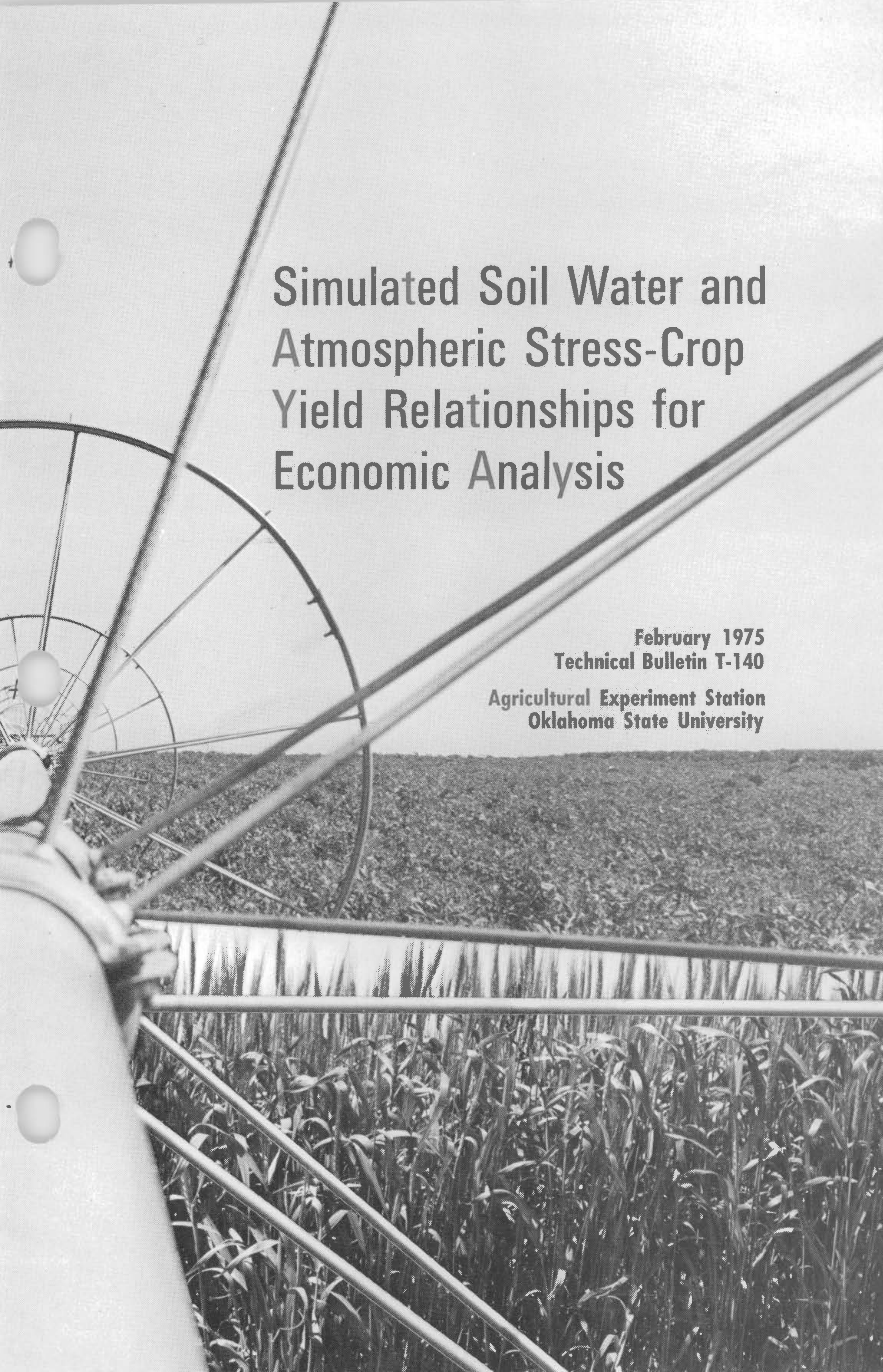

Simulated Soil Water and Atmospheric Stress-Crop Yield Relationships for Economic Analysis

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Contents

ABSTRACT

This bulletin presents a model capable of simulating soil water-crop yield relationships for the major irrigated and dryland crops produced in the Oklahoma Panhandle. The production subset of the model consists of a soil-water balance which computes daily soil water levels on the basis of rainfall, irrigation and evapotranspiration.

Critical stages of plant development are identified for wheat, grain sorghum and corn, and crop yields are determined based on the length and severity of soil water and atmospheric stress in relation to the stages of plant development. The production subset of the model is validated by simulating series of crop yields under both dryland and irrigated conditions.

The production subset is combined with a farm firm simulator designed to represent a typical irrigated farm operation in the Oklahoma Panhandle. The total acreage of each crop is divided into crop blocks, or fields, to simulate the competition for irrigation water during certain portions of the crop year. A general irrigation strategy typical of that followed by many of the better operators in the study area is simulated over a 20-year period and replicated 20 times.

The results which consist of series of crop yields for dryland and irrigated wheat, dryland and irrigated grain sorghum and irrigated corn for grain and silage, are presented in tabular form. Crop yields and amounts of irrigation water applied, as well as the variability of dryland and irrigated yields, were judged realistic by agronomists, irrigation specialists and farm management experts in the area.

The model has been applied to evaluate three water-use regulation alternatives in the central basin of the Ogallala Formation. The possibilities for additional research with this model, or a more refined model containing all crops in the area, appear substantial. For example, a model that predicts more accurately for the full range of atmospheric and soil water conditions might be used to evaluate the sensitivity of each crop to stress at each stage of plant development.

In addition, the model might be used in combination with linear programming, dynamic programming or statistical decision theory techniques to isolate optimum irrigation strategies for farmers in the area. Portions of the model may be adaptable to other semi-arid regions of this and other countries.

Simulating Soil Water and Atmospheric Stress-Crop Yield Relationships for Economic Analysis

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INTRODUCTION

The availability of large quantities of good quality underground water coupled with technological advances in irrigation pumping and distribution systems has had a significant impact on farming in the Great Plains. Irrigated acreage has increased rapidly over the last decade and current trends indicate that the growth will continue through the 1970's. Much of this additional irrigated acreage will draw its water from the Ogallala Formation, a major aquifer underlying a large portion of the Great Plains. The static water level is declining in the intensely irrigated areas of the Ogallala, including the Southern High Plains of Texas, the Oklahoma Panhandle and southwestern Kansas.

In the Central Basin of the Ogallala Formation, which is bounded on the north by the Arkansas River in Kansas and on the south by the Canadian River in Texas, withdrawals of irrigation water have exceeded natural recharge every year since 1954. [5, p. 8]. Physical exhaustion of the aquifer is not a realistic possibility. However, economic exhaustion may occur long before any hint of physical exhaustion appears. Economic exhaustion is related to the pumping and distribution costs of a unit of water, and to the value of production forthcoming from that unit of water. Economic exhaustion occurs when the per unit value in use of water pumped from the aquifer becomes less than the cost of pumping and applying the unit of water.

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Continued expansion of irrigated acreage leads to declining water levels which interact with declining pump yields to increase the per unit cost of irrigation water and, other things equal, to reduce net returns per acre of irrigated crop production over time. Sooner or later it will become uneconomic to pump water for irrigation purposes in parts of the study area. Those parts of the study area with the smallest saturated thickness of the water-bearing formation will be affected first.

Greater efficiency of water use may be achieved by increasing crop yields while maintaining or reducing the amount of water applied. Researchers have long believed that greater efficiency of water use can be achieved by more. judicious and timely application of irrigation water. This belief has sparked research into the economics of water application and the relationship between stage of plant development and soil water and atmospheric stress.

For both irrigated and dryland crops, yield is closely related to the timing and availability of soil water. Timing of water availability and irrigation applications is emphasized in this study for several reasons. First, the availability of sufficient soil water at specific stages of plant development is an important determinant of crop yield. Second, by irrigating only at critical stages of plant development, the total application of water may be reduced without significantly reducing crop yield. Third, the declining pump yields reduce the irrigator's ability to make timely applications of irrigation water. Fourth, faced with lower pump yields and timeliness of application, irrigators must adjust either their irrigation schedules or the number of acres irrigated to maintain yields and profitability of the operation.

Scheduling irrigation applications according to stage of plant development and available soil-water level may be considered too sophisticated by many irrigators. Granted, only a few regions of the United States measure available soil water at various soil depths or use the relationships that exist between soil-water stress and stage of plant development to measure the impact on yield. However, at the present time, irrigators in the study area frequently evaluate the feel of the soil as well as the appearance of the plants to determine when an irrigation application is needed. They also know when corn, wheat, and grain sorghum reach the critical stages of plant growth such as silking, boot or grain-filling, and may require additional water. Thus, growers in the study area could use information on how much the final yield is influenced by insufficient soil water at various stages of plant development to develop irrigation programs and strategies designed to increase or maintain crop yields while reducing the quantity of irrigation water pumped.

CHARACTERISTICS OF THE STUDY AREA

The Ogallala Formation extends from South Dakota through Western Nebraska, Western Kansas and Eastern Colorado. It underlies the Oklahoma and Texas Panhandles and extends into the Southern High Plains and Southwest Texas. Geologists agree that the Arkansas River in Southwestern Kansas and the Canadian River in the Texas Panhandle penetrate the formation to bedrock, thus forming three separate basins. The Central Basin of the Ogallala, bounded on the north and south by these two rivers, served as the study area for the research reported in this bulletin. The study area included eight counties in Southwestern Kansas, portions of two counties in Southeastern Colorado, the three Oklahoma Panhandle counties and seven counties in the Northern High Plains of Texas. The area encompasses approximately 11,149,000 acres. [5, p. 46]

The Central Ogallala Formation may be described as a closed basin with insignificant quantities of water entering the aquifer at the boundaries. Aquifer recharge is believed to be minimal, occurring primarily from percolation of natural precipitation. Annual rainfall averages only 15 to 19 inches from west to east across the Oklahoma Panhandle. During the growing season, average daily temperature and wind velocities are high while relative humidity is low. This combination of environmental factors leads to large water losses from evaporation pans [a measure of potential evapotranspiration (P.ET)], occasionally exceeding one inch per day. The combination of low rainfall and high P.ET reduces the opportunity for recharge of the Ogallala by percolation. Average annual recharge for the Central Basin has been estimated at 0.3 inches per year [12, p. 46] or approximately 270,000 acre feet per year [5, p. 193].

