

CROPPING STRATEGIES UNDER IRRIGATION
IN THE OKLAHOMA PANHANDLE

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Project Completion Report
Account No. 1-1-50624

E-026

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August, 1984

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SUMMARY

The economic conditions facing irrigated agriculture have placed greater emphasis on the wise and efficient use of irrigation water. This study had two thrusts: (1) to better define crop evapotranspiration (ET) under Oklahoma conditions, and (2) to better quantify the selection of a cropping strategy for a given farm.

Three methods of estimating reference crop ET (pan, FAO Blaney-Criddle, and modified Penman) were applied to weather data for the Oklahoma Panhandle region. The results from the three methods did not agree well, but the modified Penman and pan estimates did appear to be correlated. For the three summer months, a frequency analysis was made of reference crop ET.

Field water use data from a previous OSU study were compared to climatic estimates of ET based on available weather data. The results of these comparisons were somewhat inconclusive, underscoring the need for more field data on crop ET in Oklahoma. Research to address this need is in progress in the Oklahoma Panhandle.

A large scale linear programming model has been developed to optimize the selection of a cropping strategy for an irrigated farm. Input parameters relate to the soil, crops, irrigation system, and weather. A simple application of the model has been presented, along with possible model refinements.

It is hoped that this and other work can lead to improved irrigation water management, thereby making irrigated agriculture more economically viable and enhancing Oklahoma's water resources situation.

PROBLEM STATEMENT

Water management is becoming more and more critical for irrigators in Oklahoma and other areas of the High Plains. Depressed commodity prices, coupled with escalating energy costs and declining groundwater levels, have created a financial squeeze that threatens the viability of irrigated agriculture. Although partially attributable to the government Payment in Kind (PIK) program, recent reductions in irrigated acreage in the Oklahoma Panhandle reflect this growing economic concern. Since irrigation water is a costly production input, increased emphasis is being placed on its wise and efficient use.

Irrigation water management can be categorized as either pre-season or within-season. The first includes such decisions as the choice of irrigation equipment and the selection of crops to be grown. The second category is often referred to as irrigation scheduling, the process of determining when to irrigate and how much water to apply. Both of these aspects of irrigation water management require knowledge of crop water use rates. In the irrigated areas of Oklahoma, reliable measurements or estimates of crop water use are generally lacking, thereby severely limiting our ability to efficiently manage irrigation water. One thrust of this study was to begin to better define crop water use, or evapotranspiration, under Oklahoma conditions.

Crop selection is an important part of pre-season irrigation water management. The optimum mix of crops on a particular irrigated farm (i.e., the types of crops and the areas allocated to them) is influenced by a host of factors, including the soils, climate, available water supply, pumping cost, expected crop yields, and prices of commodities. Also, a cropping strategy which is selected as "optimum" prior to planting may actually turn out to be far from optimum as the season progresses. This could be due to unusual weather patterns, unexpected diseases or pests, irrigation equipment failures, or other circumstances. To be a good manager, a farmer should integrate these many factors into his decision making process. A second thrust of this study was to develop a method to better quantify the selection of a cropping strategy for a given irrigated farm situation.

RESULTS AND OBSERVATIONS

Crop Water Use Rates

Climate-Based Estimates. The estimation of crop water use (evapotranspiration) from climatic data is a well recognized practice that provides a reasonable alternative to direct field measurements. Direct measurements of evapotranspiration (ET) are site specific and expensive, but they are quite useful in calibrating ET estimating equations. For this study, emphasis was placed on climatic estimates of ET in the Oklahoma Panhandle, where nearly half of the state's irrigated land is found.

The availability of climatological data is an important consideration in selecting ET estimation methods. The most comprehensive weather station in the Oklahoma Panhandle is located at Panhandle Research Station near Goodwell. While other weather stations in this region report only precipitation and maximum and minimum temperatures, pan evaporation and wind are also monitored at Goodwell. The evaporation pan is a U.S. Weather Bureau Class A pan, and the cup anemometer for wind measurements is located very near the pan and about 0.5 m above the ground. Solar radiation and humidity data are not available for this station. The University Center for Water Research at Oklahoma State University has purchased the complete set of Oklahoma cooperative weather observations from the National Climatic Center in Asheville, North Carolina. Thirty-three years of Goodwell data (1948 through 1980) were extracted from these tapes, covering the months of

March through October. The times of the year for beginning and ending the evaporation and wind measurements varied, but these readings typically commenced sometime in April or May and ended in October. In 1949, no pan evaporation data were collected.

The closest weather stations with solar radiation data and a similar climatology to the Panhandle were found to be located at Dodge City, Kansas (Municipal Airport) and Amarillo, Texas (International Airport). Data for these stations were obtained by purchasing "SOLMET" tapes from the National Climatic Center. The SOLMET tapes contain hourly values of cumulative solar radiation and collateral meteorological data, including drybulb temperature, dewpoint temperature, and wind speed. Goodwell is situated approximately half way between Dodge City and Amarillo, with Dodge City about 190 km to the northeast and Amarillo about 170 km to the south. An average of the evapotranspiration estimates at these two sites should then be representative of Oklahoma Panhandle conditions. Twenty-five years of data were available, January of 1952 through December of 1976 for Amarillo and July of 1952 through December of 1976 for Dodge City. For the months of March through October, the hourly observations (three hourly after 1964) were converted to daily records by summing the solar radiation values, noting the maximum and minimum temperatures, and averaging the temperatures, wind speeds, and vapor pressure deficits. This reduced the data set to a more manageable size.

Of the many possible methods for estimating evapotranspiration, three were chosen for use in this study. These methods are briefly discussed in the following paragraphs. Further details may be found in Elliott (1983).

Evaporation pan data were available for Goodwell, and the pan method was logically one of the techniques selected. Evaporation from pans reflects the integrated effect of several climatic variables including solar radiation, wind, humidity, and temperature. Plants also respond to these parameters, but not in the same way as an open water surface. Care must be exercised when using pan evaporation data to estimate crop evapotranspiration, but properly sited, maintained, and calibrated evaporation pans can provide quite reliable estimates. Reference crop evapotranspiration (ET_r) is usually taken to be the product of a constant (K) and the measured pan evaporation (E_p). A publication of the Food and Agriculture Organization (FAO) was used to estimate K values for the Class A pan at Goodwell. Monthly values of ET were then calculated.

