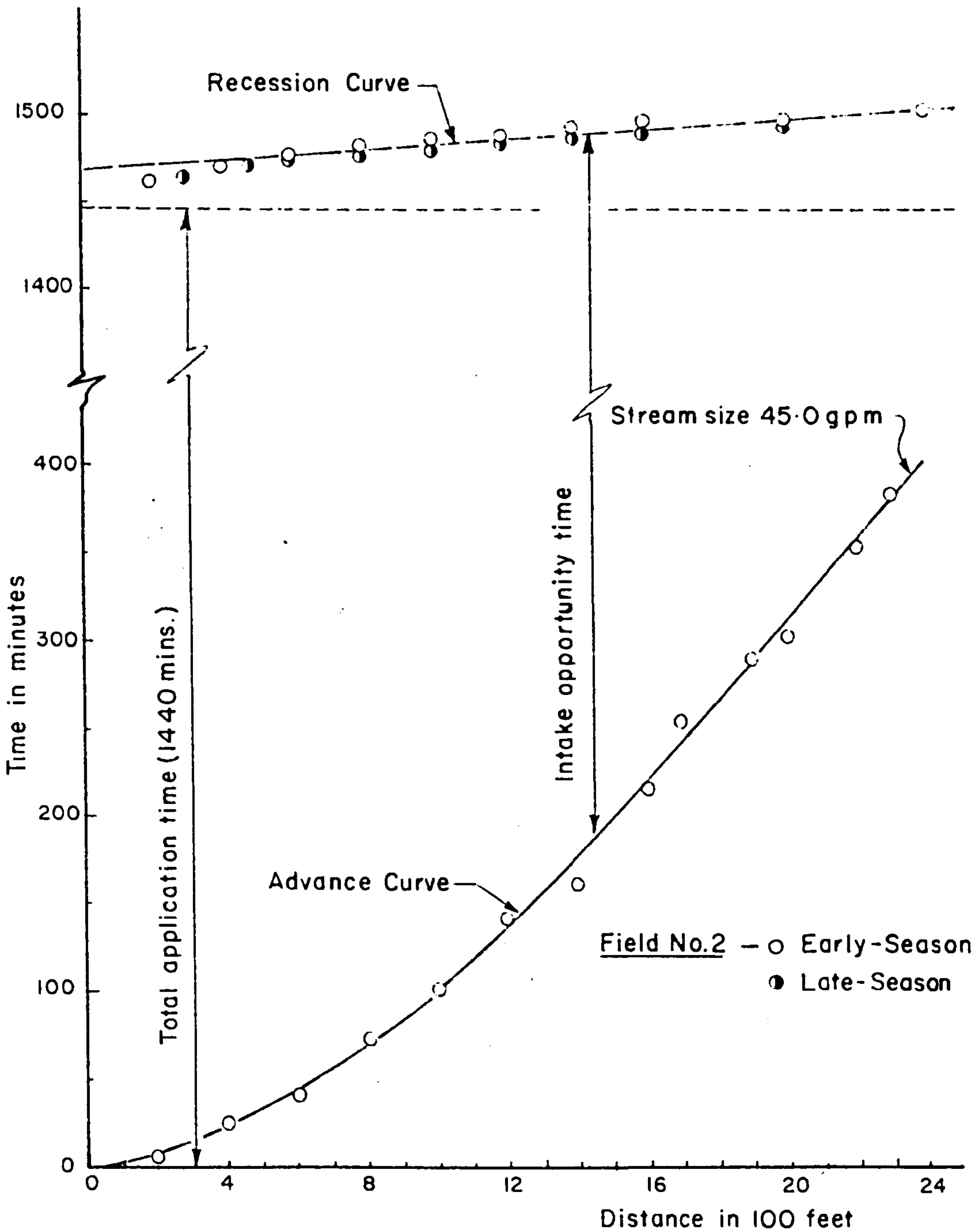
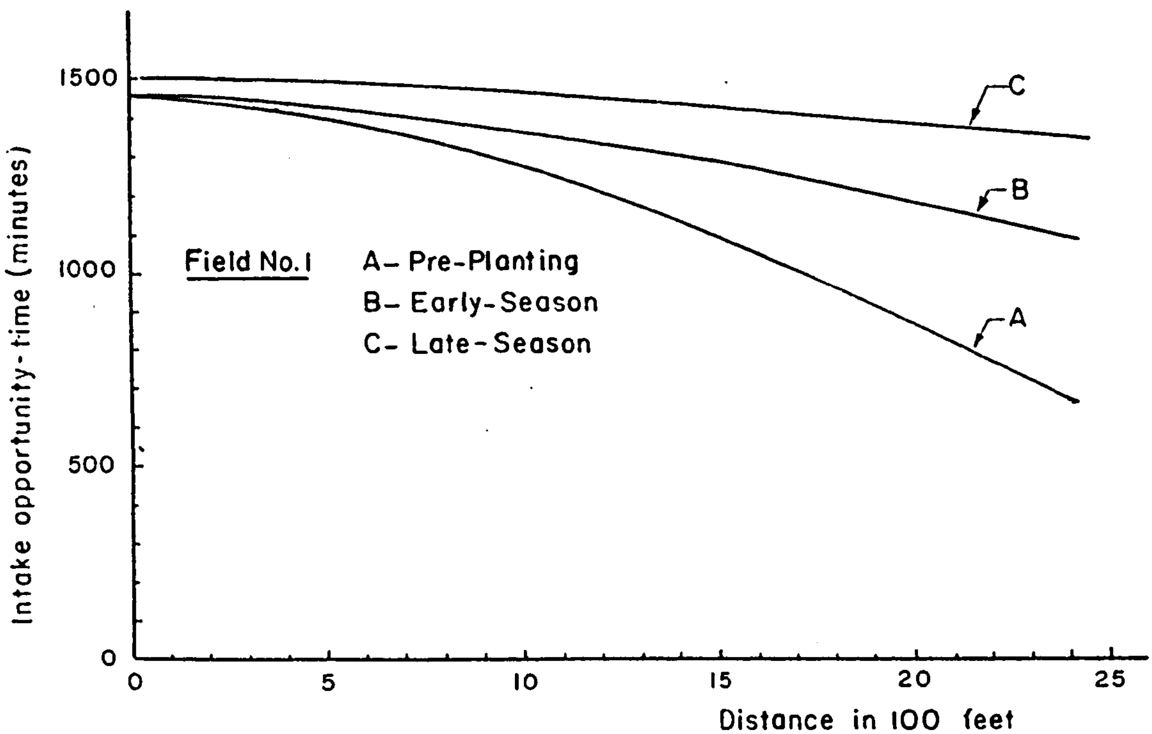


Figure 4. Typical Rate of Advance Curve, Recession Curve, and Intake Opportunity Time.



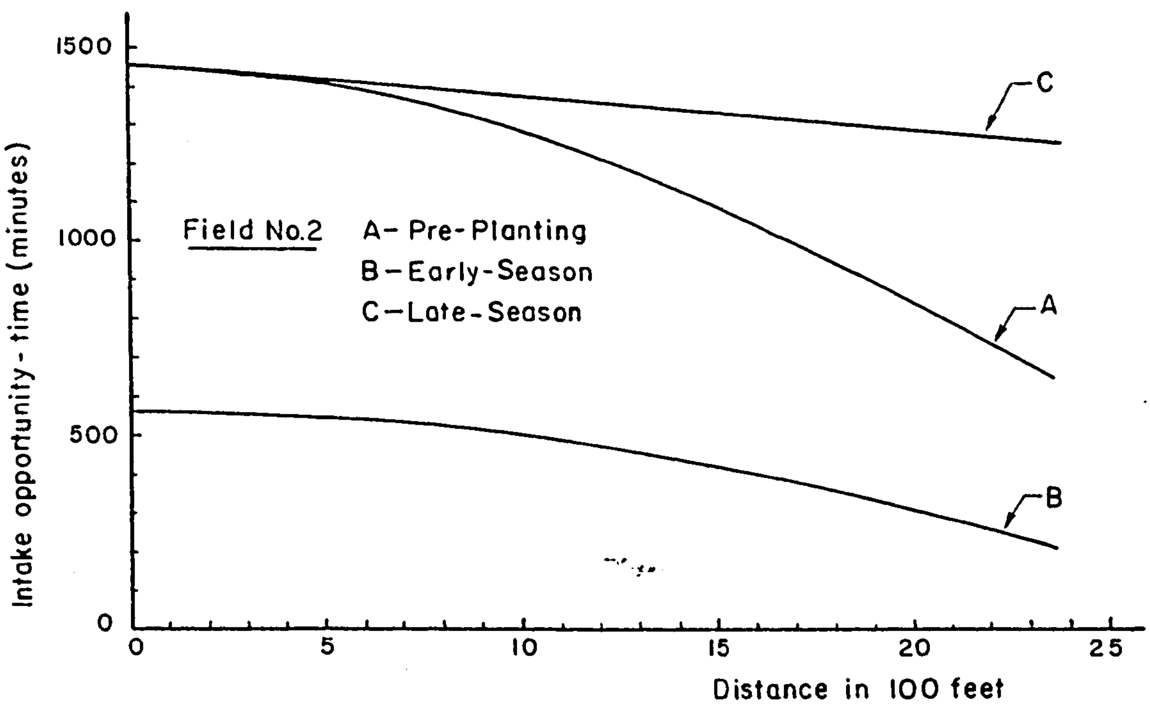
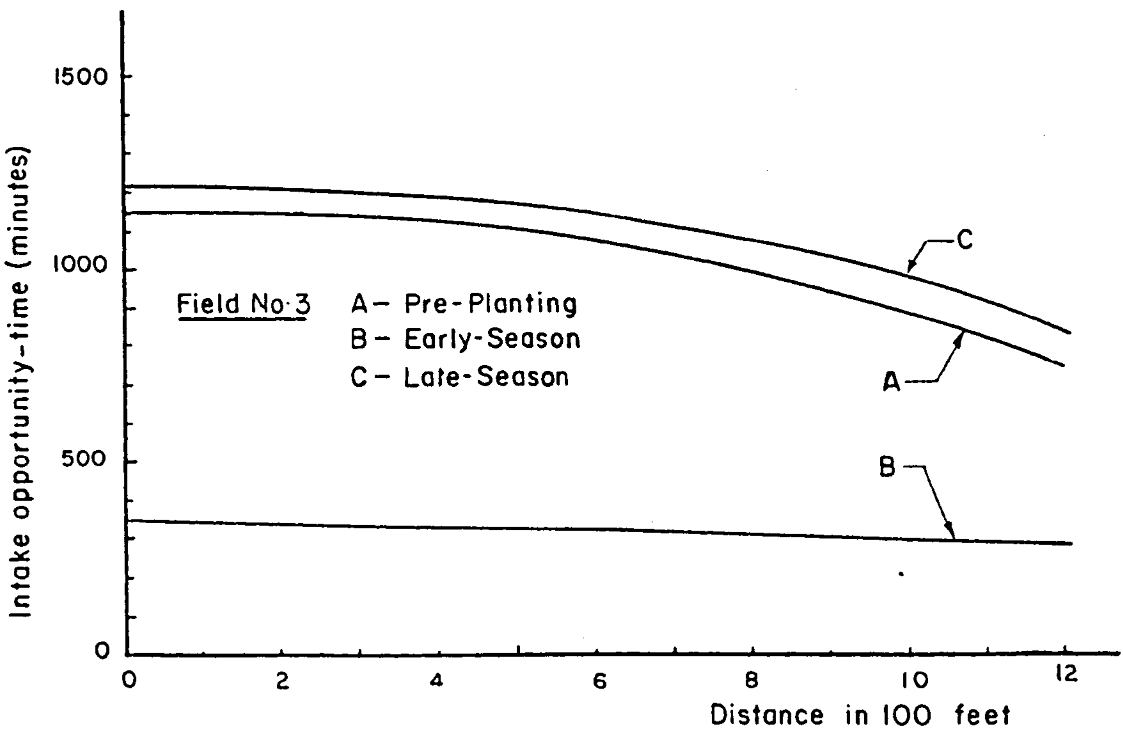