Although average annual recharge has historically exceeded annual withdrawals, a recent study indicates that the opposite has been the case each year since 1954. Withdrawals have exceeded average annual recharge by amounts ranging from 113,000 acre feet in 1954 to 2.7 million acre feet in 1964 [5, p. 8] and the difference continues to grow. In areas of intensive irrigation development, a significant lowering of the static water level has occurred. In an intensively developed area of Texas County, Oklahoma, static water levels declined from five to 30 feet during the period 1938-1966 [58]. Declining water levels result in a corresponding reduction in the pumping rate a given irrigation well can deliver. Declining water levels and pump yields increase the cost per acre inch of pumping irrigation water and, if production practices and prices are assumed to be unaffected, reduce the profitability of the irrigation operation.

The efficient use of irrigation water is in the interest of all irrigators, as well as other members of the area's population. Operators in areas of declining static water levels are probably the most concerned, but all operators would benefit directly from more efficient water usage. These benefits would accrue through reduced pumping costs per irrigated acre, increased yield per acre, larger irrigated acreage or a combination of the three. Greater efficiency of water usage would also result in increased returns for irrigators, thus benefiting other residents of the area through secondary and tertiary effects. Increasing the efficiency of the water use would also increase the number of years a grower could profitably irrigate from the Central Ogallala. Thus, the benefits of increasing the efficiency of water use are not only of short-term importance, but are expected to have a significant long-term impact on the area.

OBJECTIVES

The objectives of this study were:

1. To construct a soil-water prediction model for a commonly irrigated soil in the study area using daily rainfall, evaporation and irrigation data.
2. To identify the critical stages of plant development for the major dryland and irrigated crops in the study area.
3. To stimulate the effects of available soil water and atmospheric stress during critical stages of plant development on yield for the major dryland and irrigated crops in the study area.
4. To illustrate how the soil-water prediction models for individual crops can be combined to simulate yields on a field by field basis for the several crops commonly produced on irrigated farms in the study area.
5. To suggest the potential of such a model for analyzing agronomic and economic problems.

MODEL DEVELOPMENT

Economists are interested in the relationship between inputs, such as seed, fertilizer and irrigation water, and outputs, such as wheat, corn and grain sorghum. Much work has focused on estimating functional relationships between inputs and outputs by fitting production functions to agronomic data. For irrigated crops, these efforts usually include total annual water as an input and, thus, provide no information regarding the importance of irrigation water at different points during the season.

One of the first attempts by an economist to establish the relationship between moisture stress during the growing season and crop yield was that of Moore [28]. Moore's model did not account for the precise effect of extreme moisture stress at each stage of plant development. Subsequent soil moisture models by Fleming [14] and Shaw [47] have incorporated the interaction of soil moisture level and atmospheric demand for moisture on plant growth. Fleming's model, as well as those employed by Flinn and Musgrave [18] and Flinn [16], assume that a crop will grow at its potential rate on any day during which it is not stressed, but that growth ceases on any day during which crop stress occurs. In a more recent model, Flinn [17] assumes that both the incidence and severity of stress during various stages of plant development affect crop yield.

Considerable research has been undertaken to study the effects of various factors, including row spacing, planting rates, seeding date, fertilizer levels, and irrigation rates, on the major crops of the study area, such as grain sorghum [1, 22, 29, 30, 31, 33, 34, 35, 36, 37, 40, 49, 52, 53, 59], wheat [23, 24, 42, 45, 53], and corn [9, 11, 21, 47], as well as on a few minor crops, including alfalfa and sugar beets [38, 44]. However, relatively few studies have attempted to establish an empirical relationship between timing of water application and crop yield, and between various levels of soil-water stress at different stages of plant development and the corresponding yield reductions. Those studies emphasizing timing have been limited primarily to the major irrigated crops—grain sorghum, wheat and corn [6, 10, 32, 33, 43, 50, 52].

Several general conclusions may be drawn from the results of these research efforts. First, reductions in crop yield can occur either as a result of depleted soil water conditions or severe atmospheric conditions. Soil-water deficiency may subject plants to soil water stress resulting in growth retardation and yield reduction regardless of atmospheric conditions. Similarly, even if soil water is adequate for normal plant development, severe atmospheric conditions may demand more water than the plant is capable of transpiring and the result is growth retardation and yield reduction. The second general conclusion is that each crop has a unique set of critical stages of plant development with regard to soil-water stress which must be identified and studied. Third, the daily effects of water and atmospheric stress vary from stage to stage for a single crop and differ from crop to crop.

In this study, the model for estimating the effect of a water deficiency on crop yield is composed of two major parts. The first part computes a daily soil-water balance. In the second part, critical stages of plant development for each individual crop are identified and the effects of soil water and atmospheric stress on yield during that stage are evaluated. Tho two are combined into a dynamic soil water-crop yield system capable of simulating soil water levels throughout the growing season. The yield for each crop is then calculated on the basis of the soil water and atmospheric stress that occurred during each critical stage of plant development. The two parts of the model are discussed in the following sections.

THE SOIL-WATER BALANCE

The soil water balance is designed to make daily computations of soil water in a 51-inch Richfield clay loam soil profile. The model allows daily adjustments in soil-water content to reflect additions through rainfall and irrigations, as well as subtractions through evapotranspiration (ET). Daily net additions of soil water occur when rainfall exceeds actual ET and depletions occur when the opposite is true.

Estimating Evaportranspiration

Richfield clay loam soil was used in constructing the daily water balance because field capacity and permanent wilting point were readily available and it represented the predominant irrigable clay loam soil in the study area.[1] The amounts of water held in the 51-inch profile at field capacity and permanent wilting are 16.3 and 8.7 inches, respectively.[2] Field capacity was determined by flooding a field site and allowing soil-water drainage to occur in the absence of surface evaporation. The soil-water content at each depth decreased significantly during the first 72 hours, with a smaller rate of change noted during the following period. The average soil-water content at the end of 72 hours was taken to be field capacity (soil-water pressure was approximately –0.1 bar). The permanent wilting point was measured in the laboratory using disturbed samples and the pressure membrane apparatus. Fifteen bars of soil-water pressure was used to represent permanent wilting. The profile was assumed homogeneous with depth.

Since root concentration tends to diminish with soil depth for annual crops and because plants tend to remove water from the top of the soil profile first, the soil profile was divided into a surface layer (0 to 9 inches) and a deep layer (9 to 51 inches). ET was assumed to occur first from the upper layer and, when permanent wilting was reached in this zone, water extraction was assumed to occur from the deeper layer.

The top layer held 2.9 inches of water at field capacity and 1.5 inches at permanent wilting. The lower layer retained 13.4 inches of water at field capacity and 7.2 inches at permanent wilting. Since the lower layer is recharged by water movement through the upper layer, it was assumed that 5 percent of the available water in the upper zone

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[1] Irrigable clay and clay loam soils compose 6,167,500 acres (76.7 percent) of the 8,040,915 irrigable acres in the study area.

[2] Soil-water characteristics for the Richfield soil were obtained from a site located on the Oklahoma Panhandle State University Experiment Station, Goodwell, Oklahoma.

moved to the lower zone each day. At the wilting point, no water was transferred. For ease of calculation, no water was assumed to leave the lower zone due to percolation. This is a reasonable assumption for a semi-arid region. Also, the soil-water content was not allowed to exceed field capacity. Water inputs which caused soil water to exceed field capacity were assigned to runoff. Except for this condition, no runoff was assumed. Again, this is not an unreasonable assumption for the region since measured annual runoff is less than 0.5 inch.

Water is withdrawn from the soil profile as a result of ET. Two concepts of ET were considered. The first, potential evapotranspiration (P.ET), refers to the quantity of water which would be evaporated and transpired from a particular crop under adequate soil-water conditions. Daily amounts of P.ET can be estimated from daily pan evaporation rates [9, 41]. The second, actual ET, refers to the amount of ET which actually occurs during a given day. The latter is less than P.ET and is a function of soil-water conditions and crop conditions, and thus a function of P.ET. The two were assumed equal only when soil water was at field capacity in the upper layer of the soil profile. Once the soil-water content in the upper zone fell below field capacity, actual ET was assumed proportional to the amount of water remaining in the upper zone.

All actual ET was assumed to occur from the upper zone (0 to 9 inches) until the soil water reached permanent wilting (1.53 inches). Then water was drawn from the lower layer with actual ET being proportional to the amount of soil water remaining in the lower zone (9 to 51 inches) of the profile. Once the soil water in the lower zone of the profile reached permanent wilting (7.16 inches), actual ET was assumed to cease. At times when the top layer is near wilting and the lower near capacity, ET estimates produced by the model are too low. However, the high prevailing ET of the region quickly shifts the ET from the upper layer to the lower zone at such times so that the model does not dwell at any one transitional point for an extended period of time. In practice the relationship between ET and soil-water availability is probably nonlinear, but the approximation proved to be appropriate for this climatic region. This simple model tends to produce predictions which are compatible with results of other workers who have dealt with ET approximations [20, 25, 54, 55, 57].

The following series of equations describes, in mathematical notation, the system used to calculate actual ET on a daily basis:

$$(1)\quad AE_i = EP_i \frac{SMU_i}{2.9}, \quad 1.5 \leqslant SMU_i \leqslant 2.9$$

$$0 \leqslant \text{Soil depth} \leqslant 9''$$

$$(2)\quad AE_i = EP_i \frac{SML_i}{13.4}, \quad SMU_i = 1.5;\ 7.2 \leqslant SML_i \leqslant 13.4$$

$$9'' < \text{Soil depth} \leqslant 51''$$

$$(3)\quad AE_i = 0,\ SMU_i = 1.5 \text{ and } SML_i = 7.2$$

In the above equations, AE_i equals actual ET on day i; EP_i equals P.ET on day i; SMU_i equals inches of soil water in the upper (0-9 inch) layer on day i; SML_i equals inches of soil water in the lower (9-51 inch) layer on day i.