The second of the three methods was the FAO version of the Blaney-Criddle equation, which is based primarily on temperature. The original ET equation of Blaney and Criddle incorporated a consumptive use factor dependent on mean monthly temperature and monthly percentage of annual daytime hours, and an empirical consumptive use coefficient dependent upon the type of crop. The Soil Conservation Service modified the original consumptive use coefficient to combine a climatic factor and a crop growth stage factor. However, both the original equation and the revision have been criticized because the

crop coefficients evidently incorporate some meteorological effects. The FAO Blaney-Criddle method attempts to address this shortcoming by better defining the effect of climate on evapotranspiration. In addition to temperature, the technique considers general climatic conditions such as wind, minimum relative humidity, and the ratio of actual to maximum possible sunshine hours. The Goodwell temperature and wind data were analyzed in order to obtain averages month-by-month. The Dodge City and Amarillo data were the source of the humidity and percent sunshine estimates for Goodwell. ET_r was then calculated for each month of record.

Of the various climatic approaches, energy balance or energy balance-aerodynamic equations tend to provide the most accurate results since they are based on physical laws and rational relationships. Probably the most widely used of these combination equations (combining an energy balance and a mass transport or aerodynamic term) is the modified Penman method, which incorporates solar radiation, temperature, wind, and vapor pressure deficit data. At both Dodge City and Amarillo, ET_r was calculated using monthly mean values of these climatic parameters. The ET_r values for Dodge City and Amarillo were then averaged to provide an estimate of Penman evapotranspiration at Goodwell.

Application of the pan, FAO Blaney-Criddle, and modified Penman methods yielded three different estimates of evapotranspiration for the Oklahoma Panhandle. For the months April through September, these three methods were compared (two at a time) via the scatter plots shown in Figures 1 through 3. When missing data prevented the calculation of a particular evapotranspiration estimate, that point was not plotted. In comparing the results of the three approaches, it should be pointed out that the pan and FAO Blaney-Criddle methods yield ET_r for a grass reference crop (ET_{rg}) and the modified Penman method yields ET_r for an alfalfa reference crop (ET_{ra}). The ratio of ET_{rg} to ET_{ra} is on the order of 0.87 in arid climates.

Figures 1 and 2 indicate considerable scatter and rather weak correlations between the FAO Blaney-Criddle method and each of the other two methods. In Figure 3, it can be seen that the pan estimates are considerably lower than the modified Penman estimates. This can be only partially explained by the difference in reference crops. However there is some correlation between the two, and some indication that they are describing the same phenomenon. Based on these analyses, the FAO Blaney-Criddle method was eliminated from further consideration. This result was not entirely unexpected since the Blaney-Criddle approach is more empirical in nature and based primarily on temperature and day length.

Turning to the remaining two methods (Figure 3), one or the other yields estimates which are obviously in error. (It is also conceivable that both methods are in error.) The modified Penman approach was taken to provide a more representative estimate of the "true" reference crop evapotranspiration for the following reasons: (1) the Penman and other combination methods have generally been shown to be the most accurate techniques and the most reliable methods when local

LINE DENOTES EQUAL VALUES

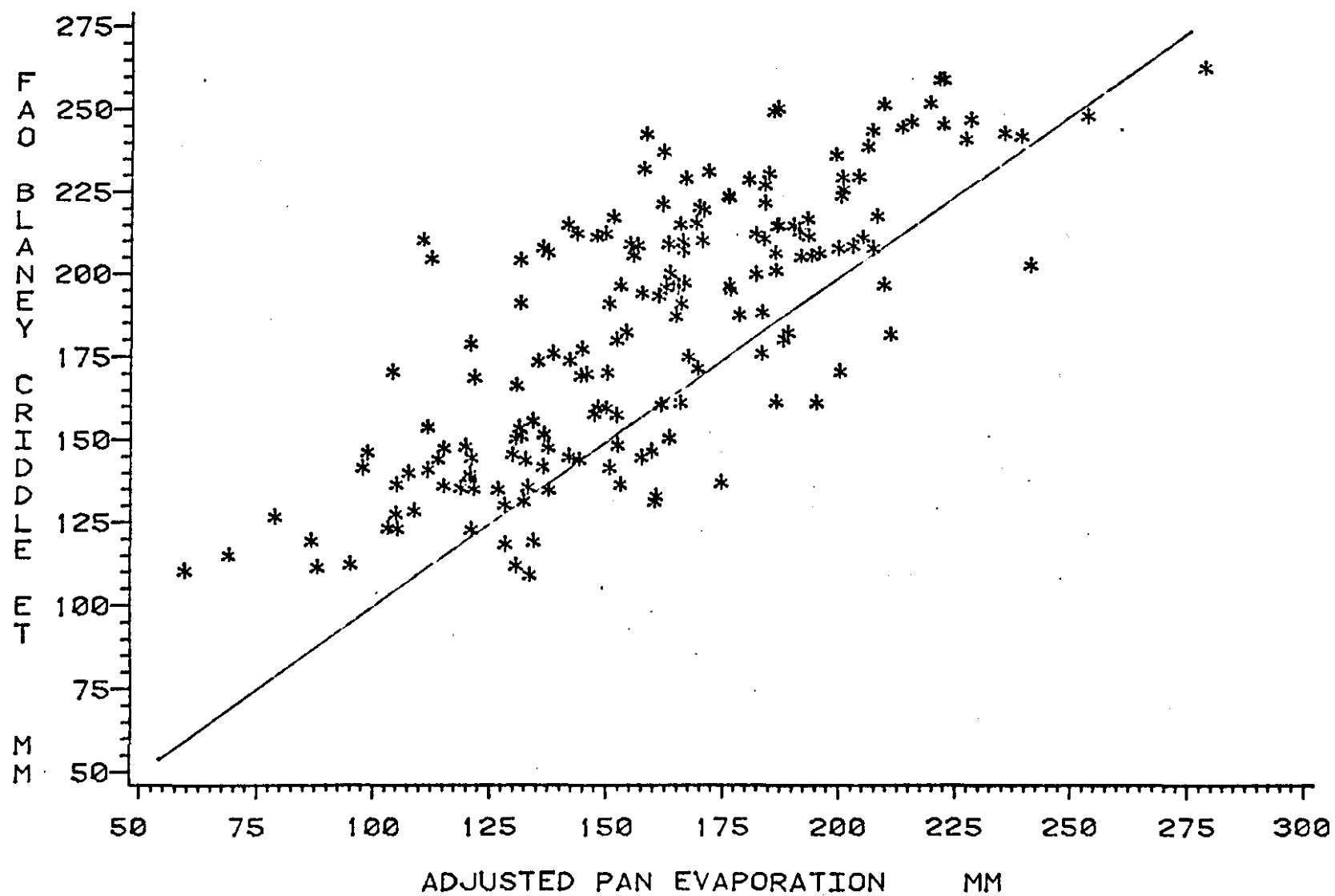


Figure 1. Monthly evapotranspiration estimates by the FAO Blaney-Criddle method (grass reference crop) and the adjusted pan evaporation method (grass reference crop) for 175 growing season months (1948-1980).

