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Rapid Response Tensiometer for Evaluating Preplant Irrigation Efficiency

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RAPID RESPONSE TENSIOMETER FOR EVALUATING PREPLANT IRRIGATION EFFICIENCY

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ABSTRACT

A study of the potential of using rapid response tensiometers to evaluate preplant irrigation was conducted at the Texas Agricultural Experiment Station, Lubbock and Halfway, Texas. Sites used for the study were an Olton loam soil at Lubbock and a Pullman clay loam at Halfway. Soil water potential was measured with both portable rapid response and permanently installed tensiometers. Soil water content was measured with a neutron probe.

Since preirrigations are performed during freezing weather, it was necessary to develop a technique to keep the permanent tensiometers from freezing. Substituting a methanol-water mixture (30% by volume), the water in the tensiometers protected the tensiometers down to temperatures of -18.8°C.

Soil water potential values for "field capacity" (-14 to -17 cbars at 60 cm; -15 to -18 cbars at 120 cm) were significantly lower than those obtained during a previous study (-23 to -25 cbars at 60 cm; -34 to -35 cbars at 120 cm). Data obtained were insufficient to explain the differences.

It was possible to install the rapid response tensiometers in 10 minutes or less. However, considerable problems were encountered once the rapid response tensiometers were installed. These included cracked bulbs and soil clay plugging the pores of the tensiometer bulbs which eventually resulted in slow response time and inaccurate readings. As long as the tensiometers were working properly, readings obtained compared favorably (within -5 cbars) with those from the permament tensiometers.

Both permanently installed tensiometer and the neutron soil moisture

probe provided good data for evaluating the efficiency of preplant irrigation from furrow irrigation. As expected, more water was applied to the soil close to the point of application with decreasing amounts applied with increasing distance from the point of application. The application efficiency was affected by the distance from the water source, flow rate, amount of water applied, and initial soil water content. Application efficiencies ranged from 22 to 76%. In general, the most efficient applications were those in which small amounts were applied to dry soils at fast flow rates.

Infiltration rates calculated using rate of advance data were comparable to those previously determined with infiltrometers.

INTRODUCTION

Throughout the world, irrigation is important in stabilizing agricultural production. According to Steinhart and Steinhart (14), 14 percent of the world's farmland, 5 percent of the United States' farmland, and 35% of Texas farmland is irrigated. Texas has a 3.4 to 3.6 million irrigated hectares which account for 53% of the crop production in the state. The High Plains of Texas is a supplementally irrigated area which receives variable rainfall (23 to 104 centimeters, an average of 46 centimeters). Although adequate rainfall is received in some years for maximum crop production, in most years it is necessary to supplement rainfall with irrigation water to stabilize and/or maximize agricultural production.

The fact that the underground water supply is diminishing on the Texas High Plains has received national attention. Hughes and Harmon (5) have estimated that a 65% reduction in cotton production, 91% reduction in grain sorghum production, and a 22% increase in wheat production in 2015 compared to 1966. It is expected that wheat will replace much of the grain sorghum as the shift to dryland occurs. Various studies are underway to minimize the effect of the diminishing water supplies. These include improved irrigation systems to better distribute water, subsurface barriers to retain water in the profile, antitranspirants to minimize plant stress, and improve crops to more efficiently utilize irrigation water and rainfall.

One of the major uses of this diminishing water supply is to fill the soil profile prior to planting or the preplant irrigation. Each year some 2.02 million hectares are furrow irrigated prior to planting. The annual operation cost for this irrigation now exceeds $50 million per year.

Surveys of pumping costs and soil water deficits indicate that the cost of this irrigation could be reduced by 50% if over irrigation were avoided.

Irrigations with furrow irrigation systems can reduce application amounts by increasing furrow stream size, smoothing furrows, watering alternate furrows or by shortening furrows. However, irrigators often do not know either the soil water deficits or the well flow within needed limits. Further, they lack a simple or inexpensive method for determining whether a particular irrigation has returned the root zone to field capacity. Therefore, they are often not convinced that they are applying more water than the soil root zone can retain against gravity. Since furrow roughness and soil intake rates are normally greater during the preplant irrigation than during summer irrigations, furrow stream sizes which are adequate during the summer result in over irrigation in the spring.

A method for indicating when a soil is near field capacity would be useful in reducing the energy and water required for preplant irrigations. Visual appearance of the calcareous subsoils of the Texas High Plains does not satisfy this need. Some calcareous subsoils that are loose and powdery in appearance actually contain large amounts of available water and are near field capacity.

One possible approach to measuring field capacity is tensiometers. Tensiometers measure a thermodynamic propery of water films as they occur in the soil. Buckingham (2) proposed that an index of this function be called "potential function" in 1907. Gardner, et al., (3), proposed that a pressure measurement on water films using ceramic wall equipment is equal to measuring the "capillary" or "pressure" potential function. Other authors Heck, (4); Richards, (9); and Rogers, (11) independently published papers suggesting the use of porous ceramic cups in soils connected to manometers or vacuum gauges to follow pressure changes inside the cup resulting from pressure changes associated with film water in the soil.

The pressure on water in unsaturated soils is negative. To avoid the use of negative numbers, terms have been used which are defined as negative pressure. Capillary or soil moisture tension is such a term, and it is from this term that the name for the instrument was derived. Suction (12) and matric suction (7), are terms used to specify the property of soil water measured by tensiometers.

The tensiometer is a simple instrument consisting of a porous cup of ceramic material connected by a tube of a desired length to a manometer or vacuum gauge. When initially placed in the soil, the tensiometer is at atmospheric pressure. Since soil water is normally at subatmospheric pressure, it exercises a suction which draws out a certain amount of water from the rigid and air tight tensiometer which causes a drop in hydrostatic pressure. This pressure drop is indicated by a manometer, vacuum gauge or an electrical transducer. Although the useful limit of most tensiometers is about 0 to -0.8 cbars of maximal potential, which is but a small part of the total range (0 to >-15 cbars) encountered in the field, it generally encompasses the greater part of the soil wetness range. Richards and Marsh (10) have shown that this range accounts for 50 to 75% of the water taken up by plants. Consequently, they are widely used where suction conditions favorable for plant growth are maintained.

During the growing season, several thousand tensiometers are installed in summer crops each year to aid in scheduling irrigations to maintain proper moisture levels in the root zone. Their use has been limited in determining the efficiency of preplant irrigations, especially in those areas of the United States where night temperatures commonly fall below freezing during the preplant irrigation season. Permanently installed tensiometers become inoperable due to water freezing in the gauges. Recently a portable rapid response tensiometer has been marketed which reportedly reaches equilibrium in 5-10 minutes after installation. Permanently installed tensiometers normally require several hours to reach equilibrium. Since daytime temperatures are often above freezing, such instruments could be used to evaluate preplant irrigations. The objective of the study was to determine whether rapid response tensiometers can be used to reliable and conveniently evaluate the adequacy of preplant irrigation.

METHODS AND MATERIALS

Methanol-Water Mixture Study

Preirrigations for many of the crops grown in the Texas High Plains are initiated in the spring of the year when freezing weather occurs. Permanently installed tensiometers become inoperable during freezing weather because the water in the gauges freezes and ruins the burdon tubes. It was therefore necessary to develop a technique to prevent the gauges from freezing for this study so that readings from permanently installed tensiometers could be compared with readings from portable rapid response tensiometers. It was decided to determine if methanol-water mixture could be used to replace the water in the tensiometers. The first step in the evaluation was to determine if the tensiometer readings and crops would be affected with such mixtures.

Six 45 cm tensiometers were installed in a circular pattern in a container with a cotton (*Gossypium hirsutum* L.) plant growing in a loam soil. The soil was allowed to dry under greenhouse conditions until the soil water potential reached -45 to -50 cbars. The air temperature in the greenhouse ranged from 15.5 to 21.1°C during the study. Fluid in alternate tensiometers was then replaced with a methanol-water mixture (30% methanol by volume), while the remaining three tensiometers contained only water. Two additional drying cycles to -50 to -60 cbars were then imposed on the soil.

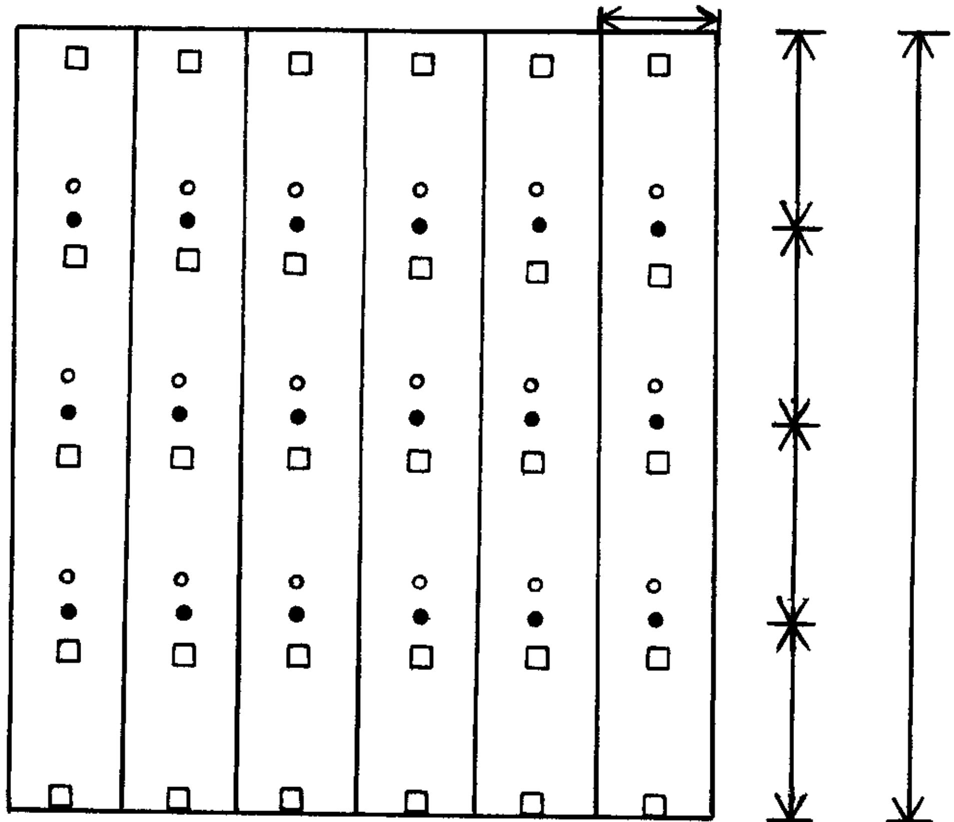
Field Studies

Sites for the rapid response study were located on an Olton loam soil at the Texas Agricultural Experiment Station (TAES) at Lubbock and on a Pullman clay loam at Halfway. Both permanently installed tensiometers (Model

R, Irrometer Co., Riverside, California 92506) and portable rapid response tensiometers (Model 2900, Soil Moisture Equipment Corp., Santa Barbara, California 93105) were used to measure soil water potential at 60 and 120 cm. Soil water content was measured with a neutron moisture meter and probe (Model 2651 Scaler-Rate meter and Model 104A Depth Moisture Probe, Troxler Electronic Laboratories, Research Triangle Park, North Carolina 27709). To determine the tensiometer and soil water content values at field capacity, an area at each site was irrigated with an excess amount of water and was allowed to drain for 5-7 days. This time period was used because of a previous study by Idris (6) at the Lubbock station which indicated that soil water potential and content changes were minimal after 5-7 days and because a producer would need to make measurements after 5-7 days in order to maintain an irrigation schedule. The soil water tension and content readings at 60 and 120 cm at the end of this period were concluded to the values for field capacity.

In the irrigation studies, the access tubes and permanently installed tensiometers were installed at three locations equidistant from each other and from the ends of the plots (Fig. 1). A soil coring rig was used to install the neutron probe access tubes. The permanently installed tensiometers were installed with a king tube. Readings with the rapid response tensiometer were made 30 cm downstream from the permanently installed tensiometers.

Three different flow rates were used at each site. The studies were conducted during 1977 and 1978 at Lubbock and 1978 at Halfway. When possible, neutron probes and tensiometer readings were obtained before and after water applications. In some cases it was not possible to obtain



* - 6-102 cm rows ** - 68 m at Lubbock *** 272 m at Lubbock
72 m at Halfway 288 m at Halfway

Instruments	Treatment No.	Treatments Lubbock 1977	(Furrow Stream Size-lps) Lubbock 1978	Halfway 1978
o - 60 cm tensiometer	1.	0.9	0.8	1.3
● - 120 cm tensiometer	2.	1.5	1.8	2.5
□ - Neutron probe access tube	3.	3.0	3.5	4.7

Figure 1. Field plot arrangement, dates of application, and flow rates in the rapid response tensiometer study at the Texas Agricultural Experiment Station, Lubbock and Halfway, Texas, during 1977 and 1978.

tensiometer readings prior to irrigation water applications because the soil was too dry.

During the irrigation water applications, the time for the furrow stream to reach each instrument location and the cross-sectional area of the furrow stream was obtained. These data were obtained at all instrument locations where the furrow stream had passed at the time it passed a new location. These data were used to evaluate rate of advance models. Flow meter measurements were used to determine the furrow stream size and the total volume of water applied at the time the furrow stream passed each instrument location and to each treatment.

RESULTS AND DISCUSSION

Methanol-Water Mixture Study

The tensiometer data with time obtained during the two drying cycles are shown in Figure 2. There was little difference during the first drying cycle in the readings of the six tensiometers before the methanol-water mixture was added. After the methanol-water mixture was added, the tensiometers containing the solution had slightly lower readings than those that contained pure water. For a tensiometer to operate, it is necessary for small quantities of the methanol-water mixture to move from the tensiometer cup into the soil immediately surrounding the cup. Since this mixture has properties different from water (i.e., specific gravity), differences in readings between tensiometers with the two different fluids might be expected. A maximum difference of 3 cbars occurred immediately following the second irrigation. In most cases the readings of the tensiometers with the mixture were only 1-2 cbars lower than the tensiometers with pure water. Such differences are not significant when tensiometers are used for scheduling irrigations. Neither the cotton plant nor the tensiometers were visibly affected by the methanol-water mixture.

