TR- 107
1980

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Automation of Pivot Sprinkler Irrigation Systems to More Efficiently Utilize Rainfall and Irrigation Water

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RESEARCH PROJECT COMPLETION REPORT

Project Number A-044-TEX

(October 1, 1977 - September 30, 1979)

Agreement Numbers

14-34-0001-8046
14-34-0001-9046

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The work on which this publication is based was supported in part by funds provided by the Office of Water Research and Technology, U.S. Department of the Interior, Washington, D. C., (Project A-044-TEX) as authorized by the Water Research and Development Act of 1978, and the Texas Agricultural Experiment Station.

TECHNICAL REPORT NO. 107
Texas Water Resources Institute
Texas A&M University

August 1980

CONTENTS

TABLES

FIGURES

APPENDIX TABLES

APPENDIX FIGURE

ABSTRACT

A study was conducted to develop automated pivot sprinkler irrigation systems and determine if such systems use less water and energy than manually operated systems. The study was conducted near Earth, Texas, using irrigation systems located on producers farms.

Sensors with transmitters and receivers were constructed and tested so that the irrigation systems can be controlled by wind, soil water tension, and rainfall. The sensors can be used separately or in combination to control the irrigation systems.

For several reasons it was not possible to determine if automated systems use less water and energy than manually operated systems. The major reason was the low capacity of the wells (114 to 204 m^3/hr) supplying the irrigation systems.

To meet crop water requirements and losses due to evaporation and runoff, the well capacity should be at least 284 m^3/hr. Since the wells could not supply adequate water, soil water tension was out of the tensiometer range for the last 60 days of the growing season. Considerable variation in soil water tension and content was noted between irrigation systems and within quadrants of each irrigation system. Systems planted to cotton would probably be easier to automate than those planted in corn because of the lower water requirements of cotton.

The wind and rainfall controls have more promise to aid in increasing water use efficiency than controls activated by soil water sensors. Wind controls could be used during preirrigation when more time is available to apply water and rainfall controls could be an aid to producers with remotely located irrigation systems.

INTRODUCTION

The Texas High Plains is a supplementally irrigated area which receives a variable rainfall of 23-104 centimeters. In some years, adequate rainfall is received for maximum crop production. In most years, however, it is necessary to supplement the rainfall with irrigation water to assure maximum crop production. Consequently, 7-102 centimeters of water from an underground aquifer are applied to some 2.7 million of the 4.9 million hectares of the area's cropland each year through furrow and sprinkler irrigation systems.

The fact that the underground water supply of the area is diminishing has been documented (Hughes and Harmon, 1969) and widely publicized. Water management practices which would increase water use efficiency would extend the life of the underground water supply and decrease the ever-increasing fuel costs.

One aspect of water management is scheduling irrigations to insure the maximum available water in the root zone during the critical stages of growth of a particular crop. Excessive soil water stress caused by the delay or inadequacy of irrigation can irreversibly reduce crop yields, growth and quality (Russell, 1959; Mayaki, 1976).

Numerous scheduling approaches exist. Techniques such as constant time intervals generally ignore the important effects of climatic variations upon crop water use and the amounts of water made available to the plants. The success of variable-time schedules based upon visual observations and experience, which many farmers use, depends to a great degree upon each irrigator's ability to accurately assess the situation in each field. Often, yield-reducing water deficits occur before plant stresses are visually detected.

Other approaches to scheduling can be grouped into those based upon (1) meteorological data, (2) plant indicators, and (3) soil indicators (Haise and Hagan, 1967). The use of these approaches in scheduling requires knowledge of the interrelationships between those factors in terms of plant water use and plant response to soil water conditions. Meteorological approaches to scheduling basically involve determination of daily atmospheric demand utilized in some form of a water budget (Pruitt, 1960). Determination of daily atmospheric demand is accomplished through the use of (1) formulas based upon the physical processes involved in evaporation and transpiration, or (2) measurements with instruments. Many formulas have been developed for use in estimating evaporative demand (Penman, 1948; van Bavel, 1966: Blaney and Criddle, 1962). These approaches vary both in their complexity and in their suitability under varying environmental conditions (Jensen, et al., 1971). Atmometers and evaporation pans are the primary instruments used in meteorological approaches to scheduling based upon instrument measurements. Evaporation pans automatically include rainfall, while atmometers do not. Both can provide good estimates of potential evaporation if properly constructed and located, but do not directly measure actual evapotranspiration (Pruitt, 1960). Some coefficient must be utilized to relate actual ET to potential evaporation. A problem with meteorological approaches, in general, is that they describe potential evaporative demand, which must be altered under moisture-limiting conditions and according to crop vegetative development (Jensen and Haise, 1963).

Several approaches involving plant indicators are used. Specific visual observation of changes in plant color, leaf movement, and wilting have been used, but many crops do not provide such "signals" until stress detrimental to yield or quality may occur (Burman and Painter, 1964; Haise and Hagan, 1967). Indicator plants more susceptible to wilting than the major crop have been used successfully in some cropping situations. Growth of specific plant parts has been shown to be correlated with plant water stress in some crops (Anderson and Kerr, 1943), and this relation has been useful in irrigation timing with some crops. Relative turgidity measurements, leaf temperature, psychrometric and pressure-bomb (Clark and Hiler, 1973) techniques are several of the many plant water status indicators found to have some application in scheduling. Hiler and Clark (1971) have described a Stress-Day Index (SDI) concept which provides a quantitative method for use in determining the stress imposed on a crop during the growing season. This method involves measurements of actual and potential transpiration or leaf water potential to determine crop susceptibility factors. Use of plant indicators in irrigation scheduling is principally limited by the expense and the amount of time involved in monitoring the plants throughout the growing season.

Soil indicators vary in both form and sensitivity. The feel and appearance of the soil may be assessed for use in estimating its moisture content. Measures of soil water content can also be used in scheduling. Gravimetric analysis is very accurate, but is too much trouble for routine use by farmers. Calibrated resistance blocks can be used for estimating soil water potential and soil water content, but the sensitivity of the instruments in the lower soil water levels and slow response time is generally inadequate for precise measurements (Bourget, et al., 1958).

Haise and Hagan (1967) have pointed out that plant response to irrigation is better correlated with soil water potential than with soil water content. The tensiometer is the instrument most commonly used for determining soil water pressure potential because it is relatively inexpensive and can provide information on the energy status of a large portion of the plant available soil water. After much experimentation with different tensiometer placement depths with many crops, Taylor (1965) suggested the use of tensiometers placed at the depth of maximum root activity as most representative of soil water potentials experienced by growing plants. The work of Taylor has been confirmed by other researchers (Robbins and Domingo, 1953; Denmead and Shaw, 1960; Rhoads and Stanley, 1973; Childs, 1977; Wilke and Allen, 1970; and Shipley, et al., 1974).

Another consideration in water management is the irrigation system. Of the 2.7 million irrigated hectares on the Texas High Plains, 2.0 million hectares are furrow irrigated and .7 million hectares sprinkler irrigated (New, 1976). The area historically has been furrow irrigated due to the cheap cost of the systems. However, center pivot sprinkler irrigation systems are increasing due to the low labor requirements, the adaptability of the system to rolling terrain and better application efficiency.

Since the introduction of the system in the 1950's considerable research has been conducted on the systems. Considerable work has been focused on proper nozzle discharges and placement to achieve a uniform distribution of applied water (Heerman and Hein, 1968; Kincaid and Heerman, 1970; Dillion, et al., 1972). Application efficiencies have been found to range from under 60 percent (Anderson and Brown, 1972) to a range of 65 to 80 percent (Keller, 1965) depending on the climate conditions and irrigation frequency and amount.

Numerous measures of sprinkler distribution uniformity have been formulated. Coefficients developed by Christiansen (1942) and Benami and Hore (1964) are widely used in evaluating sprinkler performance. The Soil Conservation Service uses a procedure developed by Heerman and Hein (1968) for evaluating performance characteristics of self-propelled center-pivot sprinkler irrigation systems.

Evaporation losses from center pivot systems on low wind days have been estimated at five to ten percent of the applied water (Anderson and Brown, 1972). Operation of sprinkler systems on windy days can be expected to result in much greater losses. Clark and Finley (1975) reported sprinkler evaporation losses of less than ten percent of applied water with stationary sprinklers operating at windspeeds under 15 km per hour, and an exponential increase up to 30 percent loss as windspeed increased.

No comprehensive analysis of evaporation and drift losses over an entire season with operation of low-pressure center pivot systems has been conducted, so any estimate of seasonal evaporation losses based upon instantaneous measurements of these losses will be subject to significant error.

Losses to runoff can be major under center pivot sprinkler systems. General recommendations for sprinkler design and management specify that application rates should not cause runoff to occur during normal operation of sprinkler systems. Since water intake characteristics depend on a number of parameters such as soil texture, porosity, crop cover, type of clay, land slope, and antecedent soil moisture, it is difficult to make predictions concerning runoff. For a great many soil and cropping conditions runoff can be reduced by increasing the speed of rotation or by decreasing sprinkler discharge (Kincaid, et al., 1969). Another approach to reducing runoff is the incorporation of furrow dikes or crop residues. Aarstad and Miller (1973) compared furrow dikes 0.7 meters in length and incorporating crop residues (11 metric tons/ha) with untreated furrows. The treated plots had only 1 percent runoff compared to the control plots with 20 to 41 percent runoff.

One area of research that has received emphasis is automated irrigation in which soil and plant sensors or time clocks activate irrigation systems to deliver water. Such systems can be developed when adequate supplies of irrigation are always available. Fischback and Wittmus (1967) have developed automated surface irrigation systems using valves developed by Haise and Paine (1972). Davis (1970) has described a system for automated subsurface irrigation. Gustafson (1974) reported that avocadoes watered with an automated drip irrigation system required only one-third to one-half the irrigation water to make equal growth of avocados (Persea americana) watered with a sprinkler system. Arlosoroff (1970) studied several methods of automating solid set irrigation systems in Israel using both evaporation pans and electro-tensiometers to aid in irrigation scheduling. He reported that where the sensitivity of the electro-tensiometer fails in specific soil moisture ranges the irrigation cycle was started by the sensor and continued until a specific quantity was supplied as determined by an automatic metering valve.

Wendt et al. (1973) reported on the effects of an automated subirrigation system on the water requirements of sweet corn (_Zea mays_ L.). He reported that automation of irrigation systems offers the possibility of significantly enhancing irrigation water use efficiency in supplementally irrigated areas.

Most automated or semi-automated irrigation systems have been designed for drip irrigation, furrow irrigation, and solid set sprinkler irrigation systems in either fully irrigated or supplementally irrigated areas. No such systems have been designed for automation of a single center pivot irrigation system. A study was initiated in 1978 with the following objectives:

1. To develop an automated pivot sprinkler irrigation system which will turn on and off according to the water needs of crops and will turn off during periods of high windspeeds.
2. To test the hypothesis that crops grown under automated pivot sprinkler irrigation systems will require less irrigation water than crops grown under manually operated pivot sprinkler irrigation systems.
3. To test the hypothesis that energy requirements of automated pivot sprinkler irrigation systems will require less energy for operation than manually operated pivot sprinkler irrigation systems.

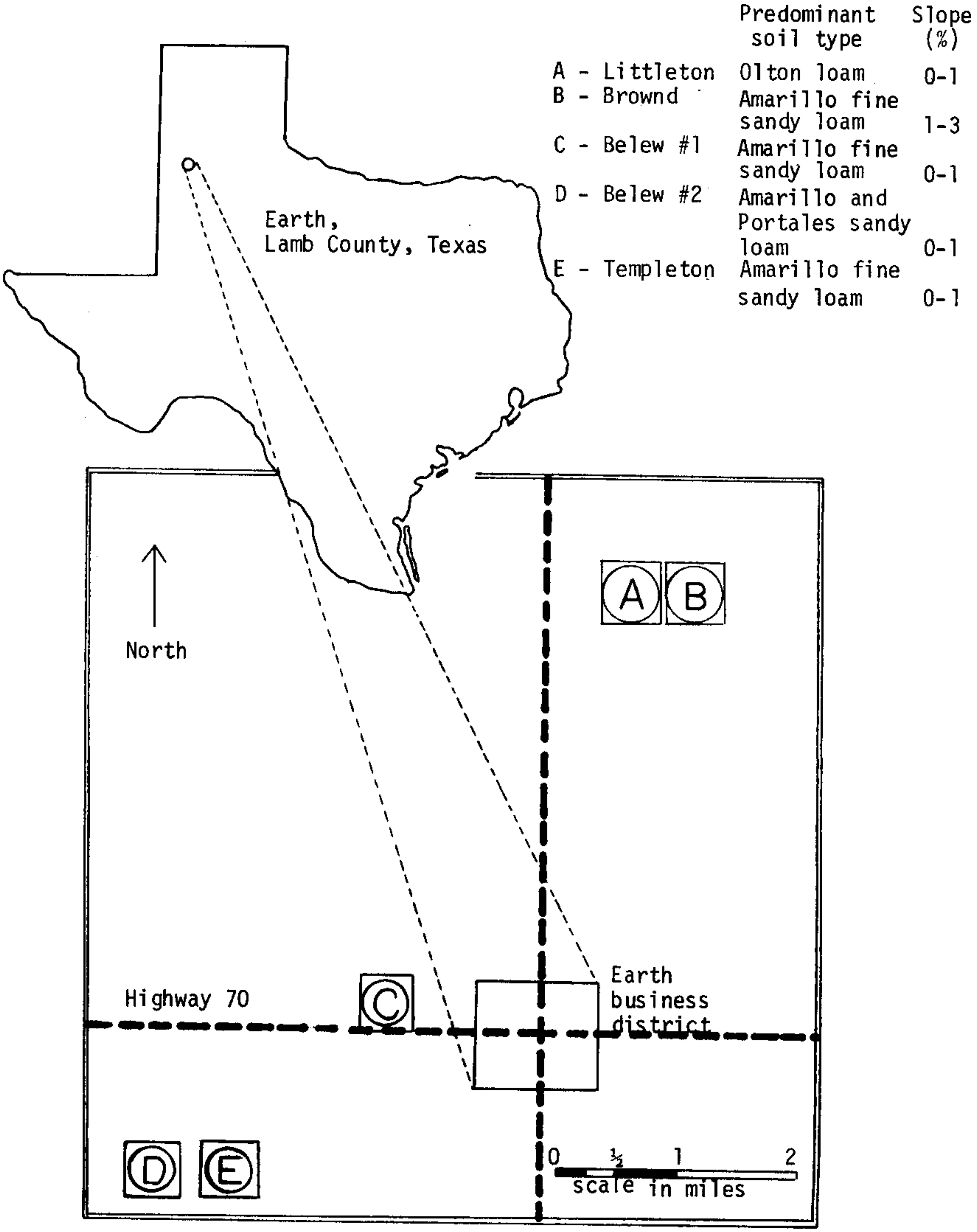
MATERIALS AND METHODS

The center pivot irrigation research was conducted as a cooperative effort between the Texas Water Resources Institute, the Texas Agricultural Experiment Station, and farmers located in the Earth, Texas area, approximately 110 km northwest of Lubbock. Specific sites of each farm, farmers, predominant soil types and slopes are shown on Figure 1. Detailed information on each site can be obtained from the thesis of Hutchmacher (1979) and the Lamb County Soil Survey (1962). Since these are large field sites, there is expected variation in soil type (Olton loam to Portales fine and sandy loam) and topography (0 to 5 percent). Each center pivot irrigated approximately 53 ha and was divided into Northwest (NW), Northeast (NE), Southwest (SW), and Southeast (SE) quadrants for purposes of discussion. The capacities of the wells for the different irrigation systems are presented in Table 1. It can be seen that the wells decreased in capacity during the two years of the study.

Table 1. Measured well flow rate (m^3/hr) for each center pivot irrigation system in the automated irrigation study at Earth, Texas during 1978 and 1979.

Location	1978	1979
Littleton	170	159
Brownd	204 to 114	159
Belew Farms #1	125	114
Belew Farms #2	136	125
Templeton	---	159

Planting and management practices during 1978 and 1979 are shown in Tables 2 and 3. The fertilizer was applied based on tests by the Texas



	Predominant soil type	Slope (%)
A - Littleton	Olton loam	0-1
B - Brownd	Amarillo fine sandy loam	1-3
C - Belew #1	Amarillo fine sandy loam	0-1
D - Belew #2	Amarillo and Portales sandy loam	0-1
E - Templeton	Amarillo fine sandy loam	0-1

Figure 1. Location of center pivot fields A, B, C, D, and E in Earth, Texas (Lamb County) - 1978 and 1979 center pivot irrigation study.

Table 2. Planting and management practices for each center pivot irrigation system in the automated irrigation study at Earth, Texas, in 1978.

	Littleton	Brownd	Belew Farms #1	Belew Farms #2
Corn variety	Funk G4507	Funk G4507	Funk 4611	Funk 4611
Date planted	April 4	April 4-5	May 8-9	May 9-10
Plant population (plants/ha)	52,000	56,000	50,000	48,000
Fertilizer applied (kg/ha)				
Preplant	224 as 18-46-0	224 as 18-46-0	140 N as NH_4	140 N as NH_4
Sidedress	246 as NH_4	246 N as NH_4 30 as Uran	140 as 12-50-0 160 N as NH_4	140 as 12-50-0 160 N as NH_4
Hail damage	moderate (May 30)	moderate (May 30)	slight (June 16)	slight (June 16)
	slight (June 16)	slight (June 16)	moderate (June 26-27)	moderate (June 26-27)
Herbicide (kg/ha)	Atrazine - 1.7	Atrazine - 1.7	Atrazine - 1.7	Atrazine - 1.7
(liters/ha)	Treflan - 1.2			

Table 3. Planting and management practices applied to each center pivot irrigation system in the automated irrigation study at Earth, Texas, in 1979.