LINE DENOTES EQUAL VALUES

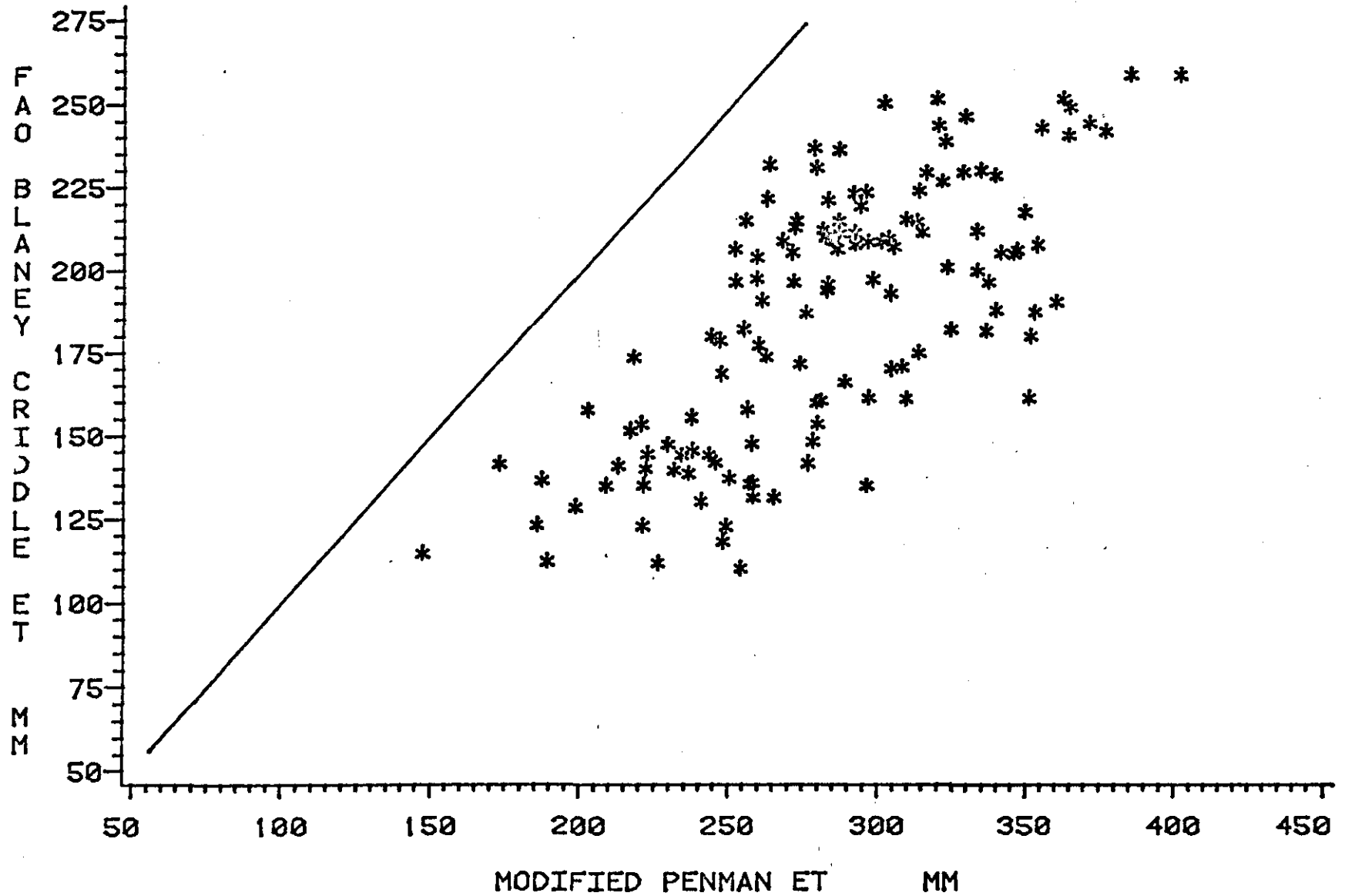


Figure 2. Monthly evapotranspiration estimates by the FAO Blaney-Criddle method (grass reference crop) and the modified Penman method (alfalfa reference crop) for 130 growing season months (1952-1976).