Figure 5. Intake Opportunity Time Curves (Fields No. 1 & 2)



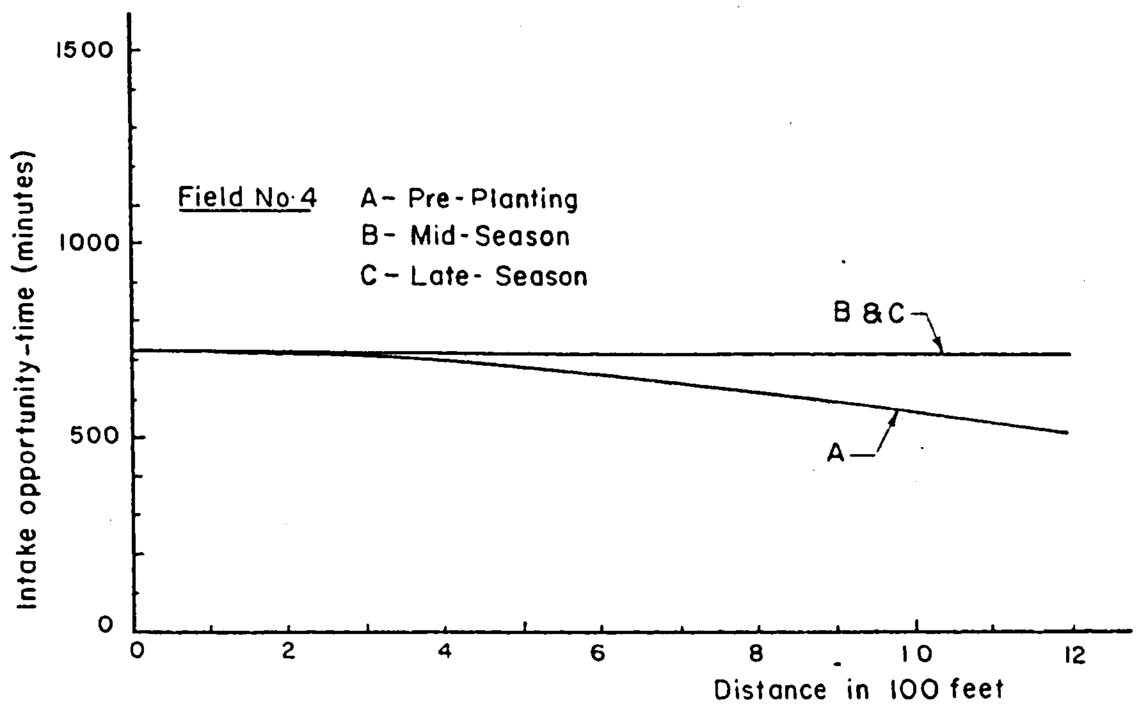
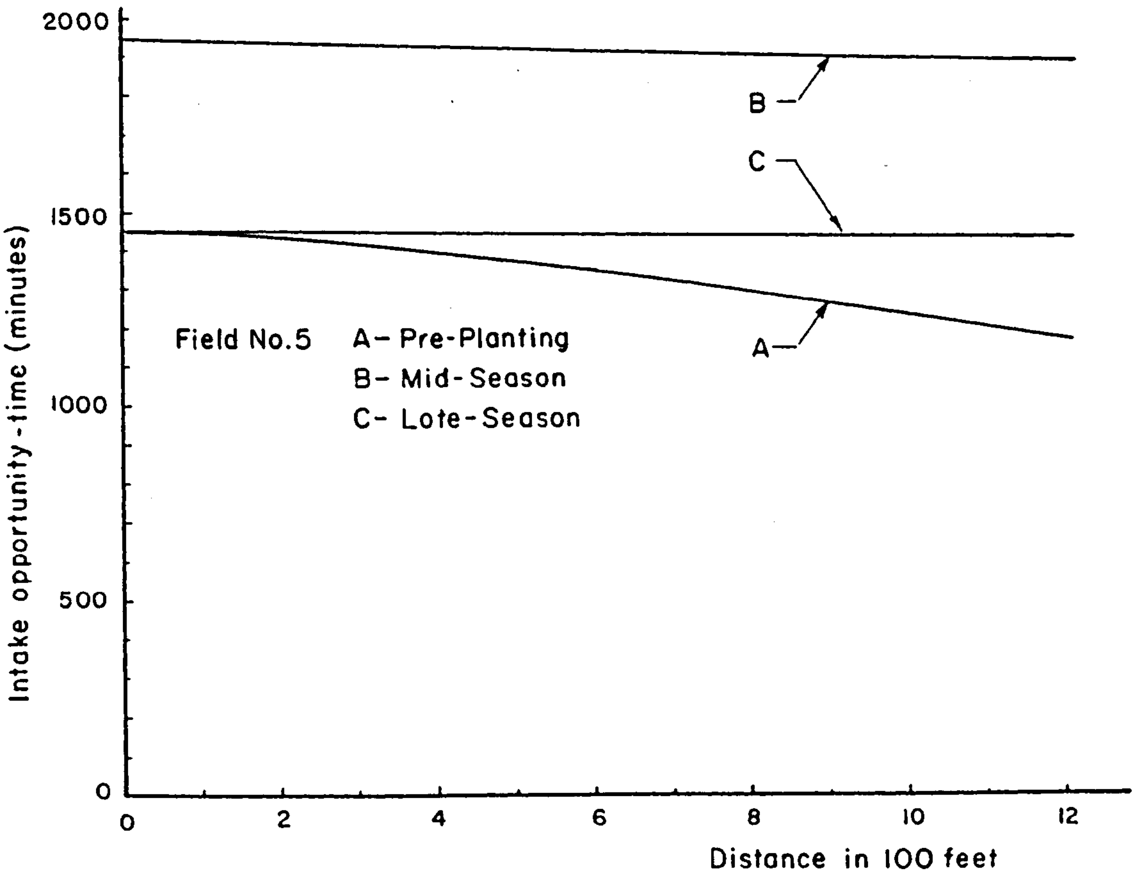


Figure 5a. Intake Opportunity Time Curve (Fields No. 3 & 4)



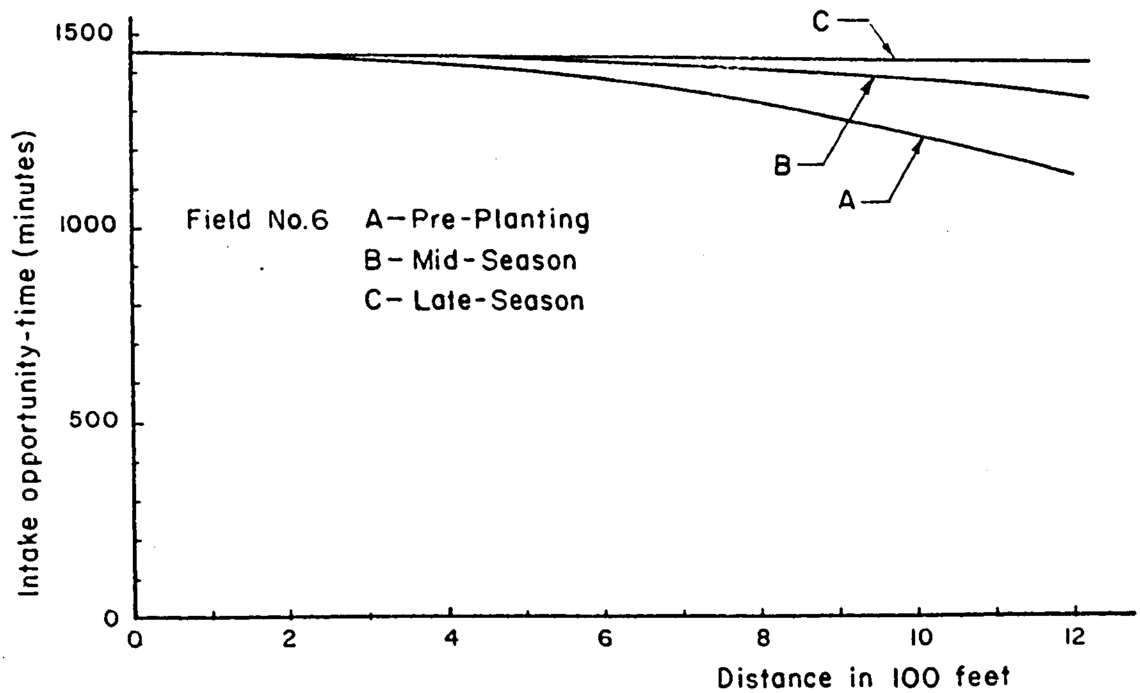


Figure 5b. Intake Opportunity Time Curves (Fields No. 5 & 6)

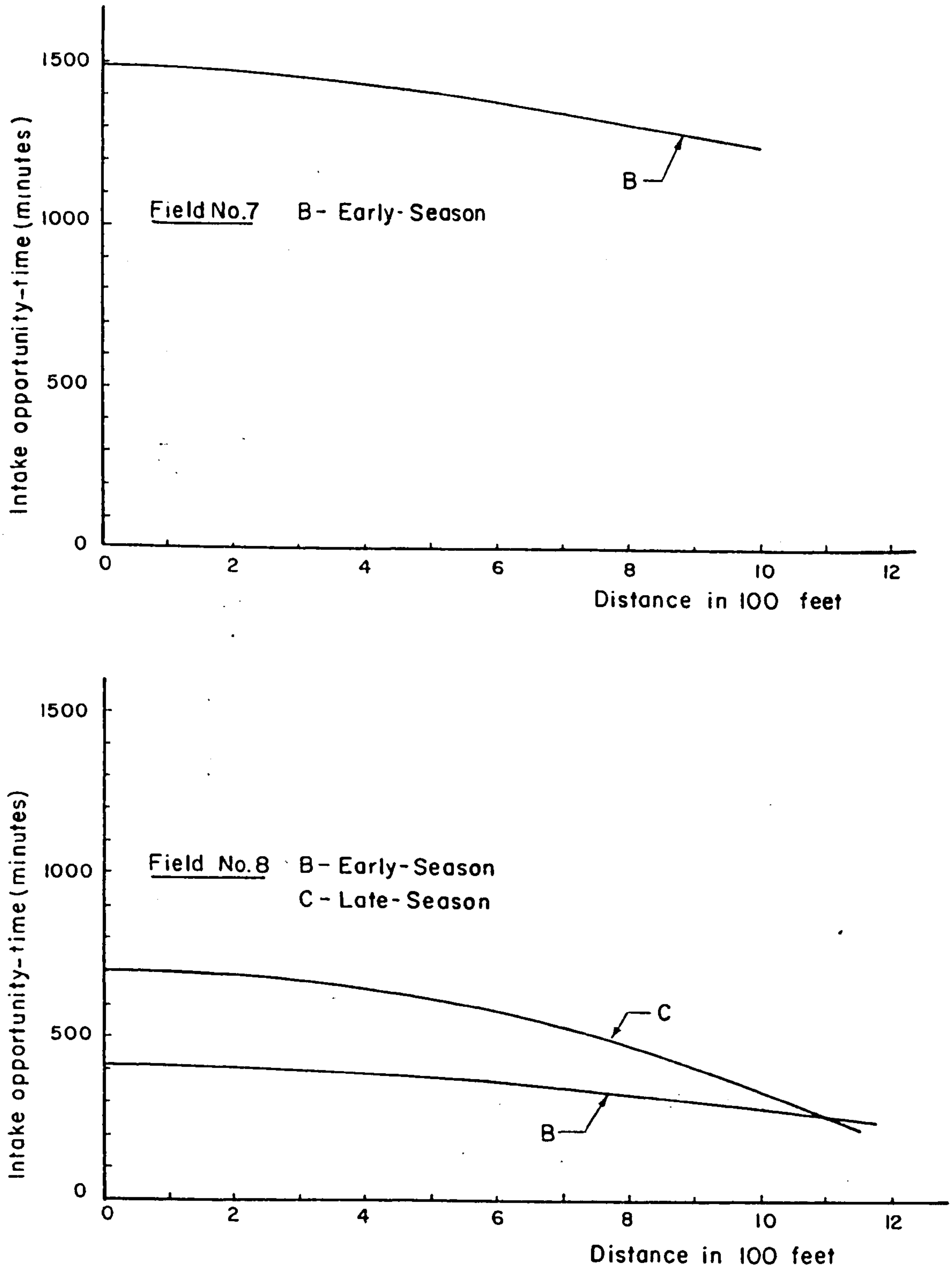


Figure 5c. Intake Opportunity Time Curves (Fields No. 7 & 8)

Data on rate of water advance can also be plotted on logarithmic paper. As indicated by some investigators (4, 13), a straight line relationship can be expected. This was found to be true for a short length of run, constant inflow rate, uniform soil texture and soil profile, and uniform slope. To determine the rate-of-water-advance curve, the observed points were plotted on logarithmic paper and the best fit straight line was drawn. However, using this relationship to draw a smooth curve through the observed points resulted in a maximum discrepancy of less than 2 percent. On Pre-Planting Irrigations the data for rate of water advance from the intermediate stations were not available. In those cases the straight-line relation method was used to interpolate the missing points.