Equation (1) states that if the soil-water content of the upper layer of the soil profile is between field capacity and the permanent wilting point of 1.5 inches, then actual ET from the upper layer is a function of P.ET and is proportional to the amount of water remaining in the upper layer. Equation (2) indicates that once soil water in the upper layer of the soil profile has been depleted to the minimum amount (1.5 inch) the actual ET is still a function of P.ET, but at a rate proportional to the amount of soil water in the lower layer. Equation (3) indicates that ET ceases when the water in both layers of the soil profile reach permanent wilting.

Except for variations in P.ET for different crops at different stages of plant development, the primary independent variables composing the water balance are taken to be rainfall and pan evaporation. To simulate daily values of soil water throughout the growing season, daily values of rainfall and pan evaporation are required. These values were generated from rainfall and pan evaporation probability density functions discussed in the following sections.

Rainfall Prabability Distributions

Rainfall throughout the study area is characterized by two predominate features. First, yearly average rainfall is very low, ranging from 15 inches in the western portion of the study area to 19 inches in the eastern part of the Oklahoma Panhandle. Second, daily and yearly rainfall are quite variable. During the 29 year period from 1941 through 1969, daily rainfall at the U. S. National Weather Service Station, Goodwell, Oklahoma, (approximately the geographical center of the study area) ranged from 0 to 5.38 inches. The long-term average number of days per year with zero rainfall was approximately 275.

To simulate soil water throughout the crop year, discrete, empirical probability distributions based upon the observed daily rainfall over 29 years, were utilized. The growing season was divided into seven monthly periods, beginning on April 1 and ending on October 31. Each month was further divided into two periods. The first period of each month was 15 days long. The second period of each month was either 15 or 16 days long depending upon whether the month had 30 or 31 days. The discrete empirical probability distributions estimated for each of the 14 periods of the growing season are presented in Table 1. Each distribution is independent of the other distributions. Generating daily rainfall events from a different distribution every two weeks takes into account differences in the actual distribution of rainfall during the growing season.[3]

Pan Evaporation Probability Distributions

Pan evaporation, like rainfall, is an integral component of the soil-water balance system. To simulate soil water throughout the growing season, daily pan evaporation values were generated for each period of the growing season. Daily pan evaporation values are generally small during the early portion of the growing season, increase to a peak level during July and August and decline to a low level in October. Plottings of daily pan evaporation observations for each period of the growing season revealed several outstanding characteristics. First, the sample data indicated that the pan evaporation distributions are positively skewed. Second, all observations are equal to or greater than zero. Third, the symmetry or skewness of the distribution is different for each 15 or 16 day period during the growing season.

The lognormal distribution, a continuous, positively skewed probability density function having all values equal to or greater than zero, was used to describe pan evaporation in this study. Using pan evaporation measurements from a Class A weather pan at the U. S. National Weather Service Station, Goodwell, Oklahoma, probability density functions were estimated for 12 periods, the first beginning on May 1 and the last ending on October 31.[4] These periods correspond exactly to the rainfall periods, except that no pan evaporation distributions were estimated for April. Estimates of the mean, variance and standard deviation for each of the pan evaporation distributions are given in Table 2.

Equation (4) may be used to generate a series of n random pan evaporation observations from a lognormal distribution with mean, m_1,

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[3] Generating daily rainfall values from a discrete probability distribution presents a problem because of the computer storage and time required. However, a very fast procedure developed by Marsaglia was utilized to generate random variates from each discrete probability density function [27, pp. 37-38].

[4] Aitchinson and Brown discuss alternative methods of estimating the parameters of a lognormal distribution. Parameters of each distribution were estimated by the method of maximum likelihood [2, p. 39].

Table 1. Discrete Daily Rainfall Probabilities by Period of the Crop Year

Inches of Rainfall	Apr. 1-15	Apr. 16-30	May 1-15	May 16-31	June 1-15	June 16-30	July 1-15	July 16-31	Aug. 1-15	Aug. 16-31	Sept. 1-15	Sept. 16-30	Oct. 1-15	Oct. 16-31
.00	.851	.871	.782	.746	.733	.786	.743	.776	.759	.800	.846	.844	.878	.862
.01-.05	.041	.023	.071	.058	.051	.051	.044	.034	.039	.062	.034	.039	.030	.030
.06-.10	.039	.023	.018	.022	.051	.039	.021	.032	.037	.022	.032	.025	.014	.026
.11-.15	.023	.016	.011	.024	.011	.021	.025	.026	.021	.015	.018	.018	.014	.009
.16-.20	.007	.007	.018	.022	.021	.007	.014	.017	.016	.015	.011	.011	.005	.017
.21-.25	.005	.005	.009	.017	.018	.021	.016	.013	.007	.004	.007	.009	.011	.002
.26-.30	.007	.011	.002	.011	.011	.009	.002	.009	.018	.013	.007	.005	.002	.011
.31-.35	.002	.002	.009	.011	.011	.009	.002	.004	.007	.009	.007	.007	.002	.006
.36-.40	.002	.002	.007	.009	.009	.007	.009	.009	.007	.007	.007	.002	.002	.004
.41-.45	.007	.005	.005	.011	.011	.005	.023	.011	.014	.007	.002		.005	.006
.46-.50	.005	.007	.007	.011	.009	.005		.002	.009	.004		.007	.005	.002
.51-.55		.007	.018	.011	.009	.002	.018	.004	.005	.002		.002	.005	
.56-.60	.005		.005	.015	.007	.002	.005	.004	.002	.004			.002	.004
.61-.65	.002	.005		.002	.005		.005	.009	.005	.002				.002
.66-.70		.002		.002			.005		.007	.002		.002		
.71-.75			.007	.002			.007	.002	.002			.005	.002	.002
.76-.80	.002	.005	.002		.005	.007		.002	.005	.002			.005	.002
.81-.85			.002	.002	.007		.005	.002	.002		.002	.005	.005	
.86-.90			.002	.002	.002		.002	.006	.002	.002	.002	.002	.002	
.91-.95	.002				.002	.009	.005	.006	.005	.002	.002		.002	.002
.96-1.00			.002	.002		.002	.007	.004	.002	.002				
1.01-1.05		.002	.005	.002	.005		.005	.002	.002	.002	.002	.002		
1.06-1.10			.002		.002		.005	.009			.002			
1.11-1.15	.002		.002	.004		.002	.002					.005		
1.16-1.20		.002	.002		.002		.005		.007		.005	.002		.002

Table 1. (Continued)

Inches of Rainfall	Apr. 1-15	Apr. 16-30	May 1-15	May 16-31	June 1-15	June 16-30	July 1-15	July 16-31	Aug. 1-15	Aug. 16-31	Sept. 1-15	Sept. 16-30	Oct. 1-15	Oct. 16-31
1.21-1.25							.005			.002	.002	.005		
1.26-1.30		.002							.002					
1.31-1.35		.002		.006			.005	.002	.005					
1.36-1.40			.002			.002				.007				.002
1.41-1.45			.002		.005	.005	.005						.002	
1.46-1.50						.002							.002	
1.51-1.55			.002				.002	.002	.002					
1.56-1.60									.002					
1.61-1.65							.002							
1.66-1.70								.002		.004	.002			.002
1.71-1.75			.002				.002			.002			.002	
1.76-1.80														
1.81-1.85					.002			.004		.002	.002			
1.86-1.90				.002	.002									
1.91-1.95				.002	.002				.002					
1.96-2.00				.004							.002			
>2.00					.002	.007	.005	.004	.007	.004	.002	.002	.002	.004

Table 2. Summary of Mean, Variance and Standard Deviation for Logarithmically Transformed Pan Evaporation Data by Periods of the Year

	x is Distributed Lognormally			y=log x Distributed Normally		
	Mean	Variance	Std. Dev.	Mean	Variance	Std. Dev.
May 1-15	.380	.060	.245	—1.177	.310	.557
May 16-31	.349	.047	.216	—1.216	.448	.669
June 1-15	.404	.060	.245	—1.027	.311	.558
June 16-30	.467	.061	.247	— .834	.229	.479
July 1-15	.455	.075	.275	— .950	.500	.707
July 16-31	.461	.063	.251	— .895	.361	.601
Aug. 1-15	.398	.049	.222	—1.229	.260	.509
Aug. 16-31	.372	.047	.218	—1.108	.308	.555
Sept. 1-15	.324	.047	.217	—1.208	.403	.634
Sept. 16-30	.275	.035	.188	—1.432	.358	.598
Oct. 1-15	.286	.051	.225	—1.339	.378	.615
Oct. 16-31	.208	.027	.164	—1.715	.338	.582

and standard deviation, s_1.

$$x_i = e^{m_1 + s_1 Z_i} \tag{4}$$

when m_1 and s_1 are the mean and standard deviation of the lognormally distributed transformed variable and Z_i represents a series of n random deviates. Generating pan evaporation values from a different distribution for each two-week period accounts for the changing distribution of pan evaporation throughout the growing season.

Simulating Soil Water During the Crop Year

Utilizing the rainfall and pan evaporation distributions, daily quantities of each could be generated during the growing season. Van Bavel [57] assumed a full profile at the beginning of the growing season in calculating drought in a humid climate. This assumption did not appear valid for the Oklahoma Panhandle where, during some years, the soil profile never reached field capacity. The estimate of the water content at the start of the season was, thus, very important. The absence of pan evaporation data for the November through April period necessitated estimation of soil water at the beginning of May based on available weather data for the previous month or months. Based on soil-water content measurements from a weather station located in the study area on a Richfield clay loam the following relation was estimated between the average soil-water content on the first day of May and the rainfall during the month of April.

$$(5)\quad SM_{bm} = \underset{}{8.69} + \underset{(0.26)}{0.22R_{ma}} + \underset{(1.05)}{2.33R_{1wa}}$$

Equation (5) was estimated by multiple linear regression, where SM_{bm} represents the soil-water content at the beginning of May, in inches; R_{ma} represents the rainfall during the month of April, in inches; and R_{1wa} represents the rainfall during the last week in April, in inches. Standard errors of the regression coefficients appear in parentheses below the equation. The correlation index for Equation (5) is 0.90.