Concurrently with the greenhouse study, New and Heald (8) initiated a field demonstration in wheat (*Triticum aestivum* L.) using tensiometers to depths of 30,60,90, and 120 cm containing the methanol-water mixture previously described. The tensiometer data from their study are shown in Figure 3. The tensiometers responded primarily to the irrigation. No data are available on the amount of irrigation water applied. There was some response to the rainfall periods in April and May but no response to the small showers received during other months. Subfreezing atmospheric

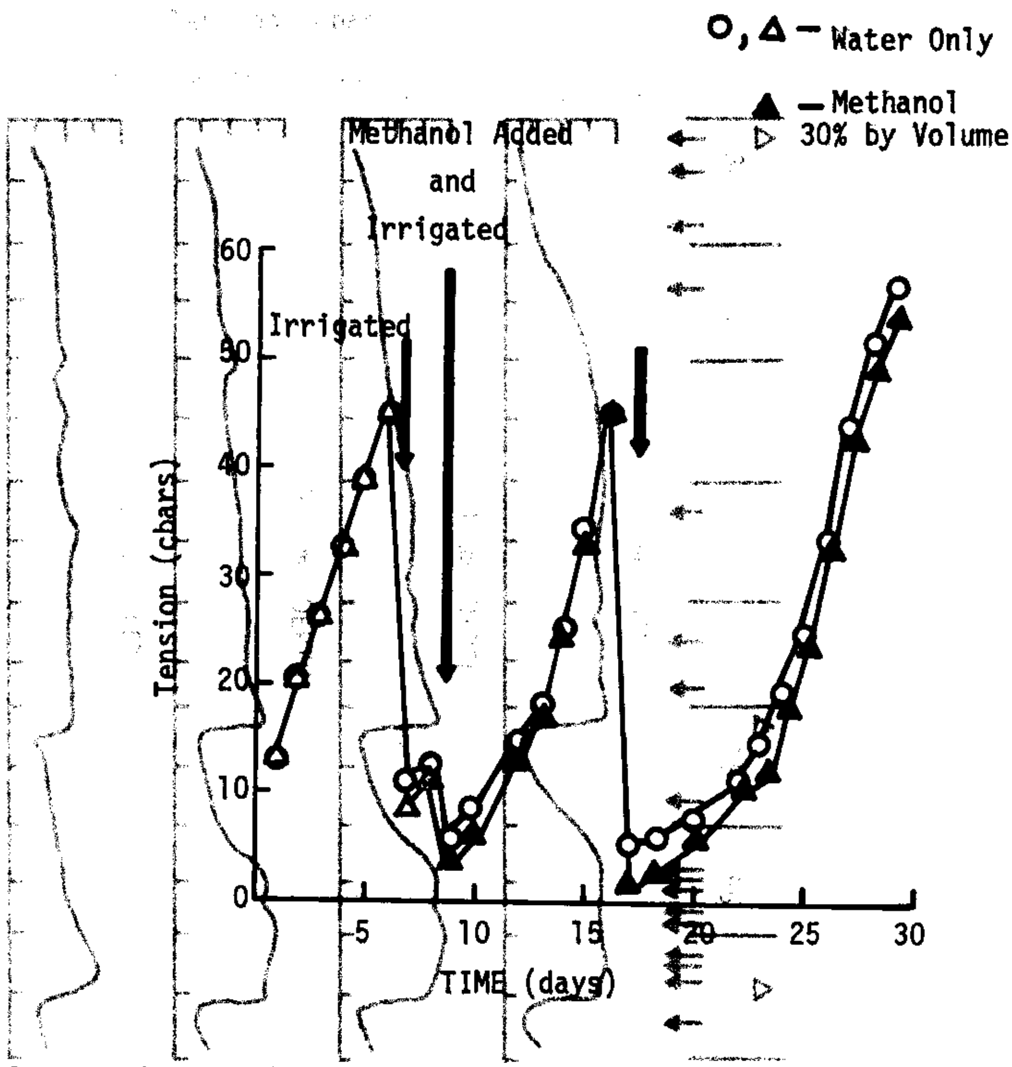


Figure 2. Tension reading of tensiometers with water and methanol-water mixture (30% by volume) in a container with cotton during three drying cycles.

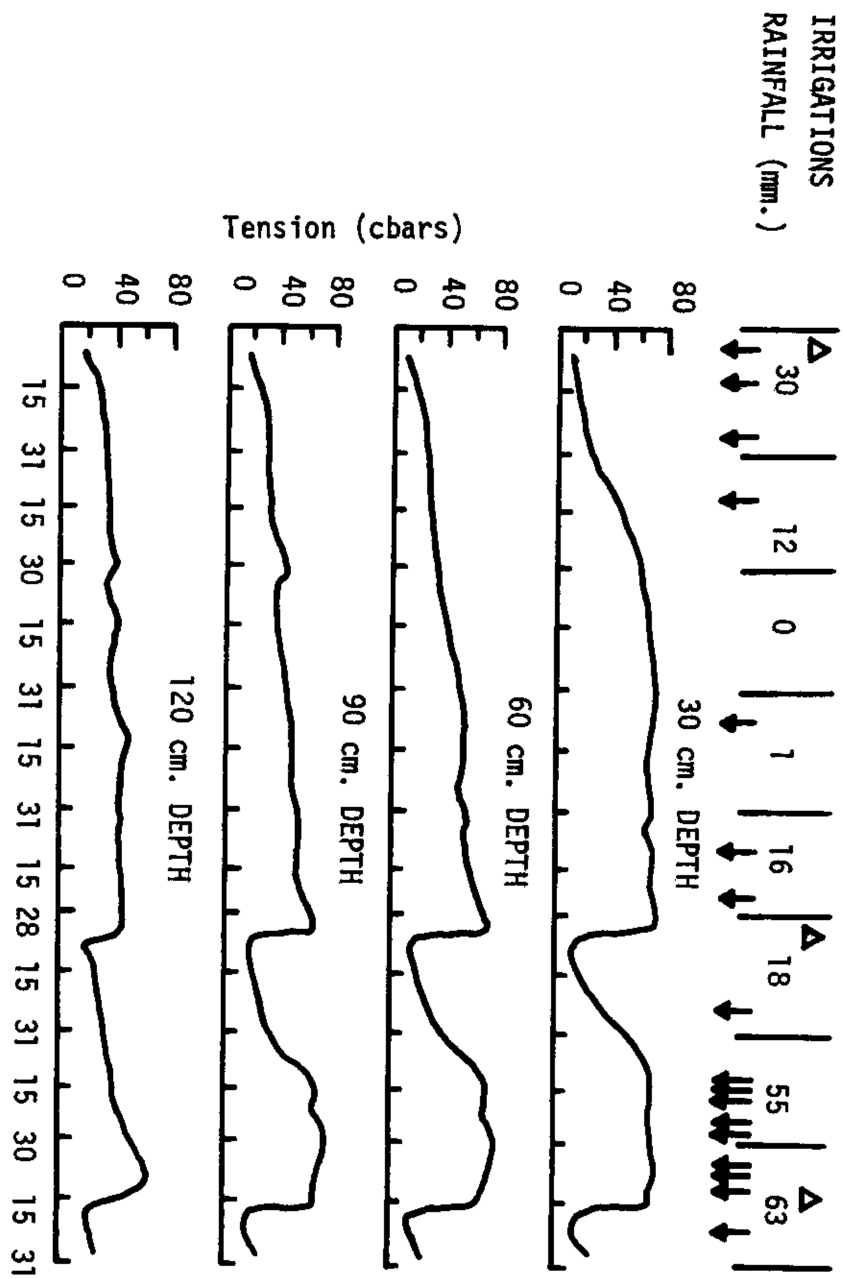


Figure 3. Tensiom readings of tensiometers with a methanol-water mixture (30% by volume) in wheat during the 1976-1977 growing season in Parmer County, Texas (New and Herald).

Table 1. Percent methanol by volume in methanol-water mixture needed to protect tensiometer gauges to various minimum temperatures.

Percent Methanol (by volume)	Minimum Temperature °C	°F
14.2	-7.8	18
20.0	-11.7	11
25.0	-16.1	3
33.3	-22.8	-9
40.0	-29.4	-21
50.0	-42.2	-44

Field Capacity Study -

The data obtained in the field capacity study are presented in Appendix Table 1. Exact values of soil water tension and soil water content for "field capacity" are difficult to obtain under field conditions due to soil variability. Statistical analyses of the data are shown in Table 2. The mean soil water potential obtained on the Pullman clay loam at Halfway and on the Olton loam at Lubbock were -13.9 and -16.7 cbars respectively at 60 cm and -15.0 and -17.5 cbars respectively at 120 cm. A student t test comparing the means of the Halfway and Lubbock locations gave values less than the 5% level of significance value of 2.228. Therefore, the hypothesis that the values obtained following drainage differ at the 5% level of probability is rejected. A previous study was conducted at a site located approximately 2 miles from the Lubbock location used in this study. In the study by Idris (6), soil water values at 60 cm and 120 cm depth were -23 to -25 cbars and -34 to -35 cbars respectively, 5-7 days following irrigation. These values are 10 to 20 cbars higher than the tensiometer values obtained in this study. The soil profiles used in this study were 30-45 cm deeper than the soil profiles used by Idris for his study. However, depth alone is not adequate to explain such differences. Due to the heteroginity of subsoils it would probably be worthwhile for producers to obtain values for temperatures were common from November through March. The lowest atmospheric temperature during the deomonstration was -18.8°C (-2°F). Wheat plants in the area of the tensiometers were not visibly affected by the methanol-water mixture.

The data obtained indicate that tensiometers can be protected from freezing by use of a methanol-water solution without significantly affecting gauge readings and without causing rapid deterioration of either tensiometers or plants. The amounts of methanol required in solutions to protect gauges to various minimum temperatures are given in Table 1.

Questions remain concerning the long term effect of the methanol-water mixture on the components of the tensiometers. Acrylics, which are commonly used for tubing used in tensiometers, are indicated to have good resistance to alcohols (15). However, little is known concerning the influence of alcohols on the other components.

The capability of using tensiometers under freezing conditions offers several possibilities for both producers and researchers. Such tensiometers could be used to schedule preplant irrigations and irrigations in winter annual crops and determine the soil water status in dormant perennial crops. Information could also be obtained on the hydraulic gradients during the winter months in soil water evaporation, irrigation return flow, and drainage studies.

their own farms until further information concerning the reasons for variations in tensiometer values. For purposes of this discussion, the soil water potential values determined in the study were used.

Values for soil water content are also presented in Table 2. The mean volume fraction values for the Pullman clay loam at Halfway and the Olton clay loam at Lubbock were respectively 0.329 and 0.300 at 60 cm and 0.322 and 0.332 at 120 cm. The values obtained from the t test comparing means indicate that they are not significantly different at the 5% level of probability.

Table 2. Statistical analyses of data obtained for "field capacity" in the rapid response tensiometer study at the Texas Agricultural Experiment Station, at Lubbock-Halfway, Texas, during 1978.

	Soil Water Potential (cbars)				Soil Water Content (volume fraction)			
Location	60 cm Depth		120 cm Depth		60 cm Depth		120 cm Depth	
	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD
Halfway	-13.9	1.5	-15.0	3.2	0.329	0.014	0.322	0.010
Lubbock	-16.7	2.2	-17.5	1.8	0.300	0.017	0.332	0.014
t values	1.455		1.250		0.164		0.064	

t value for 5% level of significance = 2.228

Water Applications and Dates of Soil Moisture Readings-

Table 3 shows the pertinent information relative to dates of soil moisture readings during 1977-78. Since the 1977 study at Lubbock was not initiated until June, there was adequate water in the profile from rainfall to obtain tensiometer readings both before and after irrigations. However in 1978, the soil was so dry that the soil water potential was not in the tensiometer range. Resistance readings from calibrated gypsum blocks showed that the potential was less -100 cbars in all plots. Consequently, it was possible to obtain only soil water content data prior to irrigation in 1978.

Although there was considerable difference in the flow rate/furrow at Lubbock in 1977 (0.9 to 3.0 lps/furrow), there was little difference in the amount of water applied (5.0 to 5.9 cm). The flow rate/furrow at Lubbock in 1978 was similar to the 1977 flow rate. However, more water was applied in 1978 than 1977, especially at the low flow rate [5.9 cm (1977) vs 10.3 cm (1978)] due to the dry soil. Much more water was applied to the soil at the Halfway site than at the Lubbock site in 1978 even though the flow rates were faster at Halfway. This was probably due to the fact that prior to irrigation the bottoms of the furrows at Halfway were run over with a tractor while the soil was dry and bottoms of the furrows at Lubbock were run over while the soil was wet.

Rapid Response Tensiometer Study-

1977

The complete data set from this study are presented in Appendix Tables 2-16. The rapid response tensiometers were first used at the Lubbock site in 1977. It was possible to install the tensiometer to the 60 cm depth in 1.6 ± 0.5 minutes and to the 120 cm depth in 4.3 ± 0.9 minutes before the area was irrigated (Table 4). Following irrigation, less time was required to install the tensiometer (1.0 ± 0.2 minutes to 60 cm and 1.3 ± 0.3 minutes to 120 cm). From this study it was concluded that the time required to install the tensiometers was not a problem.

Initially, before irrigation, the time required for the tensiometer to stabilize following installation to 60 cm was not a problem (2.6 ± 1.6 minutes). However, much more time was required to obtain stable readings at 120 cm (7.3 minutes ± 5 minutes). In one case, 18 minutes was required to obtain a stable reading (Appendix Table 2). In this case, the

Table 3. Pertinent information relative to dates of soil moisture readings and irrigation from the rapid response tensiometer study at the Texas Agricultural Experiment Station, Lubbock-Halfway, Texas, during 1977-1978.

Location	Date	Application Time (min)	Flow Rate/ Furrow (lps)	Water Applied (cm)	BI*	I*	AI*
Lubbock	1977	367	0.9	5.9	June 2	June 2-3	June 6
		169	1.5	5.4	(N + T)*		(N + T)
		78	3.0	5.0			
Lubbock	1978	630	0.8	10.3	May 10	May 10-11	May 16-17
		193	1.8	6.9	(N)		(N + T)
		81	3.5	5.1			
Halfway	1978	863	1.3	21.3	Apr 10	Apr 12-13	Apr 21
		362	2.5	17.5	(N)		(N + T)
		99	4.7	9.3			

* Dates of irrigation (I), neutron probe (N), and tensiometer readings (T) before (BI) and after (AI) irrigation.

Table 4. Statistical analyses of data concerning time required to install and obtain stable readings from the rapid response tensiometers at the Texas Agricultural Experiment Station, Lubbock and Halfway, Texas, during 1977-1978.