	SYSTEM			
	Brownd	Belew Farms #1	Belew Farms #2	Templeton
Cotton variety	GSA-71	CASCOT L-7 (S)** 5-B* (N)	CASCOT B-2 (W) PAYMASTER (E)	QUAPAW
Date planted	May 2	May 9	May 8	May 8
Plant population (1,000's) (plants/ha)	169	114 (S) 156 (N)	190 (W) 124 (E)	143 (N) 85 (S)
Fertilizer applied (kg/ha)				
Preplant	494 as 0-20-0	370 as 11-39-0	370 as 11-39-0	370 as 16-20-0
Sidedress	247 as NH_4	370 as sulfa mag 98 as NH_4	370 as sulfa mag 98 as NH_4	
Hail damage	None	None	None	None
Herbicides				
Preplant (liters/ha)	TREFLAN 2.34	TREFLAN 1.56	TREFLAN 1.56	TREFLAN 1.17
Growing season (Number of applications)	ROUNDUP (4)	ROUNDUP (3)	ROUNDUP (3)	ROUNDUP (2)

* private seed stock

** N, S, W, E - side of field

Agricultural Extension Service Laboratory in Lubbock. Samples were also obtained for texture and moisture retention analyses. These data are reported in a separate publication by Hutchmacher (1979).

Hygrothermographs (Weather Measure Corporation, Sacramento, California) were used to record daily variation in dry bulb temperature and relative humidity. Precipitation was measured with a standard U.S. Weather Bureau rain gauge with a diameter of 20.3 cm (8 inch). Windspeed and direction was recorded with a recording wind system (Model W123, Weather Measure Corporation, Sacramento, California). The anemometer and wind direction vane were mounted at a height of two meters. A solar radiation recorder (Model R-401, Weather Measure Corporation, Sacramento, California) was used to measure total daily incoming solar radiation. Duplicate equipment was located between the Littleton and Brownd Farms and between the Belew #1, Belew #2, and Templeton Farms.

Tensiometers (Model R, Irrometer Company, Riverside, California) were used to measure soil matric potential. Figure 2 shows the number of tensiometers, and the placement depths and locations in each of the quadrants. Gypsum moisture blocks were also installed in each quadrant at depths indicated in Figure 2. Electrical resistance was measured with resistance meters (Models KS-1, KS-2, KS-3, Delmhorst Instrument Company, Boonton, New Jersey) at intervals of 7-10 days. Calibrations of electrical resistance versus soil water tension were obtained for field soil samples through pressure plate studies. Soil water content was measured with a neutron moisture meter and probe (Model 2651, Scaler-Ratemeter and Model 104, Depth Moisture Probe, Troxler Electronic Laboratories, Inc., Research Triangle Park, North Carolina). A recording

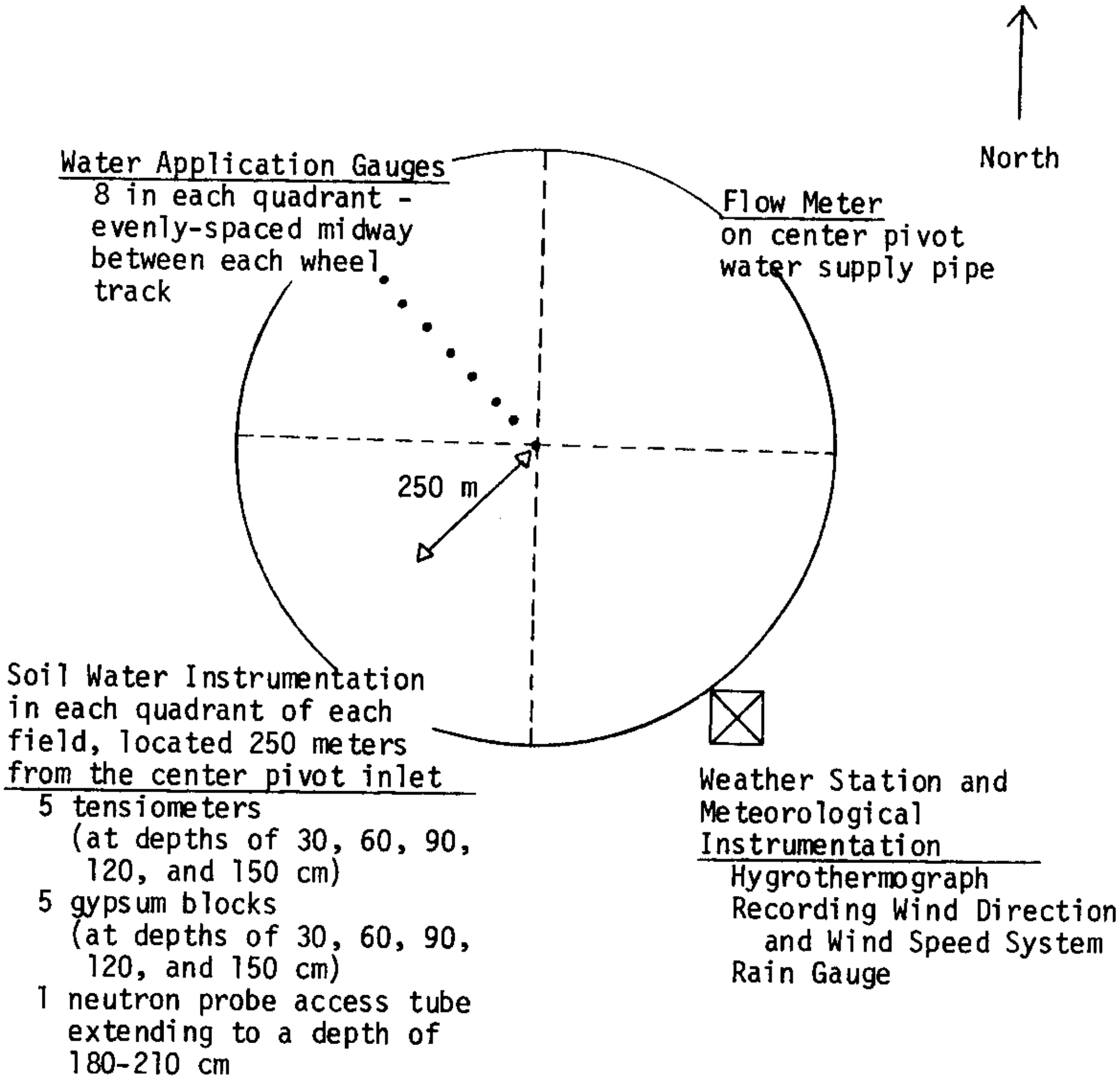


Figure 2. Location and description of field instrumentation installed in center pivot irrigation fields in Earth, Texas (Lamb County) - 1978 center pivot irrigation study.

rain gauge was placed just outside the influence of the sprinklers at each of the field sites for determination of precipitation amounts.

For purposes of evaluation of the potential to improve water management with the automated scheduling system, two center pivot systems were equipped with the automated tensiometer controls and two center pivots were operated manually by the owners of the systems. To determine the total water balance of the root zone in each field, the following water balance presented by Hillel (1971) was used.

$$\Delta W = M + Ir - N - F - (E + T)$$

where:
ΔW = change in root zone water content
M = precipitation
N = runoff
Ir = Irrigation water applied
F = percolation below the root zone
$E + T$ = evaporation plus transpiration, or evapotranspiration (ET)

A flow meter on the delivery pipe of each center pivot system was monitored for determination of applied irrigation water available from each system. To measure the amount of water reaching the crop canopy during 1978, water application cans of 6.6 cm diameter were placed on 2.5 meter tall poles at 32 locations in each field (Figure 2). The amount of water collected was measured once every one to two weeks to estimate the amount and distribution of applied water. A light spray oil was used in the cans to prevent evaporation.

Changes in root zone water content for use in the above equation were measured every 7-20 days with the neutron moisture meter and probe described previously. Evapotranspiration was estimated using a method described by Jensen et al. (1970) which involves use of the equation:

$$ET_p = .001709 \left[\frac{\Delta}{\Delta + 0.27} (R_n) + \frac{0.27}{\Delta + 0.27} (15.36) (1.0 + 0.0062W) (e_s - e_d) \right]$$

where: ET_p = evaporative flux or latent heat (expressed in cm per day)
Δ = slope of the saturation vapor pressure - temperature curve (de/dt)
R_n = daily net radiation (expressed in Langleys per day)
W = total daily wind run (expressed in km per day)
e_s = saturation vapor pressure at mean air temperature (expressed in mb pressure)
e_d = saturation vapor pressure at dew point or vapor pressure of the atmosphere (expressed in mb pressure).

Leaf area was determined on four or five whole plants from each field at every two to three weeks at each time of measurement, using an optical area meter (Lambda Instruments Corporation, Lincoln, Nebraska). Crop coefficients developed for field corn by Jensen and Haise (1963) were used with the ET_p data for development of an approximation of actual plant ET. Modifications in crop coefficients were used to take account of higher ET values following rainfall or water application (Jensen, et al., 1971). No method for separation of runoff and deep percolation was utilized, therefore, all estimates of losses determined by the water balance method and attributed to runoff and deep percolation must represent their combined magnitude.

At harvest, plant populations in all four fields were determined at three locations within each quadrant. Corn ears and cotton were harvested by hand at these locations, in plots 4.1 m long by one row wide. The corn ears were shelled, and grain yields were reported as kg/ha at 15.5 percent moisture content. Cotton was ginned and samples were sent to the Texas Tech Textile Research Laboratory for analyses. The plots sampled for yields were in close proximity to water application cans in order to better be able to relate yields to amount of irrigation water supplied at each site.

During 1978, evaluation of water distribution uniformity was based upon amounts of water collected in the eight application cans within each quadrant of each of the 4 fields studied. Uniformity coefficients developed for analysis of distribution uniformity were evaluated on a quadrant basis. The Christiansen Coefficient of Uniformity (C_u) and the Benami-Hore method (A Coefficient) were evaluated from data representing each measurement interval as well as over the entire season of irrigation for each quadrant.

Evaluations of the performance characteristics of three of the center pivot irrigation systems used during 1979 were based on the method of Heerman and Hein (1968). Uniformity of application, pattern efficiency, and application efficiency were calculated from catch can, flow meter, and timed application data on three center pivots.

RESULTS AND DISCUSSION

Evaluation of Automation

1978 Evaluation -

The automation system is similar in basic design to that tested and reported on by Wendt, et al. (1973). The basic difference is the use of the transmitted signal from the tensiometers rather than direct wiring into the system controls. Analysis of the utility of an automated scheduling system as a device to more efficiently apply water must be based on the premise that adequate flow capacity exists within the system to make the tensiometers operational and to fully irrigate the crop. Assuming the high application efficiencies and good uniformity of application generally reported for center pivot systems, and using reported data on plant water use by corn in the High Plains region, at least two of the center pivot systems included in the study during 1978 appeared to have adequate capacity to fully meet crop water requirements and maintain soil water tension within the tensiometer range.

The automated system was installed on the Littleton Farm. Several problems with the automation system hindered the actual field evaluation of the system. First, some electronic components of the transmitters and receivers were quite sensitive to diurnal changes in ambient temperatures. When the transmitter-receiver switching tensiometer system was tested in the morning, (temperatures - 16 to 22°C) the center pivot sprinkler irrigation system responded as expected. The pivot approached the transmitting tensiometer and stopped if the soil water tension of the switching tensiometer was below the level set by the switch or would continue if the tension was above the level set by the tensiometer switch. Tests conducted in the afternoon (temperatures approximately 30-35°C), were unsuccessful. It was necessary to redesign the transmitter-receiver system so it would not be sensitive to changes in temperature. The system was redesigned and evaluated during 1979. This evaluation will be discussed later.

After the difficulties with the transmitter-receiver system, the tensiometers were wired directly to the center pivot sprinkler irrigation system controls by direct wire connection on the Belew No. 1 system. The switching tensiometers were placed approximately 175 meters from the pivot, requiring a large quantity of wire. This system only operated for a very short period of time because of other problems. Problems were encountered with the well and its capacity had decreased from 204 m^3/hr to 114 m^3/hr so that the system could apply only 6 mm of water per day. Evapotranspiration potential during this period averaged 7 mm per day (Appendix Table 1). For the 60 day period after the irrigation was started, 457 mm were required to satisfy the evaporative demand (neglecting evaporation, runoff and deep percolation losses). The system had the capacity to apply only 305 mm, and only 76 mm of rainfall were received. Therefore, the center pivot irrigation system could not apply adequate water to maintain soil moisture tension within the tensiometer range.

1979 Evaluation -

During 1979, several sensors were evaluated as to their potential in automating center pivot sprinkler irrigation systems. These included windspeed, soil water tension, as well as a redesigned transmitter-receiver system. (See Appendix 1 for instruction manual.)

The major component of the windspeed control system is a wind alarm (Sierra Model 7671 Wind Speed Control, Weather Measure Corporation, P. O. Box 41257, Sacramento, CA, 95841) (Figure 3). The control was modified to include two timing circuits (up to 1 hour delay) for high windspeed and low windspeed conditions. (See Appendix Figure 1). In operation of the anemometer, a relay is closed whenever the windspeed exceeds a preset speed (adjustable threshold). After the delay period the irrigation system is turned off for the duration of the high windspeed period. When the windspeed decreases below a preset level, a delay period is initiated. After the delay period, the pivot is turned back on. The delay period was installed to protect the system against gusty winds. The system was installed and operated with a center pivot without any problems.

The transmitter-receiver pair (Sanwa Model 8020 DP, Sanwa Electric Co., 6-12 Kuwazu-cho, Higashisumiyoshi-ku, Osaka, Japan) (Figure 4) is the most complex of the automation instrumentation (see Appendix for details). Each transmitter-receiver pair contains matched crystals which can only function together. In each unit there are two operational transmitters or receivers. The receivers are designed to be installed near the control panel on the irrigation system and are powered by 120 vac. The transmitter is portable and is powered by a 12 vdc battery. The system is designed to operate continuously at a frequency of 72.16 mhz. When a switch on a sensor (i.e. - switching tensiometer) closes, a binary code is transmitted. The receiver desegregates the binary code from the carrier signal and responds by opening or closing an output switch. To change the mode on the output switch, the receiver must receive the correct binary code from the transmitter. This prevents accidental triggering of the

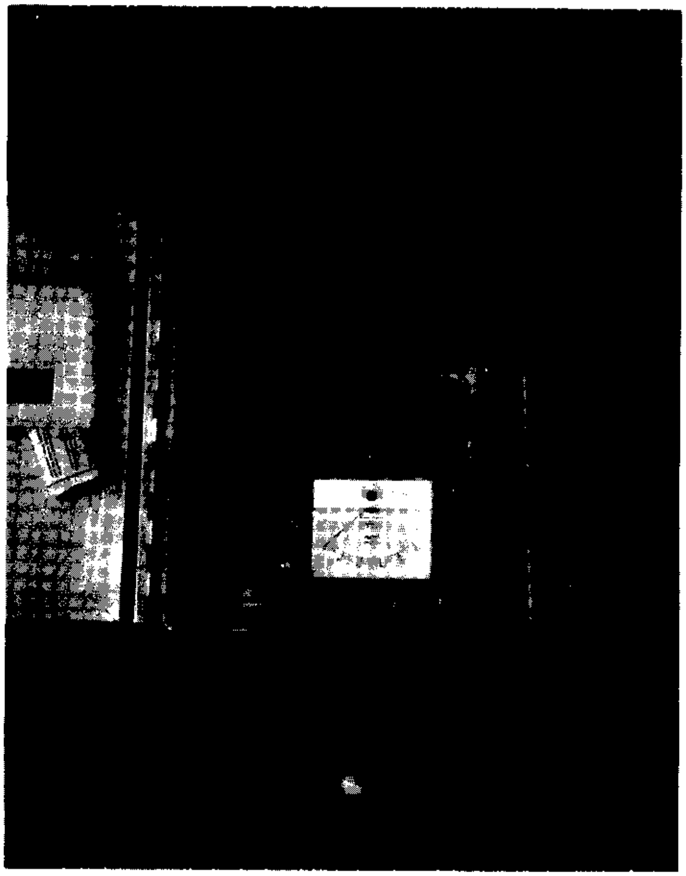


Figure 3. Sierra Model 7671 windspeed control with cup anemometer and two timing circuits designed for the automated irrigation study at Earth, Texas during 1979.

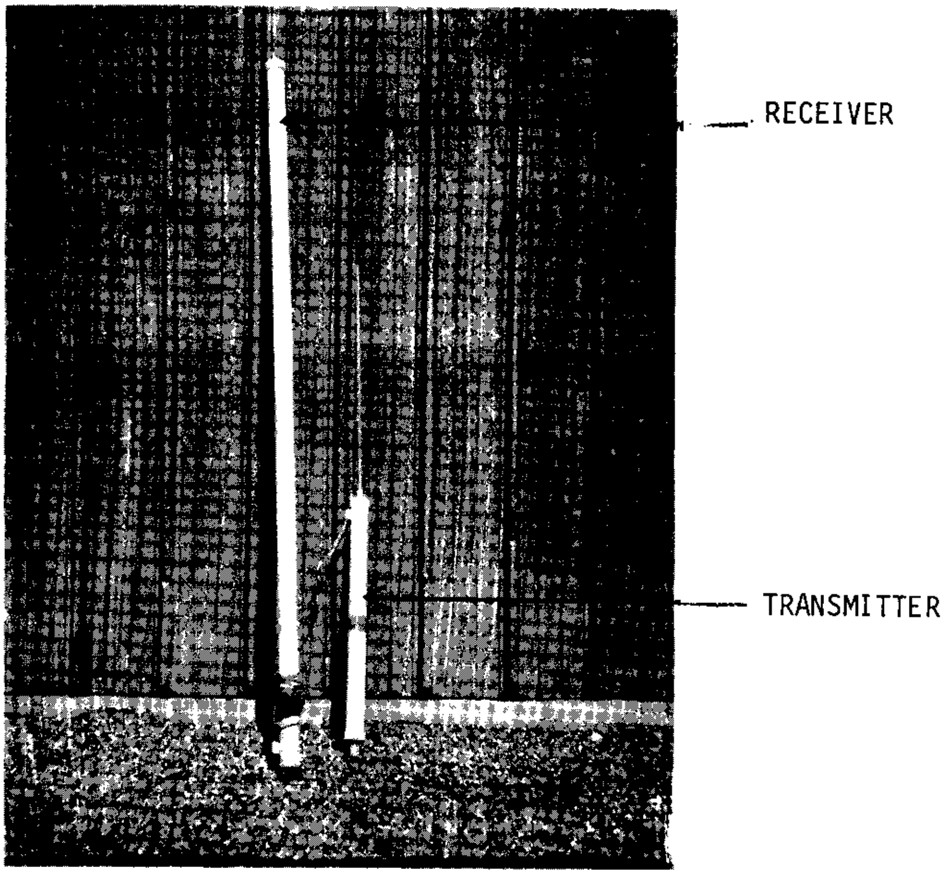


Figure 4. Transmitter-receiver pair containing (2 each) SANWA Model 8020 DP transmitter/receivers designed for the automated irrigation study at Earth, Texas during 1979.

output switch.