The soil-water balance is simulated as follows: Given the soil-water content on May 1, the level of soil-water is determined from generated daily rainfall and pan evaporation values. P.ET is calculated based on pan evaporation and the particular stage of plant development for each crop. Actual ET is calculated from the P.ET and soil-water content in the upper profile, and then from the lower profile until soil water in that layer reaches permanent wilting.

Next, rainfall is compared with actual ET. If rainfall exceeds actual ET, the difference between the two is added to the upper layer of the soil profile, with five percent of the upper layer's available water percolating to the lower profile. If the water content in the upper profile reaches field capacity, additions of soil water are made to the lower profile. When both layers reach field capacity, excess water is considered runoff. If, when rainfall is compared with actual ET, the latter exceeds the former, the total soil water content is reduced by the difference between the two. Soil water declines in the upper profile, owing to ET and water percolating from the upper to the lower profile, until permanent wilting in the upper profile is reached. Then, soil water is drawn from the lower profile until soil water in that layer reaches permanent wilting. Once both layers of the profile have reached permanent wilting point, ET ceases. Each day of the growing season, a similar set of computations was made based on soil water, rainfall and ET [26, p. 63].

Testing the Soil-Water Balance

Prior to using the soil-water balance to maintain a record of soil water throughout the growing season, a statistical test was made to insure that it was performing satisfactorily. The following validation criteria was utilized: the water balance must utilize probabilistic rainfall and pan evaporation readings and generate a distribution of soil water values that do not differ significantly from the actual distribution of soil-water content one would observe in the study area.

Soil water, which is a function of heavily skewed rainfall and log-normally distributed pan evaporation, is not normally distributed over the growing season. Thus, the frequently used parametric "t" test is inappropriate for testing the soil-water distributions.

Fortunately, nonparametric statistical tests exist which may be used to test for statistical differences between two distributions without requiring assumptions about those distributions. The Mann-Whitney U test may be used to test whether two independent groups, A and B, come from the same population; that is, whether A and B have the same distribution.[5] The actual and simulated soil-water values serve as the two groups, A and B, for the test. The results of the test are stated here in probability terms. The computed value of the test statistic, Z, is 0.802, where Z is approximately normally distributed with zero mean and unit variance. The probability of a value of Z as extreme as 0.802 under the null hypothesis is 0.412. Thus, there was no statistical basis for rejecting the null hypothesis of no difference between the actual and simulated soil-water distributions. The soil-water balance system was judged satisfactory from a statistical standpoint.

THE CROP YIELD MODEL

The next steps in development of the model were to estimate the effects on final crop yield of soil-water stress during each stage of plant development for specific crops and to integrate the water balance and stress-yield relationships into a dynamic water-yield system.

The ability of the soil-water balance to calculate soil water on a daily basis as a function of rainfall and evapotranspiration permits consideration of the effects of daily soil water and atmospheric demands on crop yields. If, on day i of stage j of crop k development, soil water is inadequate, the plant is subjected to soil water stress and final yield is reduced. Also, if on the same day atmospheric demands for soil water are greater than the plant's ability to transpire soil water to the atmosphere, plant stress occurs and final yield is further reduced. The combined effects of soil water and atmospheric stress acting to reduce yield per acre is assumed to be additive and can be expressed as

$$(6)\quad YR_{ij}{}^{k} = \theta_j{}^{k} + SMD_{ij} + b_j{}^{k}\,(P_{ij} - P_A)$$

where $YR_{ij}{}^{k}$ represents the yield reduction on day i for stage j and crop k; $\theta_j{}^{k}$ represents the coefficient reflecting yield reduction in units per day resulting from adverse soil-water conditions for stage j and crop k; SMD_{ij} represents the soil-water depletion in inches on day i for stage j; $b_j{}^{k}$ represents the coefficient reflecting yield reduction in units per day due

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[5] The null hypothesis, Ho, is that A and B have the same distribution. The alternative hypothesis is that A is larger than B [45, pp. 116-127]. For a discussion of the procedures required to use the Mann-Whitney U Test, details of the requisite computations and a detailed explanation of the results, see Mapp [26, 271-277].

to severe atmospheric demands upon the plant for stage j and crop **k**; P_{ij} represents the pan evaporation in inches on day i for stage j and P_A represents a critical pan evaporation level at or below which no yield reductions occur that are directly attributable to severe atmospheric conditions.

Equation (6) indicates that crop yield reductions for a given day and stage of plant development are the sum of soil water and atmospheric components. The coefficient $\theta_j{}^k$ must be estimated for j critical stages of plant development for each crop. The variable SMD_{ij} for Richfield clay loam soil is assumed to have the form shown in (7).

$$(7) \quad SMD_{ij} = (13.8 - SMT_{ij})/5.1, \quad SMT_{ij} < 13.8$$

where 13.8 represents the inches of soil water in the Richfield clay loam below which plants begin to suffer moisture stress and yield begins to be reduced; SMT_{ij} represents the inches of soil water which exist in the entire profile (0-51 inches) on day i of stage j; and 5.1 represents the difference between the critical moisture level of 13.8 inches and permanent wilting of 8.7 inches. Equation (7) states that as long as the soil-water content is less than 13.8 inches, SMD_{ij} increases as the total soil water content decreases, reaching 1.0 when the soil-water content reaches the permanent wilting point (8.7 inches). Thus, the daily reduction in crop yield due to soil-water conditions was assumed a linear function of the quantity of soil water between the critical moisture level and permanent wilting point.

The second term on the right-hand side of equation (6) represents the effect of atmospheric stress upon crop yield. The coefficient $b_j{}^k$ must be estimated for each of the j stages for **k** crops included in the model. Values of P_{ij} are generated daily (as part of the soil-water balance model) from lognormal distributions of pan evaporation. The value of P_A emphasizes the importance of excessive atmospheric demands upon the plant even though soil-water condition may be above the permanent wilting point. If atmospheric demands exceed the plant's ability to transpire moisture to the atmosphere, plant stress occurs and yields are reduced. A value of 0.40 inches per day was used for P_A in this study. The criterion for selecting the value of P_A, established in consultation with agronomists and agricultural engineers familiar with the region, is that the critical value of P_A would occur approximately 20 percent of the time during the vegetative stage of plant development. Pan evaporation patterns during the vegetative stages of plant development for each crop studied revealed that the value of P_A satisfying this criterion was approximately 0.40 inches per day. It was assumed that no yield reduction due to excessive atmospheric demand occurred unless pan evaporation for a given day exceeded 0.40 inches per day.

Equations (6) and (7) and the soil-water balance complete the link between daily moisture readings and crop yield reductions due to soil water and atmospheric stress. The following sections develop critical stages of plant development, water-use rates and yield reduction coefficients for each crop.

Grain Sorghum

The growing season for grain sorghum in the study area is divided into three stages defined as preboot, boot-heading and grain-filling. The actual dates on which these critical stages begin and end is variable. Factors that affect plant growth and the time at which each stage is reached include date of planting, moisture conditions at planting, fertilization level, the amount of stress which occurs at each stage of development, and timing and amounts of rainfall and irrigation received. However, in simulating crop yield as a function of soil water during these critical stages, it was necessary to assume a specific beginning and ending date for each stage. Otherwise, soil water and atmospheric stress coefficients vary, not only from stage to stage and crop to crop, but from year to year as well. Unfortunately the data to estimate such varying relationships were not available and fixed length stages were assumed.

Grain sorghum is a summer crop. Farm operators begin preplant irrigations during May, often plant about June 1 and expect emergence by June 7. From June 7 until about mid-July, soil water and atmospheric stress have little effect on final yield if soil water is adequate during the critical stages of development, which occur later in the growing season. The preboot stage occurs between the 12-inch stage and boot stage. Preboot stage was assumed to begin on July 1 and end on August 4, lasting 21 days. The boot-heading stage was assumed to begin on August 5 and end on September 1, lasting 28 days. The grain-filling stage was assumed to begin on September 2 and end on September 22, lasting 21 days. From September 23 until maturity and harvest, moisture and atmospheric stress were assumed to have no effect on final crop yield.

To approximate the relationship between ET and stages of grain sorghum development in the study area, it was assumed that pan evaporation, which is positively correlated with temperature and solar radiation, follows essentially the same pattern throughout the growing season as the concept of mean P.ET plotted by Jensen and Sletten [22, p. 8]. In their study, they show the distribution of pan evaporation values for the study area to exceed the distribution of mean P.ET values by approximately 50 percent. In this study, a measure of daily P.ET for grain sorghum was calculated as a function of pan evaporation values generated in the soil-water balance. It was assumed that P.ET equalled 25 percent of pan evaporation from the beginning of the growing season on May 1 until plant emergence on June 7. From plant emergence until July 15, when approximately 80 percent ground cover has been reached, P.ET was assumed to increase linearly from 25 percent to 55 percent of pan evaporation. Daily pan evaporation increases rapidly during this period. From July 5 until September 1, P.ET remains at 55 percent of pan evaporation, however, both values decline during this period. From September 1 until the end of the growing season, P.ET is assumed to equal 50 percent of pan evaporation, with both values reaching low levels in late September and early October.

Dryland grain sorghum and irrigated grain sorghum were handled differently within the model. Water-use curves for irrigated grain sorghum were predicated upon the assumption that adequate soil water conditions existed throughout the growing season [22, p. 8] Under adequate moisture conditions, P.ET is much higher than under dryland conditions because of the presence of more vigorous vegetation. Thus, approximation of water-use rates and P.ET utilizing the curves developed for irrigated grain sorghum is inappropriate. Still, P.ET changes during the growing season as grain sorghum develops from emergence to 80 percent of ground cover.