Location/Date	60 cm depth				120 cm depth			
Furrow Stream Size (lps)	Installation Time (Min)		Stabilizing Time (Min)		Installation Time (Min)		Stabilizing Time (Min)	
	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD
Lubbock-1977								
(before irrigation)								
3.0	1.7	0.4	2.3	1.5	4.4	1.1	5.6	6.4
1.5	1.4	0.5	3.3	2.0	4.3	0.9	6.6	4.0
0.9	1.7	0.6	2.2	1.5	4.3	0.9	9.1	5.7
All treatments	1.6	0.5	2.6	1.6	4.3	0.9	7.3	5.0
(after irrigation)								
3.0	1.0	0.2	1.4	0.4	1.3	0.3	3.9	1.2
Lubbock-1978								
3.5	-	-	10.0	-	-	-	37.0	-
1.8	-	-	17.2	7.4	-	-	17.4	7.4
All treatments	-	-	16.0	7.2	-	-	20.7	10.4
Halfway-1978								
4.7	-	-	20.7	10.8	-	-	18.2	6.2
2.5	-	-	18.7	8.4	-	-	17.0	5.2
1.3	-	-	19.7	11.4	-	-	16.2	7.4
All treatments	-	-	19.8	9.6	-	-	17.3	5.9

tensiometer was deaerated according to the manufacturer's recommendation and the same problem occurred. In an examination of the porous bulb, a crack was noted. The bulb was replaced and the time required to obtain stable readings was decreased (1.4 ± 0.4 minutes after irrigation vs 2.6 ± 1.6 minutes before irrigation at 60 cm and 3.9 ± 1.2 minutes after irrigation vs 7.3 ± 5.0 minutes before irrigation at 120 cm). From these data it was concluded that as long as the tensiometer was working properly, the time required for the readings to stablize would be no problem.

The tensiometer data were analyzed two ways (Table 5). Permanent tensiometer and rapid response tensiometer readings from 30 cm downstream were paired and analyzed using a paired data analysis presented by Bowker and Liebermann (1). The hypothesis tested was that the readings from the permanent and rapid response tensiometers were not significantly different at the 5% level of probability. As can be seen in Table 5 (column 9), the hypothesis that the pairs were equal at the 5% level of probability was accepted in only 4 of 12 analyses of 1977 data. In another analysis of the data, the hypothesis that the mean values of readings from the permanent tensiometers and rapid response tensiometers from plots irrigated at a particular flow rate were equal, was tested at the 5% level of probability. In this analysis, 7 of 12 of the analyses were accepted, and 4 of the 5 remaining were close to the acceptance level. The analyses indicated that there is so much variation between a pair of permanent and rapid response tensiometers that equal readings will be obtained less than 35% of the time. However, if a series of readings are made with both tensiometers the mean values of the readings from each tensiometer will be the same almost 60% of the time.

The importance of using mean values rather than pairing tensiometer

Table 5. Statistical analyses of data from (RRT) permanent tensiometers (PT) and rapid response tensiometers obtained at the Texas Agricultural Experiment Station, Lubbock and Halfway, Texas, during 1977 and 1978.

	COLUMN NOS. 1	2	3	4	5	6	7	8	9	10
Furrow Stream size (lps)	Depth (cm)	PT $\bar{x}$ (cbars)	RRT $\bar{y}$ (cbars)	SD_x (cbars)	SD_y (cbars)	CV_x (%)	CV_y (%)	t values for 5% level of significance	Paired Data t values	Comparison of Means t values
Lubbock 1977 Before irrigation										
3.0	60	16.6	18.3	2.1	2.6	12	14	2.571	2.00	1.82
	120	36.2	40.7	8.2	9.0	24	22		2.53	2.69
1.5	60	15.2	17.2	2.3	4.6	15	27		4.69	1.82
	120	34.5	39.0	8.4	7.9	24	20		3.05	2.81
0.9	60	17.8	18.3	4.7	0.6	26	03		4.23	0.46
	120	37.8	39.0	5.1	6.8	13	17		2.27	0.83
After irrigation										
3.0	60	9.8	17.0	2.9	8.3	30	49		2.53	5.29
	120	29.8	24.5	18.3	17.7	61	72		4.44	2.16
1.5	60	8.2	11.2	4.1	2.8	50	25		2.60	2.80
	120	22.0	20.8	5.4	7.0	25	34		3.63	0.84
0.9	60	7.6	11.0	2.4	4.5	32	41		3.14	3.12
	120	18.0	16.2	2.3	3.6	13	22		4.85	1.82
Halfway 1978										
4.7	60	16.8	9.5	1.5	5.9	09	62		5.26	6.60
	120	18.5	12.8	2.4	7.4	13	58		4.97	4.50
2.5	60	17.0	8.5	0.8	3.5	05	41	3.182	2.55	8.17
	120	18.3	11.5	1.5	7.9	08	69		2.31	5.19
1.3	60	18.5	8.5	1.3	7.0	07	82		2.02	6.94
	120	18.5	12.8	2.4	9.7	13	76		1.78	3.32
Lubbock 1978										
28-106	60	21.8	16.2	2.3	9.7	11	60	2.776	1.89	3.61
	120	52.4	36.0	9.6	24.1	18	21		1.67	6.31

$\bar{x}$ & $\bar{y}$-Means
SD_x & SD_y-Standard Deviations
CV_x & CV_y-Coefficient of Variation

values is further emphasized by other analyses in Table 5. After irrigation at Lubbock in 1977, the mean of the soil water potential at 60 cm of the 3 lps treatment of the permanent tensiometers was -9.8 cbars (column 2) and of the rapid response tensiometers it was -17.0 cbars (column 3). The student t value (2.53, column 9) from the paired data analysis indicated that the differences between pairs was not significant even though there was more than 7 cbars difference between means of the data sets. The coefficient of variation (CV) was high for both data sets (30-49 percent, columns 6 and 7). From the comparison means, a t value of 5.29 (column 10) was obtained indicating that the 7 cbar difference among means was significant.

On the other hand, there was only a small difference between means of the soil water potential values after irrigation at 120 cm in the 0.9 lps treatment at Lubbock in 1977 (permanent tensiometer $\overline{x}$ = -18.0; rapid response tensiometer $\bar{y}$ = -16.2). The t value of 4.85 obtained from the paired data analysis indicated that the difference among pairs was significant. However, the student t value of 1.82 obtained in the means comparison indicates that the difference among means was not significant. This means that if a farmer takes several readings in a field with both tensiometers, the average values from an entire field will mean more than comparing two values from one location. The rapid response tensiometer can be used, therefore, to obtain values from a field that would be comparable from permanent tensiometers. However, at a particular location in the field, it may be difficult to obtain values with the rapid response tensiometer that would compare with a permanent tensiometer.

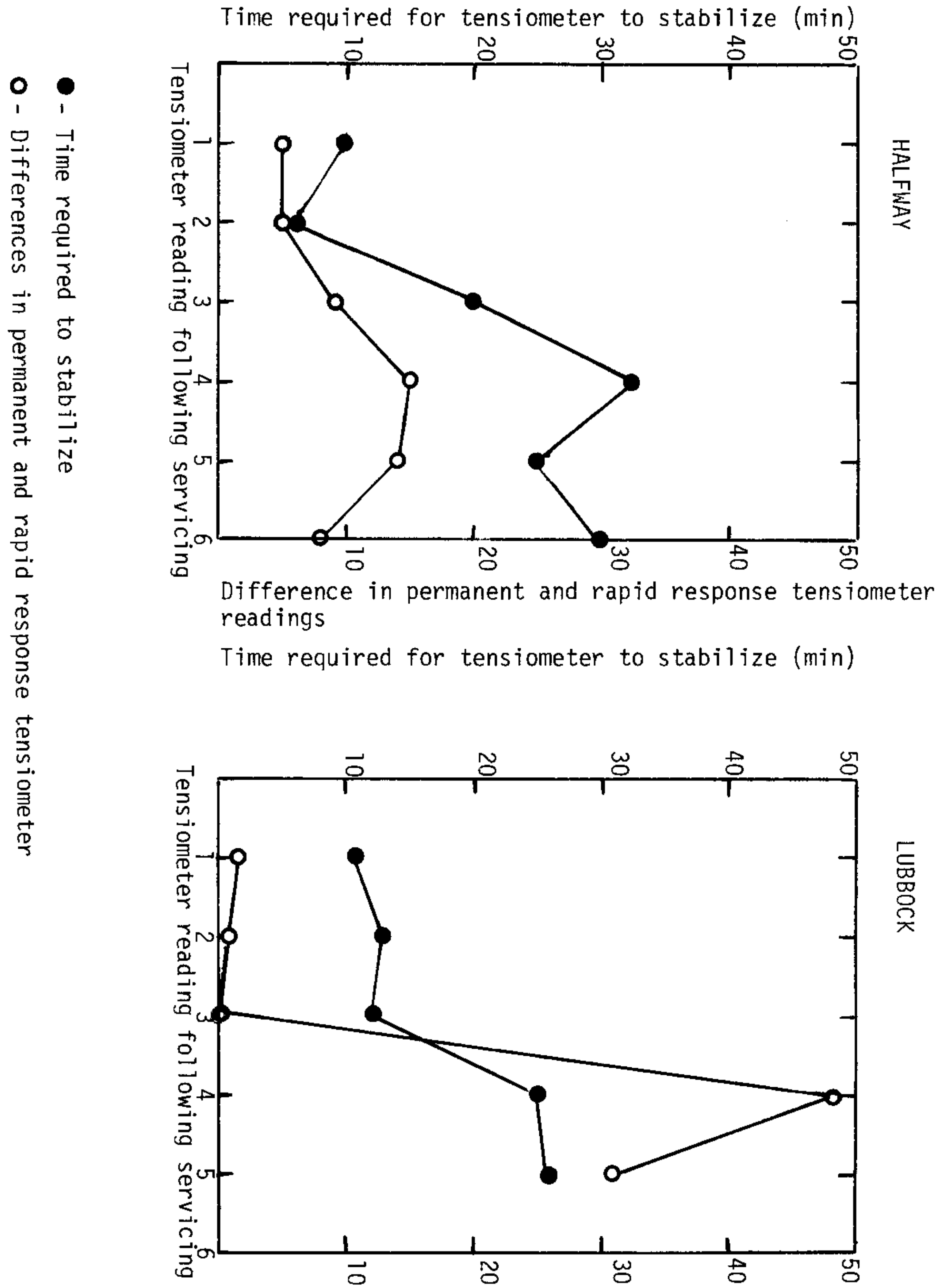
The soil water potential values at 60 cm (-15.2 to -18.3 cbars) obtained in 1977 indicate that the soil was near field capacity (-15.1 $\pm$ 3.2 cbars) prior to irrigation. Following irrigation, the values (-7.6 to -17.0 cbars) exceeded field capacity in some cases indicating that water would be lost to deep percolation.

At 120 cm the soil water potential values prior to irrigation (-36.2 to -40.7 cbars) were less than field capacity (-17.5 ± 1.8 cbars). Following irrigation, most of the tensiometer readings indicated that the profile was at field capacity (-16.2 to -29.8 cbars).

1978

The rapid response tensiometer study was continued in 1978 with plots being established at both Lubbock and Halfway. Since the soil was too dry at both location, it was not possible to obtain tensiometer data prior to applying irrigation water. Irrigation water was applied on April 12-13 and soil water potential data were obtained on April 21. Initially, the rapid response tensiometers could be installed in 1-3 minutes and stable readings that were within 1-7 cbars of the permanently installed tensiometers could be obtained within 6-12 minutes (Figure 4). However, after 2-5 readings problems were encountered with the rapid response tensiometer. The time required for the rapid response tensiometer to stabilize increased (>30 minutes in some cases) and the readings were 10-48 cbars less than the permanently installed tensiometers. The problems encountered are further emphasized in the statistical treatment of the data (Table 5). The differences in mean values (column 2 and 3, 1978 data) ranged from 5.2 to 16.4 cbars. Although the hypothesis was accepted that many of the data pairs were equal at the 5% level of probability (column 9), the hypothesis that means of a data set were equal was not accepted for any data set (Column 10). Coefficient of variation of readings for the permanently installed tensiometers ranged from 5 to 18% which is better than the

Figure 4. Time required for rapid response tensiometer to stabilize and differences in tensiometer readings in the rapid response tensiometer study at the Texas Agricultural Experiment Station at Halfway and Lubbock, Texas, during 1978.



12 to 61% variation obtained in 1977. The coefficient of variation for the 1978 rapid response tensiometer data was greater (21 to 82%) than the 1977 data (3 to 72%).

An examination of the porous tip of the rapid response tensiometer indicated that the pores were clogged with clay. It was possible to get the tensiometer to working again by sanding the porous bulb. However, after the tip was sanded 4 to 5 times, the contact with the soil became poor and it was necessary to replace the porous tip. From the study, it was concluded that a user should have a supply of sand paper and new porous tips if he plans to use currently available rapid response tensiometers in soils with a high clay content (>30%). Properly maintained, the rapid response tensiometer gives readings comparable to those of permanent tensiometers.