LINE DENOTES EQUAL VALUES

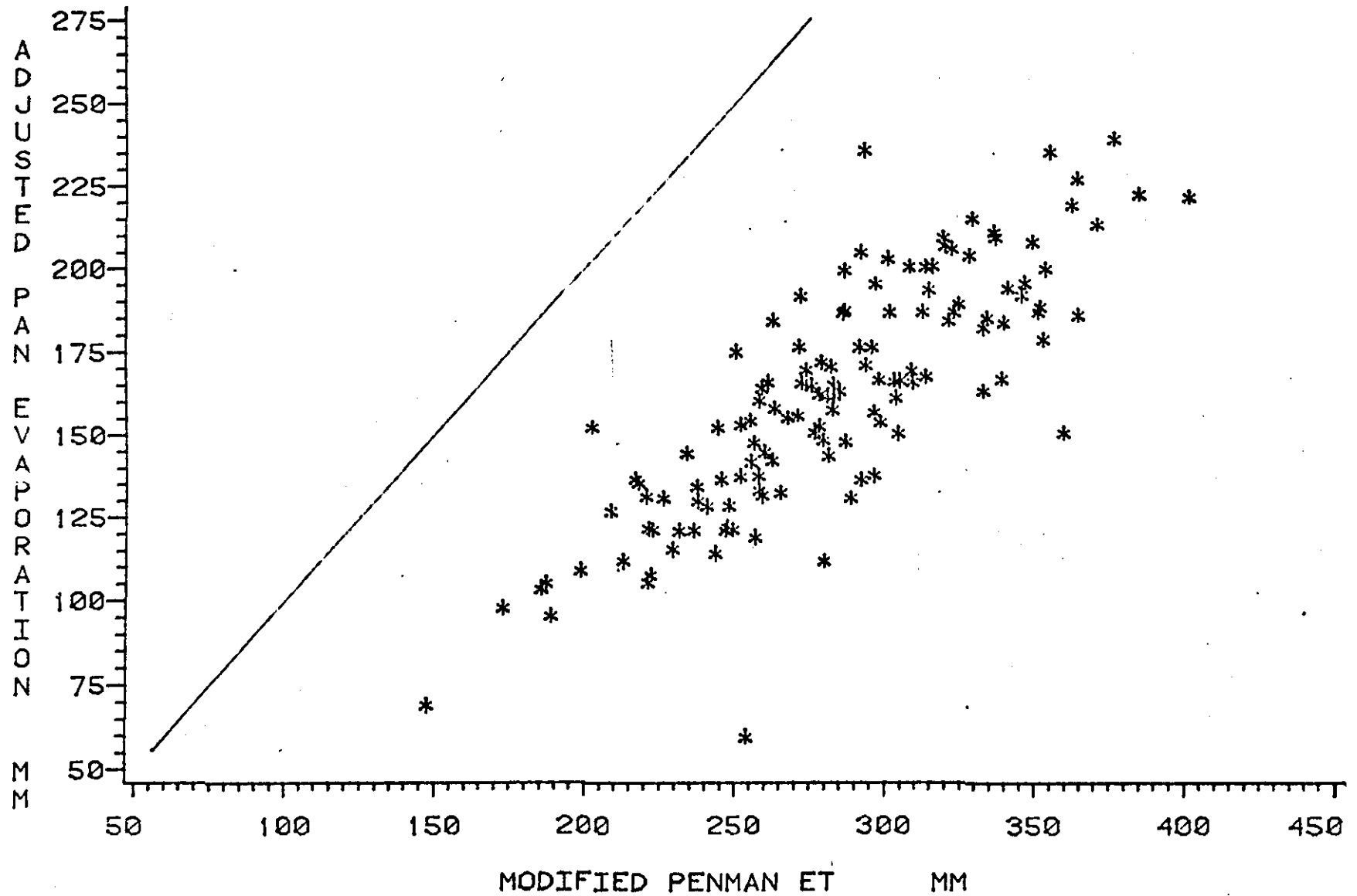


Figure 3. Monthly evapotranspiration estimates by the adjusted pan evaporation method (grass reference crop) and the modified Penman method (alfalfa reference crop) for 132 growing season months (1952-1976).

calibration data are not available; (2) the modified Penman equation is based on physical principles; and (3) there is considerable empiricism in the FAO approach to the determination of K, the pan coefficient. In fact, inspection of Figure 3 would indicate that a judiciously selected pan coefficient could result in pan estimates which closely parallel the Penman estimates. Before this approach is taken, however, one assumes that the Penman estimates are substantially "correct". The validity of this assumption can not be verified without actual field measurements of evapotranspiration. As discussed later in this report, such field measurements are currently being made.

At this point, the average of the modified Penman estimates at Dodge City and Amarillo could be used to characterize evapotranspiration in the Oklahoma Panhandle. However since Dodge City and Amarillo are each about 150 km from the Panhandle, this procedure could possibly dampen or obscure the local variability in evapotranspiration. As an alternative, it was decided to raise the general level of the pan estimates through the use of a different pan coefficient. The objective was to bring the pan estimates more nearly in line with the Penman values, while preserving the local climatic variability which should be reflected in pan evaporation. Use of the pan data also increases the period of record by about eight years as compared to the Penman data.

First an attempt was made to define the monthly pan coefficient, K, in terms of meteorological parameters. Only those months (101 in number) with less than four missing values of daily pan evaporation were used in the analysis. This hopefully eliminated any bias resulting from months with incomplete data, particularly at the beginning and end of the season. No meaningful correlations resulted when the ratio of Penman ET_{ra} to pan evaporation (i.e., the pan coefficient) was regressed on wind speed, maximum temperature, and average temperature. However when this same ratio was plotted against pan evaporation, there appeared to be a linear trend of decreasing K with increasing pan evaporation. This relationship suggested that the modified Penman ET_{ra} could be written as a quadratic function of pan evaporation:

$$ET_{ra} = b_1 E_p + b_2 (E_p)^2 \quad (1)$$

where E_p is "unadjusted" pan evaporation. A regression analysis was performed using Equation 1, and b_1 and b_2 were found to have the values 1.27 and -0.00109, respectively, with ET_{ra} and E_p in mm per month. The standard error of the regression equation was equal to 22.7 mm, corresponding to a coefficient of variation for the dependent variable (ET_{ra}) of 7.9 percent. The regression fit was not improved by the addition of an intercept term in Equation 1, since its value was very near zero. The 101 data points and the regression line are plotted in Figure 4.

A frequency analysis was carried out for the three months with highest evaporative demand (June, July, and August). Equation 1 was used to estimate alfalfa reference crop evapotranspiration from pan

LINE DENOTES QUADRATIC REGRESSION
(INTERCEPT = 0)