Research to establish realistic values for dryland grain sorghum is sparse. It was assumed that P.ET equals 25 percent of pan evaporation from the beginning of the growing season until the beginning of boot-heading stage of dryland grain sorghum development. From boot-heading stage to the end of grain-filling stage, P.ET was assumed to equal 75 percent of pan evaporation. While the potential for ET may be high, actual ET will be low because of the low soil water content on dryland grain sorghum.

Soil water and atmospheric yield reduction coefficients were developed for each of the three critical stages of grain sorghum. The study conducted by Musick and Grimes [32] at Garden City, Kansas, just north of the study area, provided valuable insights regarding the relative importance of each stage of development and the percentage reduction in yield that might be expected when grain sorghum was subjected to moisture stress for different lengths of time during each critical stage of development. The relationships developed by Musick and Grimes [32] were refined and adjusted in light of results of Stone, Griffin, and Ott [52] and in consultation with agronomists, agricultural engineers, farm management agents and irrigation specialists.[6]

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[6] Coefficients were actually synthesized and tested rather than being estimated by the use of sophisticated mathematical procedures. While it might be argued that mathematical estimation is preferable, the almost complete lack of adequate data for the study area effectively eliminated that alternative. In addition, it is emphasized that the coefficients, while probably not as accurate as implied by the use of two places to the right of the decimal point, nevertheless represent the best available estimates until more experimentation is accomplished and more data are available.

Equation (8) presents soil water and atmospheric stress coefficients for the preboot stage of grain sorghum development. Superscripts designating the crop have been eliminated.

$$(8) \quad YR_{ip} = 0.30\ SMD_{ip} + 1.30\,(P_{ip} - 0.40)$$

A soil-water stress coefficient of 0.30 for the preboot stage of grain sorghum development denotes that as soil water approaches wilting point, yield reduction approaches 0.30 bushels per day. Thus, if soil water remains near wilting point for the entire preboot stage, the potential yield reduction is approximately 6.3 bushels (0.30 X 21 days) per acre. Total yield reduction during the preboot stage is obtained by summing the daily soil water and atmospheric reductions as indicated in equation (9).

$$(9) \quad YR_{p} = \sum_{i=1}^{21} 0.30 \left(\frac{13.8 - SMT_{ip}}{5.1}\right) + 1.30\,(P_{ip} - 0.40)$$

Coefficients for the boot-heading stage are presented in equation (10) Boot-heading is the most critical stage of grain sorghum development as reflected in the larger θ_j and b_j values. Potential yield reduction due to soil water stress is 57.1 bushels per acre for this period.

$$(10) \quad YR_{ib} = 2.04\ SMD_{ib} + 1.65\,(P_{ib} - 0.40)$$

Coefficients for the grain-filling stage of grain sorghum development, shown in equation (11), indicate that adequate moisture during grain-filling is more critical to plant development and final yield than during the preboot stage, but less critical than during the boot-heading stage. Maximum potential yield reduction due to soil water stress during this stage is 26.7 bushels per acre.

$$(11) \quad YR_{ig} = 1.27\ SMD_{ig} + 1.50\,(P_{ig} - 0.40)$$

Determination of the final yield reduction for grain sorghum is accomplished by summing N daily yield reductions for each of three stages of plant development or

$$(12) \quad YR = \sum_{j=1}^{3} \sum_{i=1}^{N} YR_{ij}$$

Final yield is then computed by subtracting the grain sorghum yield reductions from the yield that would be expected if adequate moisture conditions existed throughout the entire growing season. Under adequate moisture conditions, a potential irrigated yield of 145.0 bushels per acre (8,120 pounds) was assumed. This yield is believed to be the maximum that could be attained in the study area with present varieties and cultural practices.

Farm operators raising dryland grain sorghum plant a different genotype. The dryland genotype is well suited to dryland production, but has a potential yield under adequate moisture conditions of about 100 bushels per acre (5,600 pounds). The same equations used to compute irrigated grain sorghum yield reductions were used to compute dryland yield reductions. However, one additional constraint was placed upon dryland grain sorghum production. Since it receives no irrigation water, dryland acreage must have sufficient soil water stored in the root zone, or receive sufficient rainfall during May or June if a stand is to be achieved. It was assumed that if between May 15 and June 25 soil water in the upper nine inches failed to reach one-half of its capacity (2.21 inches) or daily rainfall failed to reach 0.68 inches (that amount which would raise soil water in the upper profile from permanent wilting point to 2.21 inches), no stand was established and dryland grain sorghum yield was zero for the year. Dryland grain sorghum crop failures occur about 20 percent of the time in the study area, or about one year in five.

Wheat

Procedures similar to those for grain sorghum were utilized to synthesize soil water and atmospheric stress coefficients for the critical stages of wheat development. A study conducted by Musick, Grimes and Herron [33] in southwestern Kansas was the basic source from which many of the relationships were developed. The growing season for wheat was divided into four critical periods or stages of plant development: preboot, boot, flower, and milk.

The preboot stage was assumed to begin May 1 and end May 15, lasting 15 days. Water stress is relatively unimportant during preboot if adequate water exists during subsequent stages. Equation (13) specifies the soil water depletion and atmospheric stress parameters for the preboot stages of wheat development. The atmospheric parameter of zero indicates that wheat yield is resistant to atmospheric stress during the preboot stage. Potential yield reduction due to soil water stress was 6.8 bushels per acre.

$$(13) \quad YR_{ip} = 0.45\ SMD_{ij} + 0.00\ (P_{ip} - 0.40)$$

The boot stage was assumed to last from May 16 to May 28, or 13 days. Water stress is critical during the boot stage with potential yield reduction during this period due to soil-water stress increasing to 13.3 bushels per acre. The boot stage daily yield reduction relationships are given in equation (14).

(14) $YR_{ib} = 1.02\ SMD_{ib} + 1.10\ (P_{ib} - 0.40)$

The flower stage of wheat development was assumed to commence about May 29 and last until June 6, only 8 days. Soil-water stress is less critical than during boot stage, but more critical than during either preboot or milk stages of development, as indicated by equation (15). Potential yield reduction due to soil water stress during flower stage was 12.4 bushels per acre.

(15) $YR_{if} = 1.55\ SMD_{if} + 1.20\ (P_{if} - 0.40)$

The milk stage of wheat development was assumed to begin June 7 and end June 13, lasting 7 days. Soil-water stress is less critical than during boot or flower, but more critical than during preboot stage. The potential yield reduction due to soil-water stress during milk stage was 11.6 bushels per acre. Atmospheric demands are a more signficant source of yield reduction during the milk stage than during any other stage of development. Equation (16) represents the daily yield reduction relationships for milk stage.

(16) $YR_{im} = 1.66\ SMD_{im} + 1.50\ (P_{im} - 0.40)$

Under adequate soil water conditions, a potential irrigated wheat yield of 75.0 bushels per acre was assumed. Wheat planted for dryland production is a different genotype—one which achieves a potential yield of approximately 55.0 bushels per acre under adequate moisture and atmospheric conditions.

As with dryland grain sorghum, an additional assumption was made to account for wheat crop failure. It was assumed that if on any day from September 1 to October 31, soil water in the upper profile failed to reach one-half of capacity, or rainfall failed to equál 0.68 inches, a wheat stand was not achieved and a zero yield was indicated.

Corn Grain

Studies conducted by Dale and Shaw [6], Denmead and Shaw [10, 11] in Iowa, and Robins and Domingo [43] in the Pacific Northwest present the basic ideas and results from which the corn coefficients were synthesized. The growing season for corn was divided into five critical growth stages: first vegetative, second vegetative, silking, milk, and dough. Planting was assumed to occur May 1 with emergence May 7. The first vegetative stage begins at emergence and ends June 5, lasting 30 days. The effects of water stress are small during this initial stage if sufficient water exists during subsequent stages of development. Equation (17) presents the soil water and atmospheric relationships for the first vegetative stage of corn development. Potential yield reduction due to water stress in this stage was six bushels per acre.

(17) $YR_{iv_1} = 0.20\ SMD_{iv_1} + 0.10\ (P_{iv_1} - 0.40)$

The second vegetative stage of corn development was assumed to begin about June 6 and last 27 days, ending July 2. The importance of soil-water stress increases significantly with potential yield reduction reaching 31.1 bushels per acre. The coefficients are shown in equation (18).

(18) $YR_{iv_2} = 1.15\ SMD_{iv_2} + 0.60\ (P_{iv_2} - 0.40)$

The silking stage of corn development was assumed to last from July 3 to July 18, a total of 16 days. The increased importance of water stress during silking stage was reflected in a potential yield reduction of 48.8 bushels per acre.

(19) $YR_{is} = 3.05\ SMD_{is} + 1.60\ (P_{is} - 0.40)$

The milk stage of corn development was assumed to begin July 19 and end on August 9, lasting 22 days. Milk stage is slightly more important than the early and late vegetative stages. Yield reduction coefficients for milk stage are expressed in equation (20). Potential yield reduction was 25.1 bushels per acre.

(20) $YR_{im} = 1.14\ SMD_{im} + 0.40\ (P_{im} - 0.40)$

Finally, the dough stage of corn development was assumed to commence August 10 and end August 24, lasting 15 days. Water stress is slightly less important during the dough stage, as reflected in equation (21). Potential yield reduction due to soil-water stress was 23.6 bushels per acre.

(21) $YR_{id} = 1.57\ SMD_{id} + 0.10\ (P_{id} - 0.40)$

Potential yield for irrigated corn under adequate water and atmospheric conditions was assumed to equal 150.0 bushels per acre. This value is rarely exceeded in actual practice in the area under study.

Corn Silage

Little agronomic research relating soil-water stress and severe atmospheric demands to corn silage yield was available for the study area. Agronomists and area agents indicated that cattle feeders are demanding "grain-type" corn for corn silage and that producers are responding to market demand. Thus, it was assumed that the corn grown for silage was a "grain-type" corn and had the same critical stages of plant development and stress coefficients as corn grown for grain. Corn silage yields were estimated as a function of corn for grain yields. A corn silage yield comparable to the 150.0-bushel corn grain yield under adequate water conditions is 27.0 tons per acre. A coefficient relating corn grain and corn silage yields was obtained by dividing 27.0 tons by 150.0 bushels to get 0.18. Corn silage yield (CSY) was computed as a linear function of corn grain yield (CGY) from the relation $CSY=0.18\ CGY$.