The rain sensor (Figure 5) is an adjustable inductance type with a bucket (see Appendix for details) and an adjustable (2 to 24 hour timer). When rainfall is received, a signal is sent to the main control panel on the pivot sprinkler system, either by wires or a transmitter, and a timer is activated. The timer determines the time the irrigation system will remain deactivated and opens a solonoid to drain the rain sensor bucket and keeps it open until the irrigation system is started.

The windspeed controller was installed on the Brownd Farm in early August. The delay periods were adjusted to 12 minutes. High and low windspeed conditions were simulated by adjusting the threshold windspeed. Simulated high windspeeds turned the irrigation system off after the 12 minute delay period. Under simulated low windspeeds, the irrigation system was turned back on. The control device was tested in both manual and automatic modes. The system responded properly in both modes, and throughout the test the windspeed system performed as expected.

A transmitter-receiver-switching tensiometer system was also evaluated at the Brownd Farm in August. The receiver was placed near the pivot and wired into the control circuit. At a distance of 110 m from the center of the pivot, the battery-powered transmitter was installed. Leads from two switching tensiometers were wired in parallel and connected in series to the transmitter. The switch of one tensiometer was opened (an indication of sufficient soil water) while the switch of one tensiometer was closed (an indication of low soil water). The transmitter relayed the signal to the receiver and the irrigation system was activated. After a short period of time, the closed switch was opened, the transmitter sent the

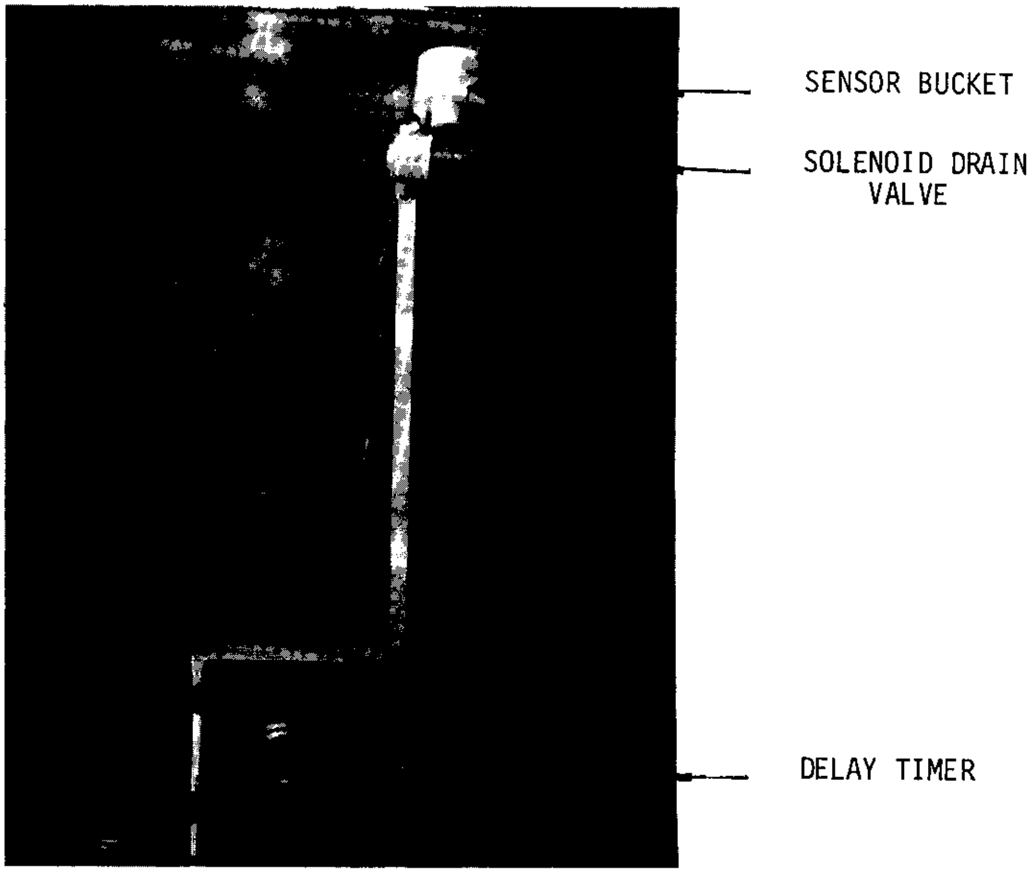


Figure 5. Rain sensor and delay timer designed for the automated irrigation study at Earth, Texas during 1979.

signal to the receiver, and the irrigation system was deactivated. During the preceding time period, the center pivot towers were allowed to move between the transmitter and receiver and no spurious responses were noted. The irrigation system was deactivated and the transmitter was moved so that the towers were between the transmitter and receiver. The tensiometer switch was closed to indicate a need for irrigation. The irrigation system was activated indicating that the interposing towers had no detrimental effect on operation. Attempts to use the transmitter at a distance greater than 110 m were not successful.

An improved transmitter-receiver system was tested at the Texas Agricultural Experiment Station in late August. The receiver was plugged into a 120 vac power source. Leads from the receiver were connected to an ohmmeter to determine when a circuit was closed by the receiver. The receiver was able to receive transmitted signals from a distance of 497 m over a grain sorghum crop 1.1 m tall.

The rainfall sensor was tested at Lubbock during September 1979. Rainfall of 13 mm was simulated over the sensor. The timer was activated and the drain opened after the preset time period. The sensor then reset itself. This procedure was repeated 3 times. A dust storm was next simulated by pouring dry soil into the sensor. No false triggering of the sensor occurred. Rainfall of 13 mm was simulated after the dust storm and the sensor performed as expected. Plant matter (leaves, dry stems) were then placed in the sensor with no false triggering. Simulated snow did not trigger the sensor until it had melted.

Unlike 1978 when the irrigation systems were operating continuously, the irrigation systems in the 1979 study were operational for only 6-8 days during the growing season. The limited irrigation caused mainly by timely rainfalls prevented full evaluation of the automation instrumentation on the irrigation systems.

From the evaluations, it was determined that wind, soil water tension, and rainfall sensors can be wired into the center pivot sprinkler irrigation systems or used with transmitter-receiver systems to activate center pivot sprinkler irrigation systems. The limitation to using such sensors in the Texas High Plains is well capacity and losses due to evaporation, runoff, and deep percolation. These will be discussed in other sections in the report.

Irrigation System Application and Distribution Studies

The application and distribution efficiency of the center pivot sprinkler irrigation systems must be known before it can be determined to what role automation can play in increasing application efficiency. Different approaches were used to estimate the efficiency of some of the systems used in the studies. As previously mentioned, in 1978, catch cans were located in each quadrant to determine the amount of water from the sprinkler that reached the corn canopy. A summary of these data are presented in Table 4.

Table 4. Comparison between the ha-mm of water pumped and depth of water collected in catch cans placed in each field of the automated pivot sprinkler irrigation study in Earth, Texas during 1978.

	Littleton	Brownd	Belew Farms #1	Belew Farms #2
Irrigation (ha-mm)	150	215	85	90
Catch can (mm)	116	171	65	80
Difference (mm)	34	44	20	10
Percent lost to evaporation	22.6%	20.5%*	24.0%	11.3%*

*Remarks - the Brownd and Belew Farms #1 systems have low angles 7° nozzles while the Littleton and Belew Farms #2 systems have high angles 23° nozzles.

It can be seen that the amount lost to evaporation varied from 11.3 to 24.0 percent with a tendency of losses to be greater from systems with high angle nozzles. Applications therefore varied from 88.7 to 76 percent of the total water pumped.

There was considerable variation in distribution of water between quadrants (Figure 6). In general, the areas with less slope received more water. As has been pointed out, distribution between quadrants can be influenced by slope, variation in well output, changes in rotation speed, and wind speed and direction. In any case, distribution between quadrants should be a major consideration in designing automated pivot sprinkler irrigation systems.

Data from the quadrants was used to calculate distribution coefficients which are presented in Table 5.

Table 5. Distribution coefficients for water application in the different quadrants in the automated center pivot irrigation study in Earth, Texas during 1978.

Quadrant	Littleton Farm		Brownd Farm	
	C_u	A	C_u	A
NW	94.5	140.2	88.3	122.2
NE	93.5	140.8	94.7	144.3
SW	96.4	151.9	91.3	124.5
SE	90.5	118.9	93.4	134.9

It can be seen that what appears to be quite a variable application (Figure 6) is given a good uniformity "rating" by the C_u method of Christiansen (1942). A C_u value greater than 85 or 90, in general indicates a very good uniformity of distribution. An explanation for this seemingly contradictory evidence is that the large variation among amounts collected

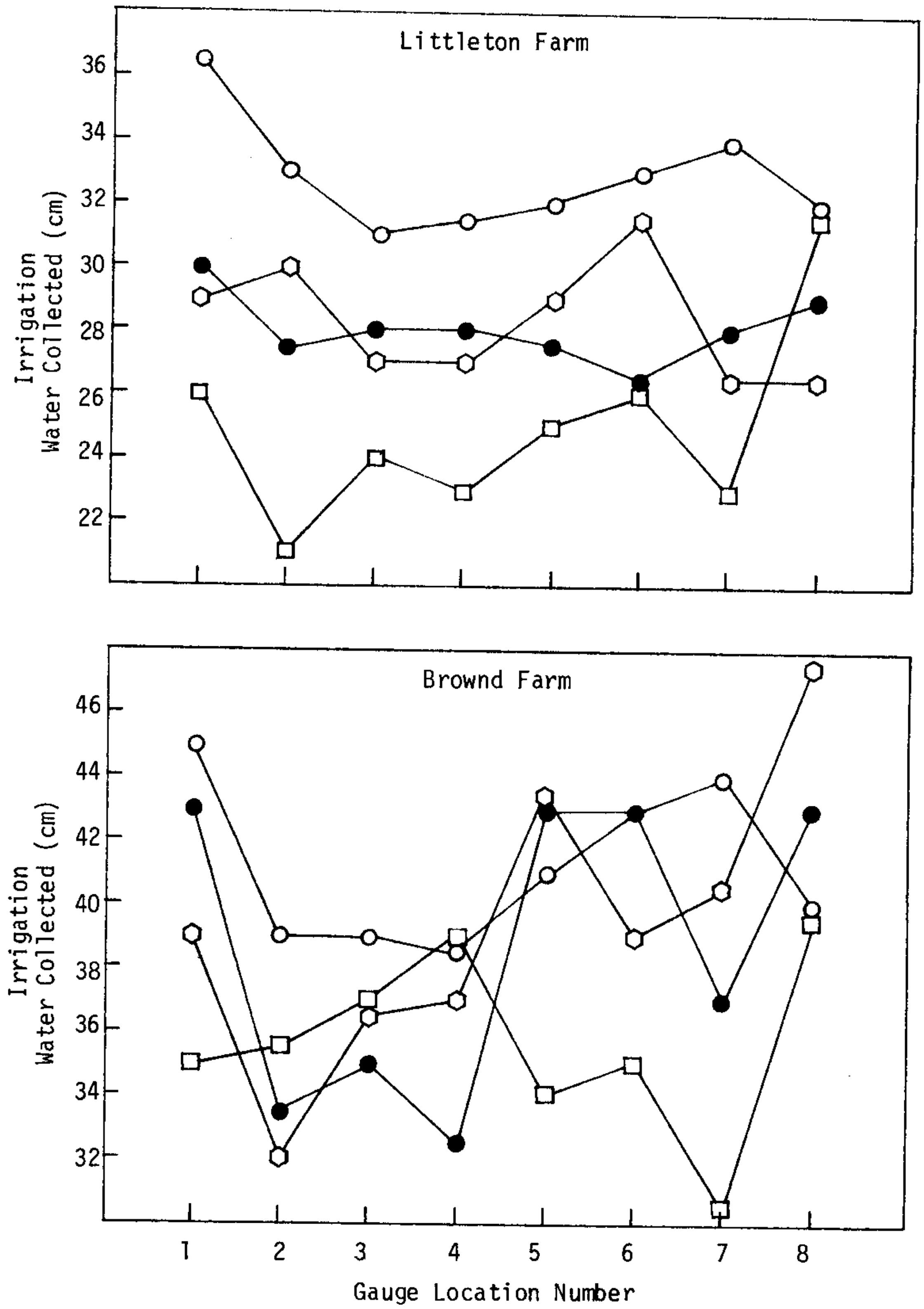


Figure 6. Irrigation water distribution in the different quadrants, as measured with water collection cans in the automated center pivot irrigation study at Earth, Texas during 1978.

within each circle of four cans makes it difficult to establish any significant differences between amounts collected in cans at different distances from the lateral.

The A coefficient values given in Table 5 give indications of poorer uniformity than demonstrated generally by the C_u values. With an A value of 100 indicating an excellent uniformity, the occurrence of great variations above 100 gives a better indication that variation in application amounts collected does occur. The values of A coefficients for the season totals exceeds 100 in every case, demonstrating that one or more of the gauges received amounts of water substantially different from the mean application. It was initially suspected that this might be related to the poor uniformity usually associated with the irrigated area within the influence of the end gun, but the cans within the influence of the end gun did not consistently receive amounts either greater or less than the average for all eight cans in any of the quadrants.

An explanation for the good distribution indicated by the C_u coefficient and the relatively poor distribution uniformity indicated by the A coefficient may lie in the fairly small sample size used in this evaluation.

While the results of this study of uniformity do not conclusively refute past studies which have indicated excellent uniformity of distribution of applied water, these results cannot be interpreted as proof of good uniformity of application with low-pressure center pivot systems. With a small sample size used for characterizing application distribution along a 400 m sprinkler lateral, the C_u coefficient alone does not appear to be a sensitive indicator of the uniformity of distribution.

To obtain better information on system efficiency, a more thorough study was conducted during 1979 using the method of Herman and Hein (1968). These data are presented in Table 6.

Table 6. Irrigation water application and system efficiency evaluation for the automated pivot sprinkler irrigation study at Earth, Texas during 1979.

	Brownd	Belew Farm #1	Belew Farm #2
Gross application (mm)	48	24	34
Average application (mm)	31	17	27
Low 25% average (mm)	22	13	17
Pattern efficiency (%)	70	77	61
Application efficiency (%)	65	70	77
System efficiency (%)	45	54	48

The application efficiencies varied from 65 to 77 percent which compares favorably with the 1978 data. The systems efficiencies varied from 45 to 48 percent which is well below the 70 to 85 percent efficiencies desired for optimum operation.

The distribution patterns for three of the irrigation systems are presented in Figure 7. It can be seen that there is considerable variation in distribution within the system.

During 1978, runoff was noted to be a problem with some irrigation systems. To obtain some estimate of this runoff, Parshall flume measurements of runoff reaching the outer boundary of the field were collected during one time period in the field with a one percent slope. The measurements were taken about two weeks prior to the tasselling stage in the development of the corn crop, and therefore do not represent bare soil conditions in which runoff would be expected to be even higher. For the period measured, the data represents runoff rates from the entire length of the pivot lateral in operation through the path shown in Figure 8. A channel was constructed at the field perimeter to collect runoff flowing to the field boundary from any furrow in this quadrant. The measured flow rate of the pivot system in this field is approximately 170 m^3 per hour, and evaporation losses were estimated to average 15 percent of the total amount applied in this field, leaving perhaps 145 m^3 per hour to reach the canopy. It can be seen in Figure 8 that runoff losses for the period measured averaged approximately 15 percent of the amount of applied water reaching the crop canopy. This data, even though it represents the area of the field most likely to have substantial amounts of runoff, is significant in that it demonstrates that there is a great potential for applied water to be redistributed on the land surface due to runoff from the point of initial application. The previous measurements could not separate runoff from deep percolation losses, but this data shows that runoff can be a major part of this loss.

Another approach was used to estimate runoff plus deep percolation losses using the previously mentioned water balance equation. These data are presented in Table 7.

Table 7. Estimated runoff (mm) for each center pivot irrigation system in the automated irrigation study at Earth, Texas during 1978 and 1979.