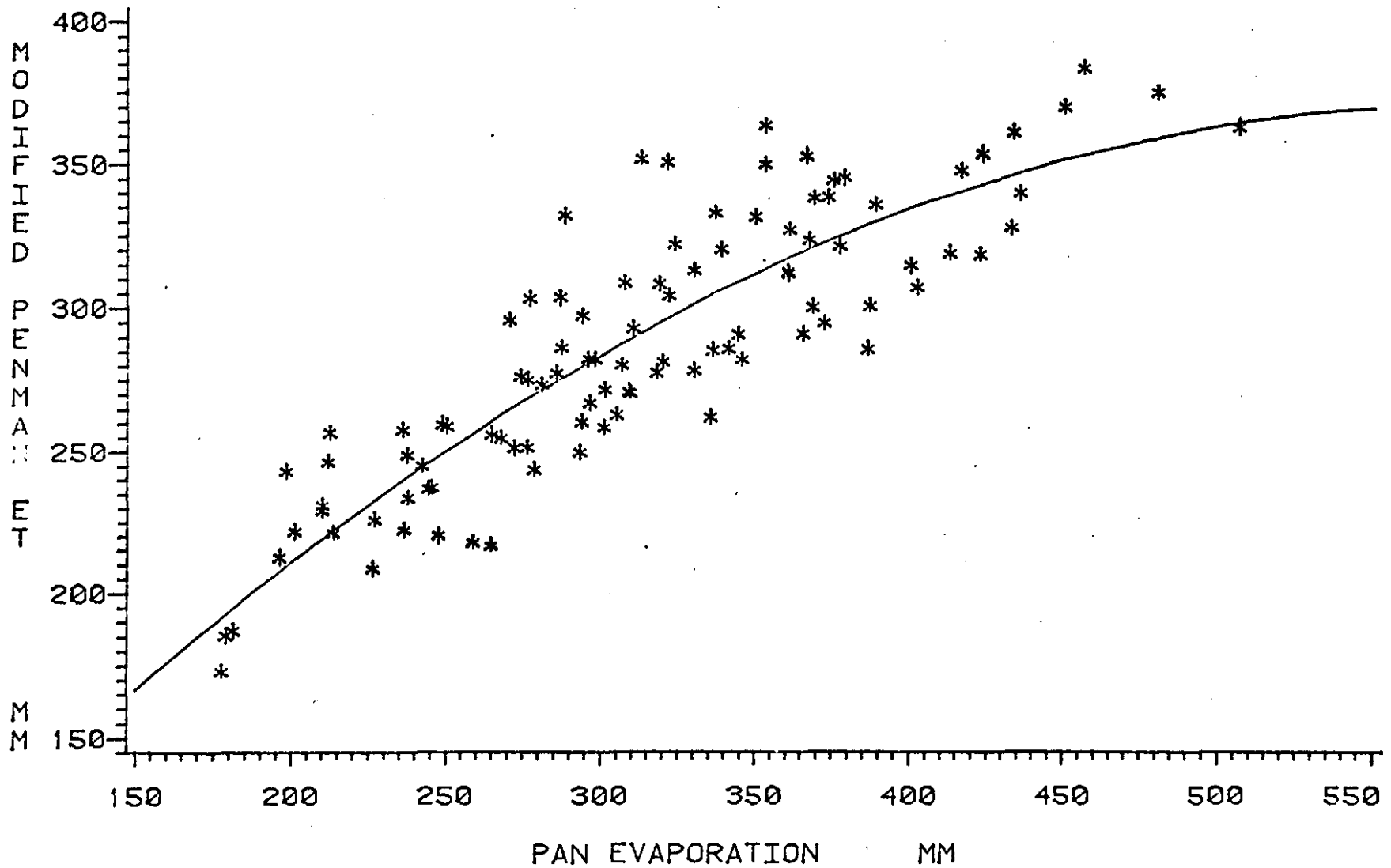


Figure 4. Monthly modified Penman evapotranspiration versus unadjusted pan evaporation for 101 growing season months (1952-1976).

evaporation. The entire period of record (1948-1980) was used, but individual months with more than three missing values of daily pan evaporation were eliminated from the analysis. This left sample sizes of 28, 29, and 27 for June, July, and August, respectively. For each month, the resulting values were ranked and plotted on normal probability paper. Visual inspection of the plots indicated that each set of data fit the normal distribution reasonably well. Using the normal distribution, then, the evapotranspiration amounts for various return periods were determined (Table 1). Frequency analyses such as the example given are an aid in evaluating the adequacy of irrigation systems over a range of possible climatic conditions. They are also helpful in assessing the risk involved with particular cropping decisions or irrigation scheduling procedures.

Table 1. Results of a frequency analysis of estimated monthly evapotranspiration (alfalfa reference crop) at Goodwell, Oklahoma.

Return Period (years)	Alfalfa Reference Crop Evapotranspiration (mm)		
	June	July	August
2	301	323	288
5	330	344	313
10	345	356	330
20	357	365	342

Correlating Climatic Estimates and Field Measurements.

Climate-based methods of estimating ET should be regionally calibrated using field measurements. Primarily due to a scarcity of field data, these calibrations have not previously been carried out under Oklahoma conditions. In a previous study¹ by John F. Stone and associates (Agronomy Department, Oklahoma State University), field water use data were collected at two Oklahoma sites during the 1973 and 1974 irrigation seasons. In the present study, these data were compared to climatic estimates of ET based on available weather data for the two sites. These sites are the Caddo Research Station (formerly the Peanut Research Station) at Fort Cobb and the Panhandle Research Station at Goodwell. During both years, the crops grown were irrigated peanuts at Fort Cobb and irrigated grain sorghum at Goodwell.

The ET measurements of Stone and associates were made using the water budget approach. Changes in soil water content were monitored with neutron probe instrumentation. Water movement downward out of the root zone was determined through tensiometer measurements. In

¹ Evapotranspiration Reduction by Field Geometry Effects, Final Technical Completion Report B-029-OKLA (14-31-0001-4120), The Oklahoma Water Resources Research Institute, November, 1976.

applying the water budget, periods of time with no irrigation and little or no rainfall were selected. It could thus be assumed that all rainfall entered the soil. These time periods varied from three to fourteen days in length and were typically about one week long. The water use data resulting from the budget were then expressed as a daily average ET in cm over the time period in question.

In making climatic estimates, six methods for determining reference crop ET were used: FAO Blaney-Criddle, FAO Radiation, Modified Jensen-Haise, Modified Penman, FAO Penman, and Pan Evaporation. These methods vary in their sophistication and in their data requirements. Further details may be found in Biamah (1983). Complete sets of the necessary weather data were not available for the two sites. At Fort Cobb, there were virtually no data for 1973 and in 1974 there were humidity, maximum temperature, wind speed, and wind direction data only. So the missing data were obtained from nearby weather stations at Anadarko and Chickasha. Oklahoma City's humidity and percent sunshine data were incorporated into the calculations where needed. Solar radiation estimates were obtained using procedures outlined by the FAO. At Goodwell, the only missing climatic data were solar radiation and vapor pressure deficits. Data from Dodge City, Kansas and Amarillo and Bushland, Texas were averaged in order to give approximate values for Goodwell. ET calculations were made based on average climatic data over the particular time period. Values of reference crop ET (either grass or alfalfa) were adjusted to peanut or grain sorghum ET using crop coefficients presented in FAO tables.

The estimated and measured ET values are presented in Tables 2 and 3 for Fort Cobb and Goodwell, respectively. For several of the time periods, it can be seen that there is considerable variability between the measured (water budget) ET and the climatic estimates. This variability is particularly evident for the 1973 Goodwell data, but no explanation for these differences is readily apparent. On the other hand, the measurements and estimates compare favorably for certain time periods, especially August 13-17, 1973 and September 4-12, 1974 at Fort Cobb, and August 3-5, 1974 and August 29 - September 4, 1974 at Goodwell. Overall, the results of these comparisons appear to be somewhat inconclusive for the following seasons: (1) the rather short length of record, (2) the limited local weather data and the accompanying need to incorporate estimates, and (3) the uncertainty in crop coefficients to convert reference crop ET to actual crop ET.