Permanent Tensiometers-

Although it was not possible to use the rapid response tensiometers successfully for a large number of readings, without encountering problems data obtained with the permanent tensiometers during the study showed that the concept of using tensiometers to evaluate preplant irrigations has merit. In 1977, soil water potential values from the premanent tensiometers (Figure 5) showed that the soil was at field capacity at 60 cm and less than field capacity in all treatments prior to irrigation. Following the application of 5.9, 5.4, and 5.0 cm of water at flow rates/furrow of 0.9, 1.5 and 3.0 lps/respectively on June 2-3, soil water potential values obtained on June 6 indicated that the amount of water at 60 cm was greater than field capacity in all treatments. Internal drainage was probably continuing. The tensiometer readings at 120 cm also decreased following irrigation. Only in the slowest flow rate (0.9 lps/row) were the tension values at field capacity at 120 cm. In the other treatments the suction

Application Rate/Row (lps)	0.9	1.5	3.0
Water Applied (cm)	5.9	5.4	5.0

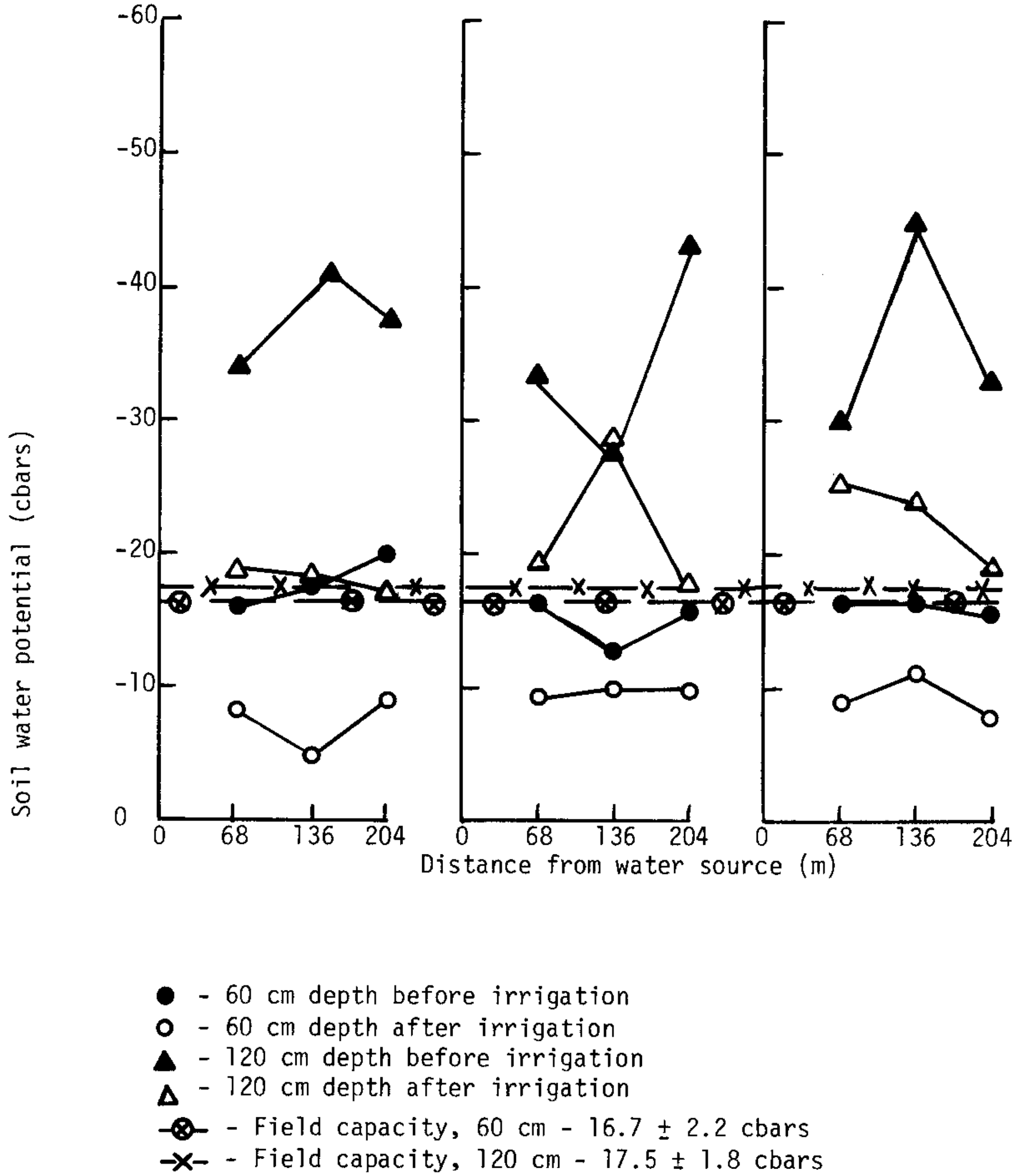


Figure 5. Soil water potential measured with permanent tensiometers at various distances from the water source before and after irrigation in the rapid response tensiometer study at the Texas Agricultural Experiment Station, Lubbock, Texas, during 1977.

values were less than the field capacity values indicating that some soil water storage remained in the soil profile.

In 1978, the soil was too dry to obtain tensiometer readings prior to irrigation. Gypsum block readings indicated the soil water tension to be greater than 100 cbars. Consequently, it was possible to obtain tensiometer readings only after irrigation. At Lubbock (Figure 6) the only root zone at field capacity the entire length of the run was the 60 cm depth in the 0.8 lps or slow application rate. Water was added to the root zone of the other two flow rates, but the soil water potential indicated that the volume of water added was not adequate to increase the potential to field capacity, especially in the middle of the field. At the 120 cm depth the soil water potential was greatest in the slowest flow rate with the readings decreasing with increasing distance from the water source indicating poor distribution of the water applied. The soil water potential was lower in the 1.8 lps flow rate (50-57 cbars) and lower still in the 3.5 lps flow rate (55-60 cbars). Soil water storage remained in all treatments following irrigation.

At Halfway only the 60 cm depth in the fast application rate (4.7 lps) was indicated by soil water potential (Figure 7) to be at field capacity throughout the length of the field. Soil water potential in other flow rates and depths indicated that the field was at field capacity from the middle of the field to the water source but not at field capacity at points past the middle of the field, especially at the 120 cm depth. With the exception of the 60 cm depth in the fast flow rate, poor distribution of irrigation water is indicated.

Such information can be used by the farmer in the decision making process.

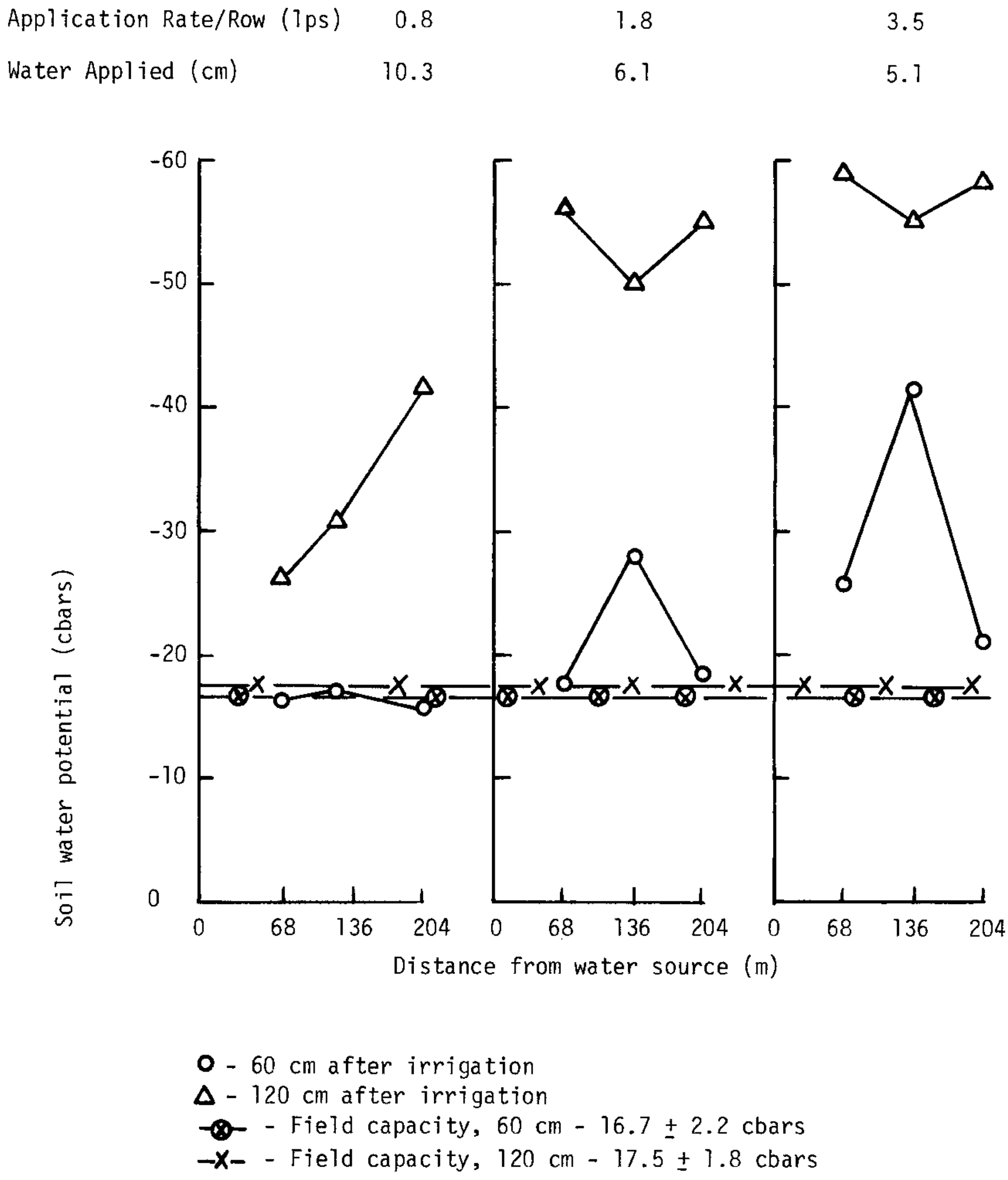


Figure 6. Soil water potential measured with permanent tensiometers at various distances from the water source after irrigation in the rapid response tensiometer study at the Texas Agricultural Experiment Station, Lubbock, Texas, during 1978.

Application Rate/Row (lps)	1.3	2.5	4.7
Water Applied (cm)	21.3	17.5	9.3

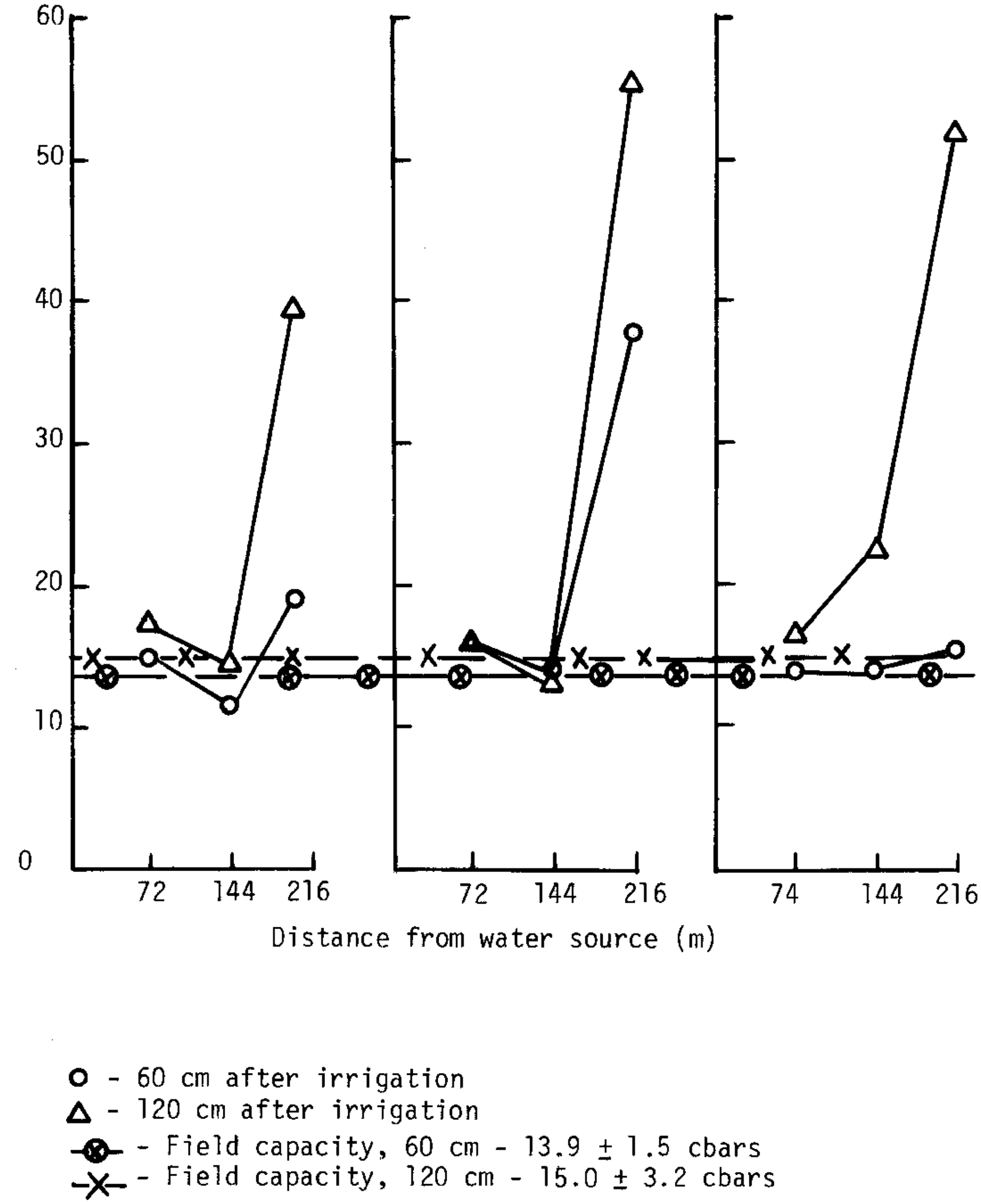


Figure 7. Soil water potential measured with permanent tensiometers at various distances from the water source after irrigation in the rapid response tensiometer study at the Texas Agricultural Experiment Station, Halfway, Texas, during 1978.

If he has an adequate supply of water to irrigate as needed and there is a high probability for rainfall, he may wish to bring only the surface 60 cm to field capacity and leave the lower zones dry for storage of rainfall. In this case, he would choose a fast flow rate that would bring the surface 60 cm of the soil profile to field capacity. If the irrigator has limited water or the probability of receiving rain is low, he may wish to bring the surface 120 cm of the soil profile to field capacity prior to planting in which case he would probably use a slow flow rate/furrow.

Soil Water Content-

In 1977, the soil profile at Lubbock was at field capacity at 60 cm and less than field capacity at 120 cm before the irrigation water was applied (Figure 8). Consequently, there was little change in the soil water content at 60 cm due to irrigation. The soil water content in the 0.9 lps flow rate was at field capacity at all depths and locations following irrigation. The 1.5 lps treatment was at field capacity at 60 cm in all locations and at 120 cm at 68 and 204 meters from the water source but not in the middle of the field, 136 meters from the water source. The profiles of the 3.0 lps treatment were all at field capacity except at the 120 cm depth 68 and 136 meters from the water source. These data support those obtained with the permanently installed tensiometers (Figure 5).

The largest changes in soil water content occurred in the 1.5 lps treatment at 68 and 136 meters from the water source. This was due to the fact that the profiles were drier prior to irrigation. All of the profiles showed changes in soil water content at 120 cm indicating the possibility of soil water movement below the 120 cm depth.