Field	Runoff (cm)	Percent of rainfall and applied irrigation water
Littleton (1978)	78	133
Brownd (1978)	85	118
Brownd (1979)	100	186
Belew Farms #1 (1979)	7	13
Belew Farms #2 (1979)	20	103
Templeton (1979)	12	36

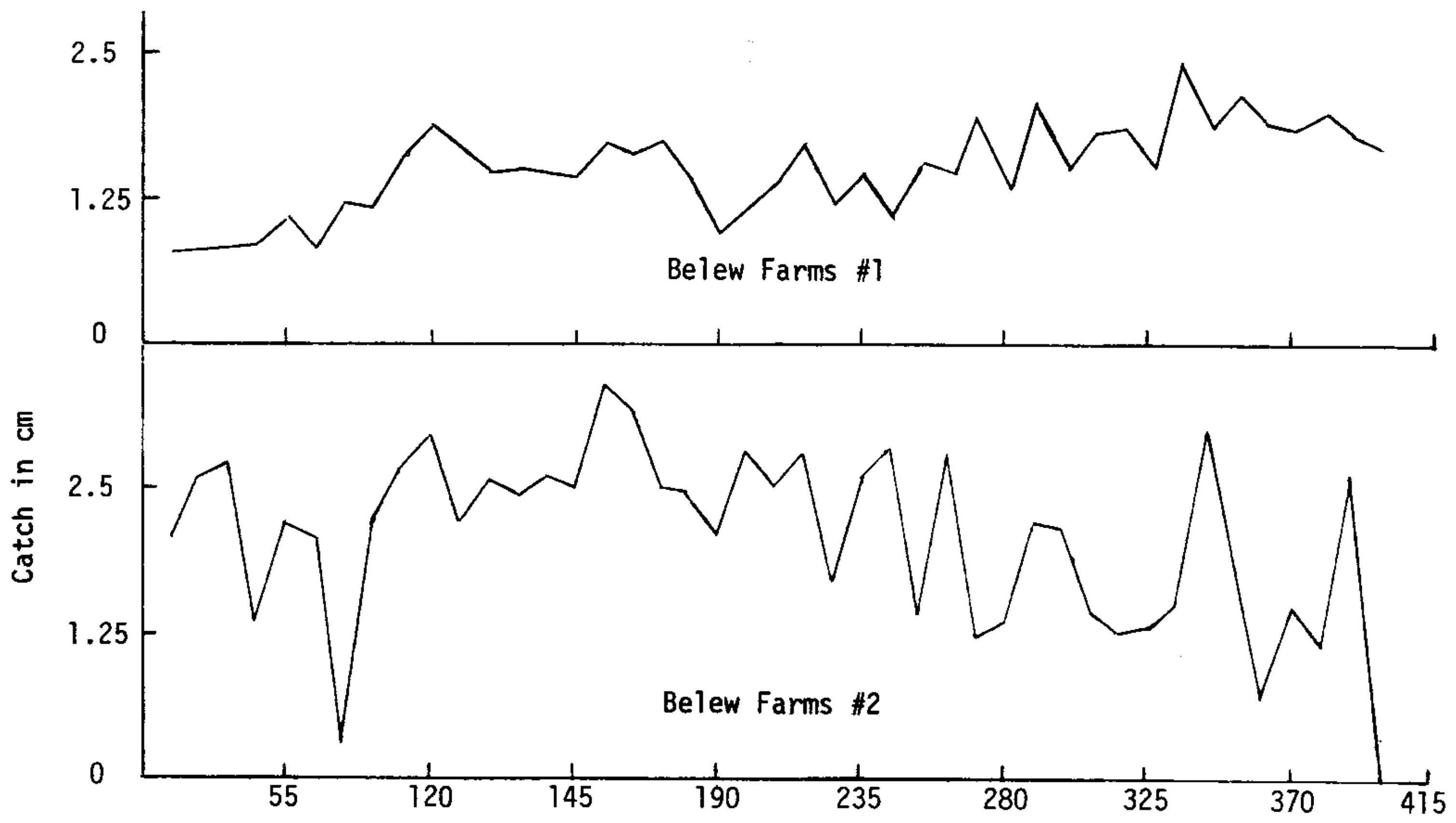


Figure 7. Irrigation water distribution patterns for 3 center pivot irrigation systems in the automated center pivot irrigation study at Earth, Texas during 1979.

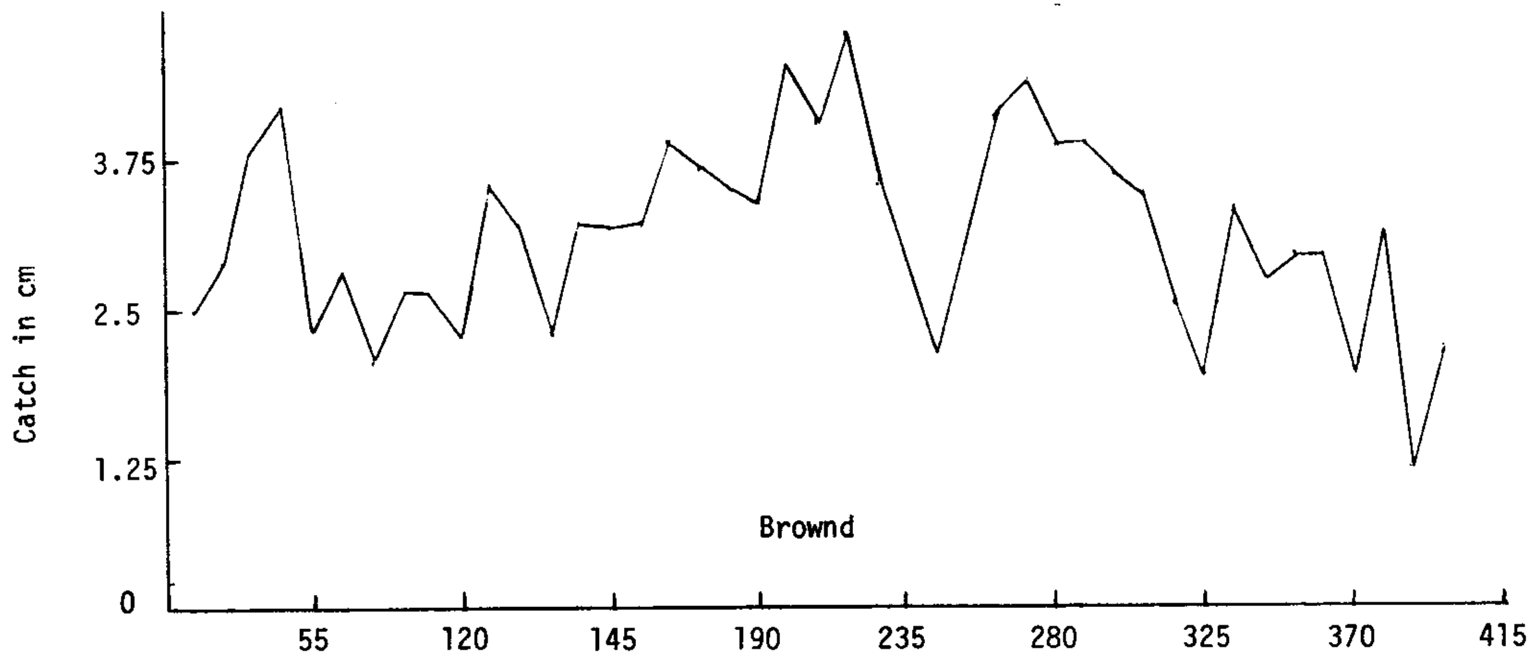


Figure 7. (Continued)

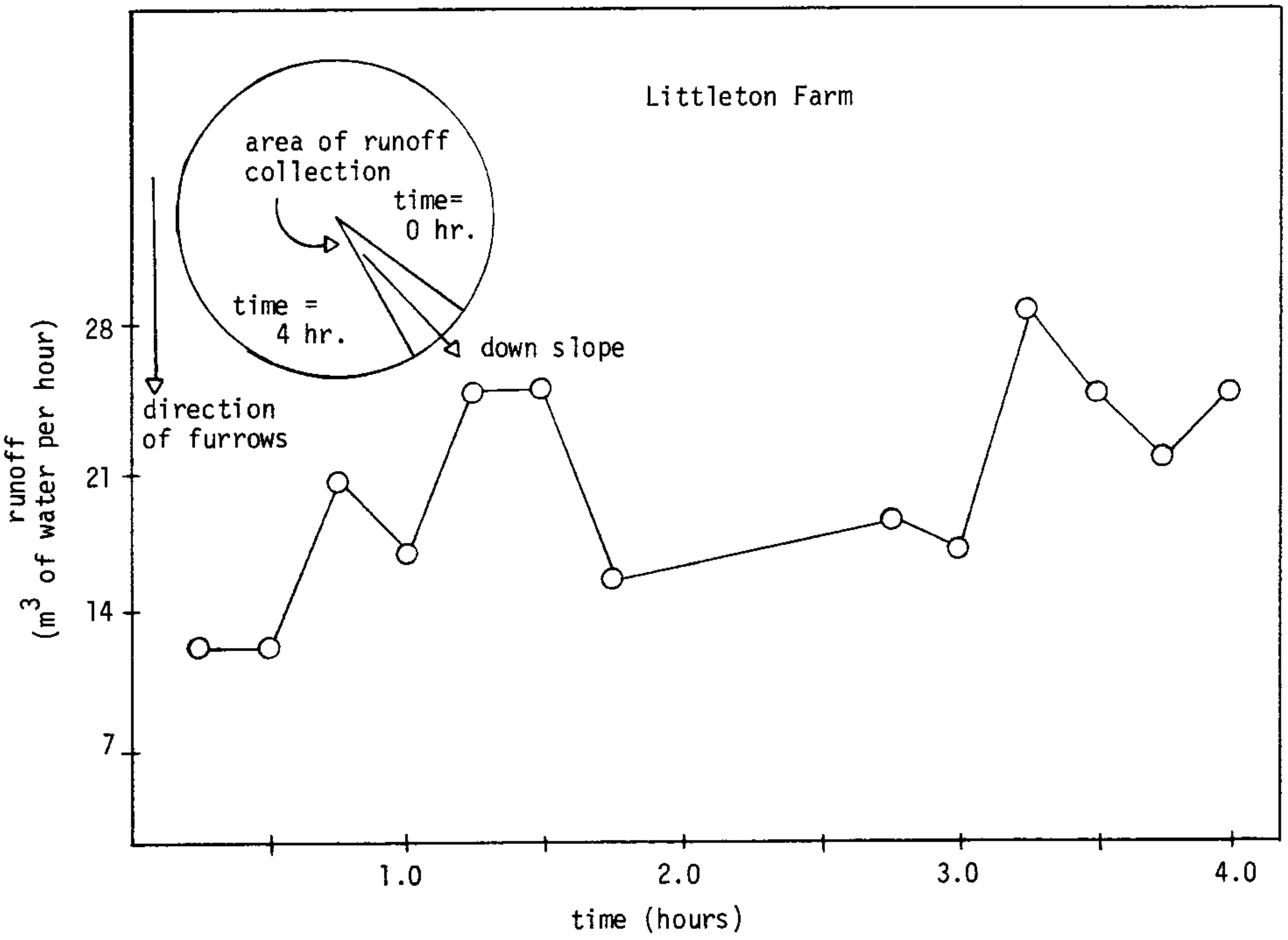


Figure 8. Runoff in the automated center pivot study near Earth, Texas during 1978.

The losses were significant both years (11.8 to 13.3 percent in 1978 and 1.3 to 18.6 percent in 1979). The sloping farms (Brownd, Littleton, and Belew Farms #2) had the highest losses. Visual observation indicated that the losses were due more to runoff in 1978 and deep percolation in 1979.

Soil Water

Summary data for soil water depletion are presented in Table 8. It can be seen that there was as much as 86 mm difference in the amount of water depleted in the quadrant of a particular sprinkler system (Belew Farm #2, 1979). The extraction of water from a particular soil type was very similar. The Brownd, Littleton, Belew Farms #1, and Templeton farms had Olton clay loam soil types. The water depletion by corn averaged 51 to 60 cm from farms with Olton clay loam, while the Belew Farm #2 with a Portales fine sandy loam had 101 mm depleted during 1978. There was a similar pattern with respect to cotton during 1979. The farms with Olton clay loam soil had depletions ranging from 91 to 97 mm while the farm with the Portales soil was depleted 135 mm. The data point out the importance of considering variability within a field, soil type and crop in scheduling irrigation and designing irrigation systems.

The soil water tension data of 1978 also show the variability between and within systems. Figures 9 and 10 show the variability (both with time and between quadrants) at 30 cm, the depth at which switching tensiometers are normally set. In addition, the data show that the tension at the 30 cm depth and the average tension for the entire profile are out of the tensiometer range for a major and critical part of the growing season even though the irrigation systems were operating continually. Similar data were obtained from the Belew farms. This is due to the inability of the irrigation

Table 8. Soil water depletion (in mm) for each center pivot irrigation system in the automated irrigation study at Earth, Texas during 1978 and 1979.

Cooperator	Quadrant NW	NE	SW	SE	Average
1978 - 150 cm profile - Corn					
Brownd	50	60	55	40	51
Littleton	50	60	50	80	60
Belew Farms #1	30	85	85	25	56
Belew Farms #2	100	115	95	95	101
1979 - 210 cm profile - Cotton					
Brownd	104	114	84	61	91
Belew Farms #1	79	104	81	102	91
Belew Farms #2	183	160	102	97	135
Templeton	117	89	94	84	97

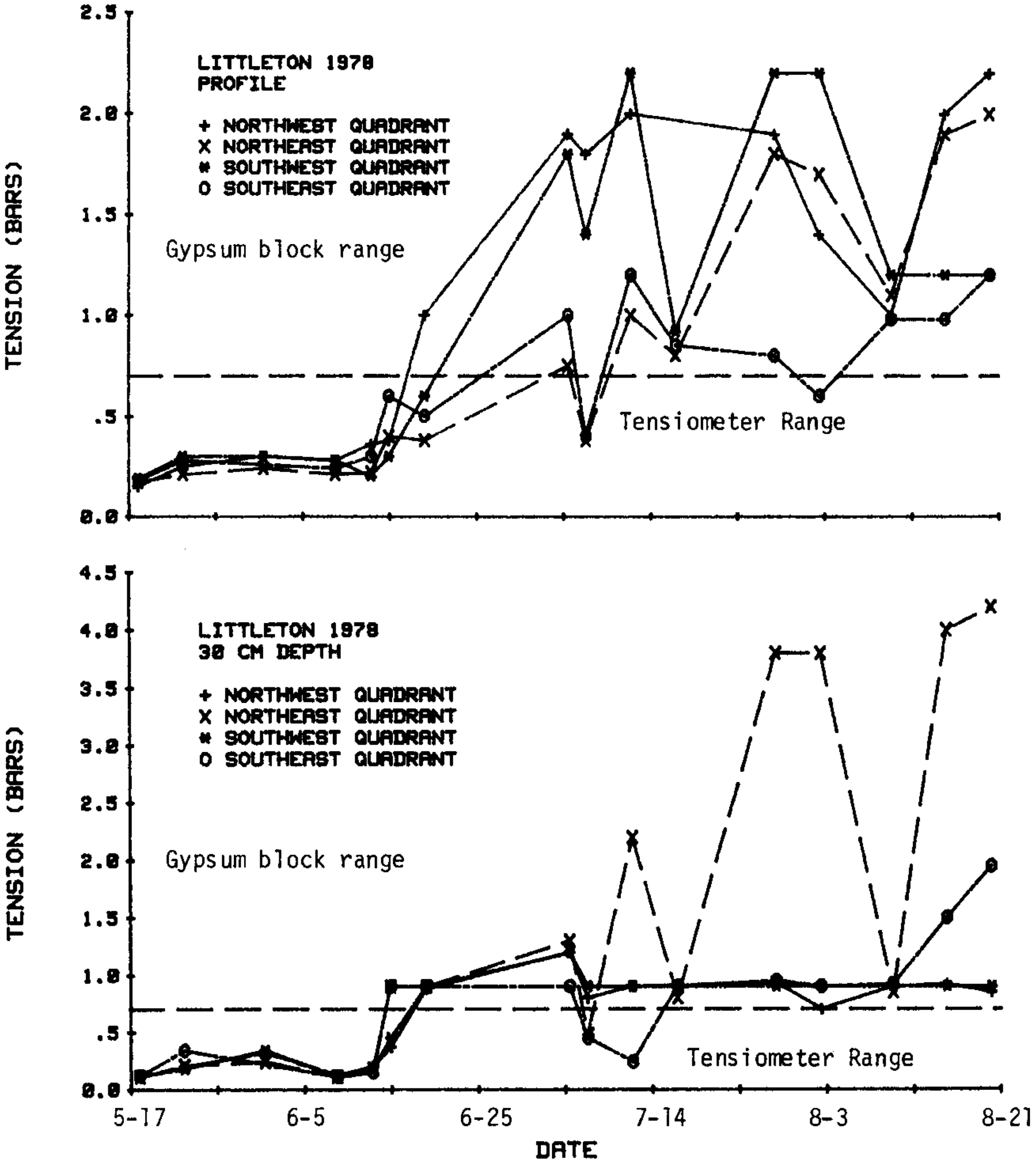


Figure 9. Soil water tension at the Littleton center pivot irrigation system at Earth, Texas, during 1978.