Small Grain Grazing

Lack of empirical data made it even more difficult to estimate soil water and atmospheric stress coefficients for small grain grazing. Small grain grazing yields on dryland acres are positively correlated with dryland wheat yields because both are winter crops grown under dryland conditions. Consequently, a linear relationship was assumed between dryland wheat yield measured in bushels per acre and dryland small grain grazing yield measured in animal unit months (AUM). A 14.0-bushel per acre dryland wheat yield was assumed equivalent to 1.8 AUM of small grain grazing [19, pp. 9-10]. A coefficient relating dryland wheat yield and small grain grazing yield was derived by dividing 1.8 by 14.0 to get 0.129. Then, small grain grazing yield in AUM (SGPY) was computed as a linear function of dryland wheat yield (DWY) in the relation $SGPY = 0.129\ DWY$.

Testing the Crop Yield Model

Model verification is always difficult. This is particularly true when the model to be tested is designed to simulate in a realistic fashion complex physical phenomenon not currently being studied under actual field conditions. Use of county averages obscures the variation in rainfall and yield, and fails to provide an adequate comparison for the relationships predicted by the crop yield equations.

Lack of sufficient experimental data reduced the verification process to one of extensive consultation with experts in various fields—agronomists, agricultural engineers, farm management and irrigation specialists and others—who had extensive professional and practical knowledge of the relationships depicted in the model. In verifying the model, particular emphasis was placed on the logical consistency of the model. Adjustments were made until the relationships made sense. Ultimately, the final test was whether or not the model could produce or simulate crop yields and water-use rates consistent with those expected in the field.

In attempting to determine whether the model could simulate realistic crop yields and water-use rates over time, a series of simulation runs were made. Each run concentrated on a particular crop and incorporated a number of irrigation application alternatives utilized in the study area. A portion of the experimental yield results produced by the model are discussed in the following paragraphs.

Grain sorghum yields were simulated under dryland and irrigated conditions. Four different irrigation practices were simulated, including preplant only; preplant and boot; preplant, boot and grain; preplant, preboot, boot and grain. The results of a 10-year simulation run are presented in Table 3. Under dryland conditions, crop failure (represented by zero yields) occurred about 20 percent of the time, as is typical in the study area. Yields ranged from zero to 25.4 bushels per acre. The mean dryland yield of 16.3 bushels per acre, as well as yield variability, were judged representative of the study area. A single preplant irrigation, which insured a grain sorghum stand, significantly reduced yield variability and increased the mean yield. With a preplant irrigation application, yields ranged from about 30 to 52 bushels per acre, averaging nearly 38 bushels per acre. The addition of an irrigation application at the boot stage of grain sorghum development had a pronounced impact on yield. Yields ranged from 59 to 91, averaging 73 bushels per acre. The effects of additional applications beyond boot stage were positive, but less pronounced. The additional irrigation application at grain stage increased the average yield to almost 91 bushels per acre while reducing yield variability slightly. The addition of a preboot irrigation application between preplant and boot applications pushed the average yield up to 118 bushels per acre with yearly yields varying from 92.5 to 135 bushels per acre. The magnitude, range and variability of yields, as well as the relative differ-

Table 3. Simulated Grain Sorghum Yields (Bushels per Acre)

Irrigation Year	Dryland	Preplant only	Preplant + Boot	Preplant + Boot + Grain	Preplant + Preboot + Boot + Grain
1	20.3	35.7	76.4	93.1	120.3
2	16.8	33.0	61.7	73.9	111.2
3	14.2	30.4	59.2	70.7	101.5
4	20.7	52.3	90.9	112.1	132.6
5	23.0	38.5	75.9	91.1	124.1
6	25.4	40.5	75.9	103.0	113.0
7	0.0	38.3	76.9	95.8	135.1
8	24.9	42.9	84.0	106.8	132.5
9	0.0	32.1	65.9	85.8	117.9
10	18.2	33.8	63.0	75.9	92.5
Mean	16.3	37.7	73.0	90.8	118.1

ences among irrigation alternatives, were judged representative of the study area.

Wheat yields were also simulated under dryland and irrigated conditions. Seven different irrigation alternatives were simulated: preplant only; preplant and boot; preplant and flower; preplant and milk; preplant, boot and milk; preplant, boot and flower; and, preplant, boot, flower and milk. The results of a 10-year simulation run are presented in Table 4. Over the 10-year period simulated, dryland wheat yield ranged from zero to 37.5 bushels per acre, averaging 14.3 bushels per acre. Crop failures, represented by zero crop yields occurred 20 percent of the time. These results were judged typical of actual dryland yields and yield variability experienced in the study area.

The addition of a fall preplant irrigation, which insured a wheat stand, had a substantial impact on yield variability and raised average yield to 33 bushels per acre. The addition of a single irrigation application, appropriately timed to correspond to the boot stage of wheat development, raised the average yield to almost 49 bushels per acre. Wheat yields ranged from 39 to 59 bushels per acre over the 10-year period

Table 4. Simulated Wheat Yields (Bushels per Acre)

Irrigation Year	Dryland	Preplant only	Preplant + Boot	Preplant + Flower
1	18.5	27.4	40.9	37.3
2	0.0	29.2	43.0	39.4
3	12.9	38.0	57.2	50.8
4	11.1	29.5	43.7	42.1
5	0.0	29.0	43.0	39.6
6	16.5	40.0	59.1	52.8
7	37.5	40.2	58.9	53.4
8	12.3	39.0	58.1	51.5
9	18.2	29.1	39.1	37.3
10	15.7	30.0	45.7	41.2
Mean	14.3	33.2	48.9	44.5

Irrigation Year	Preplant + Milk	Preplant + Boot + Milk	Preplant + Boot + Flower	Preplant + Boot + Flowr + Milk
1	33.4	47.3	53.6	58.2
2	34.9	49.6	56.2	61.1
3	44.3	59.5	62.2	63.1
4	35.4	50.2	56.4	59.3
5	34.5	49.4	56.5	60.4
6	46.1	60.5	63.7	64.0
7	46.6	64.3	67.9	68.7
8	45.4	62.8	65.0	65.1
9	34.3	45.3	52.0	59.4
10	36.2	52.3	57.8	60.7
Mean	39.1	54.1	59.1	62.0

simulated. Single additional irrigation applications at flower and milk stages have a smaller impact on average yield. These results indicate that a third irrigation application at flower stage of plant development raised average yield to 59 bushels per acre. A fourth irrigation at milk stage resulted in a small average yield increase to 62 bushels per acre. The cost of applying this fourth irrigation would likely exceed the value of the additional output forthcoming as a result of the application. Again, the range of dryland and irrigated wheat yields, and the relative yield differences between irrigation alternatives, were judged satisfactory and representative of yields observed in the study area.

Corn for grain and silage are only produced in the study area under irrigated conditions. The following five irrigation alternatives were simulated: preplant only; preplant and vegetative 2; preplant, vegetative 2, and silk; preplant, vegetative 2, silk and milk; and, preplant, vegetative 2, silk, milk and dough. Simulated corn for grain yields are presented in Table 5. With a single preplant irrigation application, yield ranged from 23 to 73 bushels per acre, averaging almost 38 bushels per acre. The addition of an irrigation application at vegetative 2 stage of corn development increased average yield to 56 bushels per acre. The addition of a third irrigation application, appropriately timed to correspond to silking stage of corn development, reduced yield variability and increased average yield to 89 bushels per acre. The fourth and fifth irrigations, applied at milk and dough stages, increased average yield to 115.5 and 121.5 bushels per acre, respectively. The range of yields, yield variability and mean yields were again judged satisfactory by experts in the field.

The above simulation results were generated under the assumption

Table 5. Simulated Corn for Grain Yields (Bushels per Acre)

Irrigation Year	Preplant only	Preplant + Vegetative 2	Preplant + Vegetative 2 + Silk	Preplant + Vegetative 2 + Silk + Milk	Preplant + Vegetative 2 + Silk + Milk + Dough
1	33.5	54.4	80.6	119.7	123.4
2	23.0	33.5	68.1	97.9	107.6
3	43.4	64.3	102.3	132.7	141.1
4	38.3	67.2	117.4	125.1	126.7
5	26.5	42.1	71.1	107.1	110.7
6	38.5	48.3	74.7	97.1	109.1
7	52.3	74.7	109.6	136.3	140.6
8	72.9	104.5	116.5	136.6	140.6
9	26.4	35.3	78.7	112.0	112.4
10	24.6	37.4	70.3	90.6	102.8
Mean	37.8	56.2	88.9	115.5	121.5

that the farm operator could irrigate each crop at each stage of development without considering competing crop uses for the irrigation water. That is, the competition of grain sorghum and corn for irrigation water during parts of July and August, and the difficulties in scheduling sufficient irrigation applications, were ignored in generating the results in Tables 3, 4 and 5. Farm operators must consider the effect of every decision not only on the one part of the business in question, but on the profitability of the whole business.

The evaluation of irrigation programs and strategies should consider not only the effect of a particular sequence of irrigations on one crop, but also the effect on other crops that may benefit from an irrigation at the same time. While an additional irrigation to one crop may increase net returns to the enterprise, allocation of part or all of the water to a second crop may result in greater net returns for the farm business. The following sections discuss an application of the water stress—crop yield model to simulate yields on a field by field basis for a representative irrigated farm in the study area.

THE WHOLE FARM MODEL

Few of the previous attempts to model soil water and atmospheric stress-crop yield relationships have attempted to incorporate these findings into a whole farm model.[7] This is a critical step if such a model is to be used by farmers to develop irrigation programs and strategies designed to increase the efficiency of water usage. This section discusses the information required to utilize the water stress-yield relationships developed in this study in simulating irrigation programs on farms in the study area. The information is developed for a representative farm firm.

THE REPRESENTATIVE FARM

The representative farm firm has been the basis for much of the farm planning work in recent years. The dangers in selecting representative farm firms and in aggregating the results are well documented in the literature [4, 7, 8, 13, 15, 39, 46, 48, 56] and will not be discussed here.