Since there were changes in soil water at 120 cm, it was decided to install the neutron probe access tubes to 150 cm at Halfway to see if the fate of

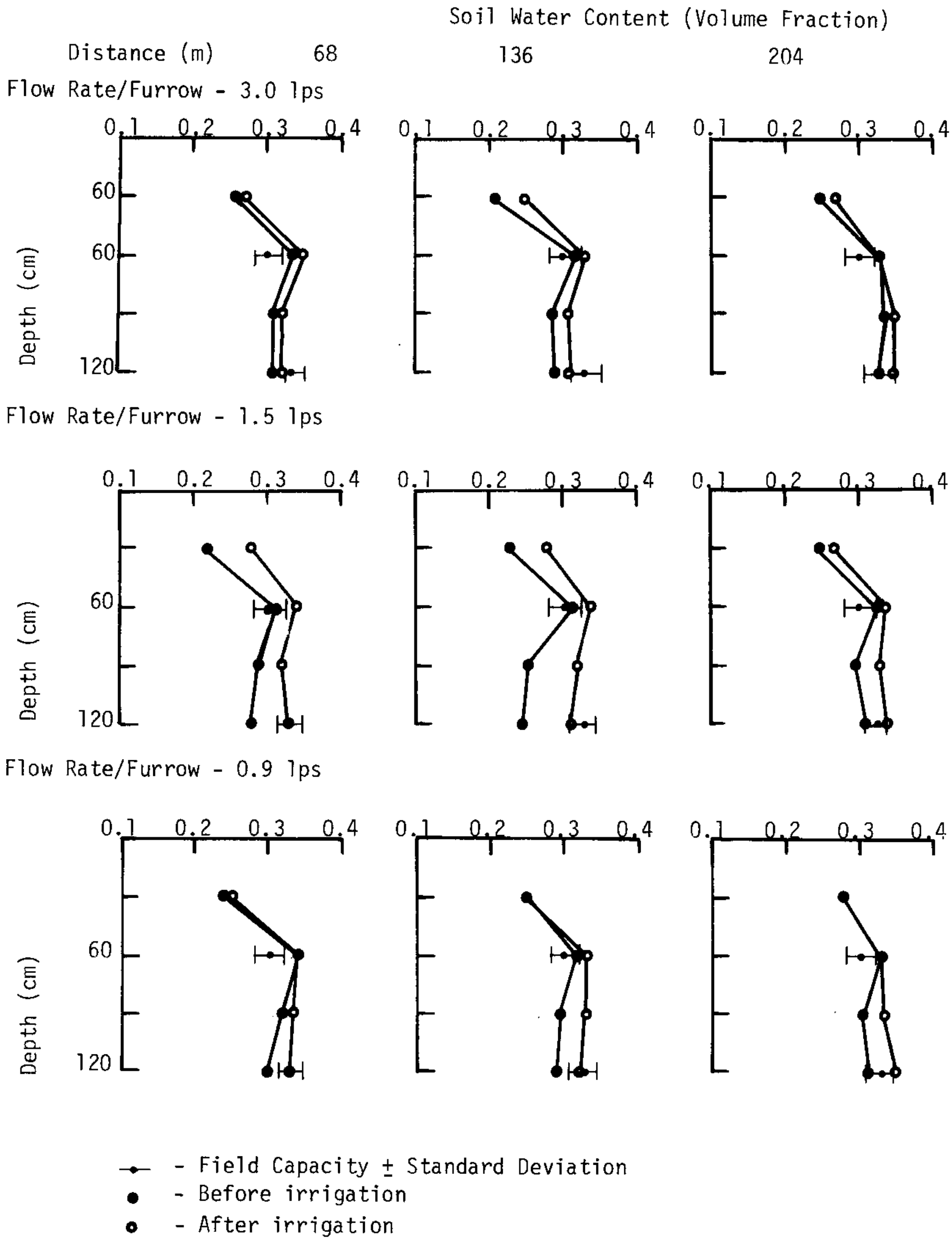


Figure 8. Soil water content at various distances from the water source before and after irrigation in the rapid response tensiometer study at the Texas Agricultural Experiment Station, Lubbock, Texas, during 1977.

applied water could be determined in more detail. The results obtained are presented in Figure 9. Since there were changes in soil water content at 150 cm it appears that the applied water moved below this depth. Most of the soil water content values were less than field capacity prior to irrigation. The amount of water added to the soil profile was dependent in part on how dry the soil profile was at the time the water was applied. For instance, the profiles at 72 and 144 meters from the water source in the 2.5 lps treatment and profile at 72 meters from the water source in the 1.3 lps treatment had water contents of 0.25 to 0.27 volume faction 60-150 cm which was less than other profiles similarly located. These profiles had the largest increases in soil water content. The distance from the water source also influenced the amount of soil water stored. Following irrigation the soil water content was highest closest to the water source and decreased with increasing distance from the water source. In general, the locations indicated to be at field capacity by soil water content readings were also indicated to be at field capacity by soil water potential (Figure 7).

Since the data from Halfway in 1978 indicated that the irrigation water was moving below 150 cm, it was decided to install the neutron probe access tubes to 210 cm at Lubbock. The results are presented in Figure 10. In only 2 out of 18 profiles there was change at 210 cm indicating that 210 cm depth is adequate to measure the depth of applied penetration of applied water in most cases. With the exception of two location (1.8 lps and 3.5 lps 136 m from the water source) the 60 cm depth was at field capacity in all treatments following irrigation. However, in only one profile (0.8 lps, 68 m from the water source) was the soil water content approaching field capacity at 120 cm. These data support the soil water potential data obtained from tensiometers (Figure 6).

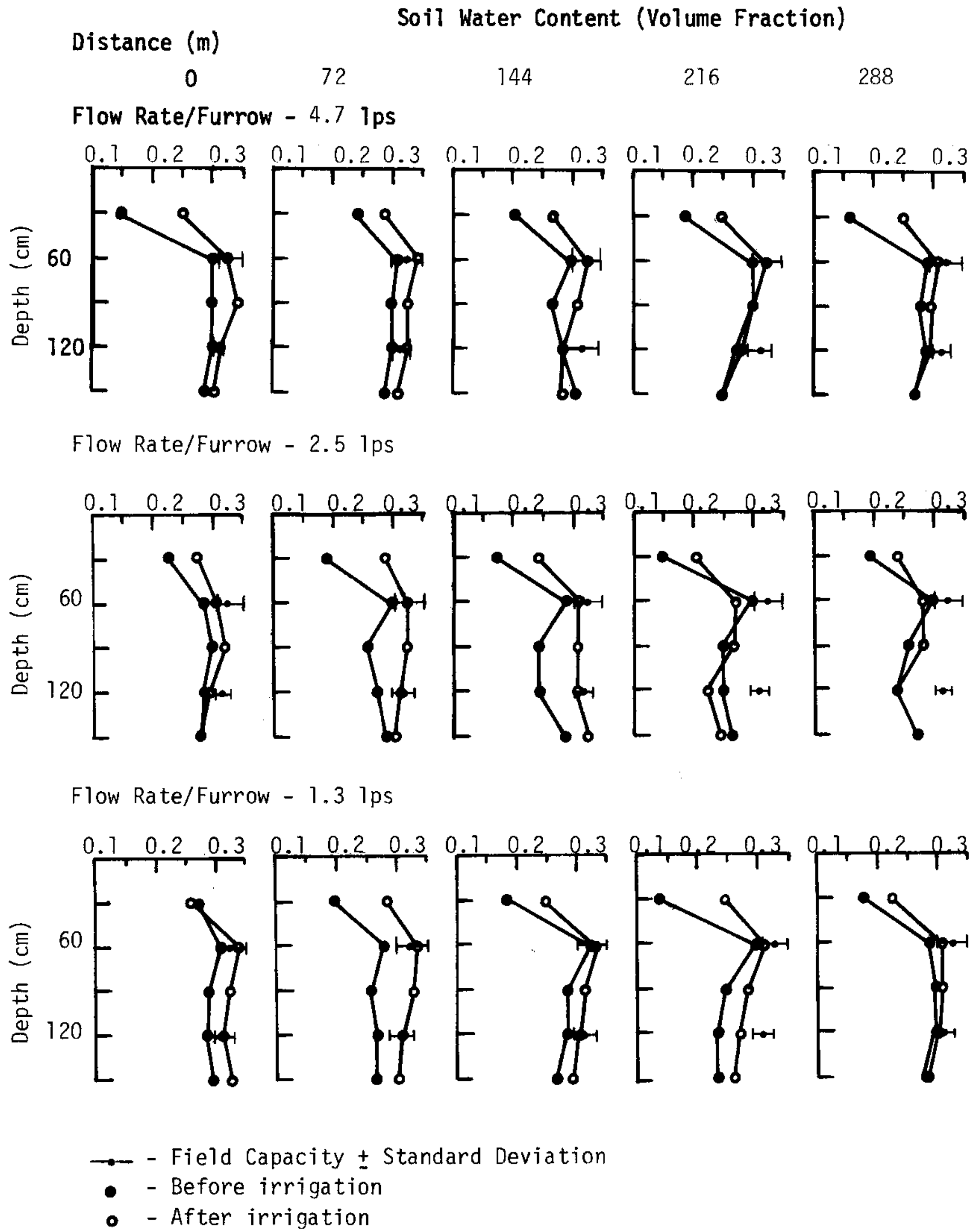


Figure 9. Soil water content at various distances from the water source before and after irrigation in the rapid response tensiometer study at the Texas Agricultural Experiment Station, Halfway, Texas, during 1978.

From the soil water content data it is possible to get some estimate of soil water storage and storage efficiency. These data are presented in Table 6. The most efficient irrigation application occurred in 1977 with the 1.5 lps flow rate. In this treatment it was possible to account for 76% of the water applied due to the low initial soil water content of this treatment (Figure 8). Other than this treatment, the efficiency relative to the amount of water stored was highest with the fastest flow rates (38.7%-Halfway-4.7 lps/furrow flow rate; 52.9%-Lubbock-3.5 lps/furrow flow rate). Even though these rates were the most efficient, less than 2 hours were required for their application. Consequently, such rates will probably not be used by the irrigator without an automated irrigation system because of the labor requirements.

Most producers use a flow rate of 0.8 to 1.3 lps/furrow. Only 22.1 to 40.0% of the water applied at these rates was stored in the root zone in this study. The 40.0% efficiency was obtained from furrow that had been compacted with tractor wheels while wet to enable the furrow stream to proceed at a faster rate. Such efficiencies are rather discouraging when one considers that over 80% of the water applied in the Texas High Plains is applied with furrow irrigation systems.

The fate of the remaining water is unknown. Some water is stored temporarily in the surface during preirrigation. However, data obtained in 1977 indicates that this is minimal if the soil has been previously irrigated or had received rainfall. In 1978, only 2 to 2.5 cm could be accounted for in the surface. The remaining water was probably lost to both evaporation and deep percolation. Deep percolation losses appeared to be especially large on the Pullman clay loam at Halfway (up to 16.1 cm) at the flow rate commonly used (1.3 lps/furrow) by producers. These losses were apparently

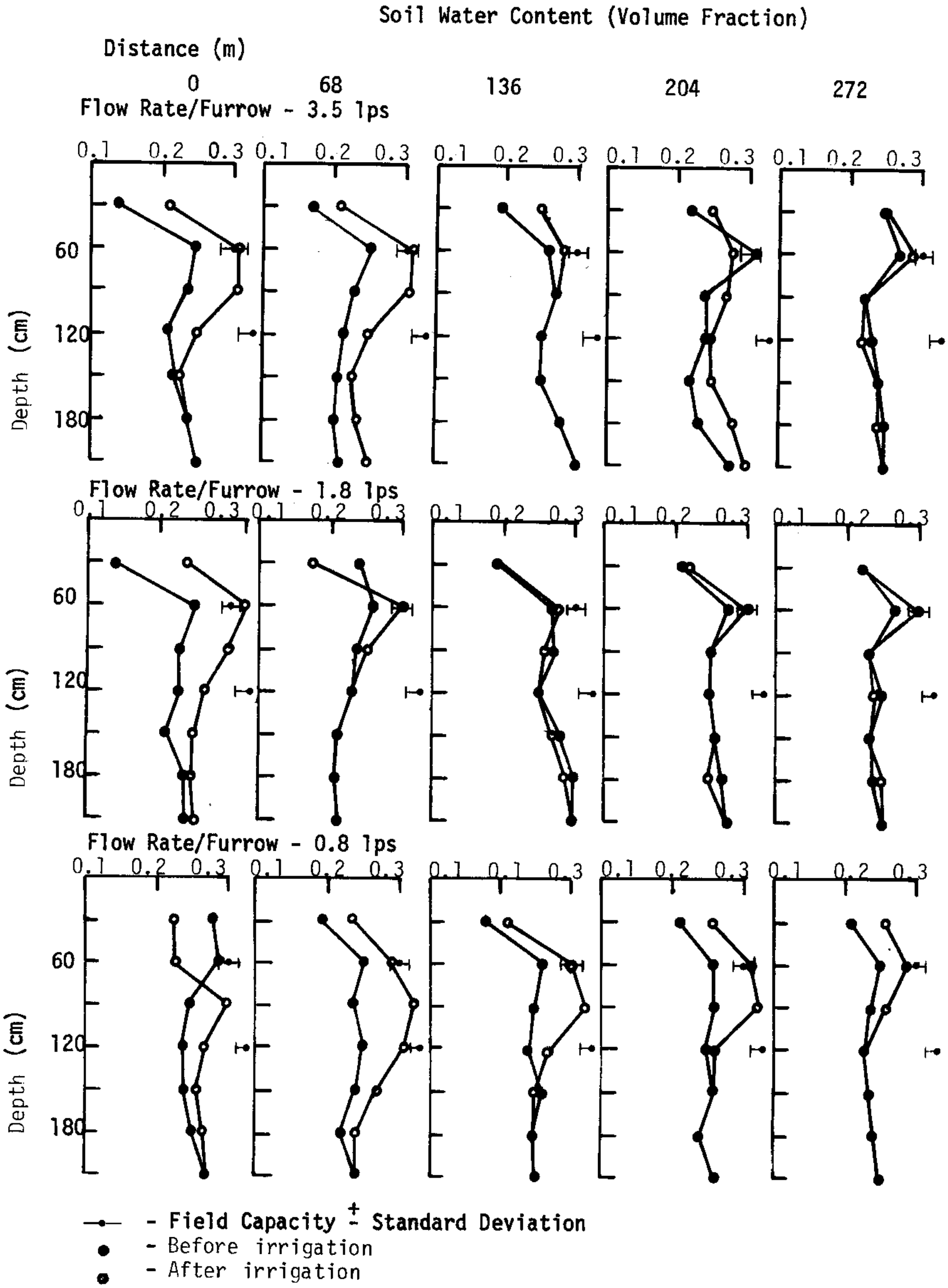


Figure 10. Soil water content at various distances from the water source before and after irrigation in the rapid response tensiometer study at the Texas Agricultural Experiment Station, Lubbock, Texas, during 1978.