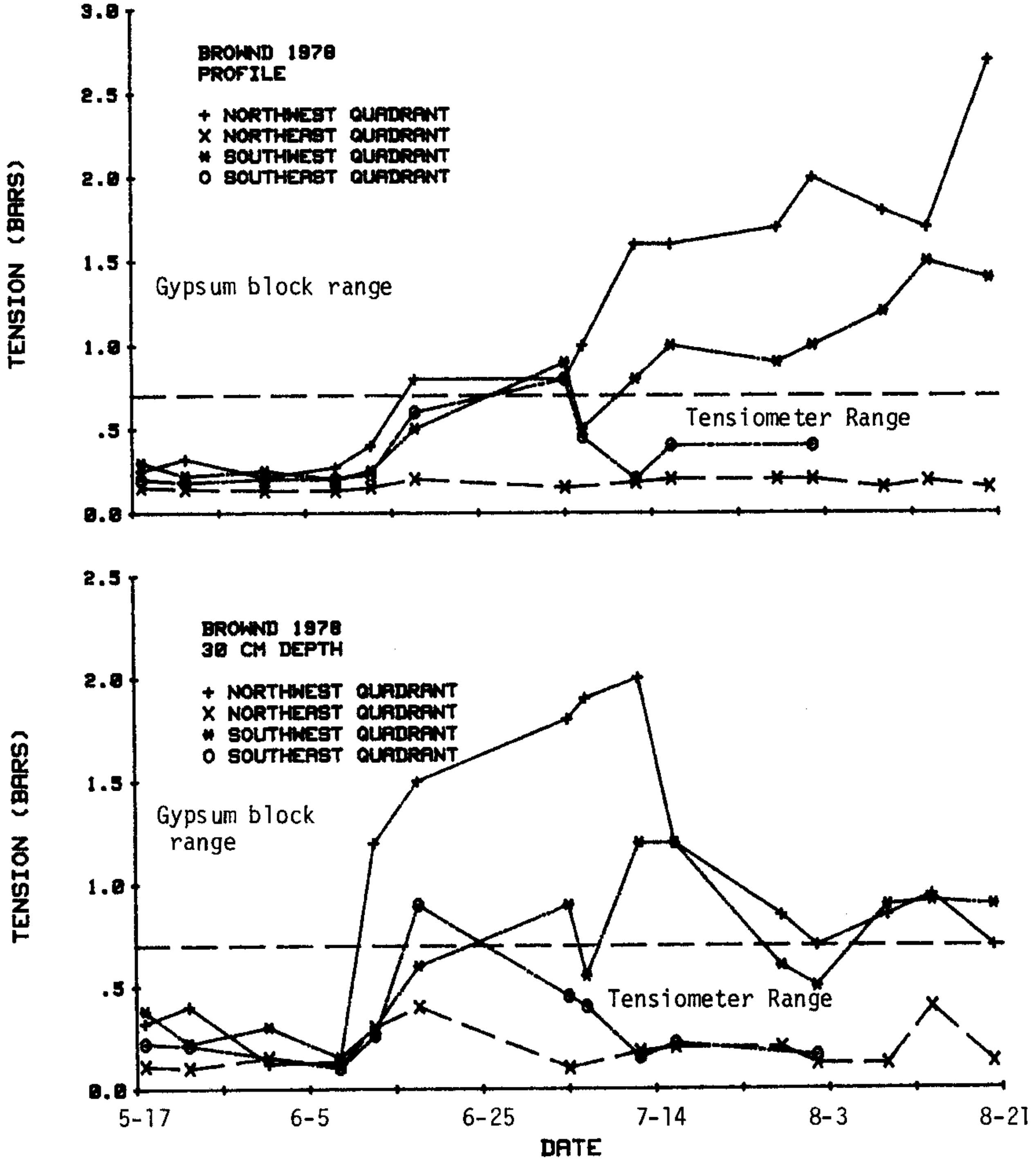


Figure 10. Soil water tension at the Brownd center pivot irrigation system at Earth, Texas, during 1978.

system to keep us with the demands of the crop. Figure 11 shows that for all of the center pivots studied during 1978, average soil water tension for all 4 irrigation systems at the 30 cm depth and the profile were not in tensiometer range for a substantial portion of the growing season.

During 1979, the same variability was noted in soil water tensions between quadrants (Figure 12) and among farms (Figure 13). The soil watertension was out of the tensiometer range for a longer period of time during the growing season 1979 than 1978. The data indicate that cotton can grown well even with soil water out of the tensiometer range while corn is much more sensitive to higher soil water tensions.

Plant Growth and Yield

The leaf area development is an important parameter in affecting plant evaporation (Ritchie and Burnett, 1971) and soil evaporation in crops with incomplete cover (Ritchie, 1972). Leaf area development for the corn and cotton crops during the two years of the study are shown in Figures 14 and 15. As has been pointed out, when leaf area index reaches 2.7 to 3.0, plant evaporation is equal to potential evapotranspiration. Corn had a leaf area index (Figure 14) in this range beginning in late June and maintained it through August which means the crop required water available to potential evapotranspiration (Appendix Table 1) if it was going to reach maximum yields. Cotton has a lower leaf area (Figure 15) than corn. This was probably the major factor causing differences in total water use by the crop. It appears that cotton would be a better crop to better use the limited water supplies of the Texas High Plains because of the smaller leaf area and lower water requirement.

Yield data are presented in Tables 9 and 10. The differences among quadrants reflects the variability previously reflected in the irrigation

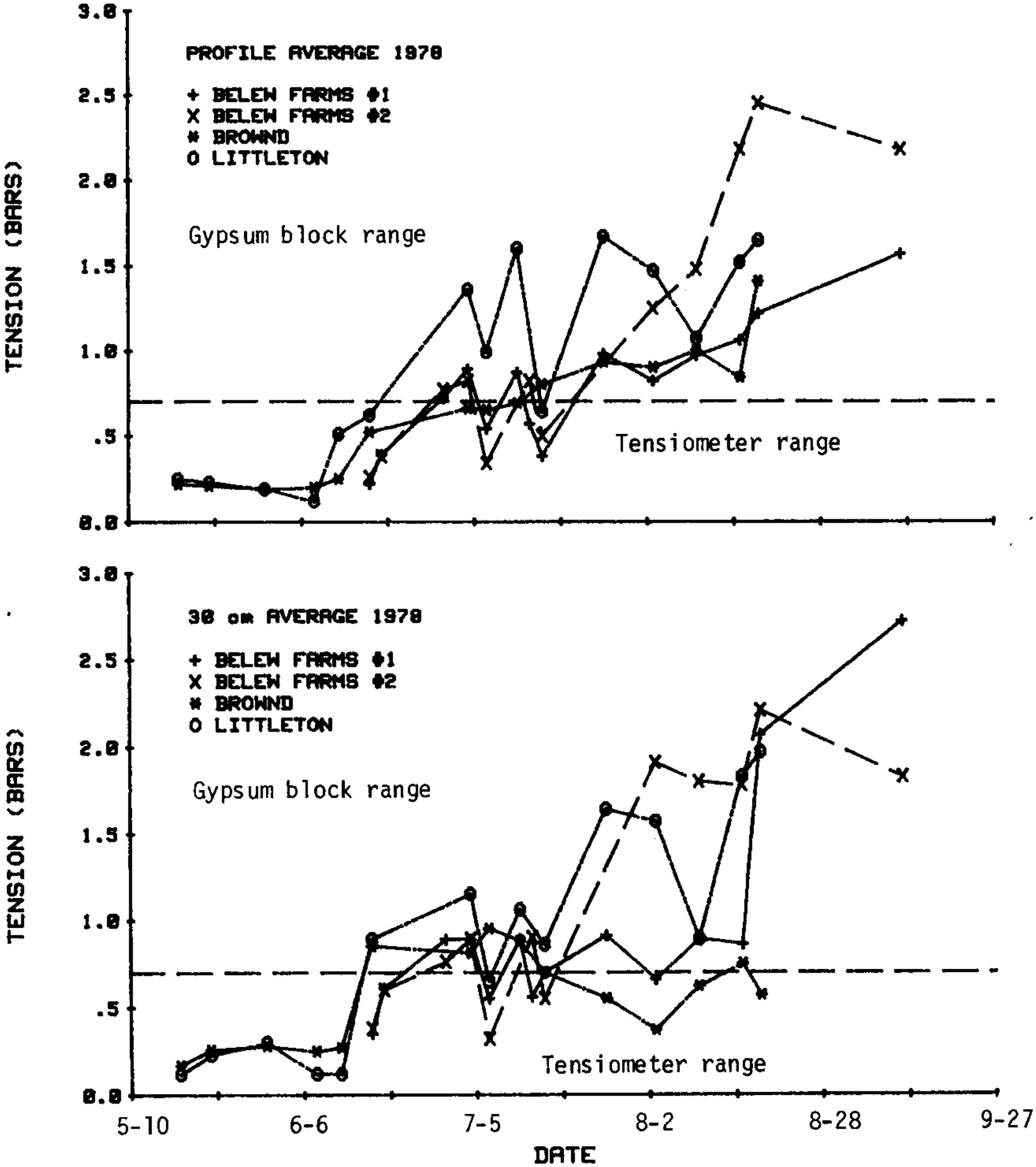


Figure 11. Average soil water tension for the center pivot irrigation systems at Earth, Texas, during 1978.

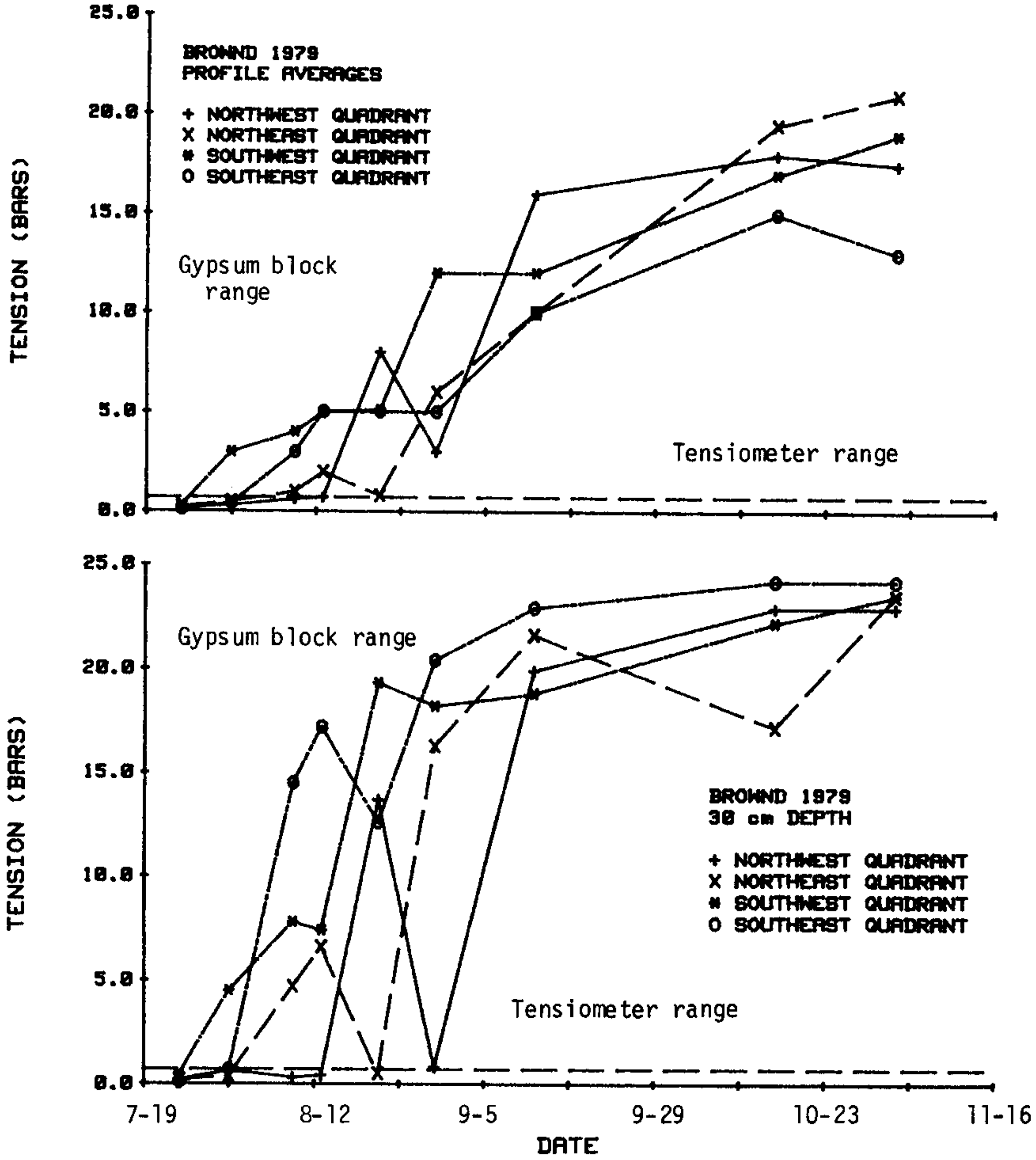


Figure 12. Soil water tension at the Brownd center pivot irrigation system at Earth, Texas, during 1979.

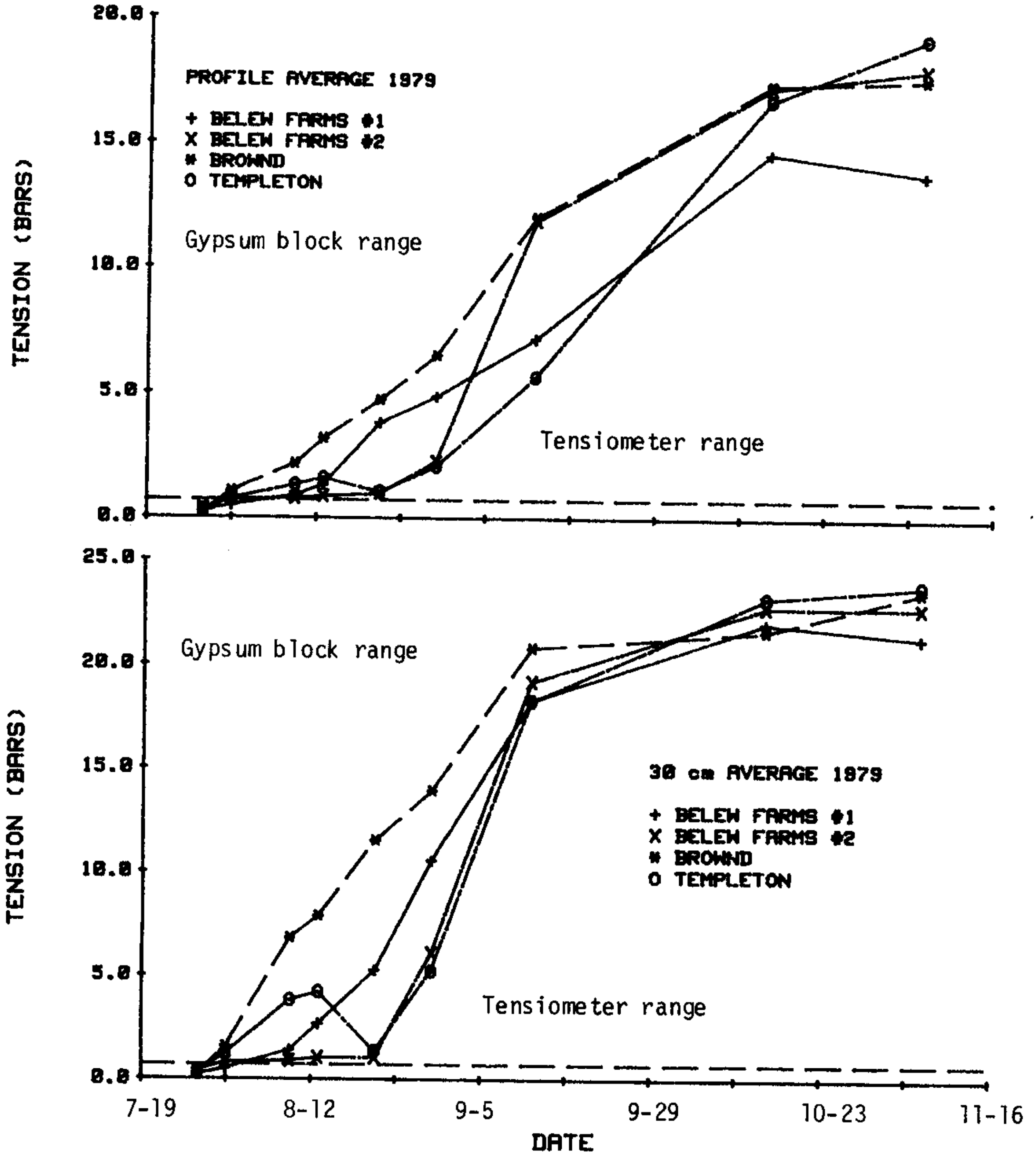


Figure 13. Average soil water tension for the center pivot irrigation systems at Earth, Texas, during 1979.