Field observations indicate that the rate of water advance changes with stream size and furrow surface condition. A slower advance can be expected in Pre-Planting and Early-Season Irrigation while the rate is faster in the Mid-Season and Late-Season Irrigation. This is because the surface soil is rather rough and dry in Pre-Planting and Early-Season Irrigation.

Typical data on rate of water recession are plotted in Figure 4. Field observation indicate little change in the rate of water recession as the season progressed.

As can be seen in Figure 4, drawing a straight line best fit for a group of recession curves taken at different irrigation times on the same field does not introduce significant errors.

d. Intake Characteristics.

The intake characteristics of interest in an irrigation evaluation are the average instantaneous intake rate and the accumulated intake depth (15). The intake values are computed from the inflow and outflow measurements. An example of the computation of the furrow intake rates is shown in Table 4.

The intake rate values were plotted against elapsed time on logarithmic paper. Then the best fit straight lines through the plotted points were drawn and the equation for these lines determined in the form of $I_f = KT^n$.

where I_f = Furrow intake rate in gallons per minute per 100 feet.

K = Furrow intake rate at unit time.

T = Average elapsed opportunity time.

n = Measured slope of the line.

The equivalent field intakes are computed from the formula $I = \frac{11.55}{w} I_f = K'T^n$ (15).

where I = Equivalent field intake rate in inches per hour.

w = Furrow spacing in inches (use twice the furrow spacing wherever alternate furrows are irrigated).

K' = Equivalent field intake rate at unit time.

Clock-Time hours	Elapsed time-minutes				Inflow g.p.m.	Outflow g.p.m.	Loss in furrow g.p.m.	Intake-rate g.p.m./100'
	Sta. 0+00	Sta. 12+00	Sta. 22+00	Average				
9.25	Start							
11.04	99	0	-		41.0			
11.40	135	36	-	85	41.0	16.8	24.2	2.02
11.55	150	51	-	100	41.0	19.7	21.3	1.77
12.10	165	66	-	115	41.0	21.4	19.6	1.63
12.35	190	91	-	140	42.3	22.9	19.4	1.62
17.00	455	356	-	406	50.3	36.2	14.1	1.17
9.25	Start							
16.07	402	-	0		46.2			
16.40	435	-	33	234	46.2	15.1	31.1	1.41
16.50	445	-	43	244	46.2	16.0	30.2	1.37
18.30	545	-	143	344	45.4	19.8	25.6	1.16

Table 4. Example of Computation of Furrow Intake Rate

The accumulated intake curves are computed by the formula $F = \frac{K'}{60(n+1)} T^{n+1}$ and plotted on the same graphs (15).

Where F = accumulated intake depth in inches.

The basic intake rate is the rate at elapsed time (minutes) equal to -600n.

The intake characteristics as presented in Figures 6 through 12 are the result of plotting the values of the intake data from both the upper half and the entire field. In general the furrow intake rate tends to be higher in the upper end due to a larger stream size (2).

e. Irrigation Efficiencies

1) Water Application Efficiency (E_a)

The concept of water application efficiency was developed by Israelsen to measure the efficiency with which water delivered was being stored within the root zone of the soil where it could be used by plants (10).

$$E_a = 100 \frac{W_s}{W_f}$$

where E_a = water application efficiency

W_s = water stored in the soil root zone during irrigation

W_f = water delivered to the field

Depth of water applied during irrigation was calculated by a graphical method from accumulated intake and the intake opportunity time as shown in Figure 13.

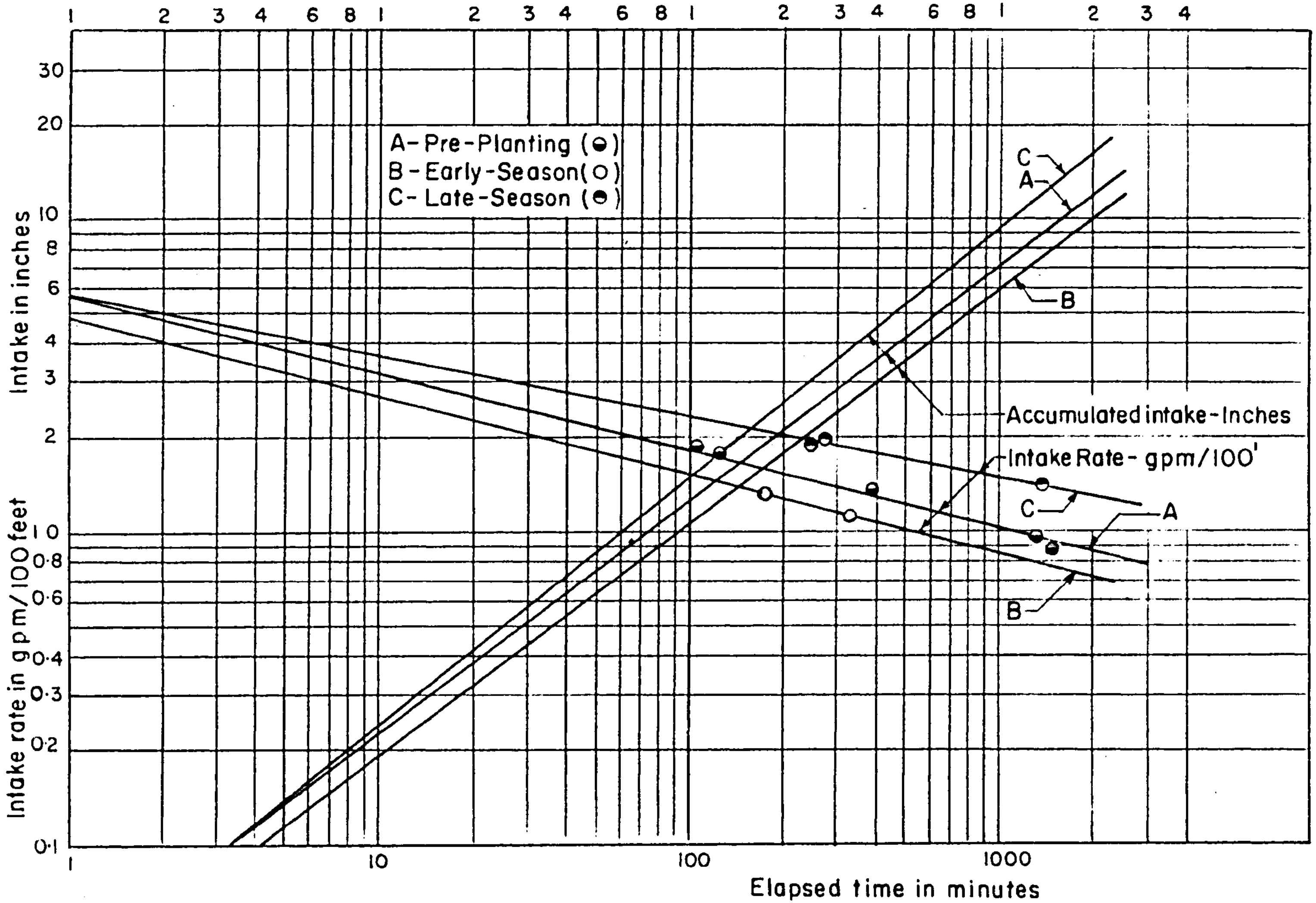


Figure 6. Intake Characteristics (Field No. 1)

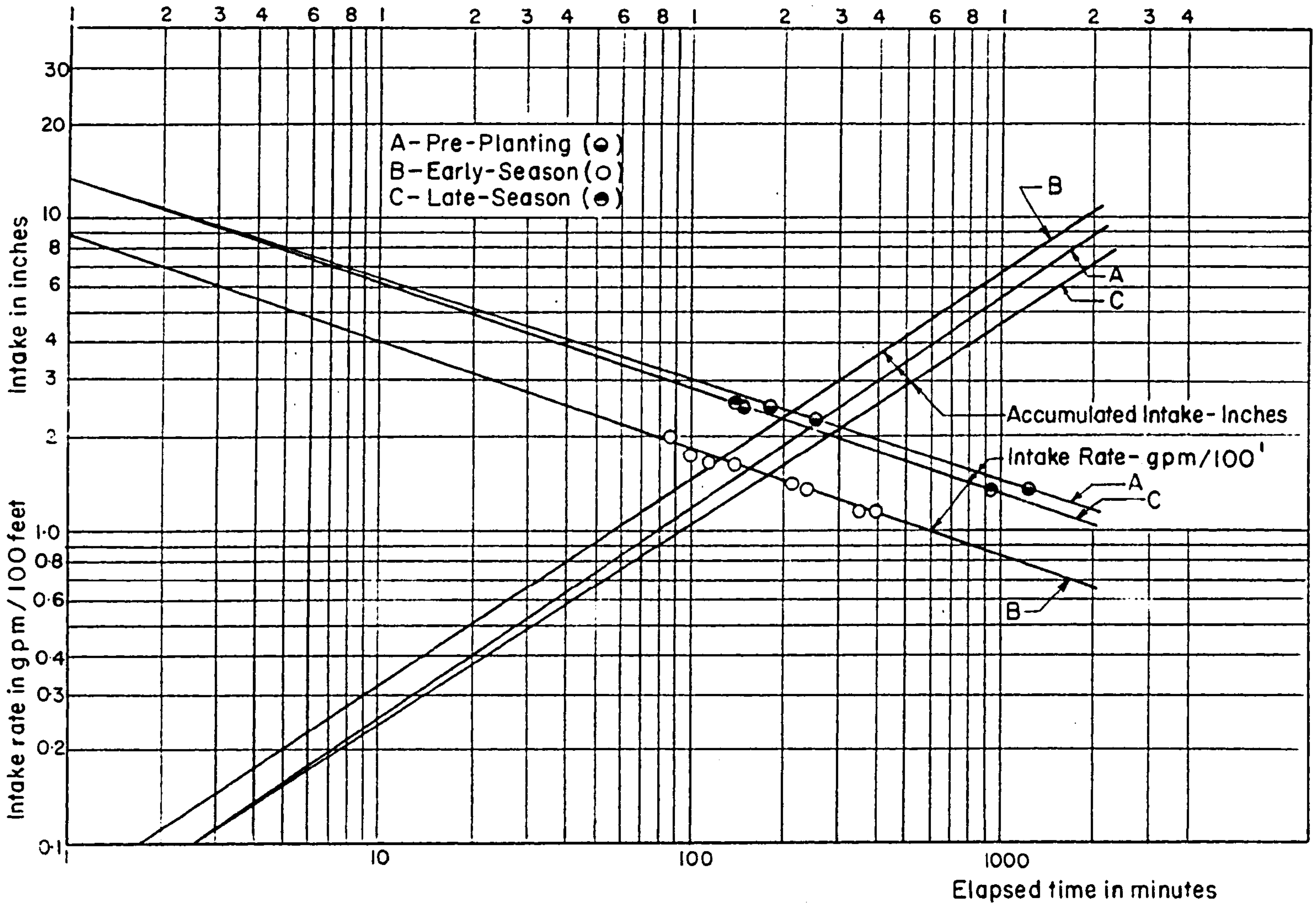


Figure 7. Intake Characteristics (Field No. 2)