Table 6. Water applied, water stored and storage efficiency in the rapid response tensiometer study at the Texas Agricultural Experiment Station, Lubbock and Halfway, Texas, during 1977 and 1978.

Location	Date	Application Rate/ Furrow (lps)	Water Applied (cm)	Water Stored (cm)	Percent Stored	Depth Estimate (cm)
Lubbock	1977	0.9	5.9	2.0	34.0	30-120
		1.5	5.4	4.1	76.0	30-120
		3.0	5.0	2.2	44.0	30-120
Lubbock	1978	0.8	10.3	4.1	40.0	30-120
		0.8	10.3	4.7	45.6	30-210
		1.8	6.1	2.0	32.8	30-120
		1.8	6.1	2.3	37.7	30-210
		3.5	5.1	2.7	52.9	30-120
		3.5	5.1	2.5	49.0	30-210
Halfway	1978	1.3	21.3	4.7	22.1	30-120
		2.5	17.5	4.2	24.0	30-120
		4.7	9.3	3.6	38.7	30-120

from unsaturated flow as content changes do not indicate that water moved through as a wetting front because the soil water content did not reach field capacity at 120 cm depth. However, changes in soil water did occur at 120 cm and below indicating that water was moving below the root zone.

In summary the distribution of water in furrow irrigation is affected by distance from the water source, flow rate, the amount of water applied and initial soil water content. In most cases, efficiencies are low and considerable amounts of water are apparently lost to deep percolation, especially at the flow rates commonly used by producers. The potential exists to increase water application efficiencies by 100% through better design of furrow irrigation systems or new irrigation systems.

Infiltration Calculations-

An empirical equation which describes the intake rate behavior of irrigation furrows under a wide range of conditions is the Kostiakov-Lewis (16) equation:

$$y = k\ t_o\alpha \quad [1]$$

in which y is the accumlative infiltration at a point in liters per second per meter of furrow length, t_o is the time in minutes that the point has been wet and k is a constant based on the flow rate and cross-sectional area of the furrow stream, and α is a constant based on the rate of advance of the furrow stream with time. The first derivative of the above equation is:

$$dy/dt = \alpha k t^{\alpha-1} \quad [2]$$

which represents the cange in infiltration with time or the infiltration equation.

It has also been pointed out by various researchers that the infiltration rate can be described by the equation:

$$I = Kt^n \quad [3]$$

where I is in liters per second per meter of furrow, n is a constant based on the rate of advance, and k is a constant based on the flow rate and cross-sectional area of the furrow stream. The two equations are therefore the same.

The values for k and α in equation [1] were calculated according to the procedure proposed by Wilke and Smerdon (16) from the data presented in Appendix Tables 14-16. The values for k and n in equation [3] were calculated according to the procedure of Smerdon and Hohn (13). The equations obtained using the 2 methods of calculation are in Table 7.

It can be seen that the slopes of the infiltration equations obtained from the first derivative of the accumulative infiltration equation increased. This is not surprising because the k values are a function of the flow rate which results in a larger cross-sectional area. The slopes of the infiltration equation using the approach of Smerdon did not follow a similar pattern. Their approach is more sensitive to irregularities in the field. Both fields had low places. The furrow streams had to build a head before it could proceed. This caused some deviation in the rate of advance curves.

The infiltration curves are plotted in Figures 11 and 12. The curve from the fast rate using Wilke's approach drops faster than the remaining curves which are grouped similar to other previously reported data (16).

The Lubbock data, regardless of method of calculations, show deviations similar to those previously reported. Again, the curve with the greatest slope is the fast flow rate according to Wilke's calculations. The curves from the Smerdon and Hohn approach were higher than those from the approach by Wilke and Smerdon. The 720 hour estimates for the fastest flow rate using the calculations according to Wilke and Smerdon were similar to

Table 7. Infiltration as determined from rate of advance data obtained in the rapid response tensiometer study at the Texas Agricultural Experiment Station, Lubbock and Halfway, Texas, during 1978.

Location	Flow rate (lps)	$y=kt^{\alpha}$	$^{dy}/_{dt}={}^{\alpha}kt^{\alpha-1}$	$I=Kt^{n}$
Halfway	1.3	$y=0.075t^{0.632}$	$^{dy}/_{dt}=0.048t^{-0.368}$	$I=0.0538K^{-0.237}$
	2.5	$y=0.128t^{0.550}$	$^{dy}/_{dt}=0.073t^{-0.450}$	$I=0.0741K^{-0.300}$
	4.7	$y=0.758t^{0.173}$	$^{dy}/_{dt}=0.128t^{-0.827}$	$I=0.0651K^{-0.210}$
Lubbock	0.8	$y=0.115t^{0.464}$	$^{dy}/_{dt}=0.053t^{-0.536}$	$I=0.0738K^{-0.484}$
	1.8	$y=0.142t^{0.447}$	$^{dy}/_{dt}=0.057t^{-0.553}$	$I=0.0546K^{-0.401}$
	3.5	$y=0.302t^{0.235}$	$^{dy}/_{dt}=0.070t^{-0.765}$	$I=0.0826K^{-0.666}$

y=accumulative infiltration (liters/meter of row)

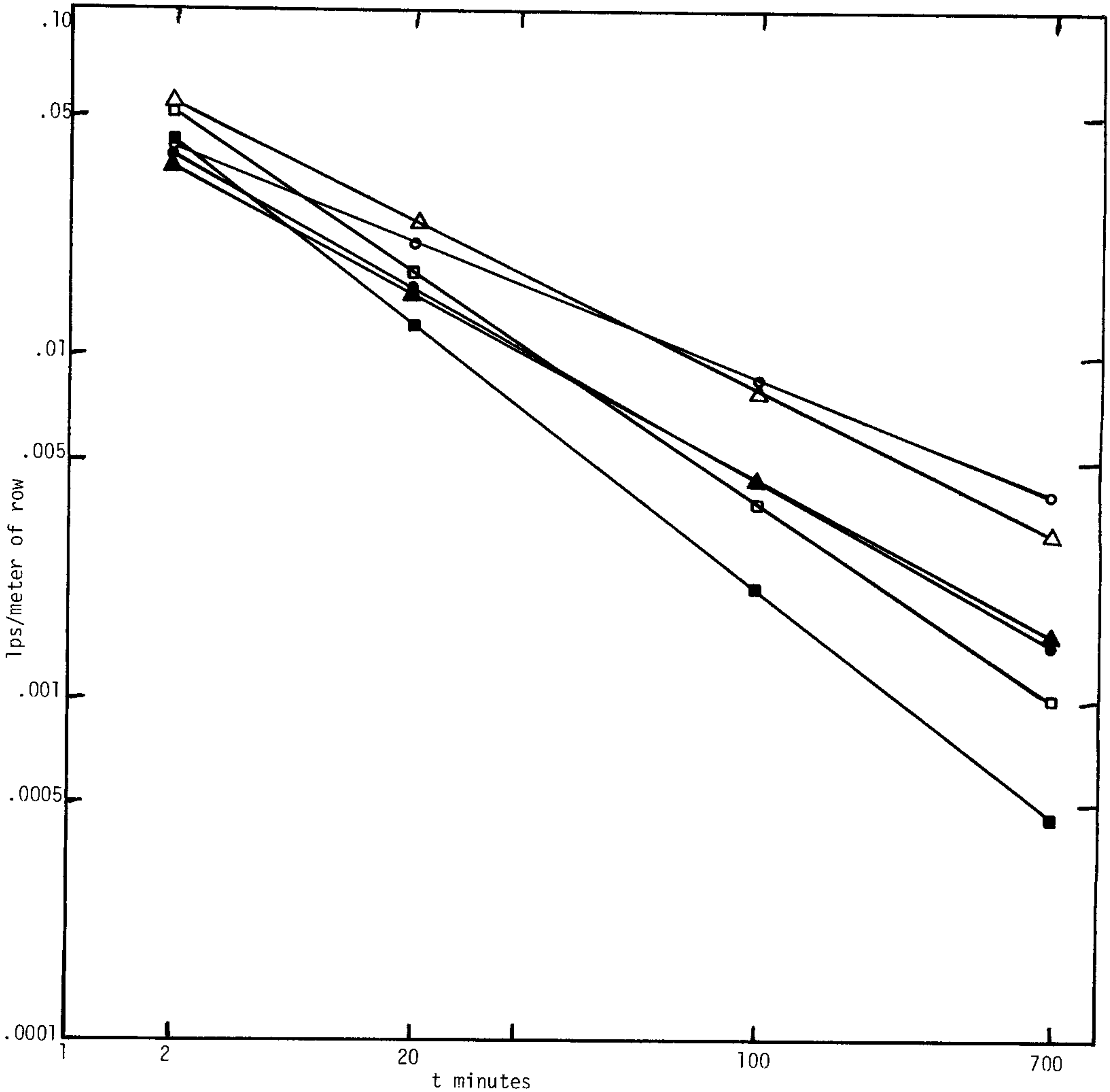
t=time in minutes

k & K=constants based on flow rate and cross-sectional area of the furrow stream

n & α=constants based on the rate of advance

I & $^{dy}/_{dt}$=Infiltration rate (lps/meter of row) previously determined steady state infiltration rates of .0045 to .0092 lps/min/meter of furrow (0.1 to 0.2 in/hr).

The approach of using rate of advance data to estimate infiltration is an inexpensive approach that can be used by anyone in irrigation research with existing equipment. Such an approach does not have the problems with equipment and point source determinations encountered with ring infiltrometers.



Kostiakov-Lewis Equation (First derivative) (16)

▲ - 0.8
● - 1.8
■ - 3.5

Smerdon-Hohn Equation (13) Flow Rate/Furrow (lps)

△ - 0.8
○ - 1.8
□ - 3.5

Figure 11. Infiltration determined from two different methods of calculation using rate of advance data obtained in the rapid response tensiometer study at the Texas Agricultural Experiment Station, Lubbock, Texas, during 1978.

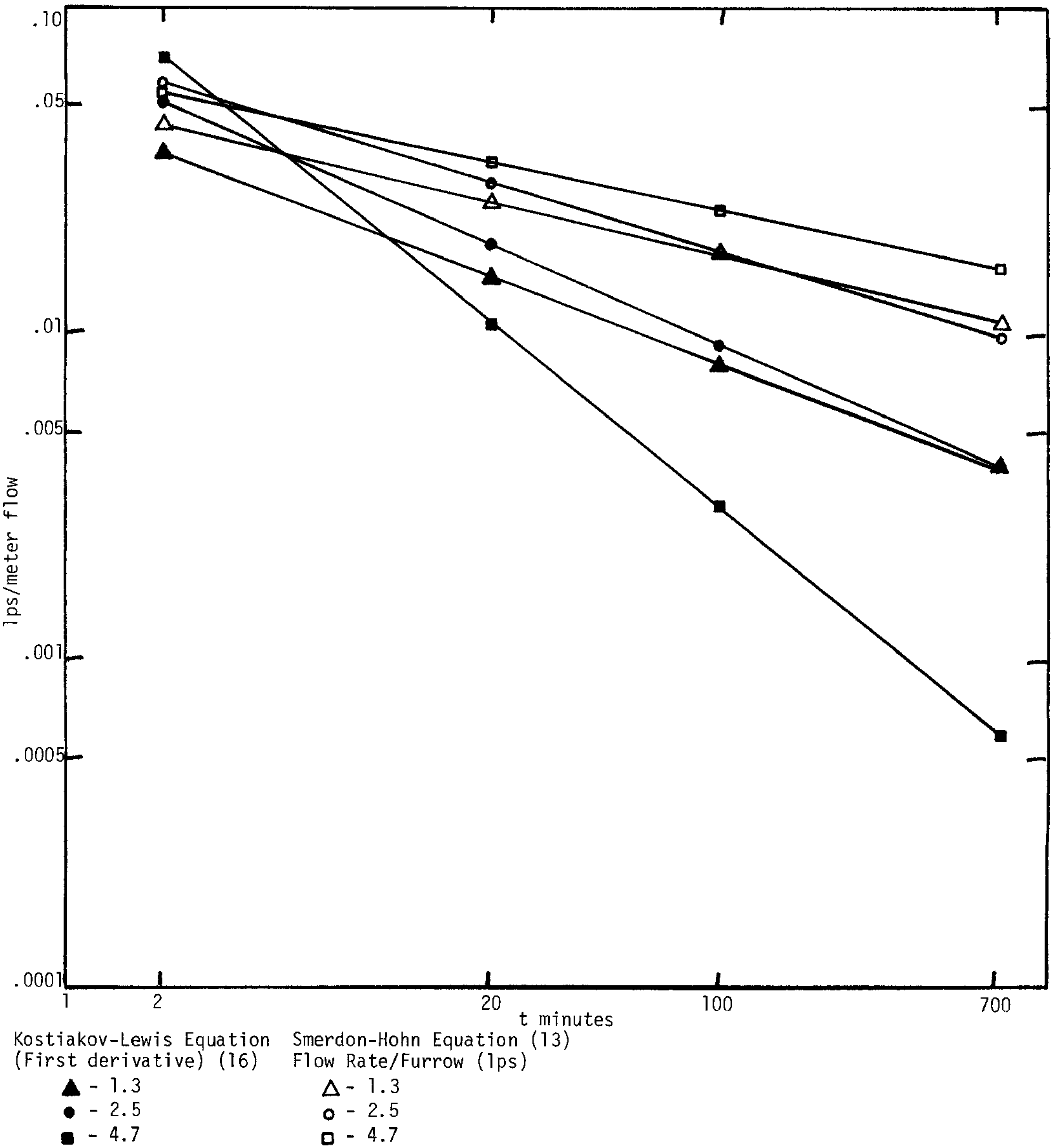


Figure 12. Infiltration determined from two different methods of calculation using rate of advance data obtained in the rapid response tensiometer study at the Texas Agricultural Experiment Station, Halfway, Texas, during 1978.

CONCLUSIONS AND RECOMMENDATIONS

Major problems were encountered in using the portable rapid response tensiometers in the Olton loam and Pullman clay loam soils used in the study. The bulbs of the rapid response tensiometer are fragile and care must be taken to prevent them from cracking. Cracks cause slow response time and erroneous readings.

The high clay content (>30%) of the soils used in the study also created problems. The clay soil clogged the pores of the tensiometer bulb after 3 to 5 readings. It was possible to get the tensiometers operable again by sanding the tips of bulbs. However, after the bulbs were sanded 2 to 3 times it was necessary to replace it with a new bulb because the sanding decreased the diameter to the point that it made poor contact with the soil. It is recommended that a user of the rapid response tensiometers have a supply of sandpaper and new porous tips if he plans to use currently available rapid response tensiometers with a high clay content (>30%). When the portable rapid response tensiometer was working properly, data were obtained that compared favorably with the permanently installed tensiometer. We found that the best data were obtained when several readings were obtained and averaged. If readings were obtained with the two tensiometers for a particular location, significant differences will occur between pairs of readings due to soil variability.