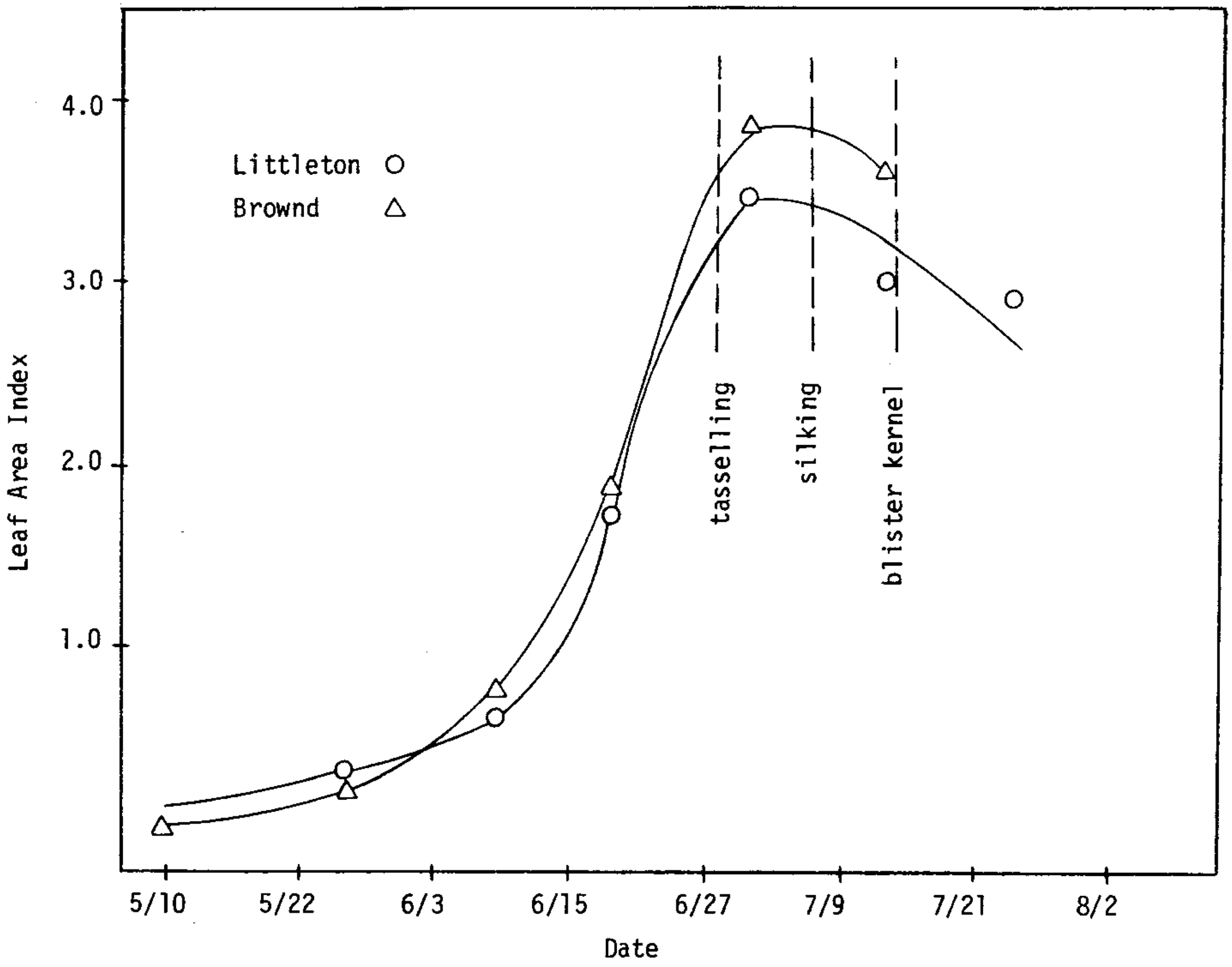


Figure 14. Leaf area development of corn in the automated center pivot sprinkler irrigation study at Earth, Texas, 1978

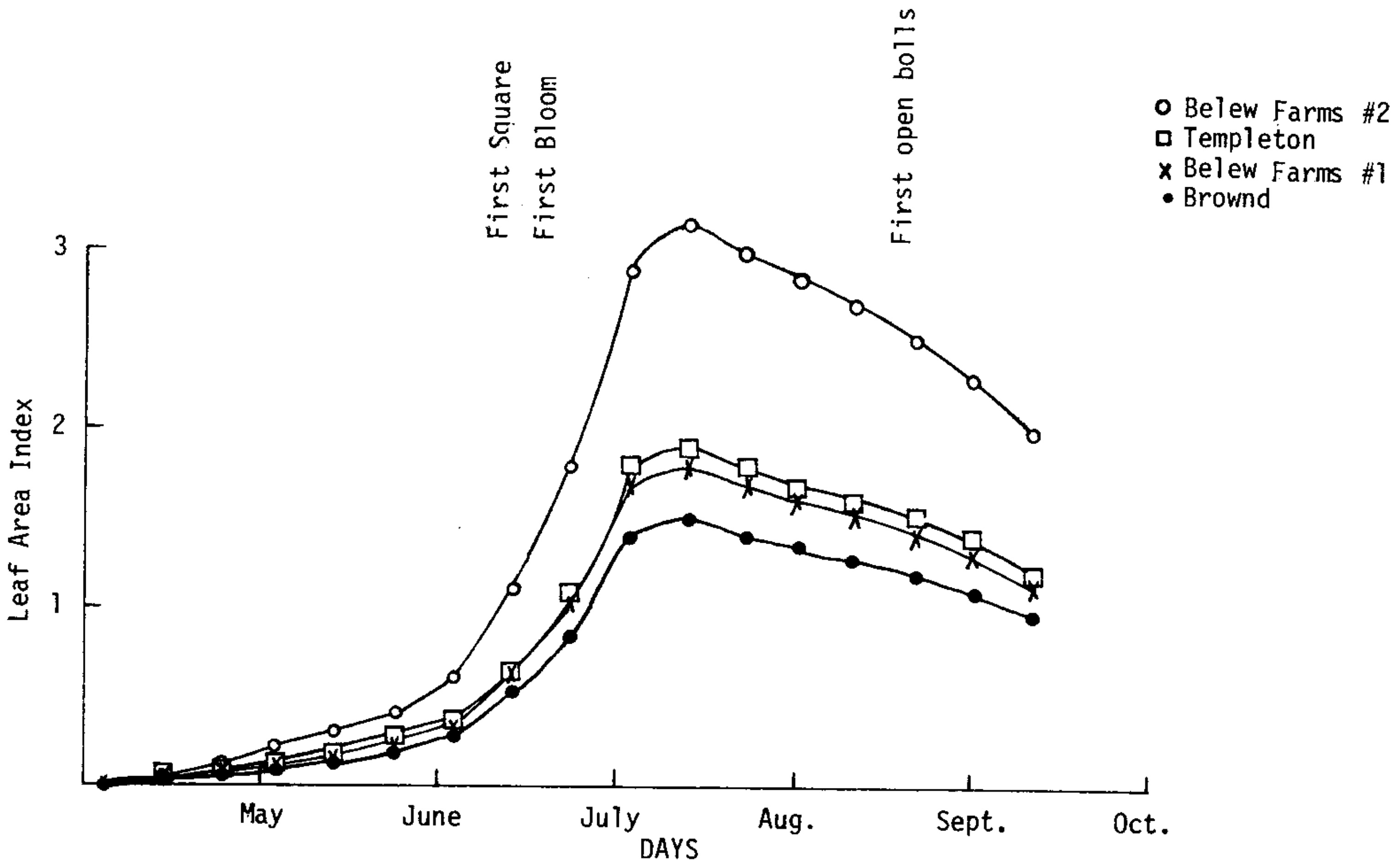


Figure 15. Leaf area development of cotton in the automated center pivot sprinkler irrigation study at Earth, Texas, 1979.

Table 9. Corn yield data from each quadrant of the automated center pivot sprinkler irrigation study at Earth, Texas during 1978.

	Total Yield per Hectare (kg/ha)			
Location	Littleton	Brownd	Belew Farms #1	Belew Farms #2
NW	9,832	9,303	4,403	5,204
NE	8,259	9,162	5,646	5,476
SW	7,939	8,138	5,383	6,532
SE	9,061	10,939	3,312	6,470
Average	8,821	9,572	5,001	5,920
yield per unit of irrigation water (kg/ha-mm)				
	58.8	44.5	58.8	65.8
yield per unit of total applied water (kg/ha-mm)				
	51.0	40.7	55.0	53.8

Table 10. Cotton yield data from each quadrant of the automated center pivot sprinkler irrigation study at Earth, Texas, during 1979.

	Total Yield per Hectare (kg/ha)			
Location	Brownd	Belew Farms #1	Belew* Farms #2	Templeton
NW	646	547	480	505
NE	492	487	580	623
SW	623	495	539	638
SE	599	539	615	762
Average	590	517	553	632
yield per unit of irrigation water (kg/ha-mm)				
	16	26	33	16
yield per unit of total applied water (kg/ha-mm)				
	1.2	1.1	1.2	1.3

*Varieties Cascot B-2 (NW, SW) and Paymaster (NE, SE) were significantly different at .9 using F test statistics.

and soil water data. There was not much difference in the yield of cotton per unit of total applied water. However, there were major differences in the corn yield per unit of applied water. The system with the highest well capacity had the highest yield but lowest yield per unit of water.

Irrigation Water and Automation Costs

Irrigation water costs for both irrigated corn and cotton are presented in Table 11. Corn irrigation costs in 1978 were 4 to 5 times the cost of irrigating cotton in 1979. This is because corn has a higher water requirement than cotton and more rainfall was received in 1979 (Appendix Table 3). Corn received 65-116 mm/ha of irrigation water compared to 33-60 mm/ha for cotton.

Table 11. Irrigation water costs in the automated sprinkler irrigation study at Earth, Texas during 1978 and 1979.

Location	1978 - Corn			1979 - Cotton		
	mm* applied	$/ha-mm	Total $	mm* applied	$/ha-mm	Total $
Littleton	20820	.262	5456.46	---	---	---
Brownd	29948	.168	5031.26	4864	.255	1240.20
Belew Farms #1	11911	.152	1810.40	2593	.210	544.60
Belew Farms #2	12551	.221	2773.85	2264	.252	570.60
Templeton	---	---	---	5320	.246	1308.72

*Total for 53 ha

The cost of components for automation is presented in Table 12.

Table 12. Costs of components used for automation in the automated sprinkler irrigation study at Earth, Texas during 1978 and 1979*.

Transmitter-receiver pair	$100
Windspeed controller	700
Rain sensor	200
Switching tensiometers	38

*Costs do not include design costs or labor and component costs (wire, timer, relays, etc.) to install the units on irrigation systems.

If a producer has a high capacity ($\geq$284 m^3/hr) and efficient irrigation system, he should consider automation to further decrease irrigation costs.

SUMMARY AND CONCLUSIONS

There is no question that center pivot sprinkler irrigation systems can be successfully automated. In this study, sensors were constructed by which the systems can be controlled by wind, soil water tension, and rainfall. The sensors can be used either separately or in combination to control the systems. The requirements of objective one were therefore fulfilled.

For several reasons, it was not possible to test the hypotheses of the other two objectives. The major reason was the capacity of the wells which supplied the irrigation systems. The wells were reputed to have capacities of 227 to 272 m^3/hr. However, after the study was initiated it was apparent that the well capacities were much lower (114 to 204 m^3/hr) and were decreasing each year (11 m^3/hr).

If the efficiency of application was 100 percent, there would be no problem in a well with a capacity of 170 m^3/hr supplying water equal to the evapotranspiration potential. However, there were other losses. Evaporation losses varied from 11 to 24 percent of the water applied. Runoff up to 15 percent of the water applied was measured and values from 1.3 to 18.6 percent were calculated. This was due to differences in the type of soil, slope, and changing infiltration rates with time. For a system in which 40 percent of the water was lost from evaporation and runoff, a well capacity of 284 m^3/hr would be required to meet crop requirements, and losses from evaporation and runoff.

Since the systems could not supply water adequate to meet water requirements in addition to the losses, the crops depleted the soil water so that the soil water tension was out of the tensiometer range for the last

60 days of the growing season. Considerable variation in both soil water potential and content between quadrants of each sprinkler system was noted. This indicates that a large number of soil water measurements will be required in each quadrant to obtain an adequate representation of soil water conditions.

With respect to automation of center pivots, the following recommendations are made:

1. The capacity of the wells supplying the center pivot sprinkler irrigation systems in the Texas High Plains should be at least 284 m^3/hr to take care of peak crop water demands as well as evaporation and runoff losses before automation during the growing season is considered.
2. Distribution of water by center pivot sprinkler irrigation systems in this study was poor. Pump efficiencies were also poor. Together these caused low irrigation system efficiencies. Such losses in water and energy should be minimized before automation is considered.
3. The windspeed controller probably has the most promise to increase water use efficiency in the Texas High Plains. It would be very useful during the pre-irrigation period when time is available to apply water and evaporation losses can range from 20 to 40 percent of the water pumped due to high windspeeds.
4. Soil water sensors can be used to control automation only if adequate well capacity is available during the growing season. If such capacity is available, tensiometers appear adequate to control systems planted to corn. Since cotton produces quite

well with soil water out of the tensiometer range in the Texas High Plains, sensors other than tensiometers should probably be used.

5. Rainfall sensors have more immediate application in the Texas High Plains than soil water sensors, especially where the irrigation systems are remote. It is desirable to stop irrigation systems during rains to decrease runoff from soil types such as those involved in this study. Also, stopping the irrigation systems minimizes the possibility of damage due to lightening.
6. Evaporation losses could be minimized by irrigating only at night. However, the well capacity of 284 m^3/hr would have to be increased at least 50 percent. With relatively cheap crops (cotton, corn, etc.) it is doubtful if the producer could pay for the extra cost.
7. Runoff losses could be eliminated and better use could be made of rainfall by installing furrow diking under the center pivots. This is occurring to a certain extent since the producers begin to realize the magnitude of the losses.
8. The crop should be a major consideration in automation of irrigation systems. Crops with high leaf area like corn require more water in the Texas High Plains than cotton which has a low leaf area.
9. Available soil water of the various soil types should also be a consideration in the automation of irrigation systems. In this study, the Portales soil had approximately 40 mm more available water for both corn and cotton than the Olton soil.

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Appendix Table 1. Potential ET as determined from meteorological measurements in the center pivot irrigation study at Earth, Texas, during 1978.

Date	ET_p	Date	ET_p	Date	ET_p
	cm day^{-1}		cm day^{-1}		cm day^{-1}
May 10	.447	June 7	.599	July 5	.648
11	.841	8	.693	6	.689
12	.574	9	.747	7	.678
13	.583	10	.891	8	.712
14	.741	11	.937	9	.719
15	.754	12	.886	10	.684
16	.696	13	.570	11	.688
17	.737	14	.813	12	.678
18	.713	15	.846	13	.686
19	.566	16	.876	14	.671
20	.424	17	.853	15	.704
21	.353	18	.853	16	.693
22	.584	19	.785	17	.699
23	.619	20	.759	18	.694
24	.513	21	.775	19	.553
25	.386	22	.881	20	.673
26	.219	23	.892	21	.599
27	.467	24	.782	22	.455
28	.503	25	.889	23	.237
29	.574	26	.800	24	.513
30	.833	27	.669	25	.587
31	.742	28	.569	26	.800
June 1	.573	29	.585	27	.687
2	.229	30	.504	28	.667
3	.373	July 1	.643	29	.676
4	.458	2	.670	30	.663
5	.295	3	.630	31	.591
6	.428	4	.619	Aug. 1	.645

Continued

Appendix Table 1. (Continued)

Date	ET_p	Date	ET_p	Date	ET_p
	cm day^{-1}		cm day^{-1}		cm day^{-1}
Aug. 2	.592	Aug. 17	.797	Sept. 1	.517
3	.396	18	.671	2	.390
4	.249	19	.337	3	.266
5	.377	20	.499	4	.441
6	.612	21	.637	5	.549
7	.595	22	.612	6	.566
8	.387	23	.613	7	.413
9	.459	24	.638	8	.327
10	.582	25	.559	9	.466
11	.640	26	.507	10	.528
12	.616	27	.630	11	.655
13	.626	28	.451	12	.716
14	.595	29	.450	13	.626
15	.646	30	.453		
16	.706	31	.550		

Appendix Table 2. Potential ET as determined from meteorological measurements in the center pivot irrigation study at Earth, Texas, during 1979.

Date	ET_p	Date	ET_p	Date	ET_p
	cm day^{-1}		cm day^{-1}		cm day^{-1}
May 1	.191	May 29	.754	June 26	.602
2	.500	30	.607	27	.719
3	.198	31	.117	28	.780
4	.505	June 1	.127	29	.699
5	.716	2	.173	30	.803
6	.912	3	.432	July 1	.795
7	.892	4	.429	2	.800
8	.874	5	.216	3	.663
9	.889	6	.622	4	.701
10	.638	7	.739	5	.485
11	.599	8	.218	6	.701
12	.447	9	.544	7	.665
13	.714	10	.671	8	.785
14	.925	11	.638	9	.782
15	.813	12	.752	10	.810
16	.754	13	.833	11	.846
17	.759	14	.813	12	.831
18	.785	15	1.000	13	.785
19	.871	16	.831	14	.747
20	.546	17	.859	15	.655
21	.038	18	.983	16	.396
22	.376	19	.993	17	.399
23	.579	20	.767	18	.264
24	.378	21	.859	19	.323
25	.307	22	.691	20	.485
26	.493	23	.686	21	.432
27	.665	24	.795	22	.607
28	.660	25	.632	23	.650