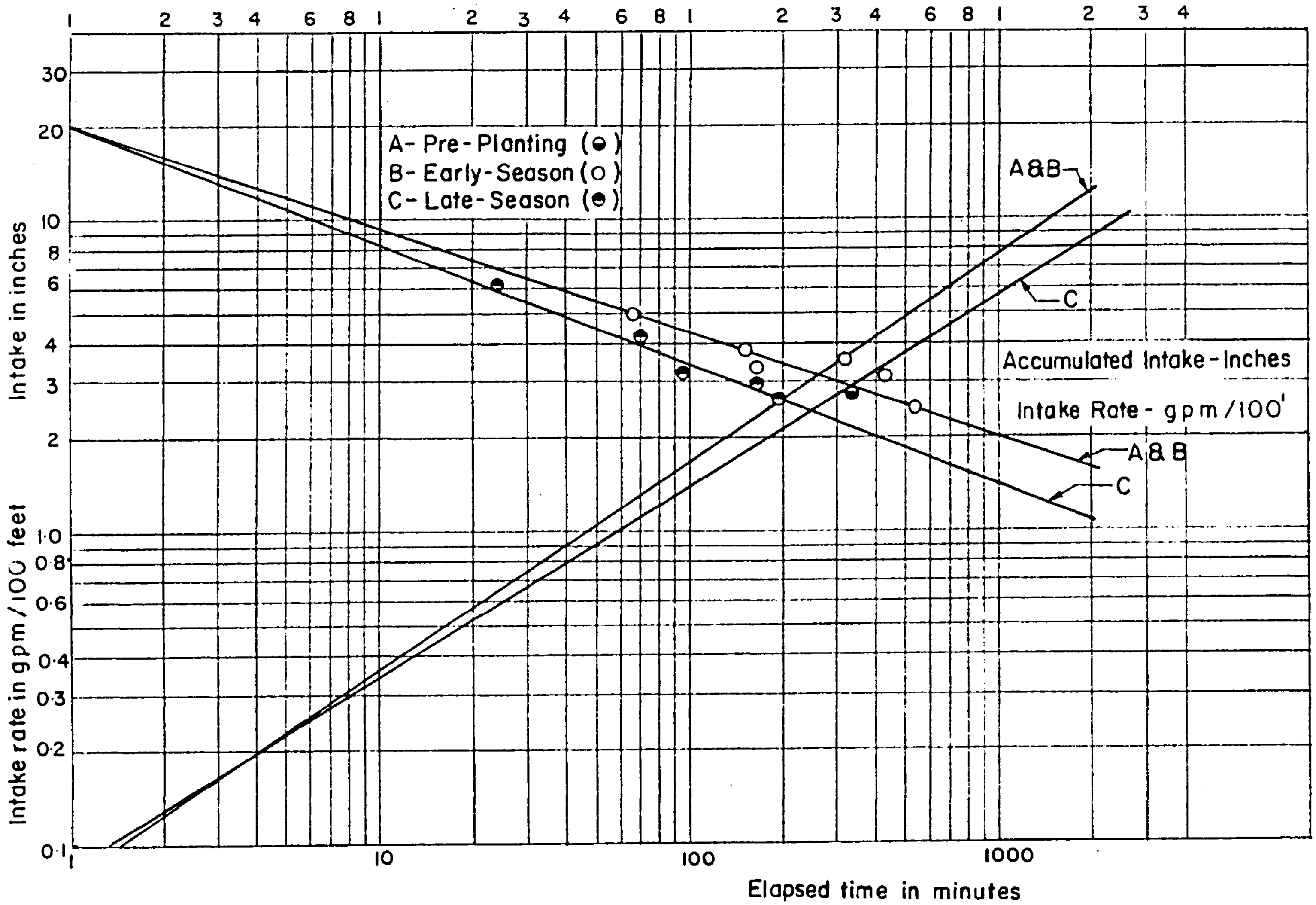


Figure 8. Intake Characteristics (Field No. 3)

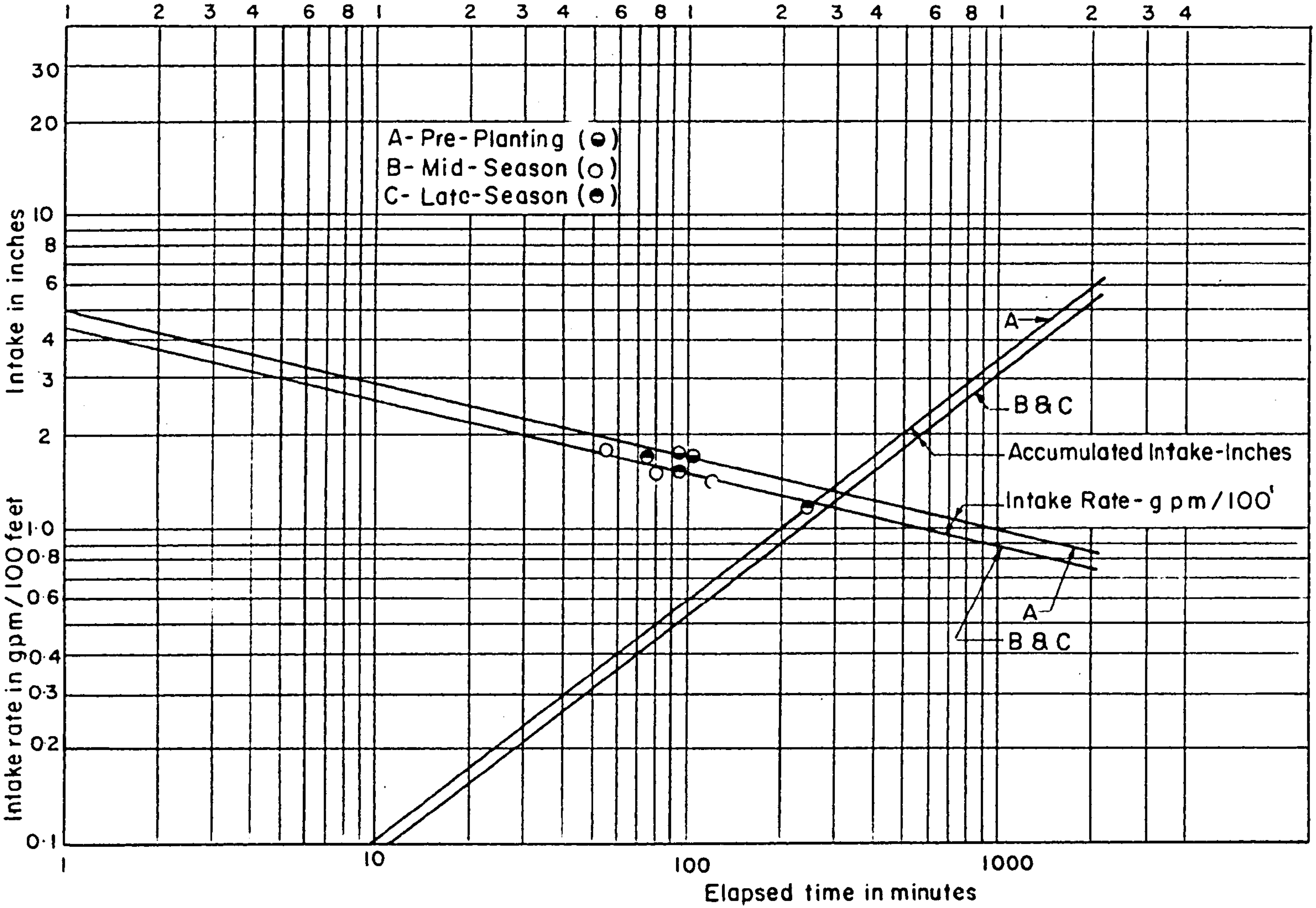


Figure 9. Intake Characteristics (Field No. 4)

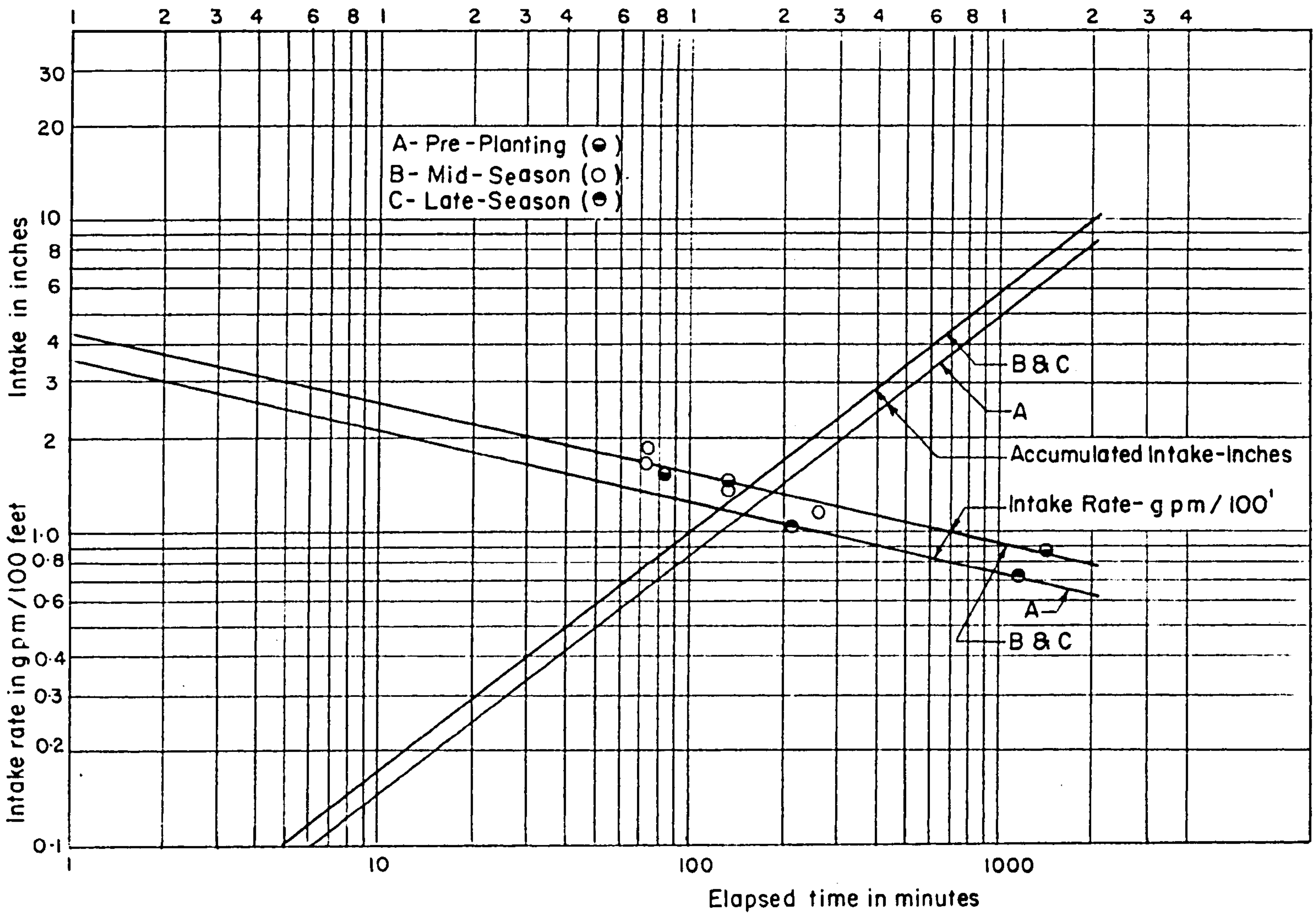


Figure 10. Intake Characteristics (Field No. 5)