One might argue that there is no truly representative farm operation for the study area. Farms vary in size from less than 30 acres to more

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[7] A digital computer model designed to allocate irrigation water resources among crops and among farms under conditions of a limited water supply was developed by Anderson and Maass [3]. Rather than simulating daily rainfall, pan evaporation, evapotranspiration and soil water for various crops during each of several stages of plant development, the model focuses on water requirements for each crop and computes the percentage loss in yield associated with a missed irrigation during various parts of the growing season.

than 30 sections. Farm types exhibit considerable variation as well. Many are strictly dryland operations and some are fully irrigated. Cropping patterns and farm organizations vary considerably with some farms being strictly cash grain operations while many others incorporate livestock to utilize grazing from cash grain crops. One common characteristic of virtually all cash grain farms is that the primary crops grown are wheat, grain sorghum and corn, with wheat and grain sorghum acreages being much greater than corn acreage. In addition to cash grain farms, there are many ranches with hundreds or thousands of acres of rangeland for grazing by various livestock enterprises.

While it may be desirable to apply the procedure discussed above to a variety of representative firms one modal representative irrigated farm operation for the study area is used to illustrate the procedure discussed. This modal operation was synthesized from individual farm surveys taken from a random sample of 78 irrigation operators in the study area during the summer of 1970.[8] The distribution of farm sizes for the 78 operations revealed that the modal farm size is between 500 and 1,000 acres and that the farm sizes representing the greatest number of farms tend to be associated with intervals containing multiples of 640 acres—full sections of land. Closer examination revealed that the largest number of farms range in size from 601 to 700 acres. Since farms have a tendency to be even sections in size, a modal representative farm of 640 acres, or one section, was defined for this study.

Representative Farm Organization

Surveys from the 78 randomly sampled farm operations were utilized to develop the organization for the representative farm. Cropland composes 595 of the 640 acres. Of the remaining 45 acres, 40 are in dryland non-tillable pasture and five are taken up by the home, farm buildings and roads. The organization of production is presented in Table 6. A total of 315 acres of cropland are irrigated. Grain sorghum and corn compose 230 acres of irrigated summer crops and the remaining 85 irrigated acres are planted in winter wheat. There are 30 acres of dryland grain sorghum and 85 acres of dryland wheat.

Each of the above crops is divided into one or more crop blocks and a daily soil water level is computed for each block. Each dryland crop is planted in a single crop block. Irrigated wheat and corn are each planted in two crop blocks. Irrigated grain sorghum is planted in four crop blocks. The acreage in each block appears in parentheses in Table

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[8] The random sample of 78 irrigated operators was a portion of a more extensive survey taken by Wyatte L. Harmon and Roy E. Hatch, Agricultural Economists, Farm Production Economics Division, Economic Research Service, U. S. Department of Agriculture, in connection with a study undertaken by USDA in essentially the same study area.

Table 6. The Organization, Wheat and Feed Grain Allotments and Conserving Base for A Representative Cash Grain Farm, Central Ogallala Formation

Cropland	**(Acres)**
Irrigated Grain Sorghum	170
Block G1 (80)	
Block G2 (40)	
Block G3 (30)	
Block G4 (20)	
Irrigated Wheat	85
Block W1 (65)	
Block W2 (20)	
Irrigated Corn	60
Block C1 (40)	
Block C2 (20)	
Dryland Grain Sorghum	30
Block G5 (30)	
Dryland Wheat	85
Block W3 (85)	
Idle or Fallow	66
Small Grain Graze Out	84
Lost to Turnrows	15
Total Cropland	595
Pastureland	
Dryland Non-Tillable Pasture	40
Total Pastureland	40
Other Land	
Home, Buildings and Roads	5
Total Other Land	5
Total Land in Farm	640
Allotments	
Wheat	185
Feed Grain Base	120
Conserving Base	55

6. The farm operator is assumed to irrigate each crop a block at a time. Thus, if pumping capacity is insufficient to irrigate an entire crop, perhaps only one block suffers severe water stress rather than the entire crop suffering moderate stress.

All grain sorghum is assumed harvested for grain. Two-thirds of the corn is harvested for grain and one-third for silage. The remaining 165 acres of cropland are divided among three land use categories—66 acres are idle or fallow, 84 acres are in small grain graze-out and 15 acres are assumed lost due to turnrows, ditches, etc. Graze-out small grain may be grazed from about November 1 until May 15. The representative farm also contains 40 acres of native pasture. The homestead, buildings and roads are assumed to occupy the remaining five acres. The representative farm firm has a 185-acre wheat allotment, 120-acre feed grain base and 55-acre conserving base.

The analytical models employed in this study make no attempt to determine an optimum organization of production. Thus, the organization of production developed from the random sample of farms is adopted as the starting point for simulation of soil water—crop yield relationships.

The operator of the representative farm was assumed to have one irrigation well and distribution system capable of pumping at a rate of 1,000 gallons per minute. The representative farm was assumed to be located over an adequate water situation within the Ogallala Formation.

A General Irrigation Strategy

It is not difficult to prescribe an optimum irrigation strategy for the farm operator under static conditions. Static economic theory indicates the rational operator should utilize each unit of irrigation water in its highest value use so that the marginal value product of the last unit applied just equals its marginal resource cost.

The optimal strategy prescribed under static conditions is difficult to apply under the dynamic conditions faced by the irrigator in the field. Static theory implies the ability to change water applications instantaneously from one crop to another. Theoretically, a change would occur whenever water has a higher use value on a different crop. In practice, once the operator begins to irrigate, he finds it economical to add from 1.0 to 3.0 inches of water to the soil profile of a crop before changing the irrigation set to another crop or another field. Thus, even though water as a resource appears to be infinitely divisible, problems of indivisibilities exist. However, these indivisibilities do not invalidate the economic concepts of applying water to its highest valued uses.

Each irrigation operator has an idea of critical water requirement periods for each crop being irrigated. In addition, he knows which of the crops that require water during a specific period has the highest use value for the irrigation water available. He applies water during a specific period first to the crop which has the highest use value (marginal value product) for that unit of irrigation water. Once that crop has received an irrigation application, the crop or crop block having the highest marginal value product for the next unit of irrigation water receives the next irrigation application. At a later period of the growing season, the operator may switch crop priorities in response to changes in the value of irrigation water among crops.

Delineation of Irrigation Periods

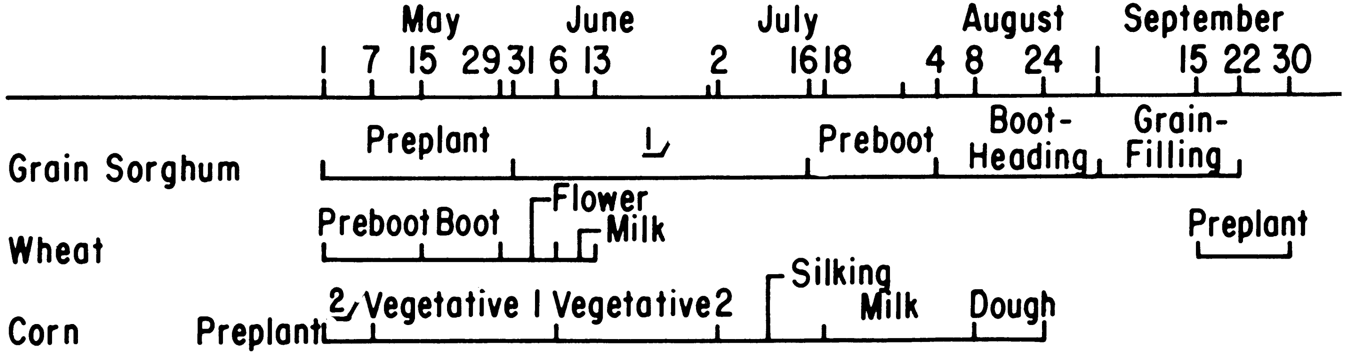
This line of reasoning led to the development of a series of irrigation strategies for the growing season. Table 7 presents a crop calendar covering the period May 1 through September 30. The crop calendar shows the critical stages of plant development for grain sorghum, wheat and corn. Of great importance are the periods when two or more crops are in direct competition for irrigation water. A glance at the crop calendar reveals that grain sorghum, corn and wheat all compete for water from May 1 until June 13, when wheat reaches the end of milk stage. From June 14 until September 15 both grain sorghum and corn compete for available water and from September 16 to 30, both grain sorghum and wheat compete for the available water.

The entire period covered by the crop calendar is divided into five irrigation periods. The basis for selecting the beginning point of each period is the beginning of a critical stage of plant development for a crop. Irrigation Period 1 begins on May 1, at the beginning of the growing season, and lasts until May 15, just prior to the beginning of boot stage for wheat. During this period, 14 days are assumed available for constant pumping by the irrigation system. The highest irrigation priority is for a preplant irrigation application on grain sorghum. Unless grain sorghum receives a preplant irrigation, the possibility of not achieving a stand exists. Water stress during the preboot stage for wheat has little effect on final yield if sufficient soil water exists during subsequent periods. Therefore, wheat is the second priority crop during Period 1. Corn is assumed to receive 6.0 inches in preplant applications and is thus the lowest priority crop during Period 1.

Irrigation Period 2 begins on May 16, when wheat reaches boot stage, and lasts until June 6 when the late vegetative stage for corn begins. Irrigation water application on wheat during boot stage has a higher marginal value product than applications on grain sorghum or corn. Once wheat has received a boot-stage application, the second priority crop, corn, receives water. Then, unless soil water under wheat, the top priority crop, has fallen to a very low level, grain sorghum, the third priority crop, receives an irrigation application. Period 2 is assumed to have 20 days during which the irrigation system can operate at full capacity.