Continued

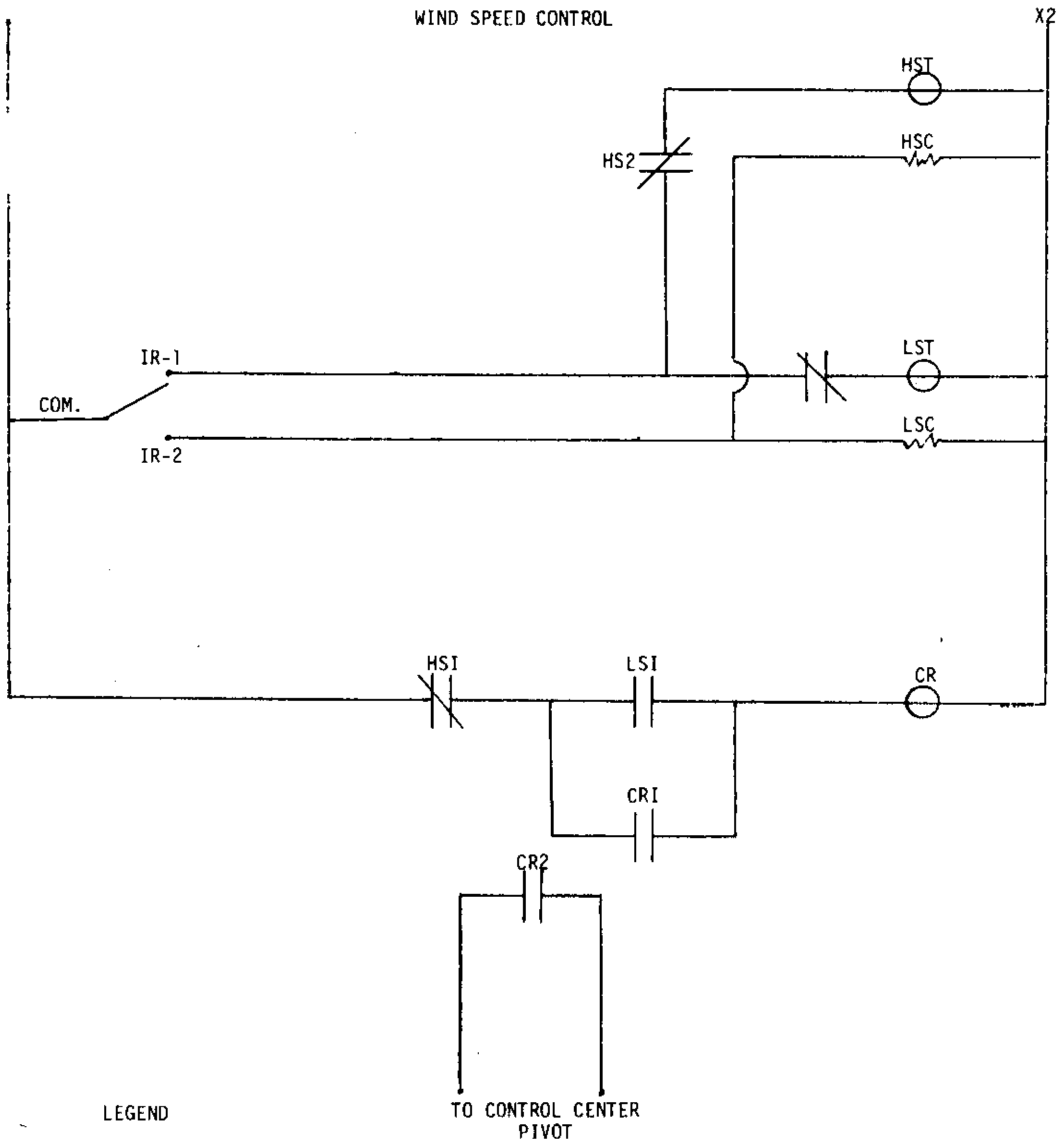
Appendix Table 2. (Continued)

Date	ET_p	Date	ET_p	Date	ET_p
	cm day^{-1}		cm day^{-1}		cm day^{-1}
July 24	.627	Aug. 22	.653	Sept. 20	.485
25	.632	23	.396	21	.376
26	.660	24	.495	22	.498
27	.658	25	.523	23	.544
28	.716	26	.282	24	.551
29	.701	27	.478	25	.516
30	.564	28	.528	26	.488
31	.574	29	.536	27	.640
Aug. 1	.592	30	.505	28	.916
2	.630	31	.480	29	.500
3	.610	Sept. 1	.559	30	.523
4	.577	2	.493		
5	.660	3	.323		
6	.681	4	.538		
7	.683	5	.531		
8	.653	6	.569		
9	.663	7	.536		
10	.533	8	.523		
11	.602	9	.549		
12	.602	10	.554		
13	.640	11	.561		
14	.508	12	.554		
15	.493	13	.541		
16	.396	14	.173		
17	.368	15	.348		
18	.541	16	.333		
19	.564	17	.315		
20	.556	18	.386		
21	.551	19	.498		

Appendix Table 3. Rainfall (cm) for each system in the automated center pivot irrigation study at Earth, Texas, during 1978 and 1979.

Month	1978				1979			
	Littleton	Brownd	Belew Farms#1	Belew Farms#2	Templeton	Brownd	Belew Farms#1	Belew Farms#2
March	---	---	---	---	1.02	.91	.84	.84
April	---	---	---	---	5.38	2.43	3.03	1.16
May	4.72	4.34	5.32	4.96	T*	T	T	T
June	13.66	12.62	12.43	10.60	T	T	T	T
July	3.96	3.80	2.79	2.05	---	5.49	---	---
August	.80	.25	2.10	1.23	4.42	.66	1.91	2.69

*T-Trace



LEGEND

IR - Input Relay
HST - High Speed Timer
HSC - High Speed Clutch
HSI - High Speed Contacts
LST - Low Speed Timer
LSC - Low Speed Clutch
LSI - Low Speed Contacts
CR - Control Relay

Description of Operation

1 R-1 - Closes on low speed
1 R-2 - Closes on high speed
CR-2 Closes after 1 hr of low speed and stays closed until 1 hr of high speed.

Appendix Figure 1. Schematic of modification to Sierra Model 7671 Windspeed Control for use in automated center pivot irrigation study at Earth, Texas, during 1978 and 1979.

INSTRUCTION MANUAL

Precision 2080

Remote Control System 9

Precision Electronics
4905 40th Street
Lubbock, Texas 79416

TABLE OF CONTENTS

Page

REMOTE CENTER CONTROL TENSIOMETERS

RAIN SENSOR

FIGURES

Number Page

REMOTE CENTER CONTROL TENSIOMETERS

Introduction

The Precision 2080 Remote Control System 9 is designed to operate reliably under rigorous field conditions. The self-contained units are constructed of military grade components. The units are shock mounted and filled with nitrogen and a drying agent to minimize the effects of the ambient environment. To further insure reliability each transmitter (Figure 1) and receiver (Figure 2) is composed of two independent operating units. Therefore, the system will still be operational if one of the transmitters or receivers becomes inoperable. A list of the operating characteristics of the transmitter-receiver units (Sanwa Electric Co., 6-12 Kuwazu-cho, Higashisumiyoshi-ku, Osaka, Japan) is as follows:

Temperature Range - 15-140 degrees F.
Operation - continuous
Frequency - 72.160 mhz
Modem - digital (true) proportioned
Type - super heterodyne
Range - 1200 ft. minimum, 3200 ft. receiver @ 4% incline
Power consumption - transmitter - 156 D.C. MA.
Power consumption - receiver - 260 D.C. MA.
R.F. output - 500 milliwatts max.

Installation

The receiver requires a 120 vac. 60 cycle source in the control box (Figure 3). The receiver is fused internally to prevent damage from high voltage. It is automatically reset when the voltage becomes normal. The universally coded connections are connected in parallel to the "run" or

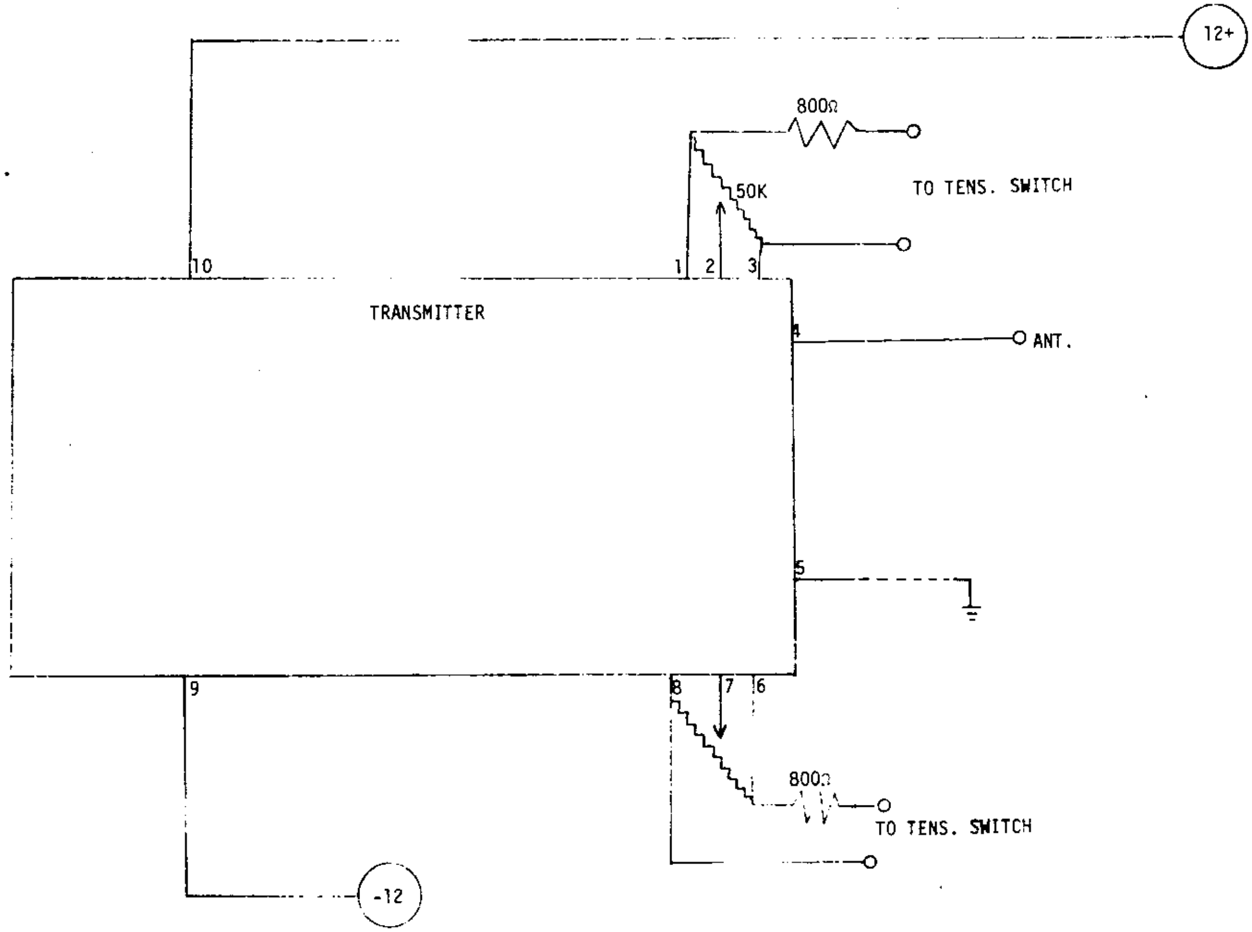


Figure 1. Block diagram of Sanwa Model 8020 DP transmitter with leads to switchable tensiometers

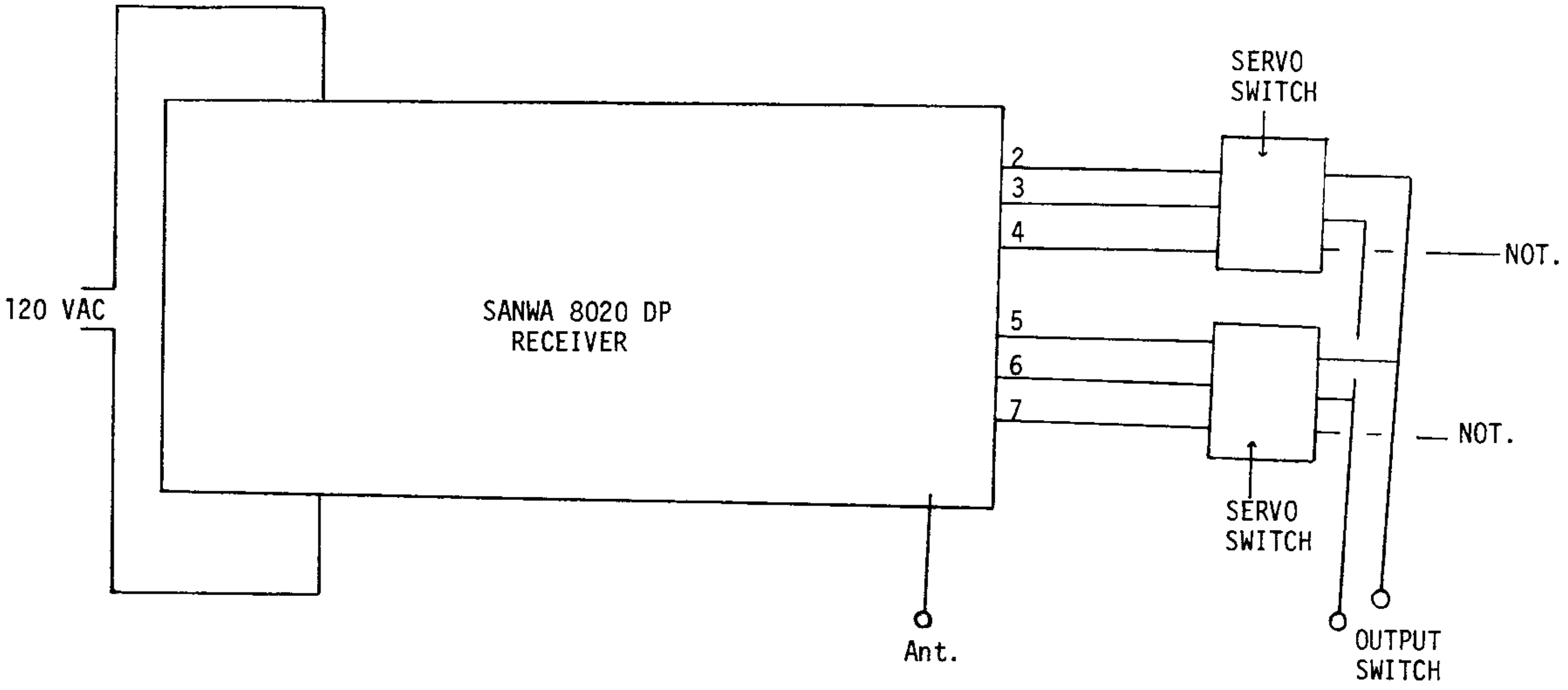
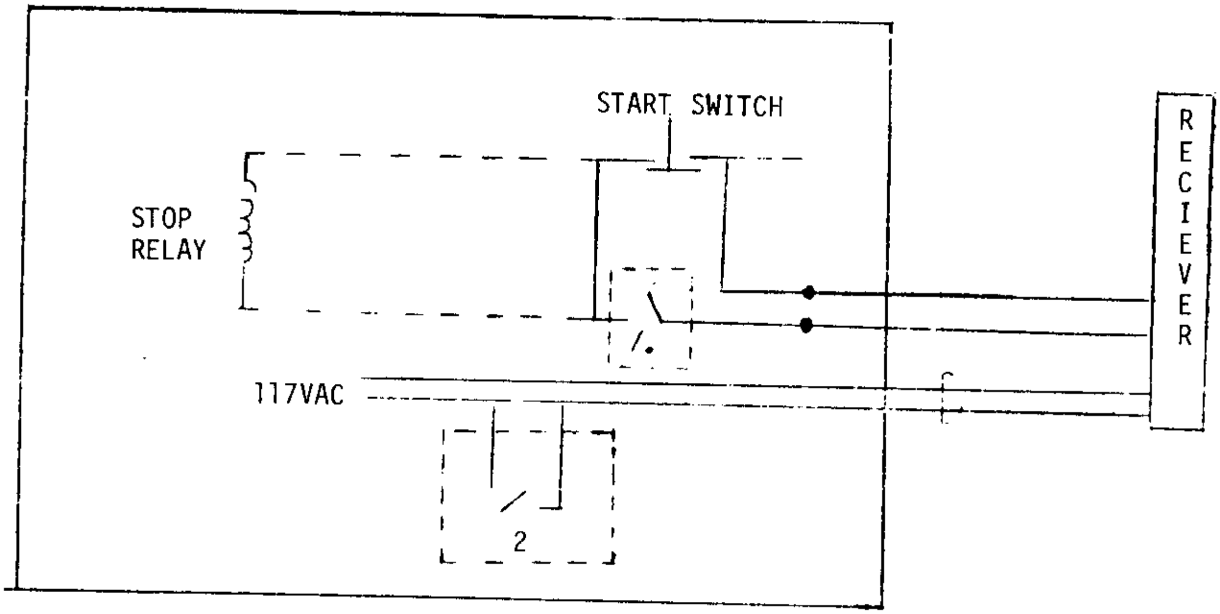


Figure 2. Block diagram of Sanwa Model 8020 DP receiver with servo switches and output switch installed in center pivot.



Main Control Panel on Pivot Center

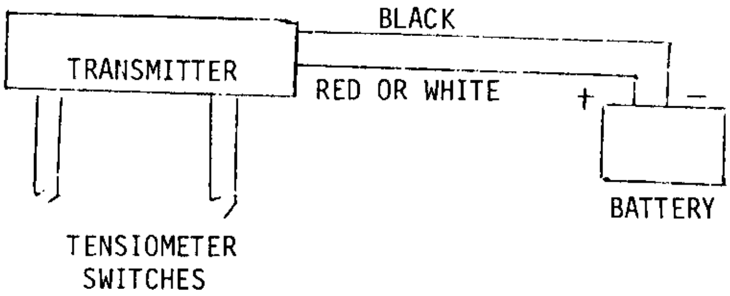


Figure 3. Block diagrams of Sanwa Model 8020 DP transmitter and receiver installations.

"auto" switch of the control box. The internal switch in the receiver is mechanical and can carry a load of 10 amps @ 120 vac. Contact of the antenna to a power switch should be avoided to prevent damage to the receiver.

It is recommended that the receiver unit be installed at the base of the pivot between the transmitter unit and the pivot control panel (Figure 4).