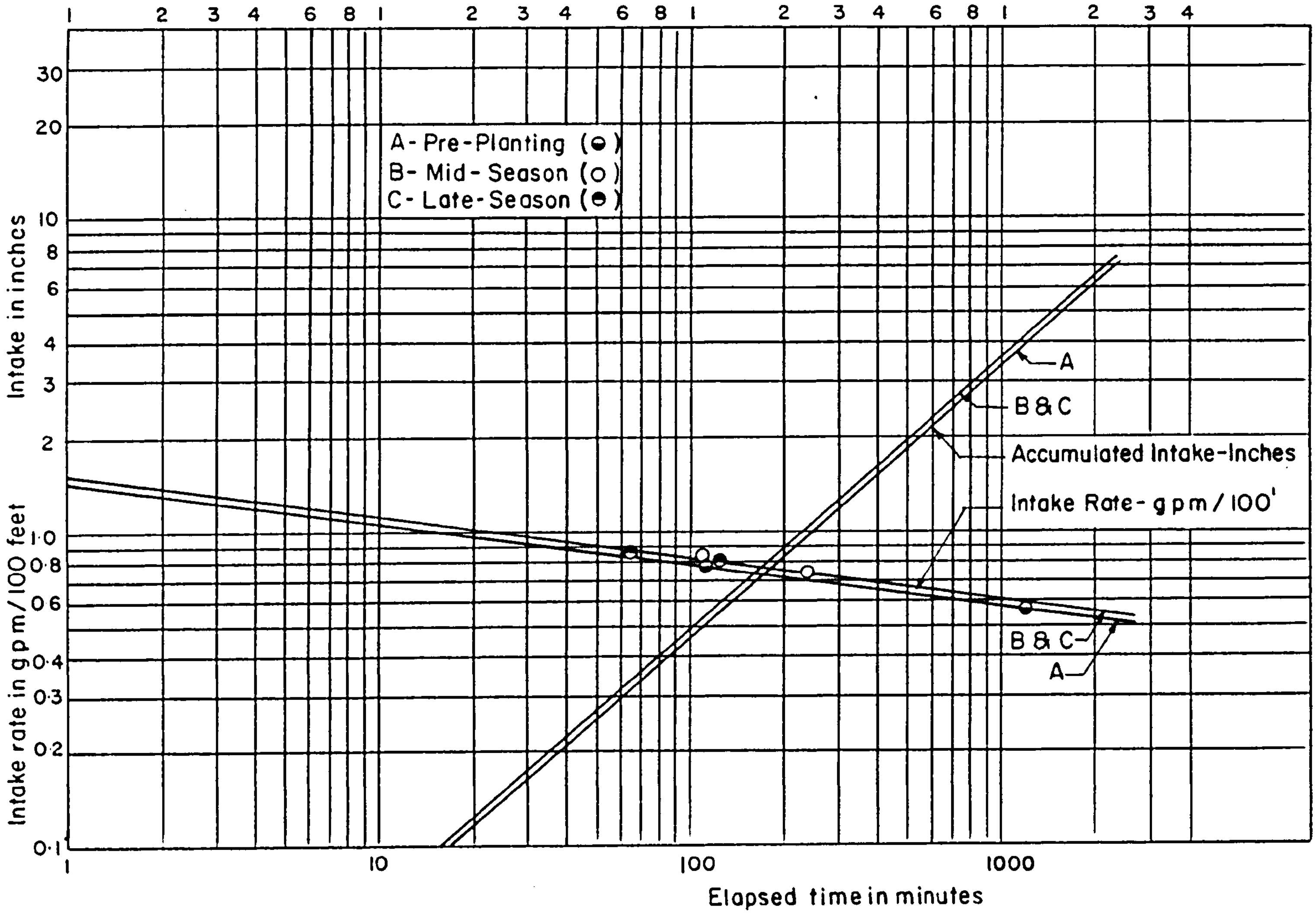


Figure 11. Intake Characteristics (Field No. 6)

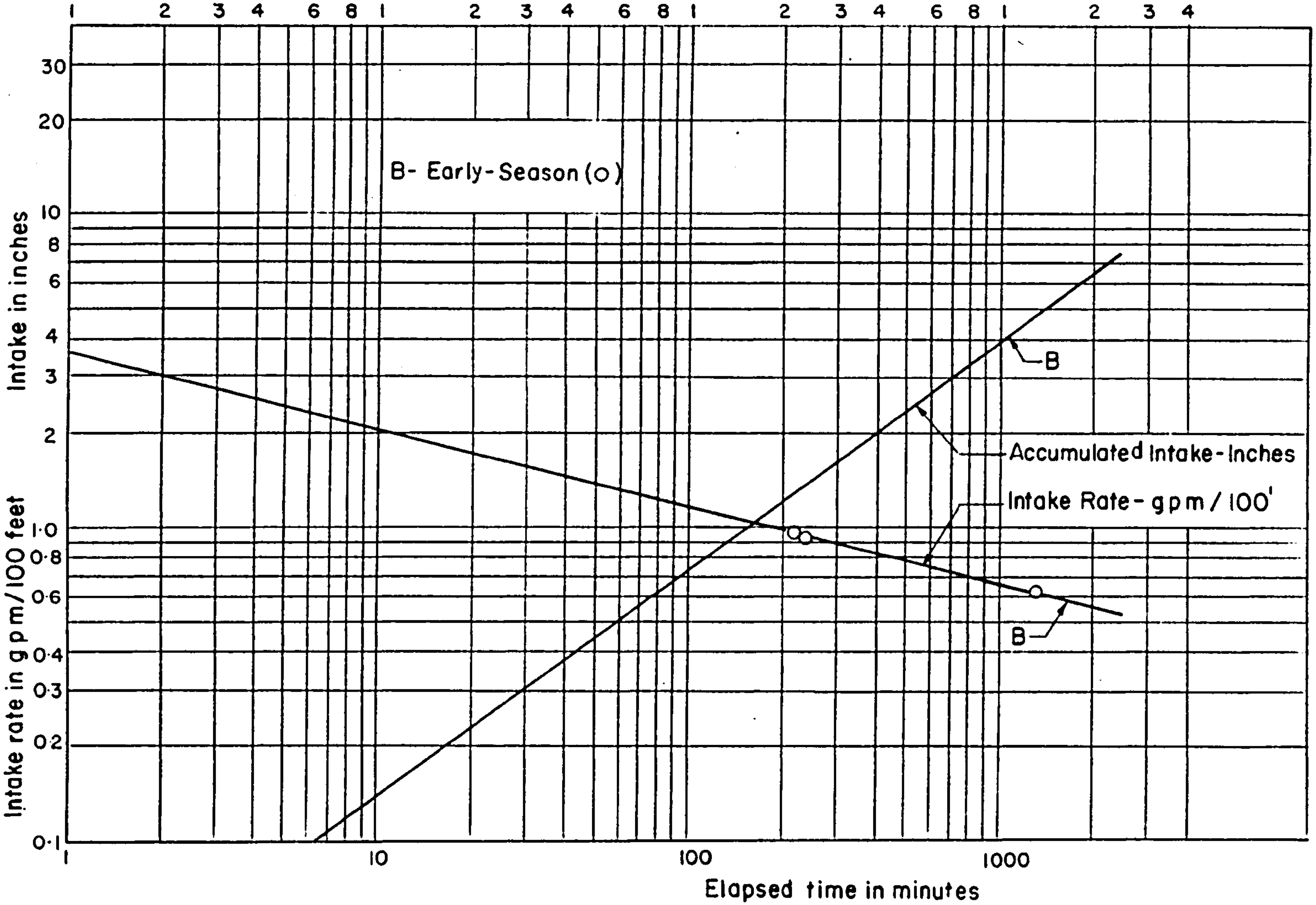


Figure 12. Intake Characteristics (Field No. 7)

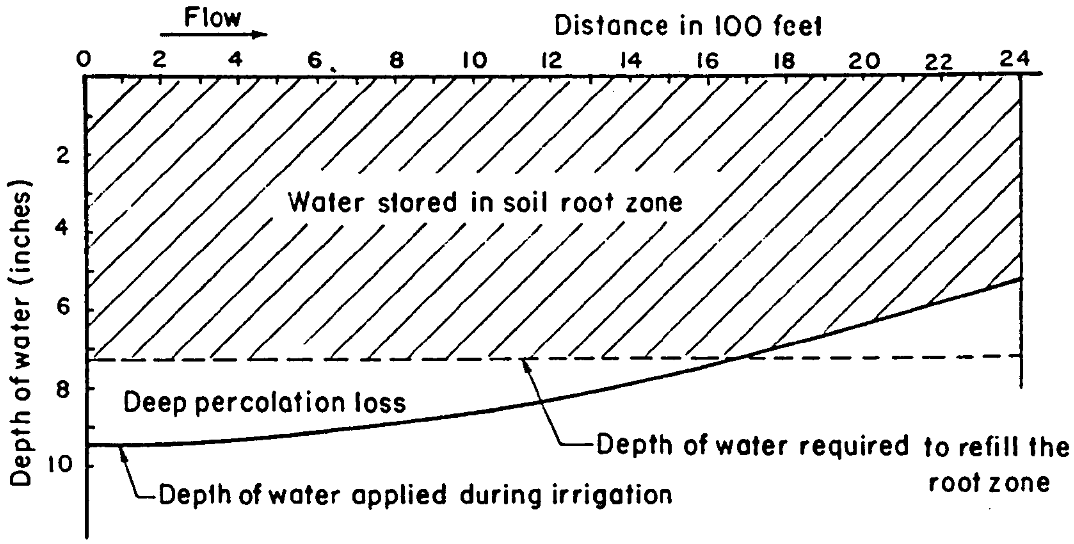


Figure 13. Sample Calculations of Water Applied and Water Stored in the Soil Root Zone.

The shaded area in Figure 13 represents the amount of the water stored in the soil root zone also calculated graphically and expressed in inches of water.

The amount of water delivered to the field was calculated from the inflow rate and time measurements. The total volume of water in gallons is the sum of all inflow rate measurement in gallons per minute multiplied by the appropriate time interval in minutes. Total volume in gallons was converted to average depth of water in inches by the formula $W_f \text{ (inches)} = \frac{12V}{7.48\ w\ L}$.

where V = total volume of water delivered in gallons

w = furrow spacing in feet (use twice the furrow spacing wherever alternate furrows are irrigated).

L = length of run in feet

Table 5 shows the depth of water delivered to the field (W_f), the depth of water stored in the soil root zone (W_s), and the water application efficiency (E_a).

2) Water Storage Efficiency

Water storage efficiency calculations as presented in Table 6 assume no runoff from the field. The concept of water storage efficiency directs attention to how completely the water requirement of the root zone is satisfied during the irrigation (10).

Table 5. Depth of Water Stored in the Root Zone (W_s), Depth of water Delivered to the Field (W_f), and Water Application Efficiency (E_a).