The suction values obtained for "field capacity" of 14 to 18 cbars at 60 cm and 15 to 18 cbars at 120 cm were essentially the same for both locations. However, these values were 10 to 20 cbars less than values obtained in a previous study. Until the reasons for the differences can be delineated, it is recommended that the irrigator determine field capacity for a particular field. This can be done by irrigating a soil with several rows and allowing it to drain for 1 to 2 weeks before taking tensiometer readings.

Although it was not possible to use the portable rapid response tensiometers successfully for a large number of readings, data obtained with the permanently installed tensiometers show that the concept of using tensiometers to evaluate preplant irrigation has merit. The data with the permanent tensiometer obtained showed that the distribution and efficiency of water applications was affected by initial soil water content, distance from the water source, flow rate, and the amount of water applied. The most efficient applications are obtained when small amounts (≈ 5 cm) of water are applied to a dry soil at a fast flow rate. However, the time involved in applying the fast flow rates is ofter less than two hours. Currently, it is not feasible for the irrigator to use such fast flow rates and short times due to the labor requirements. The previous limitation of using tensiometers in freezing weather due to water freezing in the tensiometers was overcome by substituting methanol-water mixtures for the water.

The soil water content data supported the permanently installed tensiometer data. Additionally, information concerning the amount of water stored in the crop root zone was obtained. The data indicated that the amount of water in the profile had a major effect on the amount of water stored. With a dry profile, it was possible to account for 76% of the water applied. With a profile with some stored water, when water was applied at a slow application rates to a soil, it was possible to account for only 22% of the water applied.

In 1978 the amount of applied water stored ranged from 33 to 53% at Lubbock and 22 to 39% at Halfway. One factor causing this difference may have been that the bottoms of the furrows at Lubbock were packed with tractor wheels following a shower, while the furrows at Halfway were packed while dry. The efficiencies obtained are rather discouraging when one considers that 80% of the water applied in the Texas High Plains is applied with furrow irrigation systems. Deep percolation losses through unsaturated flow are indicated.

The use of rate of advance data to estimate infiltration is an inexpensive approach that can be used by anyone in irrigation research with existing equipment. Such an approach does not have the problems with equipment and point source determinations encountered with ring infiltrometers.

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HALFWAY LOCATION				LUBBOCK LOCATION			
60 cm Depth Tensiometer Reading (cbars)	Soil Water Content (Volume Fraction	120 cm Depth Tensiometer Reading (cbars)	Soil Water Content (Volume Fraction)	60 cm Depth Tensiometer Reading (cbars)	Soil Water Content (Volume Fraction)	120 cm Depth Tensiometer Reading (cbars)	Soil Water Content (Volume Fraction)
14	0.337	16	0.320	13	0.306	14	0.341
14	0.345	20	0.333	16	0.289	19	0.312
16	0.316	16	0.331	17	0.309	17	0.330
16	0.340	18	0.324	18	0.307	20	0.338
14	0.345	14	0.331	17	0.325	19	0.328
14	0.327	17	0.325	21	0.265	18	0.332
14	0.324	14	0.316	16	0.309	17	0.360
14	0.302	10	0.303	17	0.292	15	0.332
12	0.319	10	0.310	18	0.288	18	0.310
11	0.333	15	0.326	14	0.314	18	0.337
13.9*	0.329	15.0	0.322	16.7	0.300	17.5	0.332
1.5**	0.014	3.2	0.010	2.21	0.017	1.8	0.014

* Mean

** Standard Deviation

Appendix Table 1. Tensiometer and soil water content data following drainage after the addition of excess irrigation water at the Texas Agricultural Experiment Station, Lubbock and Halfway, Texas, 1978.

Appendix Table 2. Permanent (PT) and rapid response (RRT) tensiometer readings and time required to install (I) and obtain stable (S) readings from the rapid response tensiometers before irrigation at the Texas Agricultural Experiment Station during 1977.

	30 cm depth				120 cm depth			
Furrow Stream Size (lps)	Tensiometer Readings (cbars) PT	RRT	Time Required (min) I	S	Tensiometer Readings (cbars) PT	RRT	Time Required (min) I	S
3.0	16	19	2.0	-	34	34	4.0	-
	19	19	1.5	-	41	56	6.0	-
	14	16	1.5	-	37	40	3.5	-
	18	22	2.0	1	26	34	3.0	1.8
	15	18	2.0	2	49	46	5.5	2.0
	18	15	1.0	4	30	34	4.5	13.0
1.5	15	11	1.0	1	33	36	5.0	1.5
	11	12	1.0	3	34	31	3.0	7.0
	16	20	1.5	5	40	54	5.5	13.0
	18	20	1.7	6	33	36	3.7	4.0
	15	18	1.5	2	21	40	4.0	9.0
	16	22	2.0	3	46	37	4.5	5.0
0.9	10	19	2.0	2	29	30	3.5	14.0
	19	18	2.0	1	40	37	5.0	7.0
	17	22	2.5	1	41	43	5.5	7.0
	22	17	1.0	1	39	34	3.0	2.5
	16	19	2.0	4	43	41	4.7	6.0
	23	15	1.0	4	35	49	4.0	18.0

Appendix Table 3. Permanent (PT) and rapid response (RRT) tensiometer readings and time required to install (I) and obtain stable (S) readings from the rapid response tensiometers after irrigation at the Texas Agricultural Experiment Station, Lubbock, Texas, during 1977.

Furrow Stream Size (lps)	30 cm depth Tensiometer Readings (cbars) PT	RRT	Time Required (min) I	S	120 cm depth Tensiometer Reading (cbars) PT	RRT	Time Required (min) I	S
3.0	7	8	1.2	1.0	28	17	1.0	3.0
	15	28	1.2	1.5	66	60	1.6	6.0
	8	17	0.7	1.5	25	21	1.0	4.0
	11	11	0.7	1.0	23	19	1.4	3.5
	9	26	1.0	2.0	23	19	1.7	3.0
	9	12	-	-	14	11	-	-
1.5	10	14	-	-	19	17	-	-
	0	10	-	-	31	30	-	-
	9	11	-	-	17	21	-	-
	9	9	-	-	20	17	-	-
	10	8	-	-	26	28	-	-
	11	15	-	-	19	12	-	-
0.9	10	7	-	-	22	15	-	-
	4	8	-	-	18	15	-	-
	10	10	-	-	17	19	-	-
	7	13	-	-	15	13	-	-
	6	9	-	-	18	13	-	-
	9	19	-	-	18	22	-	-

Appendix Table 4. Permanent (PT) and rapid response (RRT) tensiometer readings and time required for rapid response tensiometer readings to stabilize (S) at the Texas Agricultural Experiment Station, Lubbock, Texas, during 1978.

Furrow Stream Size (lps)	30 cm depth Tensiometer Readings (cbars) PT	RRT	Time Required (min)	120 cm depth Tensiometer Readings (cbars) PT	RRT	Time Required (min)
3.5	23	23	10	57	22	37
1.8	25	27	12	60	58	11
	21	22	10	41	40	13
	19	20	14	60	60	12
	21	6	23	58	10	25
	23	6	27	43	12	26
0.8	Readings not made					

Appendix Table 5. Permanent (PT) and rapid response (RRT) tensiometer readings and time required for the rapid response tensiometer readings to stabilize (S) at the Texas Agricultural Experiment Station, Halfway, Texas, during 1978.

Furrow Stream Size (lps)	30 cm depth Tensiometer Readings (Cbars) PT	RRT	Time Required (Min)	120 cm depth Tensiometer Readings (Cbars) PT	RRT	Time Required (Min)
4.7	16	11	10	20	27	12
	15	20	6	15	14	10
	16	7	20	19	10	18
	18	3	33	21	8	26
	19	6	25	16	7	23
	17	10	30	20	11	20
2.5	17	12	12	19	22	12
	16	11	11	17	12	13
	17	6	25	20	9	22
	18	5	27	17	3	21
1.3	18	12	10	21	24	8
	17	16	12	16	17	12
	19	0	22	20	2	22
	20	6	35	17	8	23

Replication No.	Depth (cm)	Distance (m) 68		136		204		Distance (m) 68		136		204		Distance (m) 68		136		204	
		6/2[1/]	6/6	6/2[2/]	6/6	6/2	6/6	6/2	6/6	6/2	6/6	6/2	6/6	6/2	6/6	6/2	6/6	6/2	6/6
Lubbock 1977				0.9 lps						1.5 lps						3.0 lps			
1	60	10	10	19	4	17	10	15	10	11	10	16	9	16	7	19	15	14	8
	120	29	22	40	18	41	17	33	19	34	31	40	17	34	28	41	26	37	25
2	60	22	7	16	6	23	9	18	9	15	10	16	11	26	23	49	23	30	14
	120	39	15	43	18	35	18	33	20	21	26	46	19	26	23	49	23	30	14
Lubbock 1978				0.8 lps						1.8 lps						3.5 lps			
			5/16[3/]		5/16		5/16		5/16		5/16		5/16		5/16		5/16		5/16
1	60		16		17		18		73		36		22		22		50		26
	120		32		28		53		58		57		55		59		59		61
2	60		17		18		14		24		21		16		30		36		17
	120		22		34		34		55		43		56		60		52		56
Halfway 1978				1.3 lps						2.5 lps						4.7 lps			
			72		144		216		72		144		216		72		144		216
			4/21[4/]		4/21		4/21		4/21		4/21		4/21		4/21		4/21		4/21
1	60		16		14		13		--		14		22		14		16		20
	120		18		14		22		--		17		64		14		35		52
2	60		14		11		24		16		14		54		14		12		13
	120		16		15		56		16		10		47		20		10		52

1/ Before irrigation on 6/2 and 6/3
2/ Before irrigation on 6/2 and 6/3
3/ Before irrigation on 5/10 and 5/11
4/ Before irrigation on 4/12 and 4/13

Appendix Table 6. Permanent tensiometer data (cbars) from the rapid response tensiometer study at the Texas Agricultural Experiment Station, Lubbock and Halfway, Texas, during 1977 and 1978.

	Replication I						Replication II					
	68*		136*		204*		68*		136*		204*	
Depth (cm)	6/2	6/6	6/2	6/6	6/2	6/6	6/2	6/6	6/2	6/6	6/2	6/6
			3.0+						3.0+			
30	0.258	0.281	0.186	0.235	0.250	0.275	0.255	0.265	0.228	0.263	0.239	0.264
60	0.320	0.338	0.304	0.318	0.313	0.320	0.349	0.351	0.328	0.344	0.336	0.345
90	0.303	0.318	0.310	0.304	0.348	0.362	0.322	0.335	0.265	0.312	0.321	0.337
120	0.286	0.296	0.326	0.312	0.326	0.352	0.328	0.343	0.251	0.301	0.324	0.341
			1.5+						1.5+			
30	0.230	0.299	0.243	0.257	0.250	0.276	0.215	0.253	0.224	0.253	0.242	0.263
60	0.307	0.329	0.288	0.320	0.341	0.344	0.307	0.341	0.335	0.347	0.326	0.329
90	0.294	0.322	0.228	0.325	0.303	0.328	0.288	0.327	0.282	0.308	0.302	0.324
120	0.285	0.312	0.252	0.328	0.304	0.330	0.267	0.338	0.248	0.299	0.307	0.328
			0.9+						0.9+			
30	0.209	0.251	0.265	0.253	0.276	0.279	0.261	0.247	0.237	0.246	0.273	0.277
60	0.334	0.335	0.325	0.335	0.331	0.333	0.338	0.338	0.323	0.322	0.332	0.332
90	0.317	0.326	0.314	0.327	0.319	0.339	0.315	0.331	0.277	0.329	0.297	0.325
120	0.296	0.321	0.332	0.332	0.313	0.360	0.311	0.332	0.241	0.310	0.299	0.337

* Distance from water source (m)

+ Flow rate/furrow (lps)

Appendix Table 7. Soil water content data (volume fraction) from the rapid tensiometer study at the Texas Agricultural Experiment Station, Lubbock, Texas, during 1977.

Appendix Table 8. Soil water content data (volume fraction) from the 3.5 lps treatment of the rapid response tensiometer study at the Texas Agricultural Experiment Station, Lubbock, Texas, during 1978.

	Distance from water source (meters)									
	0		68		136		204		272	
Depth (cm)	5/10	5/16	5/10	5/16	5/10	5/16	5/10	5/16	5/10	5/16
30	0.160	0.156	0.198	0.209	0.154	0.244	0.248	0.235	0.258	0.252
60	0.241	0.305	0.260	0.306	0.270	0.293	0.298	0.299	0.274	0.282
90	0.241	0.314	0.220	0.226	0.268	0.263	0.246	0.246	0.239	0.233
120	0.218	0.265	0.205	0.200	0.258	0.242	0.247	0.243	0.240	0.228
150	0.223	0.223	0.176	0.172	0.259	0.251	0.229	0.228	0.256	0.249
180	0.227	0.222	0.200	0.194	0.292	0.280	0.257	0.226	0.268	0.254
210	0.237	0.234	0.204	0.200	0.302	0.288	0.272	0.247	0.265	0.257

	Distance from water source (meters)									
	0		68		136		204		272	
Depth (cm)	5/10	5/16	5/10	5/16	5/10	5/16	5/10	5/16	5/10	5/16
30	0.127	0.261	0.154	0.217	0.239	0.252	0.183	0.245	0.244	0.237
60	0.249	0.321	0.242	0.277	0.251	0.275	0.312	0.325	0.281	0.302
90	0.228	0.308	0.248	0.252	0.267	0.268	0.234	0.239	0.208	0.208
120	0.196	0.240	0.233	0.242	0.251	0.251	0.240	0.250	0.213	0.214
150	0.225	0.228	0.244	0.246	0.245	0.252	0.204	0.206	0.225	0.232
180	0.248	0.255	0.205	0.215	0.275	0.280	0.244	0.239	0.226	0.233
210	0.269	0.274	0.220	0.233	0.299	0.302	0.277	0.286	0.232	0.240

Appendix Table 9. Soil water content data (volume fraction) from the 1.8 lps treatment of the rapid response tensiometer study at the Texas Agricultural Experiment Station, Lubbock, Texas, during 1978.