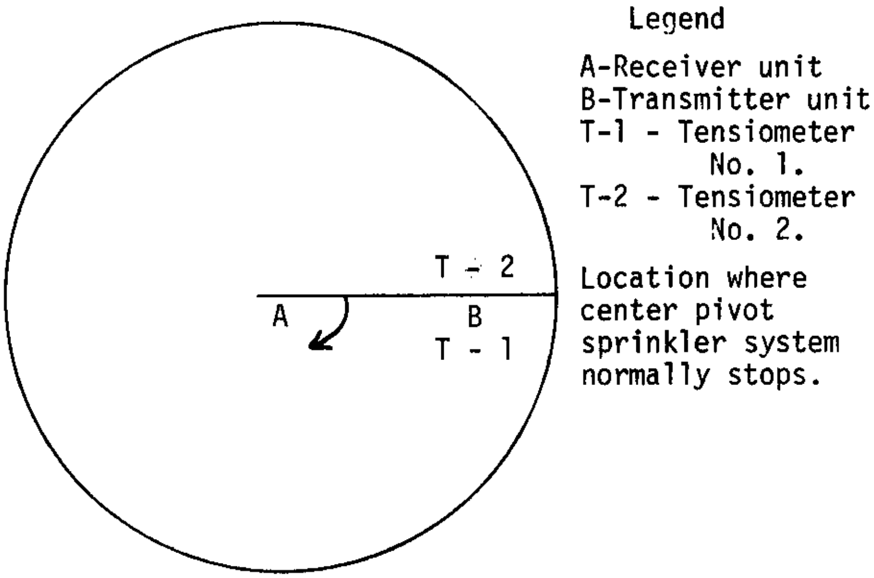


Figure 4. Schematic of recommended locations for transmitter unit, receiver unit, and tensiometers in a center pivot irrigation system.

Attach the wires to the control panel as indicated in Figure 3. If the wires are installed backwards, the receiver will not be damaged, but it will not operate.

Place the transmitter unit firmly in the ground as indicated in Figure 4. Install the tensiometers so that a tensiometer is located on each side of the center pivot in the normal stopped position. Connect the power wires to a 12 vdc. battery (black wire to negative and red or white wire to positive).

If power is applied in reverse, the unit will not be damaged, but it will not function.

Operation

When the soil moisture tension in either tensiometer T-1 or T-2 increases greater than preset level (usually 50-70 cb) the switch of the switching tensiometer closes and activates the transmitter. The signal is received by the receiver on the sprinkler and the system will continue until the switch opens. With the current design, the irrigation system will start when the switch of either tensiometer closes but will not stop until the switches of both tensiometers are open. Other designs which could be used include hooking switching tensiometers in series so that the irrigation system could not be activated until the switches on all tensiometers are closed.

Theory of Operation

To provide reliability, a continuous carrier frequency is modulated with a 20KC frequency to decrease outside interference. The transmitter operates continuously to minimize effects of signals from other sources (ie - spillover from another transmitter in the same locale, a stronger signal or a faulty transmitter on another frequency). The modulated signal also tends to keep the receiver "locked on" the transmitter. Since the possible combinations of codes are 2^{64} x 20,000, it is virtually impossible to randomly cause the receiver to accept spurious signals to activate irrigation system. If one of the transmitter-receivers fails, the remaining one can continue operation, when a switch (ie - switching tensiometer closes). When the switch is opened, a pulse code (3 place) is transmitted. The receiver must desegregate the code from the modulated frequency and actuate a servo mechansim which closes or opens the output switch. Once the output state has been changed, the proper code must be once again received to change the output switch. This insures that the switch will stay on during temporary power failures. This feature allows the operator to turn the receiver on or off without regard to transmitter status. The switching circuit to the transmitter is capable of causing the appropriate action with a short circuit condition with a resistance of 10 Meg. ohms.

The transmitter operates at 12 volts D.C. The connections to the battery are color coded red or yellow to positive and black or green to negative. There is internal polarity protection internally to prevent damage to the electronics if polarity is reversed. The connections to the switching mechanisms are indiscriminate with respect to polarity. Any type switch can be used as "Bounce characteristics" are compensated for internally. If the switch is to be located more than 1000 ft. from the transmitter, 16# gauge wire is recommended.

Maintenance

There are no user servicible components in either the transmitter or reciever. Long life is assured through the use of solid state components. Proper storage (protect from extreme heat or cold) will help prolong service years.

RAIN SENSOR

Introduction

In some irrigated areas, a significant amount of rainfall is received during the growing season. In this situation it may be desirable to have a rain sensor to deactivate the irrigation system when a significant amount of rainfall is received. The system developed for this study is designed to be safe and maintenance free. It is flexible in that it may be used with or without tensiometers and with or without transmitters and receivers.

Installation

Install the rain sensor outside the center pivot sprinkler irrigation system as indicated in Figure 5.

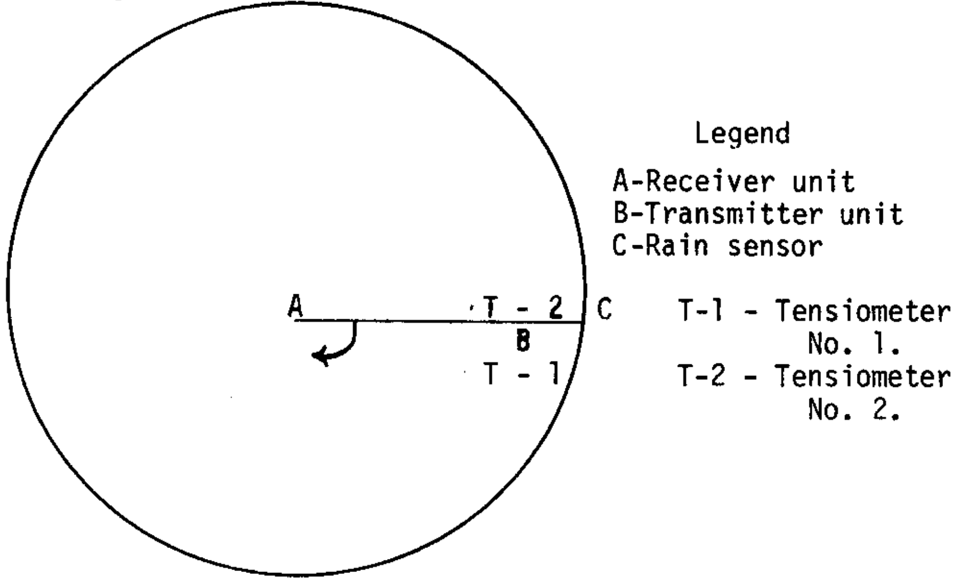


Figure 5. Schematic of recommended locations for transmitter unit, receiver unit, tensiometers, and rainfall sensor in a center pivot irrigation system.

After installation, set manual switch to the "On" position. Then set "On" keys (tabs) on the timer to desired positions. The number of hours between any two tabs is the amount of time the system will remain "Off" once the sensor has been activated. A minimum of two (2) and a maximum of twenty-four (24) hours "Off" time is possible. Next, set the "Off" tabs to the time you want the drain valve to open. Once opened it will remain open until the cycle is complete. Set the variable metal probe to the level of water needed to trigger the system (Figure 6). This is variable from 1.27 cm (0.5 in) to 3.81 cm (1.5 in). Tighten the lock screw if needed to prevent movement of the element. Attach the two wires to the transmitter in series with the other control switches (Figure 7). Set time wheel to any "On" tab; apply power.

The rain sensor may be installed in other ways. The transmitter-receiver installation can be bypassed so that the sensor is wired directly to the control panel of the center pivot sprinkler irrigation system. The sensor may also be used with or without tensiometers.

Operation

When the amount of rainfall received reaches the top of the variable probe, the electronic circuit is activated. After a delay of three minutes the circuit to the transmitter is opened. The transmitter will stop transmitting and the center pivot irrigation system will stop. The irrigation system will remain stopped for the period of time set on the time. After this period, the circuit will close. If either of the tensiometer switches is closed, the transmitter will again start sending signals and the irri-

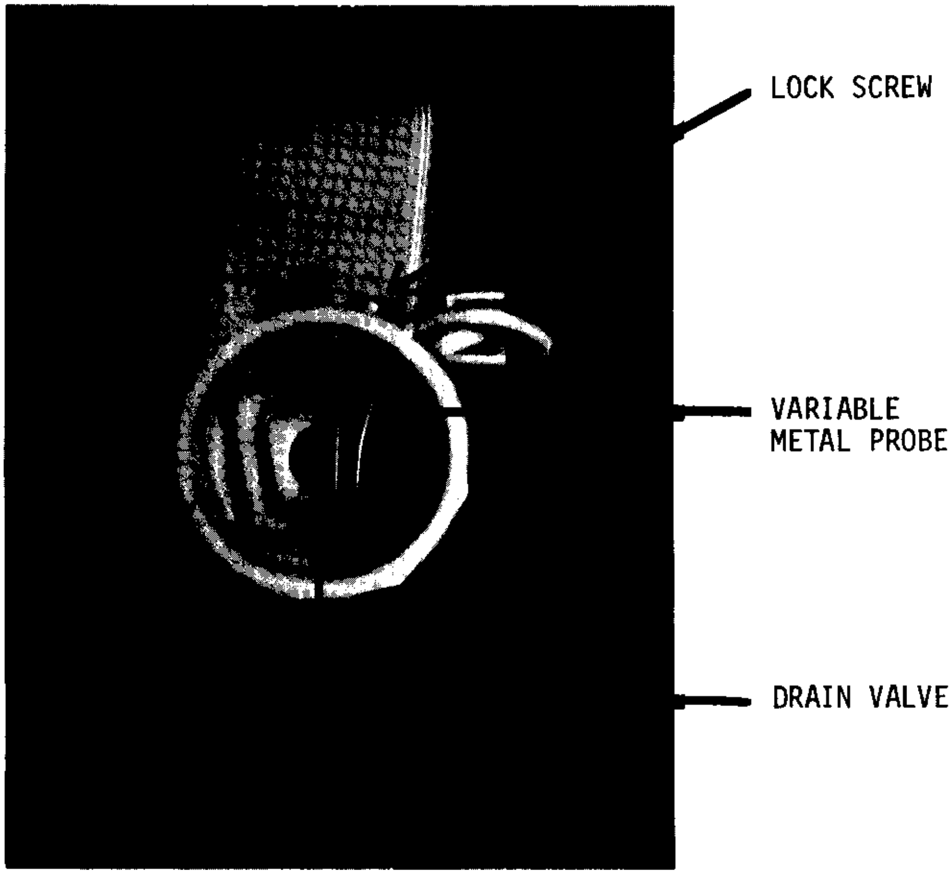


Figure 6. Rain sensor with variable metal probe, lock screw, and solonoid controlled drain valve.

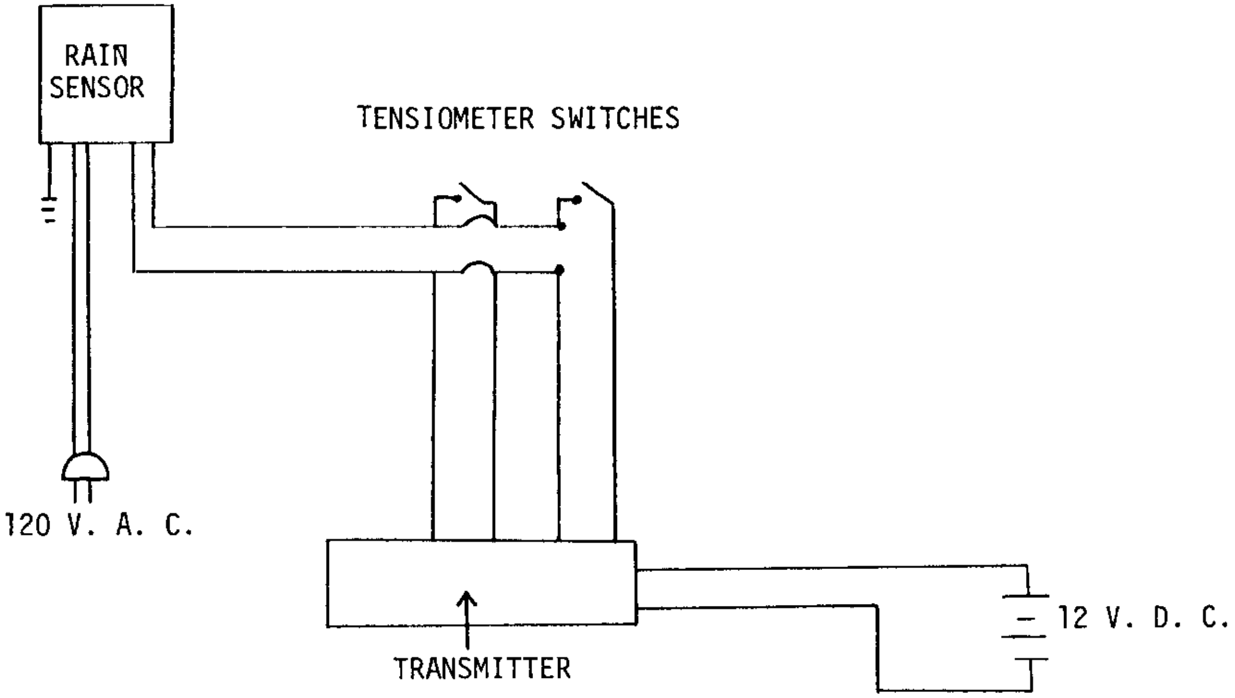


Figure 7. Block diagram of rain sensor-tensiometer installation.

gation system will begin operating. If both tensiometer switches are open, the irrigation system will remain stopped.

Theory of Operation

The heart of the unit is a solid state induction module (Figure 8). Basically it senses the inductance of the space between the two sensing elements. This triggers a "Trace" diode. After a delay of three minutes, the circuit to the transmitter is opened. The delay eliminates false triggering of the sensor as the level of water must contact both probes for three minutes continuously.

After the switch has opened, the timer will start and continue for 2 to 24 hours until it trips the next "On" tab. The solonoid on the sensing cup will open and remain open until the cycle is complete. When the cycle is complete, the output switch will close after 1.5 minutes. This delay prevents the output switch from closing from a power failure after a timing cycle has started and allows the electronic sequencing to reset.

Maintenance

1. No mechanical or electrical maintenance is required during operation. However, the rain sensor may be cleaned while the sprinkler system is operating. First disconnect the power to the transmitter, then set the manual switch in the "Off" position and the drain valve will open for flushing. After flushing turn the manual switch on and apply power to the transmitter.

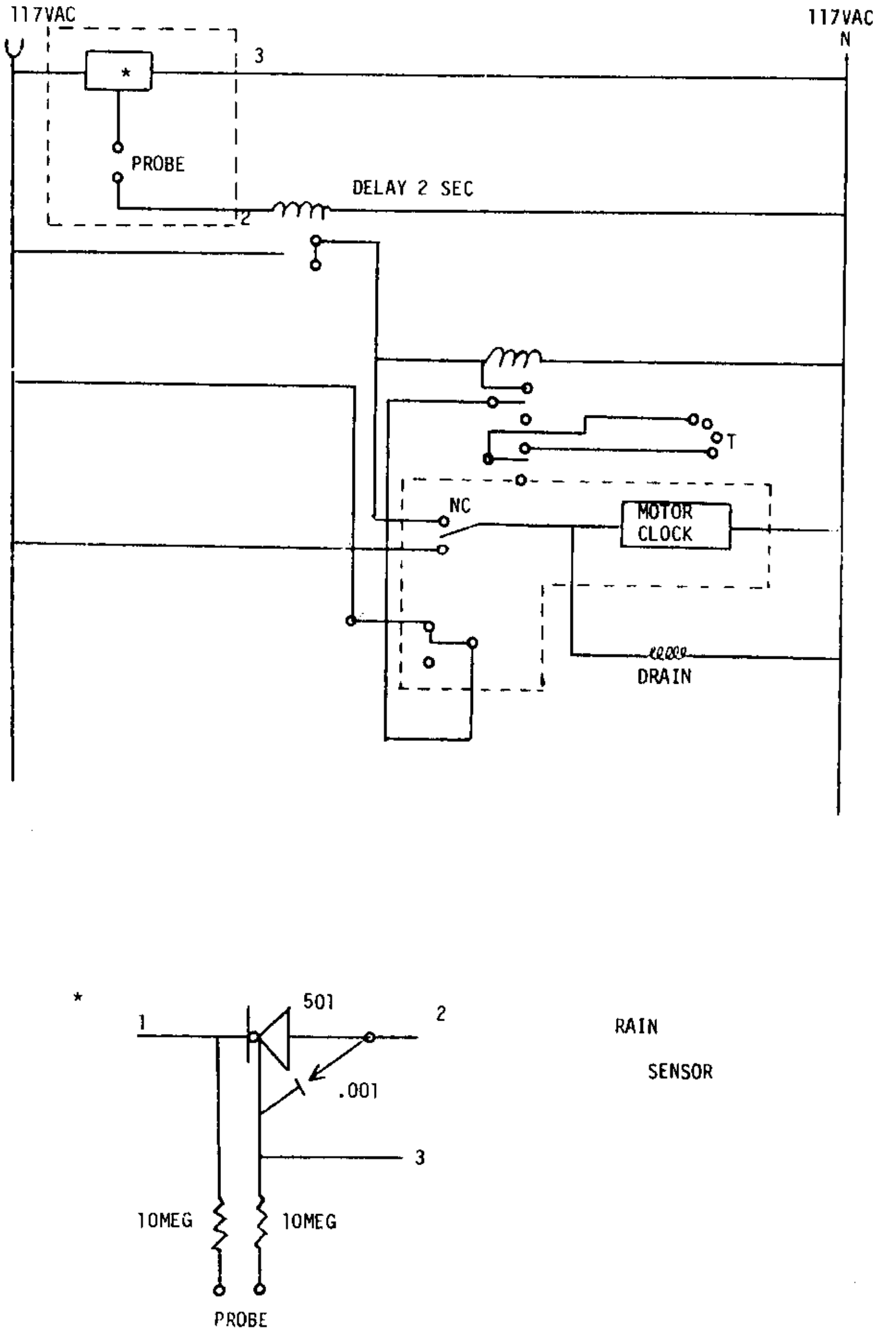


Figure 8. Block diagram of rain sensor electronics.

2. If the unit is not used for six (6) months, the clock motor <u>MUST</u> be run continuously for at least one week prior to installing the unit in the field. This is to distribute the oil in the hermetically sealed gear box and assure start-up of the clock motor. If moving gears cannot be seen, turn the motor "On" and "Off" until the gears start moving.