Field No.		Pre-Planting	Early/Mid-Season	Late Season
1	W_s*	6.92	5.01	7.00
	W_f**	10.26	10.60	16.70
	E_a***	94.7	100.0	100.0
2	W_s	6.30	3.76	5.32
	W_f	8.32	5.64	6.53
	E_a	86.1	91.0	100.0
3	W_s	6.06	5.80	2.80
	W_f	11.25	11.30	3.57
	E_a	100.0	100.0	41.7
4	W_s	2.60	2.40	2.40
	W_f	4.63	5.61	5.27
	E_a	48.2	36.6	38.3
5	W_s	6.20	7.94	7.50
	W_f	10.24	16.30	13.10
	E_a	57.6	100.0	100.0
6	W_s	4.40	4.75	4.80
	W_f	11.05	12.10	11.42
	E_a	37.8	49.8	46.3
7	W_s	-	4.95	-
	W_f	-	10.70	-
	E_a	-	95.8	-
8	W_s	-	3.07	3.94
	W_f	-	3.07	3.94
	E_a	-	58.8	54.0

* W_s = Depth of water stored in the Root Zone in inches.
** W_f = Depth of water delivered to the field in inches.
*** E_a = Water application efficiency in percent.

Table 6. Water Storage Efficiencies.

Field No.	Water Storage Efficiencies (percent)		
	Pre-Planting	Early/Mid-Season	Late-Season
1	67.5	47.3	41.9
2	75.7	66.7	81.4
3	53.9	51.4	78.4
4	56.1	42.7	45.5
5	60.5	48.7	57.2
6	39.8	39.3	42.0
7	-	46.2	-
8	-	100.0	100.0

The formula used to determine water storage efficiency is:

$$E_s = \frac{100W_s}{W_n}$$

where E_s = water storage efficiency

W_s = water stored in the root zone

W_n = water required to refill the root zone prior to irrigation.

RESULTS AND DISCUSSION

Water application efficiencies and water storage efficiencies for the field studies as presented in Table 5 and 6 show great variation with many factors. Some factors are length of run, soil texture, stream size, intake rate, and total application time. Water application efficiencies ranged from 39.3 percent to 100 percent with the average of 59.0 percent. Water storage efficiencies ranged from 36.6 percent to 100.0 percent with the average of 68 percent. For good irrigation practices, both efficiencies should be high. In many cases only a small fraction of the needed water is being applied. The water application efficiencies under such practices are essentially 100 percent, and yet the irrigation practice is poor as is indicated by low water storage efficiency.

Because of numerous factors influencing irrigation efficiencies, it is impossible to study the effect of one factor without considering the others. Also, with a small number of samples, it would be difficult to be certain which major factors will affect the irrigation efficiencies. Because the nature of the loss in deep percolation differs from the runoff loss, it is necessary to study each loss separately.

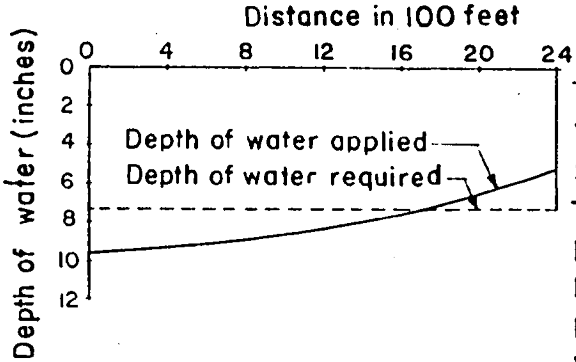
Irrigation efficiencies varied with different factors in this study. With proper management an efficient irrigation can be attained if the major causes of water losses are known. These causes will differ from one irrigation to another in the same field. Each irrigation must be considered individually. Figures 14 through 20 give complete details of the three irrigation evaluations in each field.

Field No. 1 (Figure 14). The rate of water advance was very slow during the pre-planting irrigation. A larger stream size is required to improve water distribution. As the water reaches the lower end of the field, the stream should be reduced to decrease runoff. Slow advance of the water resulted in insufficient percolation in the lower end of the field and deep percolation in the upper end of the field. Water storage efficiency of 100 percent would be achieved if the application were increased to 31.0 hours. This would result in a deep percolation loss of 27.0 percent of the total water delivered to the soil moisture reservoir.

In early-season and late-season irrigation, the effect of slow water advance was not so great. The major cause of loss was excessive application time. This was because the irrigator tried to operate within a 24-hour set. Water application efficiency could have been greatly improved by reducing application time to 17.4 hours in early-season irrigation and 15.0 hours in late-season

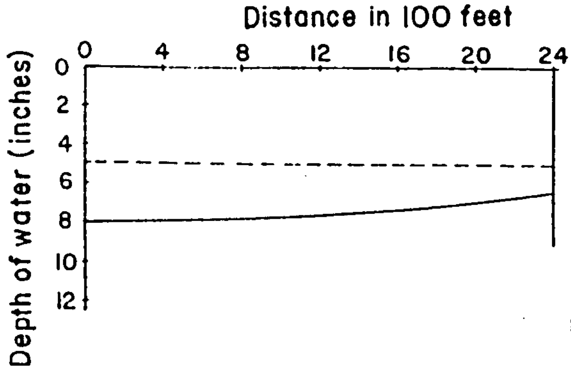
Field No· I ;	Length of run	2400 feet
	Soil texture	Fine
	Slope	0·33 percent

Pre-Planting (April 7, 1965)



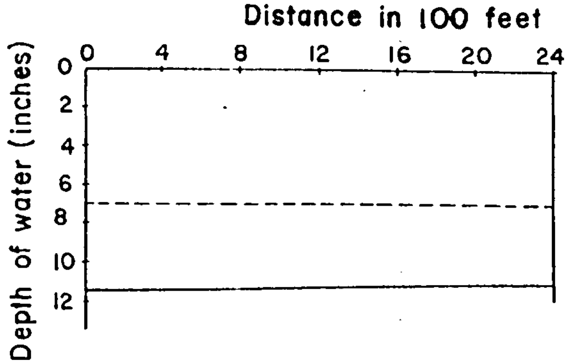
Total advance time	840	mins·
Water required	7·32	inches
Stream size	30·7	g·p·m·
Total application time	24	hours
Basic intake rate	1·7	g·p·m·/100'
Runoff loss		23·0 %
Deep percolation loss		10·5 %
Water application efficiency		67·5 %
Water storage efficiency		94·7 %

Early-Season (June 17, 1964)



Total advance time	420	mins·
Water required	5·01	inches
Stream size	30·6	g·p·m·
Total application time	24	hours
Basic intake rate	1·4	g·p·m/100'
Runoff loss		29·1 %
Deep percolation loss		23·6 %
Water application efficiency		47·3 %
Water storage efficiency		100·0 %

Late-Season (Aug· 24, 1964)



Total advance time	210	mins·
Water required	7·00	inches
Stream size	48·1	g·p·m·
Total application time	24	hours
Basic intake rote	2·3	g·p·m·/100'
Runoff loss		32·3 %
Deep percolation loss		25·8 %
Water application efficiency		41·9 %
Water storage efficiency		100·0 %

Figure 14. Summary of Irrigation Evaluations (Field No. 1)

irrigation. The stream should have been reduced as soon as the water reached the lower end of the field. Although the stream is limited by the capacity of the furrow and the amount of erosion permissible on the soil, a 48.1 g.p.m. stream could have been used instead of 30.7 g.p.m. in pre-planting and early-season irrigations.

Field No. 2 (Figure 15). Alternate furrow irrigation was used for all three evaluations. The overall efficiencies were good. Water storage efficiency was 86.7 percent. To get 100 percent water storage efficiency the water should have been applied for 38 hours, but losses due to deep percolation and runoff would have been increased. Although a rather large stream size was used, the advance of water was slow. This was because of the limitation of a rather flat slope, and rough and dry surface soil.

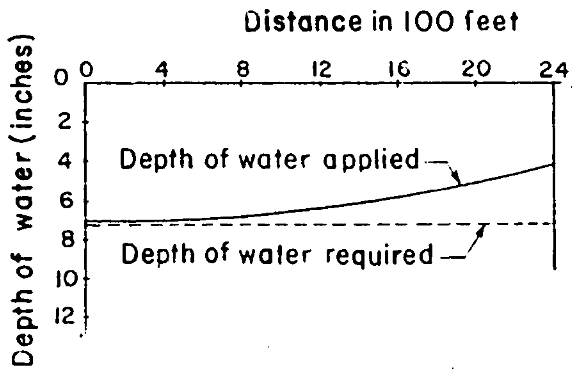
The same slow advance occurred on early-season irrigation but the irrigation pattern was different. The water was applied for 9 hours and was then changed to the adjacent furrow. To completely fill the soil moisture reservoir in the root zone a total application time of 14 hours in one furrow should have been used.

In the late-season irrigation, rapid advance of water provided good water distribution, even with the small stream used. Irrigation efficiencies were high.

Field No. 3 (Figure 16). The coarse textured soil and rather flat slope provided high intake rate. The irrigator

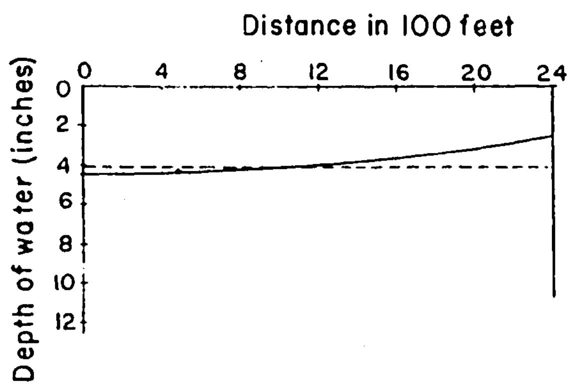
Field No· 2; Length of run 2400 feet
Soil texture Fine
Slope 0·11 percent

Pre-Planting (March 20, 1965)



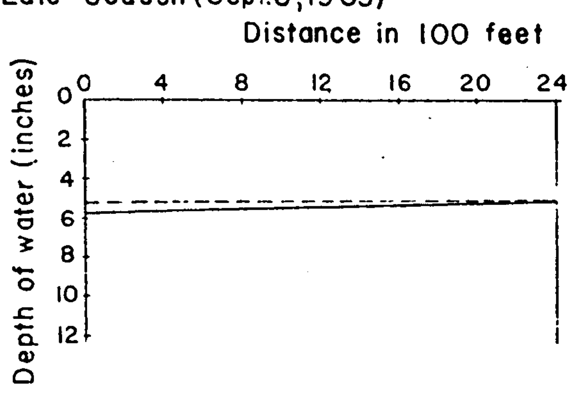
Total advance time	840	mins
Water required	7·32	inches
Stream size	49·7	g·p·m
Total application time	24	hours
Basic intake rate	2·5	g·p·m·/100'
Runoff loss		24·3 %
Deep percolation loss		—
Water application efficiency		75·7 %
Water storage efficiency		86·1 %

Early-Season (June 22, 1964)



Total advance time	400	mins·
Water required	4·14	inches
Stream size	45·0	g·p·m·
Total application time	9	hours
Basic intake rate	1·5	g·p·m/100'
Runoff loss		38·1 %
Deep percolation loss		1·5 %
Water application efficiency		66·7 %
Water storage efficiency		91·0 %

Late-Season (Sept. 8, 1965)

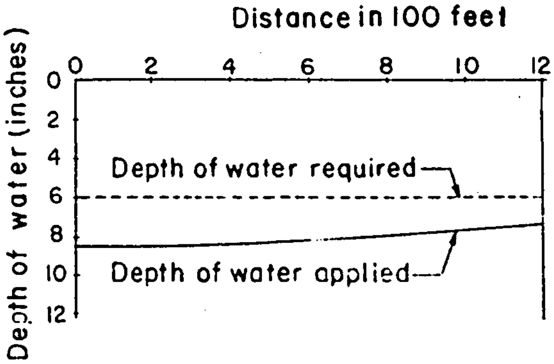


Total advance time	260	mins·
Water required	5·32	inches
Stream size	39·0	g·p·m
Total application time	24	hours
Basic intake rate	2·3	g·p·m·/100'
Runoff loss		14·8 %
Deep percolation loss		3·8 %
Water application efficiency		81·4 %
Water storage efficiency		100·0 %