The results of this analysis have underscored the need for more field data on crop water use in Oklahoma. During the 1984 irrigation season, research to address this need is in progress at the Panhandle Research Station at Goodwell (Figures 5-8). Neutron probe measurements for determining water use are being taken on five irrigated crops and at two irrigation treatment levels. It is hoped that this larger, season-long data base will be useful in better defining crop ET. Additionally, a microprocessor-based weather station has been installed at the same site. This station is recording, in machine readable form, all of the climatic parameters needed as inputs to the various ET estimation procedures. Thus more detailed calibration and validation of the climate-based methods should be possible.

TABLE 2. Climatic estimates and water budget measurements of peanut evapotranspiration at the Caddo Research Station, Fort Cobb, Oklahoma, during selected time periods of the 1973 and 1974 irrigation seasons.

Method	PEANUT EVAPOTRANSPIRATION (mm/day)							
	1973 Irrigation Season			1974 Irrigation Season				
	August 3-10	August 13-17	August 20-27	July 30- August 9	August 12-16	August 19-23	September 4-12	
FAO Blaney-Criddle	5.7	5.9	6.0	5.4	5.9	5.7	3.6	
FAO Radiation	6.7	6.7	6.8	6.1	6.0	5.8	4.3	
Modified Jensen-Haise	8.4	8.9	9.0	6.9	7.4	7.3	4.9	
Modified Penman	8.0	7.8	8.1	8.3	8.4	8.3	5.9	
FAO Penman	7.1	7.1	7.2	8.0	8.0	8.0	4.9	
Pan Evaporation	5.3	5.6	6.8	4.0	4.2	3.3	3.8	
Water Budget	3.4	7.3	4.8	4.2	5.4	7.1	4.4	

TABLE 3. Climatic estimates and water budget measurements of grain sorghum evapotranspiration at the Panhandle Research Station, Goodwell, Oklahoma, during selected time periods of the 1973 and 1974 irrigation seasons.

Method	PEANUT EVAPOTRANSPIRATION (mm/day)							
	1973 Irrigation Season			1974 Irrigation Season				
	July 23-27	August 1-15	August 20-28	August 3-5	August 5-14	August 14-20	August 29- Sept. 4	
FAO Blaney-Criddle	5.5	5.1	6.5	5.2	5.4	6.8	3.8	
FAO Radiation	7.1	7.3	7.3	5.0	6.4	7.4	4.8	
Modified Jensen-Haise	9.8	10.1	10.4	6.2	8.1	10.0	5.9	
Modified Penman	9.5	9.4	14.6	8.5	9.7	13.3	7.2	
FAO Penman	8.2	8.4	11.6	6.3	7.5	9.9	5.5	
Pan Evaporation	7.4	7.0	9.8	5.3	7.7	10.6	4.5	
Water Budget	1.7	2.0	1.4	5.9	4.3	3.9	4.1	



Figure 5. Determination of soil moisture in alfalfa with a neutron probe.



Figure 6. Tensiometer installation in corn.



Figure 7. Microprocessor-based weather station.



Figure 8. Weather data logger, printer, and cassette storage.

Selection of a Cropping Strategy

The Linear Programming Model. The model developed for choosing a cropping strategy is an application of linear programming, a technique which is well suited to resource allocation problems. Linear programming maximizes (or minimizes) an objective function, subject to linear constraints. In this case, the objective is to optimize net returns and the constraints include such factors as land area, irrigation water supply, pumping time, and available soil moisture capacity.

The objective function is

$$\text{Maximize } \left[\sum_{i=1}^m (a_i y_i p_i) - (QHC + L) \sum_{i=1}^m \sum_{j=1}^n t_{ij} - \sum_{i=1}^m (a_i c_i) \right] \quad (2)$$

where m = number of crops being considered

n = number of days being considered

a_i = area planted to crop i

y_i = projected yield of crop i per unit area

p_i = projected price of crop i per unit yield

Q = pump discharge volume per unit time

H = total pumping head

C = pumping energy cost per unit volume per unit head

L = cost of irrigation labor per unit of pumping time

t_{ij} = pumping time for crop i on day j

c_i = other production costs per unit area for crop i (seed, fertilizer, pesticides, machinery and fuel, labor, etc.)

The unknowns appearing in the objective function are the a_i 's and the t_{ij} 's. The other variables defined above are input parameters and may be considered constants for a given problem. Capital costs for irrigation equipment are not considered since it is assumed that an irrigation system is already in place.

The land area constraint is

$$\sum_{i=1}^m a_i \leq A \quad (3)$$

where A is the total potentially irrigated land area. The constraints on daily pumping time are

$$\sum_{i=1}^m t_{ij} \leq t_{\max} \quad (\text{for each } j) \quad (4)$$

where t_{\max} is the specified maximum allowable daily pumping time ($t_{\max} \leq 24$ hours).

The remaining constraints deal with daily soil water budgets. For each crop:

$$(D_o + P_1 - ET_1 - D_{\min,1})a + E_aQt_1 - S_1 \geq 0 \quad (5)$$

$$(D_o + P_1 - ET_1 - D_{\max,1})a + E_aQt_1 - S_1 \leq 0 \quad (6)$$

$$(D_o + P_1 - ET_1) a + E_aQt_1 - S_1 - R_1 = 0 \quad (7)$$

$$R_1 + (P_2 - ET_2 - D_{\min,2})a + E_aQt_2 - S_2 \geq 0 \quad (8)$$

$$R_1 + (P_2 - ET_2 - D_{\max,2})a + E_aQt_2 - S_2 \leq 0 \quad (9)$$

$$R_1 + (P_2 - ET_2) a + E_aQt_2 - S_2 - R_2 = 0 \quad (10)$$

⋮
⋮
⋮

$$R_{n-1} + (P_n - ET_n - D_{\min,n})a + E_aQt_n - S_n \geq 0 \quad (11)$$

$$R_{n-1} + (P_n - ET_n - D_{\max,n})a + E_aQt_n - S_n \leq 0 \quad (12)$$

$$R_{n-1} + (P_n - ET_n) a + E_aQt_n - S_n - R_n = 0 \quad (13)$$

Equations 5-7 are written for day 1, equations 8-10 for day 2, and equations 11-13 for day n. The crop subscript i has been deleted to simplify the expressions. The parameters are defined as follows:

D_o = initial depth of available water in crop root zone on day 1

P_j = precipitation depth infiltrating into the soil on day j

ET_j = crop evapotranspiration on day j

$D_{\min,j}$ = minimum allowable depth of available water in crop root zone on day j

$D_{\max,j}$ = maximum possible depth of available water that can be stored in crop root zone on day j

a = crop area

E_a = application efficiency of the irrigation system (ratio of water stored in root zone to total water applied)

Q = pump discharge volume per unit time

t_j = pumping time for this crop on day j

S_j = volume of deep percolation ("surplus" water) out of the crop root zone on day j

R_j = volume of "residual" available water remaining in the crop root zone at the end of day j (and carried over to day (j+1))

Note that each term in the equations represents a water volume rather than a water depth. If written as depths instead of volumes, the variable "a" would appear in the denominator and the constraints would

no longer be linear. The soil water budgets are written for the "average" field condition. Due to the time required to complete an irrigation, some areas of the field would be wetter than others.

It is evident that this linear programming approach results in a large number of constraints (rows in the matrix), totaling $(1 + n + 3mn)$. The number of variables (columns in the matrix) is $(m + 3mn)$. For the case of 3 crops and a 100 day irrigation season, the matrix would have 1001 rows and 903 columns. The potential size of the matrix suggests the use of a linear programming algorithm suited to such large scale problem solving.

The IBM program product entitled Mathematical Programming System Extended/370 (MPSX/370) is supported by the Oklahoma State University Computer Center. This is a versatile linear programming package which is particularly applicable to large problems. The solution is carried out by the ordered execution of a set of procedures which are specified in a control language program. The control language is powerful in that only a few statements are needed to set up and carry out a linear programming solution.

Input data, in card image format, are read using the CONVERT procedure. The input data must be provided in three sections called ROWS, COLUMNS, and RHS. Data cards in the ROWS section specify the name to be assigned to each row of the matrix and the type of constraint represented by the row. The constraint type is one of the following: equality, greater than or equal to, less than or equal to, or no constraint (representing the objective function row). Data cards in the COLUMNS section specify the names of the columns, the values of all non-zero matrix elements, and the name of the row in which each element is to be entered. Finally, data cards in the RHS section are used to define the values of all non-zero elements in the "right-hand side" of the constraint rows.

The size of this input data file necessitates that it be computer generated. A FORTRAN program was developed to produce an input data file in the format specified by MPSX. The program consists largely of repetitive WRITE statements and their accompanying FORMAT statements. The FORTRAN program also reads the input parameter data for the particular problem and calculates the values of the elements in the linear programming matrix. The input parameters which must be specified are as follows:

- 1) total potentially irrigated land area (A)
- 2) soil's available water capacity (depth of water per unit depth of soil)
- 3) maximum allowable daily pumping time (t_{\max})
- 4) pump discharge volume per unit time (Q)
- 5) total pumping head (H)
- 6) overall efficiency of the pumping plant
- 7) application efficiency of the irrigation system (E_a)
- 8) cost of energy per unit volume pumped per unit head, at 100 percent efficiency
- 9) cost of irrigation labor per unit of pumping time (L)

- 10) calendar days on which the simulation is to begin and end
- 11) number of crops being considered (m) and their names
- 12) projected crop yields per unit area (y_i)
- 13) projected crop prices per unit yield (p_i)
- 14) crop production costs (other than irrigation water) per unit area (c_i)
- 15) crop planting dates
- 16) crop effective cover dates
- 17) minimum crop root zone depths (at planting)
- 18) maximum crop root zone depths (at effective cover)
- 19) polynomial constants for crop curves
- 20) allowable soil moisture depletions expressed as percent of total available water in crop root zone
- 21) initial depths of available water in crop root zones
- 22) daily precipitation data
- 23) daily values of reference crop evapotranspiration

The planting dates, effective cover dates, crop curve constants, and reference crop evapotranspiration values are used in calculating the daily evapotranspiration for each crop. The root zone depths are used in determining the total available water capacity. It is assumed that the root zone depth increases linearly from a minimum at planting to a maximum at effective cover. Since the model incorporates deterministic weather inputs, one or more years of historical data may be used. The dynamics of climate within an irrigation season must of course be addressed through irrigation scheduling.

An Example Application. To demonstrate how the model might be applied, let us consider the selection of a cropping strategy for a system with the following assumed characteristics:

- 1) land area = 55 ha (136 ac)
- 2) soil's available water capacity = 15 cm/m (1.8 in/ft)
- 3) maximum daily pumping time = 24 hrs
- 4) pump discharge = 65 L/s (1030 gpm)
- 5) total pumping head = 100 m (328 ft)
- 6) overall pumping plant efficiency = 65%
- 7) irrigation application efficiency = 75%
- 8) energy cost at 100% efficiency = \$0.02/ha-cm m (\$0.0752/ac-ft ft)
- 9) irrigation labor cost = \$1/pumping hr
- 10) simulate June 1 through August 31 (calendar days 152 through 243)
- 11) two crops (alfalfa and corn)
- 12) alfalfa yield = 14.6 t/ha (6.5 tons/ac)
corn yield = 7.53 t/ha (120 bu/ac)
- 13) alfalfa price = \$82.70/t (\$75/ton)
corn price = \$118/t (\$3/bu)
- 14) other production costs for alfalfa = \$412/ha
other production costs for corn = \$552/ha
- 15) alfalfa growth starts on April 1 (day 91)
corn is planted on May 1 (day 121)
- 16) alfalfa cuttings occur on days 135, 165, 195, 225, and 255
corn effective cover is reached on July 25 (day 206)
- 17) alfalfa root zone depth at start of growth = 1.8 m (5.9 ft)
corn root zone depth at planting = 0.15 m (0.49 ft)

- 18) maximum root zone depth for alfalfa = 1.8 m (5.9 ft)
maximum root zone depth for corn = 1.2 m (3.9 ft)
- 19) crop curve constants taken from Kincaid and Heermann (1974)
- 20) for both crops, allowable depletion = 50% of total available water
- 21) available water depth for alfalfa on June 1 = 20 cm
available water depth for corn on June 1 = 6 cm
(each of these represents about 3/4 of total available water capacity based on the root zone depth at that time)
- 22) 1968 precipitation records
- 23) 1968 evaporation pan data converted to alfalfa reference crop evapotranspiration (after Elliott, 1983)

The crop yield, price, and production cost values (items 12-14) were obtained from current crop enterprise budgets for the Oklahoma Panhandle region (Agricultural Economics Department, Oklahoma State University). In selecting the 1968 climatic data as representative (items 22-23), thirty-three years of weather records for Goodwell, Oklahoma were analyzed. For the three summer months, the long term average temperature, precipitation, and evaporation were most nearly matched with the 1968 data. It was assumed that all precipitation infiltrated into the soil (the maximum daily rainfall during these three months was 2.90 cm). Data for a summer with unusually mild or severe evaporative conditions could obviously give different model results. The sensitivity of optimum crop mix to weather patterns is an important area for additional study.