	Distance from water source (meters)									
	0		68		136		204		272	
Depth (cm)	5/10	5/16	5/10	5/16	5/10	5/16	5/10	5/16	5/10	5/16
30	0.108	0.226	0.129	0.160	0.210	0.203	0.178	0.187	0.213	0.179
60	0.235	0.313	0.272	0.313	0.304	0.319	0.259	0.298	0.275	0.292
90	0.226	0.312	0.239	0.255	0.265	0.260	0.231	0.230	0.228	0.226
120	0.212	0.286	0.201	0.201	0.249	0.247	0.236	0.241	0.236	0.230
150	0.209	0.275	0.182	0.181	0.254	0.247	0.222	0.241	0.226	0.224
180	0.220	0.254	0.190	0.194	0.279	0.275	0.252	0.224	0.233	0.235
210	0.233	0.244	0.220	0.220	0.298	0.291	0.270	0.271	0.241	0.235

	Distance from water source (meters)									
	0		68		136		204		272	
Depth (cm)	5/10	5/16	5/10	5/16	5/10	5/16	5/10	5/16	5/10	5/16
30	0.180	0.252	0.144	0.194	0.169	0.185	0.242	0.258	0.229	0.259
60	0.270	0.329	0.244	0.287	0.239	0.265	0.293	0.309	0.260	0.304
90	0.241	0.264	0.232	0.249	0.269	0.261	0.267	0.266	0.233	0.230
120	0.237	0.242	0.245	0.245	0.250	0.245	0.258	0.260	0.256	0.254
150	0.218	0.226	0.232	0.228	0.297	0.294	0.287	0.289	0.244	0.241
180	0.238	0.247	0.220	0.215	0.315	0.305	0.285	0.287	0.252	0.256
210	0.248	0.253	0.206	0.208	0.304	0.298	0.282	0.279	0.255	0.260

Appendix Table 10. Soil water content data (volume fraction) from the 0.8 lps treatment of the rapid response tensiometer study at the Texas Agricultural Experiment Station, Lubbock, Texas, during 1978.

	Distance from water source (meters)									
	0		68		136		204		272	
Depth (cm)	5/10	5/16	5/10	5/16	5/10	5/16	5/10	5/16	5/10	5/16
30	0.163	0.234	0.175	0.237	0.193	0.216	0.214	0.246	0.211	0.191
60	0.286	0.324	0.242	0.289	0.266	0.309	0.270	0.307	0.242	0.274
90	0.252	0.272	0.254	0.319	0.267	0.333	0.250	0.316	0.232	0.228
120	0.224	0.224	0.242	0.296	0.249	0.265	0.243	0.249	0.216	0.210
150	0.233	0.231	0.224	0.235	0.253	0.254	0.234	0.228	0.215	0.212
180	0.258	0.265	0.205	0.210	0.273	0.272	0.201	0.206	0.233	0.231
210	0.261	0.265	0.224	0.227	0.284	0.281	0.252	0.252	0.238	0.232

	Distance from water source (meters)									
	0		68		136		204		272	
Depth (cm)	5/10	5/16	5/10	5/16	5/10	5/16	5/10	5/16	5/10	5/16
30	0.192	0.228	0.199	0.236	0.167	0.209	0.208	0.271	0.200	0.135
60	0.288	0.339	0.252	0.292	0.246	0.288	0.249	0.314	0.258	0.299
90	0.252	0.333	0.216	0.310	0.230	0.307	0.266	0.328	0.253	0.285
120	0.258	0.319	0.258	0.327	0.222	0.276	0.265	0.278	0.251	0.252
150	0.254	0.285	0.248	0.302	0.257	0.246	0.279	0.287	0.259	0.265
180	0.247	0.283	0.229	0.237	0.219	0.217	0.279	0.282	0.249	0.253
210	0.272	0.283	0.245	0.252	0.209	0.210	0.274	0.276	0.251	0.258

Appendix Table 11. Soil water content data (volume fraction) from the 4.7 lps treatment of the rapid response tensiometer study at the Texas Agricultural Experiment Station, Halfway, Texas, during 1978.

	Distance from water source (meters)									
	0		72		144		216		288	
Depth (cm)	4/10	4/21	4/10	4/21	4/10	4/21	4/10	4/21	4/10	4/21
30	0.156	0.246	0.263	0.276	0.181	0.261	0.177	0.244	0.134	0.229
60	0.313	0.318	0.330	0.345	0.304	0.331	0.309	0.314	0.268	0.318
90	0.348	0.344	0.323	0.334	0.371	0.306	0.286	0.289	0.249	0.296
120	0.321	0.325	0.313	0.331	0.274	0.278	0.287	0.262	0.271	0.280
150	0.304	0.307	0.288	0.315	0.279	0.264	0.247	0.237	0.261	0.253

	Distance from water source (meters)									
	0		72		144		216		288	
Depth (cm)	4/10	4/21	4/10	4/21	4/10	4/21	4/10	4/21	4/10	4/21
30	0.145	0.256	0.220	0.279	0.240	0.267	0.190	0.250	0.202	0.266
60	0.296	0.327	0.320	0.345	0.293	0.319	0.303	0.333	0.309	0.300
90	0.258	0.332	0.283	0.317	0.260	0.317	0.318	0.310	0.299	0.294
120	0.279	0.325	0.289	0.333	0.	0.	0.252	0.294	0.299	0.299
150	0.278	0.309	0.286	0.309	0.	0.	0.258	0.262	0.286	0.293

Appendix Table 12. Soil water content data (volume fraction) from the 2.5 lps treatment of the rapid response tensiometer study at the Texas Agricultural Experiment Station, Halfway, Texas, during 1978.

	Distance from water source (meters)									
	0		72		144		216		288	
Depth (cm)	4/10	4/21	4/10	4/21	4/10	4/21	4/10	4/21	4/10	4/21
30	0.282	0.287	0.217	0.269	0.209	0.264	0.137	0.248	0.171	0.242
60	0.304	0.312	0.316	0.346	0.312	0.328	0.304	0.324	0.311	0.326
90	0.337	0.340	0.275	0.341	0.246	0.312	0.241	0.284	0.261	0.287
120	0.315	0.323	0.277	0.325	0.262	0.	0.239	0.229	0.244	0.236
150	0.301	0.310	0.299	0.315	0.267	0.	0.230	0.224	0.256	0.249

	Distance from water source (meters)									
	0		72		144		216		288	
Depth (cm)	4/10	4/21	4/10	4/21	4/10	4/21	4/10	4/21	4/10	4/21
30	0.181	0.267	0.166	0.290	0.140	0.229	0.158	0.174	0.208	0.233
60	0.281	0.301	0.285	0.316	0.286	0.303	0.292	0.253	0.303	0.272
90	0.264	0.312	0.256	0.330	0.234	0.302	0.254	0.287	0.264	0.278
120	0.263	0.266	0.274	0.331	0.223	0.303	0.260	0.245	0.261	0.266
150	0.266	0.262	0.286	0.328	0.304	0.328	0.275	0.260	0.292	0.297

Appendix Table 13. Soil water content data (volume fraction) from the 1.3 lps treatment of the rapid response tensiometer study at the Texas Agricultural Experiment Station, Halfway, Texas, during 1978.

	Distance from water source (meters)									
	0		72		144		216		288	
Depth (cm)	4/10	4/21	4/10	4/21	4/10	4/21	4/10	4/21	4/10	4/21
30	0.350	0.264	0.214	0.290	0.135	0.243	0.111	0.226	0.114	0.252
60	0.327	0.356	0.323	0.340	0.303	0.324	0.315	0.329	0.268	0.311
90	0.296	0.329	0.284	0.339	0.274	0.329	0.262	0.324	0.258	0.272
120	0.301	0.310	0.276	0.324	0.282	0.316	0.254	0.304	0.270	0.266
150	0.302	0.319	0.275	0.324	0.271	0.293	0.245	0.291	0.250	0.244

	Distance from water source (meters)									
	0		72		144		216		288	
Depth (cm)	4/10	4/21	4/10	4/21	4/10	4/21	4/10	4/21	4/10	4/21
30	0.205	0.267	0.179	0.269	0.232	0.269	0.163	0.272	0.242	0.211
60	0.316	0.336	0.253	0.337	0.342	0.338	0.290	0.315	0.309	0.311
90	0.279	0.344	0.240	0.322	0.293	0.317	0.240	0.234	0.329	0.328
120	0.275	0.329	0.260	0.319	0.286	0.310	0.231	0.231	0.320	0.328
150	0.290	0.328	0.260	0.308	0.271	0.304	0.241	0.237	0.312	0.321

Row No.	Application Rate 1.3 lps: Time (min)*	Depth of Water (mm), Distance from water source (m): 0	68	136	204	Application Rate 2.5 lps: Time (min)*	Depth of Water (mm), Distance from water source (m): 0	68	136	204	Application Rate 4.7 lps: Time (min)*	Depth of Water (mm), Distance from water source (m): 0	68	136	204
3	20	61	-	-	-	16	46	-	-	-	23	48	-	-	-
	123	58	33	-	-	78	84	48	-	-	42	99	46	-	-
	553	51	30	48	-	225	46	61	25	-	65	63	107	61	-
	782	51	25	46	30	340	46	58	58	41	95	79	71	63	36
4	20	56	-	-	-	16	36	-	-	-	23	48	-	-	-
	123	79	33	-	-	105	114	43	-	-	39	109	48	-	-
	553	51	61	38	-	220	84	74	53	-	59	91	119	46	-
	812	15	20	51	28	330	46	48	56	41	86	84	51	61	46
3	20	41	-	-	-	15	51	-	-	-	20	46	-	-	-
	182	79	46	-	-	48	71	56	-	-	35	114	48	-	-
	462	48	48	33	-	170	56	76	-	-	78	104	79	51	-
	692	-	-	-	-	222	23	61	66	46	110	53	79	94	30
4	20	61	-	-	-	7	48	-	-	-	20	66	-	-	-
	182	74	46	-	-	105	71	66	-	-	35	99	51	-	-
	467	43	51	28	-	170	63	76	43	-	87	99	76	30	-
	692	-	-	-	-	222	36	63	56	56	115	51	79	94	41

*Time following initiation of irrigation (min)

Appendix Table 14. Depth of water (mm) in center of water furrow in selected rows of different application rates at different distances (m) downstream for the water source in the rapid response tensiometer study at the Texas Agricultural Experiment Station, Halfway, Texas, during 1978.

Row No.	Application Rate 3.5 lps					Application Rate 1.8 lps					Application Rate 0.8 lps				
	Time (min)*	Depth of Water (mm) Distance from water source (m)				Time (min)*	Depth of Water (mm) Distance from water source (m)				Time (min)*	Depth of Water (mm) Distance from water source (m)			
		0	68	136	204		0	68	136	204		0	68	136	204
3	45	25	-	-	-	13	38	-	-	-	10	53	-	-	-
	225	15	18	-	-	48	33	43	-	-	25	53	56	-	-
	390	38	25	38	-	88	33	43	35	-	38	51	53	-	-
	535	35	30	43	48	153	30	43	33	51	80	58	53	-	-
4	45	41	-	-	-	13	35	-	-	-	10	53	-	-	-
	225	23	13	-	-	48	33	41	-	-	25	53	71	-	-
	380	48	25	43	-	88	38	48	38	-	41	51	71	48	-
	535	46	25	48	53	153	38	48	41	51	70	53	61	38	43
3	45	33	-	-	-	13	30	-	-	-	12	38	-	-	-
	230	18	18	-	-	43	30	28	-	-	21	43	51	-	-
	470	38	23	33	-	113	33	43	33	-	37	46	51	51	-
	620	33	25	35	43	178	33	51	46	46	57	41	46	43	48
4	45	38	-	-	-	13	33	-	-	-	12	43	-	-	-
	230	23	13	-	-	43	30	38	-	-	23	46	48	-	-
	475	35	28	38	-	113	38	53	38	-	39	53	53	61	-
	622	38	28	35	48	176	38	56	51	85	57	35	51	66	51

*Time following initiation of irrigation (min)

Appendix Table 15. Depth of water (mm) in center of water furrow in selected rows of different application rates at different distances (m) downstream from the water source in the rapid response tensiometer study at the Texas Agricultural Experiment Station, Lubbock, Texas, during 1978.

	Halfway 1978-Time (Min)							Lubbock-Time (Min)							
	Row Number									Row Number					
Distance (m)	1	2	3	4	5	6	Distance (m)	1977	1978	1	2	3	4	5	6
A/R* 1.31ℓ								A/R* 0.9ℓ	A/R* 0.8ℓ						
72	20	20	20	20	20	20	68	36		60	45	45	45	45	45
144	272	108	123	123	118	113	136	127		210	285	225	225	234	255
216	-	228	553	553	553	553	204	231		375	430	390	380	375	385
288	-	692	782	812	812	812	271	367		495	535	535	535	550	545
72	20	20	20	20	20	20	68			45	45	45	45	45	45
144	152	157	182	182	25	172	136			245	250	230	230	235	210
216	277	542	462	467	325	467	204			455	460	470	475	380	-
288	-	782	692	-	692	692	271			590	600	620	622	641	-
A/R* 2.5ℓ								A/R* 1.5ℓ	A/R* 1.8ℓ						
72	18	18	16	16	19	20	68	12		13	13	13	13	13	13
144	78	70	78	105	78	85	136	53		43	43	48	48	68	48
216	180	190	225	220	220	230	204	101		73	73	88	88	118	113
288	362	350	340	330	300	320	271	169		-	153	153	168	168	-
72	15	14	15	7	7	15	68			13	13	13	13	13	13
144	70	80	48	105	50	70	136			33	43	43	43	33	38
216	170	250	170	170	230	210	204			63	113	113	113	63	71
288	265	277	222	222	265	258	271			148	178	178	178	148	158
A/R* 4.7ℓ								A/R* 3.0ℓ	A/R* 3.5ℓ						
72	23	23	23	23	23	25	68	5		10	10	10	10	10	10
144	45	40	42	39	42	40	136	23		28	27	25	25	32	32
216	52	60	65	59	75	75	204	46		53	48	38	41	51	53
288	92	85	95	86	100	100	271	82		76	72	80	70	73	76
72	20	20	20	20	20	20	68	6		12	12	12	12	12	12
144	35	38	35	35	35	35	136	28		22	24	21	23	32	35
216	100	78	78	87	100	100	204	37		37	40	37	39	47	62
288	130	113	110	115	113	118	271	75		53	59	57	57	68	79

*A/R-Application Rate

Appendix Table 16. Time required for furrow streams to reach different locations from the water source in the rapid response tensiometer study at the Texas Agricultural Experiment Station at Halfway and Lubbock, during 1977 and 1978.