Figure 15. Summary of Irrigation Evaluations (Field No. 2)

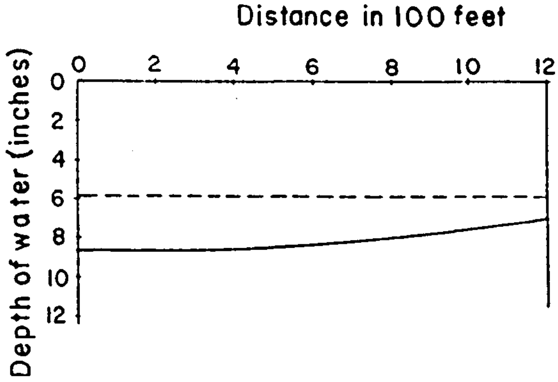
Field No. 3;	Length of run	1200 feet
	Soil texture	Coarse
	Slope	0.14 percent

Pre-Planting (March 15, 1965)



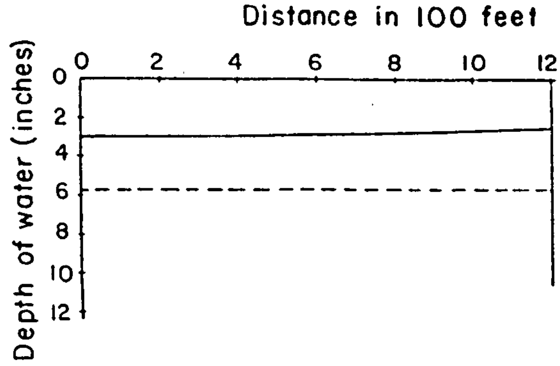
Total advance time	420	mins.
Water required	6.06	inches
Stream size	45.0	g.p.m.
Total application time	19	hours
Basic intake rate	3.4	g.p.m./100'
Runoff loss		28.3 %
Deep percolation loss		17.8 %
Water application efficiency		53.9 %
Water storage efficiency		100.0 %

Early-Season (June 26, 1964)



Total advance time	390	mins.
Water required	5.80	inches
Stream size	43.1	g.p.m.
Total application time	20	hours
Basic intake rate	3.4	g.p.m./100'
Runoff loss		27.4 %
Deep percolation loss		21.2 %
Water application efficiency		51.4 %
Water storage efficiency		100.0 %

Late-Season (August 27, 1964)



Total advance time	85	mins.
Water required	6.72	inches
Stream size	47.1	g.p.m.
Total application time	5.7	hours
Basic intake rate	2.5	g.p.m./100'
Runoff loss		21.6 %
Deep percolation loss		—
Water application efficiency		78.4 %
Water storage efficiency		41.7 %

Figure 16. Summary of Irrigation Evaluations (Field No. 3)

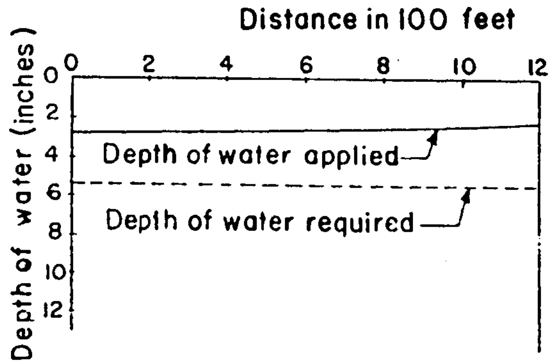
used large streams and the alternate furrows were irrigated. This seemed to increase the rate of water advance and better water distribution was obtained. The only problem was the lateral water movement. The irrigator stopped water when water had soaked completely across the beds. The water application time should have been 12 hours in both pre-planting and early-season irrigations in order to minimize loss due to deep percolation. Additional observations indicated that in some furrows where larger streams were used, the water was cut off at the end of 12 hours. Evaluation in this field showed that an efficient irrigation could be attained on even a course textured soil if maximum length of run was within ¼ mile.

On late-season irrigation, water application efficiency was high when the water was stopped because of rain.

Field No. 4 (Figure 17). This field was located adjacent to field No. 3. The silty loam soil had a lower intake rate than field No. 3. The same irrigation pattern was used as in field No. 3, but a smaller stream was applied. Insufficient application time was observed for all irrigtions. The water advanced fast enough to get good distribution. Runoff loss was great therefore application efficiencies were low. A better irrigation could have been attained if smaller streams were used and every furrow were irrigated. This would provide more intake and reduce runoff.

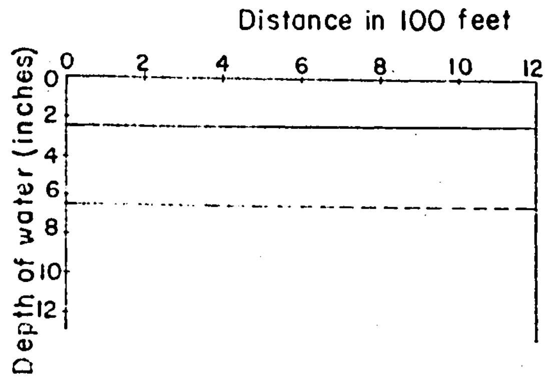
Field No. 4; Length of run	1200 feet
Soil texture	Medium
Slope	0.12 percent

Pre-Planting (March 17,1965)



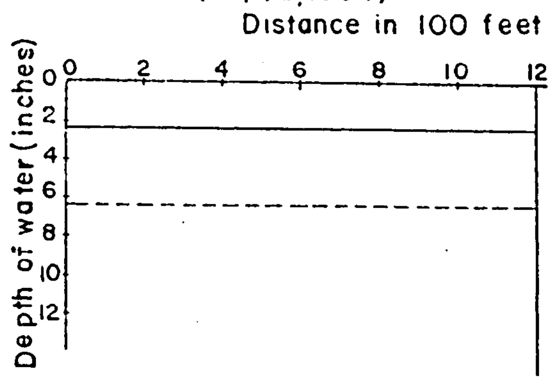
Total advance time	280	mins.
Water required	5.40	inches
Stream size	28.9	g.p.m.
Total application time	12	hours
Basic intake rate	1.6	g.p.m./100'
Runoff loss		43.9%
Deep percolation loss		—
Water application efficiency		56.1 %
Water storage efficiency		48.2%

Mid-Season (July 30,1964)



Total advance time	45	mins.
Water required	6.57	inches
Stream size	35.0	g.p.m.
Total application time	12	hours
Basic intake rate	1.4	g.p.m./100'
Runoff loss		57.3 %
Deep percolation loss		—
Water application efficiency		42.7 %
Water storage efficiency		36.6 %

Late-Season (Sept. 2, 1964)



Total advance time	45	mins.
Water required	6.27	inches
Stream size	32.8	g.p.m.
Total application time	12	hours
Basic intake rate	1.4	g.p.m./100'
Runoff loss		54.5%
Deep percolation loss		—
Water application efficiency		45.5 %
Water storage efficiency		38.3 %

Figure 17. Summary of Irrigation Evaluations (Field No. 4)

Field No. 5 (Figure 18). On pre-planting irrigation the small stream used provided slow advance of water. The application time was insufficient to refill the root zone. Two days would have been required for 100 percent water storage efficiency. Runoff loss was very high and unpreventable. A flatter slope would have improved the efficiencies.

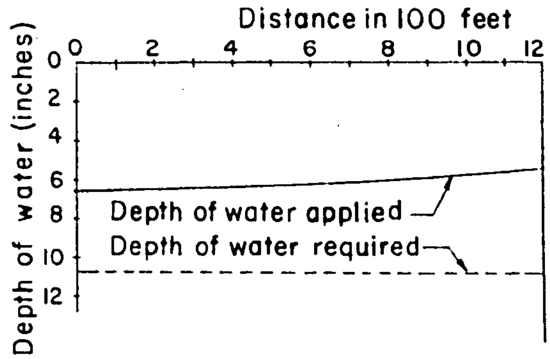
On late-season irrigation almost perfect irrigation was obtained as far as deep percolation loss was concerned. Runoff loss could not be reduced by stream cutback because full flow was needed to maintain a large wetted cross-section on the steep slope.

Field No. 6 (Figure No. 19). This field has low intake rate and steep slope. Even with the small stream used, runoff loss was great and insufficient water was applied on every irrigation. Achievement of 100 percent water storage efficiencies would have required an additional day each irrigation. This would be too long for cotton to safely tolerate saturation of the upper root zone. The physical characteristics of the field limit efficient water application unless the tail water is reused.

Field No. 7 (Figure 20). Only early-season irrigation was evaluated. This irrigation was the best any farmer could get from low intake soil with great runoff loss.

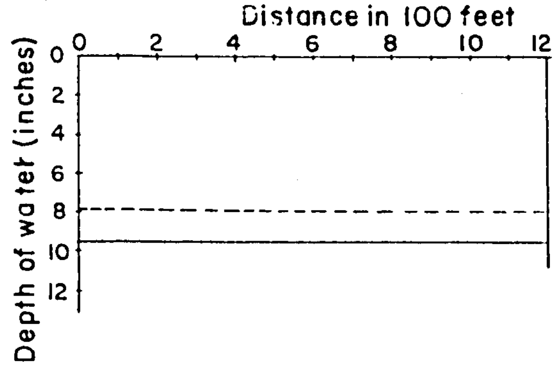
Field No. 5 ;	Length of run	1200 feet
	Soil texture	Medium
	Slope	0·36 percent

Pre-Planting (March 21, 1965)



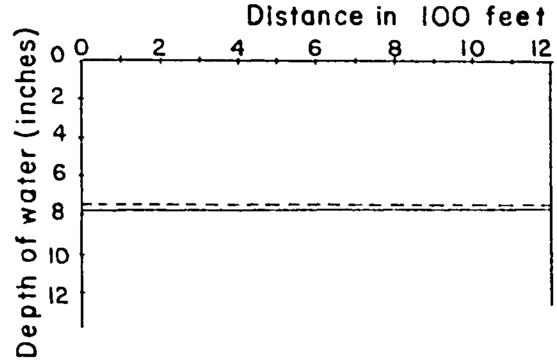
Total advance time	320	mins.
Water required	10·75	inches
Stream size	15·8	g.p.m.
Total application time	24	hours
Basic intake rate	1·2	g.p.m./100'
Runoff loss		39·5 %
Deep percolatiom loss		—
Water application efficiency		60·5%
Water storage efficiency		57·6%

Mid-Season (August 8, 1964)



Total advance time	100	mins.
Water required	7·94	inches
Stream size	19·5	g.p.m.
Total application time	32	hours.
Basic intake rate	1·4	g.p.m./100'
Runoff loss		41·5 %
Deep percolation loss		—
Water application efficiency		48·7 %
Water storage efficiency		100 %

Late-Season (Sept. 1, 1964)

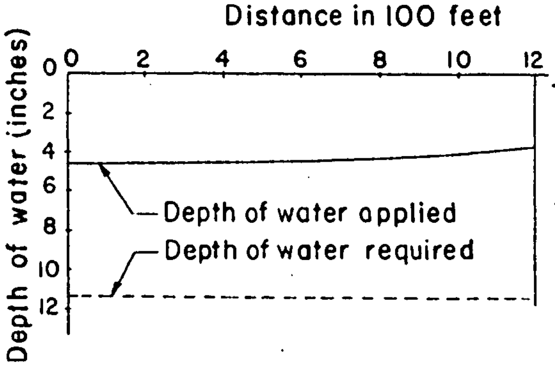


Total advance time	60	mins.
Water required	7·50	inches
Stream size	20·5	g.p.m.
Total application time	24	hours
Basic intake rate	1·4	g.p.m./100'
Runoff loss		40·9 %
Deep percolation loss		1·9 %
Water application efficiency		57·2 %
Water storage efficiency		100 %