When the above hypothetical data set was used as an input to the linear programming model, the optimum solution was to plant the entire 55 ha to alfalfa. As a simple check of the model, several of the key input parameters were varied and additional runs were made. These results are presented in Table 4. The input parameter changes affected the optimum solution in the expected manner (at least qualitatively). An increase in corn price caused a shift from alfalfa to corn as the preferred crop. When the cost of energy was tripled, the optimum solution was still 55 ha of alfalfa but net returns declined significantly. Finally, when pump discharge or maximum daily pumping time was reduced, the total irrigated area dropped below 55 ha due to insufficient water.

The intent of this example is not to provide definitive conclusions relative to a cropping strategy, but rather to demonstrate an application of the model. Alfalfa and corn are somewhat similar in that they both have a fairly high water demand. If crops such as wheat and grain sorghum (the other two major crops in the Oklahoma Panhandle) were included in the model, the relative timing and magnitude of water use would no doubt be more of a factor. As with any model, the quality of the results can be no better than the quality of the input data. As discussed previously in this report, there is a definite need to better define evapotranspiration rates for irrigated crops in Oklahoma.

Model Refinements. In addition to looking at more crops, several possible model refinements will be investigated. The alloca-

TABLE 4. Model results for the example application.

Input Parameters*				Optimum Solution		
Corn Price (\$/t)	Pump Discharge (L/s)	Energy Cost (at 100% efficiency) (\$/ha-cm m)	Maximum Daily Pumping Time (hrs)	Area to Alfalfa (ha)	Area to Corn (ha)	Net Returns (\$)
118	65	0.02	24	55	0	31,200
197	65	0.02	24	0	55	36,700
118	40	0.02	24	44	0	24,400
118	65	0.06	24	55	0	9,200
118	65	0.02	16	48	0	27,200

*All other input parameters are constant in this example and are assigned the values presented in the text.

tion of land to dryland crops could be easily incorporated as an option. This addition would impact the model formulation only in the objective function and the land area constraint. As energy prices rise and groundwater levels decline, more and more attention is being paid to the dryland option.

It would also be a simple matter to let the model user specify upper or lower limits on the area allocated to one or more crops. For instance, a farmer may have special reasons for growing or not growing a certain crop. These constraints could be included in the model.

The current model assumes a fixed crop yield for a given level of production inputs and a given soil moisture constraint. Linear programming does not have the capability of addressing the dynamics of the yield-water interaction, as some crop growth models attempt to do. However incorporating a yield-water relationship, perhaps in the form of a simple water production function, should improve the model. Here again, the lack of necessary data can be a problem.

Finally, the model does not dictate a minimum application depth for a given irrigation. Conceivably, the optimum solution could call for very light, frequent irrigations, which are not in accordance with most field irrigation practices. This situation did not appear to be a problem in the limited number of runs that were made. However, it would be desirable to be able to impose a constraint on minimum irrigation depth within the linear programming framework.

GROUPS BENEFITING

A number of groups will benefit from this study and further research in crop water use and the selection of cropping strategies. These groups include farmers and farm managers, personnel of the Cooperative Extension Service and Soil Conservation Service, water policy decision makers, and peer researchers.

NEW CONTRIBUTIONS

The evapotranspiration estimates for the Oklahoma Panhandle, although somewhat preliminary at this time, fill a void in available knowledge and have value beyond the scope of this project. Such estimates are vital inputs in decision making. They are needed not only in irrigation water management research, but also for practical, farm-level, irrigation scheduling procedures. The end result can be improved water and energy conservation in irrigated agriculture.

The cropping strategies model is a new contribution that serves to better quantify the process of crop selection by farm decision makers. A number of factors need to be considered in the selection of a cropping strategy, and the model helps one to objectively evaluate these factors.

Since agriculture is the largest water user in Oklahoma and since water availability and cost are becoming initial concerns, the results of this and other irrigation water management research efforts can have a significant positive influence on the water resources situation of the state.

PUBLICATIONS

Elliott, R. L. and S. J. Ehrle. 1984. Computerized Crop Scheduling for the Oklahoma Panhandle. ASAE Paper No. 84-2096, presented at the Summer Meeting of the American Society of Agricultural Engineers, Knoxville, Tennessee, June 24-27.

Biamah, E. K. 1983. Comparison Between Field Measurements and Climatic Estimates of Crop Water Use in Oklahoma. Unpublished Report for the Master of Agricultural Engineering Degree, Oklahoma State University, Stillwater, December.

Elliott, R. L. 1983. Evapotranspiration Estimates for the Oklahoma Panhandle. ASAE Paper No. SWR-83-301, presented at the Southwest Region Meeting of the American Society of Agricultural Engineers, North Little Rock, Arkansas, April 13-15.

MEETINGS AND PRESENTATIONS

ASAE Summer Meeting, Knoxville, Tennessee, June 24-27, 1984.
Presented ASAE Paper No. 84-2096 entitled "Computerized Crop Scheduling for the Oklahoma Panhandle".

Ogallala Aquifer Symposium II, Lubbock, Texas, June 4-7, 1984.

Water: Key to Agriculture's Future, Stillwater, Oklahoma, May 9, 1984.
Presented paper entitled "Irrigation Scheduling Technologies and Their Application".

ASAE Winter Meeting, Chicago, Illinois, December 13-16, 1983.

ASAE Summer Meeting, Bozeman, Montana, June 26-29, 1983.

ASAE Southwest Region Meeting, North Little Rock, Arkansas, April 13-15, 1983.
Presented ASAE Paper No. SWR-83-301 entitled "Evapotranspiration Estimates for the Oklahoma Panhandle".

International Symposium on Plant Production and Management Under Drought Conditions, Tulsa, Oklahoma, October 4-6, 1982.