Figure 18. Summary of Irrigation Evaluations (Field No. 5)

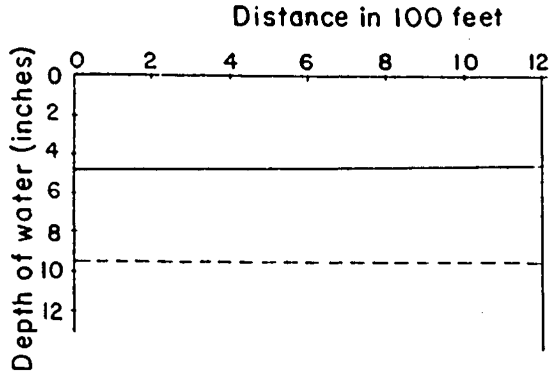
Field No· 6;	Length of run	1200 feet
	Soil texture	Fine
	Slope	0·43 percent

Pre–Planting (March 15, 1965)



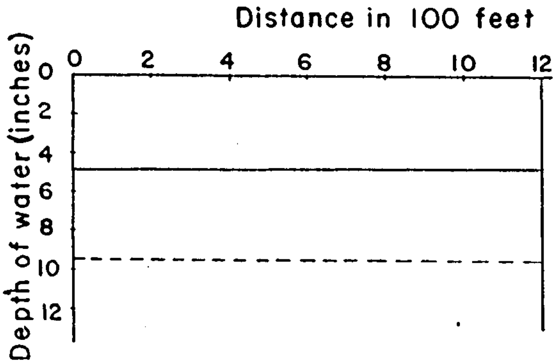
Total advance time	340	mins·
Water required	11·64	inches
Stream size	17·2	g.p.m.
Total application time	24	hours
Basic intake rate	0·8	g.p.m./100'
Runoff loss		60·2 %
Deep percolation loss		—
Water application efficiency		39·8 %
Water storage efficiency		37·8 %

Mid–Season (July 29, 1964)



Total advance time	140	mins·
Water required	9·54	inches
Stream size	18·8	g·p.m·
Total application time	24	hours
Basic intake rate	0·9	g.p.m./100'
Runoff loss		60·7 %
Deep percolation loss		—
Water application efficiency		39·3 %
Water storage efficiency		48·9 %

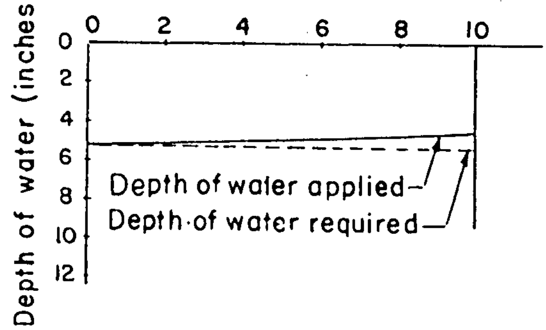
Late–Season (Sept. 6, 1964)



Total advance time	60	mins·
Water required	9·46	inches
Stream size	17·8	g.p.m.
Total application time	24	hours
Basic intake rate	0·9	g.p.m/100'
Runoff loss		58·0 %
Deep percolation loss		—
Water application efficiency		42·0 %
Water storage efficiency		46·3 %

Figure 19. Summary of Irrigation Evaluations (Field No. 6)

Field No· 7 ;	Length of run	1000 feet
	Soil texture	Fine
	Slope	0·01 percent



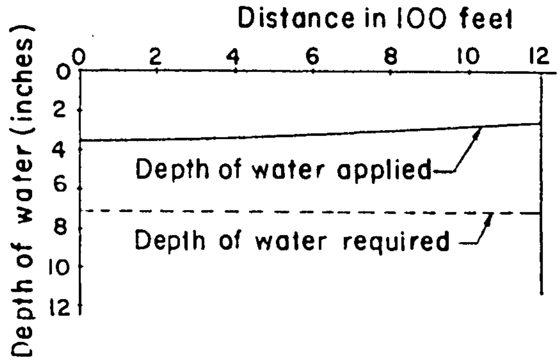
Total advance time	290	mins·
Water required	5·17	inches
Stream size	13·9	g.p.m.
Total application time	24	hours
Basic intake rate	1·0	g.p.m./100'
Runoff loss		53·7%
Deep percolation loss		—
Water application efficiency		46·8%
Water storage effciency		95·8%

Figure 20. Summary of Irrigation Evaluations (Field No. 7)

Field No. 8 (Figure 21). The water application efficiencies were high in this field but water storage efficiencies were low. Application time was too short to bring the root zone up to field capacity. This field illustrates the general truth that it is relatively easy to have high application efficiency when storage efficiency is low.

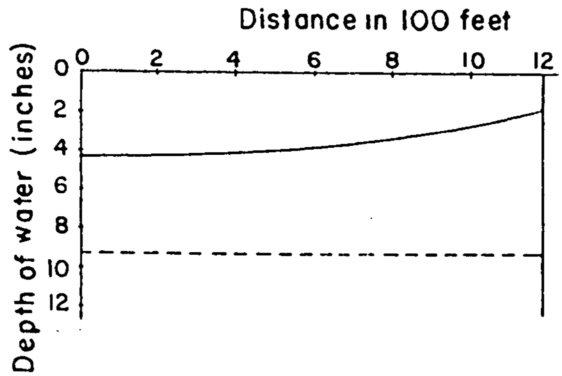
Field No. 8 ;	Length of run	1185 feet
	Soil texture	Fine
	Slope	Dead level

Early-Season (June 13, 1964)



Total advance time	160	mins.
Water required	5·22	inches
Stream size	27·1	g.p.m.
Total application time	5·5	hours
Basic intake rate	1·6	g.p.m./100'
Runoff loss		—
Deep percolation loss		—
Water application efficiency		100 %
Water storage efficiency		58·8%

Late-Season



Total advance time	480	mins.
Water required	7·30	inches
Stream size	15·9	g.p.m.
Total application time	7·3	hours
Basic intake rate	1·4	g.p.m./100'
Runoff loss		—
Deep percolation loss		—
Water application efficiency		100 %
Water storage efficiency		54·0 %

Note. Intake rate estimated from $I_f = 6{\cdot}35\,T^{-0{\cdot}27}$

Intake rate estimated from $I_f = 5{\cdot}56\,T^{-0{\cdot}27}$

Figure 21. Summary of Irrigation Evaluations (Field No. 8)

CONCLUSIONS

Field evaluations of furrow irrigation system were made on 8 fields with three different times of cotton irrigations in the area of Avra Valley. These fields represented the common irrigation practices. Results of these studies lead to the following conclusions;

1. Water application and water storage efficiencies vary widely from field to field and from time to time in the same field. Water storage efficiencies ranged from 39.3 percent to 100 percent with an average of 59.0 percent. Water storage efficiencies ranged from 36.6 percent to 100 percent with an average of 68 percent.

2. With the proper irrigation management, efficient furrow irrigation could be attained from most of the fields studied as in field No. 1 through 5. Improper stream size, application time, effect of stream cut back, and irrigation pattern are the most important factors. On field No. 1, a small stream size was used in pre-planting irrigation, and excessive application time occurred in early and mid-season irrigation resulting in high deep percolation loss. On field No. 2, water storage efficiency would have been increased in early-season irrigation with proper application time. On field No. 3, excessive application time was used in pre-planting and early-season irrigation resulting in high deep

percolation loss. Too low application time occurred in late-season irrigation. On field No. 4, every furrow should be irrigated to provide high intake. On field No. 5, change in application time would be required in pre-planting and mid-season irrigations.

3. Lack of attention during irrigation was a major cause of water loss especially when breaking-over occurred on fields with large furrow stream size.

4. On fields of low intake rate (basic intake rate less than 1.0 g.p.m. per 100 feet) and short runs, run-off loss resulted in low water application efficiencies and low storage efficiencies. Efficient furrow irrigation could not be attained because of the limitation that the total application time should be less than the time the upper root zone of the plant can safely tolerate being saturated as in fields No. 6 and 7.

5. Irrigation on dead level slope proved to be efficient with fields of low intake rate and short run as in field No. 8 because of no runoff. Re-use of tail water on a lower field or pumping back to the system would increase overall farm irrigation efficiency.

6. Irrigation patterns affect the efficiencies of furrow irrigation. Irrigation on alternate furrows may result in higher rates of water advance which are appropriate for fields of high intake and long runs. Every furrow should be irrigated on fields of low intake rate.

7. The depth of water applied in the upper portion of furrows is higher than that calculated from the average intake rate of the entire furrow, because the stream size is largest in the upper portion of the furrow. This effect is greatest where small stream sizes results in a small outflow stream and insufficient water applied on the lower portion of the field.

8. In the fields where intake rate changes with variations of soil texture or where the head of water applied changes, variations in stream size and intake rate result in poor water distribution and low farm irrigation efficiency. The stream size and application time used in a particular portion of such a field should be individually determined by the irrigator.

LITERATURE CITED

1. Bishop, A.A., Relation of Intake Rate to Length of Run in Irrigation, Trans. of Am. Soc. of Civil Eng., Paper No. 3344 Vol. 127, 1962 Part III. Discussed by Willardson.

2. Boudurant, J.A., Developing a Furrow Infiltrometer, Agr. Eng. 38:602-604, 1957.

3. Criddle, W. D., D.K. Fuhriman, V.E. Hansen, and O.W. Israelsen, Water-Application Efficiencies in Irrigation, Utah Agr. Exp. Sta. Bul. 311, 1944.

4. Criddle, W.D., S. Davis, C.H. Pair and D.G. Shockley, Methods for Evaluating Irrigation Systems, Agricultural Handbook No. 82, U.S.D.A. Soil Conservation Service, April 1956.

5. Davis, J. R., Estimating Rate of Advance for Irrigation Furrows, Preceedings of ARS - SCS Workshop on Hydraulics of Surface Irrigation, ARS 41-43 U.S.D.A. October 1960.

6. Erie, J.L., Evaluation of Irrigation Measurements, for presentation at the 1960 Winter Meeting ASAE, Memphis, Tennessee, Dec. 4 - 7.

7. Fok, Y.S., Analysis of Overland Flow on a Porous Bed with Applications to the Design of Surface Irrigation Systems, Ph.D. Dissertation, Utah State University, Logan, Utah, 1964.

8. Hall, W.A., Estimated Irrigation Border Flow, Agr. Eng. Vol. 37, Apr. 1956.

9. Hansen, Vaughn E., New Concepts in Irrigation Efficiency, Trans. Am. Soc. Agr. Eng., Vol. 3, No. 1, pp 55-61, 1960.

10. Hansen, V.E., and O.W. Israelsen, Irrigation Principles and Practices, New York : John Wiley and Sons, 1962, pp 288-296.

11. Lewis, M.R. and W.E. Milne, Analysis of Border Irrigation, Agr. Eng. Vol. 19. June, 1938.

12. Robinson, A.R., Orifice Plates For Furrow Flow Measurement, Colorado Agr. Expt. Sta. Res. Report No. 323, Fort Collins, Colorado, Dec. 7, 1959.

13. Smerdon, E.T., and C.M. Hohn, Relationships between the Rate of Advance and Intake Rate in Furrow Irrigation, Texas Agr. Exp. Sta., MP - 509, Texas A&M, April, 1961.

14. Turner, J.J., Personal Communications, 1963.

15. U.S.D.A., A Method for Determining Intake Characteristics of Irrigation Furrows, ARS 41-31, April, 1959.

16. U.S.D.A., Cotton Irrigation in the Southwest, ARS 41-26, May, 1959.

17. University of Arizona, The Climate of Arizona, Ariz. Agr. Exp. Sta. Bul. 279, Tucson, Sept. 1956.

18. University of Arizona, unpublished record of Agricultural Engineering Department, 1965.