Irrigation Period 3 begins on June 6, with initiation of the second vegetative stage of corn development, and last until August 5 when grain sorghum begins the boot-heading stage of development. Of the total period, 56 days are assumed available for full-time pumping. During Period 3, corn has top priority on water use. The potential yield reduction from soil-water stress is greater for corn than for grain sorghum or

Table 7. Delineation of Critical Stages of Plant Development, Irrigation Priorities and Irrigation Strategies



Critical Periods	(1) May 1-May 15	(2) May 16-June 5	(3) June 6-August 4	(4) August 5-September 15	(5) Sept. 16-30
Irrigation Priorities [3]	G,W,C	W,C,G	C,G	G,C	G,W
Pumping Days	14	20	56	39	14

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[1] No stage name is given to grain sorghum between preplant irrigation applications and preboot stage. Moisture stress during this period has little effect if moisture is adequate during subsequent stages of development.

[2] Plant emergence occurs between May 1 and May 7.

[3] Irrigation priorities G, W and C represent grain sorghum, wheat and corn, respectively. All blocks of the crop listed first in a critical period are irrigated before any block of the second or third priority crops.

wheat. The milk stage of wheat development occurs during part of Period 3, however, since wheat was the top priority crop during Period 2, it is eliminated from irrigation consideration during Period 3. Therefore, the second priority crop during Period 3 is grain sorghum. Water stress from June 1 to August 5 has little effect on final grain sorghum yield if sufficient water is applied during preplant, as well as during subsequent critical stages.

Irrigation Period 4 begins on August 5, with initiation of grain sorghum boot-heading stage, and concludes on September 15 when water is required to complete grain-filling applications on grain sorghum and begin preplant irrigation applications on wheat. Thirty-nine days are assumed available for full time pumping. The boot-heading stage of grain sorghum development is critical from the standpoint of soil water. The marginal value product of water applications on grain sorghum during this period are far greater than for corn during the dough stage of development. Grain sorghum is the top priority crop during Period 4 and corn, the only other crop competing for water, has second priority.

Irrigation Period 5 begins on September 16 when preplant applications for winter wheat must be scheduled. Grain sorghum remains the top priority crop during this period. The reason grain sorghum rather than wheat has top priority is that during the last of August to mid-September period, operators will be irrigating grain sorghum to insure successful yields on a crop already in the ground before concentrating on preplant irrigations for wheat. Fourteen days are assumed available for constant irrigation waterpumping during Period 5.

The five periods encompass the irrigation season as it relates to critical stages of plant development for the major crops of the study area. In the next sections, the generalized irrigation strategies are discussed and specific strategies for each of the five periods are developed as they were programmed in the simulation model.

Irrigation Strategies by Periods

Application of irrigation water depends upon the level of soil water existing in the soil profile of a crop. If soil water in the entire profile for a crop equals or exceeds 50 percent of available soil water or 12.5 inches, no irrigation water is applied. If available soil water falls below the 50 percent available level during a critical stage of development, significant yield reductions can occur. Thus, the model assumes that the decision to irrigate is made when the level of soil water falls below 12.5 inches. If sufficient water is available and actual ET is not great, the entire crop may receive a 3.0-inch addition to the soil profile. However, if plants on the part of the field already irrigated begin to show signs of water stress before the entire application can be completed, irrigators are assumed to reduce the application rate on the remaining acres, and return to the original portion of the crop to begin a new application. These assumptions appear reasonable based on the actions of irrigators in the area.

Varying irrigation rates on shifting numbers of acres during different stages of plant development is extremely difficult to handle from a modeling standpoint. Therefore, as indicated in Table 6, total acreage of each irrigated crop is divided into several blocks. The 170.0 acres of irrigated grain sorghum are not irrigated at one time. Instead, the 170.0 acres are divided into four blocks of 80.0 acres, 40.0 acres, 30.0 acres and 20.0 acres. Similarly, 85.0 acres of irrigated wheat are divided into two blocks—65.0 acres in the first and 20.0 in the second. Also, 60.0 acres of irrigated corn are divided into a 40.0-acre block and a 20.0-acre block.

The general procedure for scheduling and executing irrigation applications is the same for every period and may be discussed in general terms. Each period has a set of crop irrigation priorities as outlined in Table 8. The priorities determine the order in which soil water values are checked against the critical value (usually 50 percent available soil water or 12.5 inches). Assume the order of priorities is (1) grain sorghum, (2) wheat and (3) corn, as it is for Period 1. On the first day of the period, soil water for the first block of grain sorghum, G1, is checked against 12.5 inches. If soil water for G1 equals or exceeds 12.5 inches, no irrigation application is scheduled for G1 and soil water for G2 is checked against 12.5 inches, etc. If all four grain sorghum blocks have soil water in excess of 12.5 inches, then soil water for the first block of wheat (W1), the second priority crop, is checked against 10.98 inches. This process continues as long as soil water for each block exceeds the critical level. After soil water for both blocks of the third priority crop, corn, has been checked against 10.98 inches, and soil water for all blocks is found to exceed that level, the day is incremented to day 2 of the period and soil water under the first block of the first priority crop is again checked against 12.5 inches. In the above example, no irrigation applications would be scheduled during day 1 of Period 1.

Now consider the usual situation where an irrigation application is required. Assume that on day 1 of the period, soil water under G1 is less than 12.5 inches. The farm operator schedules an irrigation application for G1. Ideally, once an application has begun, he would like to add 3.0 inches of soil water to the G1 profile. Due to ET, and water losses from leakage and seepage, all the water pumped at the well does not find its way into the soil profile of the irrigated crop. Only about two-thirds of the water pumped from the aquifer enters the soil profile for plant use. Therefore, 4.5 inches must be drawn from the aquifer

Table 8. Water Levels at Which Irrigations are Scheduled and Priorities Established by Irrigation Periods

	Irrigation Period											
	1			2			3		4		5	
Irrigation Priority Order	**GS**	**W**	**C**	**W**	**C**	**GS**	**C**	**GS**	**GS**	**C**	**GS**	**W**
Inches of Soil Water at which Irrigations are Scheduled	12.50	10.98	10.98	12.50	12.50	12.50	12.50	10.98	12.50	12.50	10.98	12.50
Inches of Soil Water at Which Priority on Water is Established	9.45	10.98	10.98	10.98	10.98	10.93	10.98	9.45	10.98	10.98	9.45	9.45

to insure a real 3.0-inch addition to the soil profile. Based on the requirement of 4.5 acre inches per acre, the irrigation water requirement is computed from (22).

$$(22)\ WR_{ij} = 4.5\ AC_{ij}$$

where WR_{ij} equals the water requirement, block i, crop j; and AC_{ij} equals the acres planted in block i, crop j.

Then the water requirement is compared with the pumping capacity for the period. Pumping capacity is computed based on gallons per minute delivered by the irrigation system as follows:

$$(23)\quad BPC_i = (GPM \times 1440.0 \times DAYS_i)/27{,}155.0$$

where BPC_i equals the beginning pumping capacity for period i in acre inches; GPM equals the irrigation system pumping capacity in gallons per minute and is assumed to equal 1000 gallons per minute; 1440.0 equals the number of minutes per day; $DAYS_i$ equals the number of days in period i; and 27,155.0 equals the number of gallons per acre inch.

Assuming that pumping capacity for the period equals or exceeds the water requirement for G1, the irrigation application is initiated. The number of days required to apply WR_{ij} acre inches is computed and no other crops can be irrigated until the application on G1 has been completed. The total application is divided by the number of days required to apply it, and the appropriate proportion is added to soil moisture each day. Once the application on G1 is complete, the remaining pumping capacity for the period is computed and soil water under the second block of the top priority crop, G2, is checked against 12.5 inches. If soil water exceeds 12.5 inches, soil water under G3 is checked, etc. If, however, G2 soil water is less than 12.5 inches, its water requirement is computed using equation (22) and is then compared to the remaining pumping capacity for the period. If sufficient capacity exists, the irrigation is scheduled, the number of days required to complete the application is computed and the appropriate amount of water per day added to the soil profile. No other crop may be irrigated until the application on G2 has been completed.

The G2 water requirement is deducted from pumping capacity for the period, and then soil water for G3 is checked against 12.5 inches. This procedure continues unaltered until one of the four following events occurs. (a) The water requirement for any block of a crop exceeds the remaining pumping capacity for the period. (b) The number of days remaining in the period is insufficient to allow a full irrigation. (c) A block of higher priority reaches a low soil water level while a low priority crop is being irrigated. (d) The period comes to an end. These events will be considered in turn.

(a) If the water requirement for a block of a crop exceeds the remaining pumping capacity for the period, based on a 4.5-inch application per acre, the number of acre inches which can be applied per acre is computed. If that number equals or exceeds 1.5 acre inches per acre, the irrigation is scheduled and the application made. If at least 1.5 inches per acre cannot be applied, no irrigation is made to the block in question.

(b) If the number of days remaining in the period is insufficient to allow a full irrigation, water is applied at the computed rate per day until the period ends.

(c) If a block of higher priority reaches a low soil water level while a lower priority crop or block is being scheduled for irrigation, the irrigation application on that block is reduced to 1.5 acre inches per acre. Then soil water for the higher priority crop is checked, and a full 4.5-inch irrigation application is made, assuming time and pumping capacity exist to complete the application.

(d) When the period comes to an end, no further irrigations are scheduled based on crop priorities for the current period. Soil water under block 1 of the highest priority crop in the next period is checked against 12.5 inches.

The same procedure continues through all five of the irrigation periods. At the end of the crop year, crop yields on each block of each crop are computed based on soil water and atmospheric stress suffered during the critical stages of development and accumulated throughout the growing season.

Crop priorities and soil water levels at which irrigations are scheduled vary from period to period during the growing season. These differences are also highlighted in Table 8. During Period 1, irrigation applications on the top priority crop, grain sorghum, are scheduled when soil water falls below 50 percent available or 12.5 inches. Once a preplant application is made on all blocks of grain sorghum, wheat and corn would have priority unless available soil water under grain sorghum falls to ten percent or 9.45 inches. That is, once a preplant irrigation application has been made, a stand is insured and water stress will do little damage to grain sorghum, unless it is quite severe, until Period 3 is reached. Achieving a stand on grain sorghum is so important that wheat and corn irrigations are scheduled only if available soil water falls to the 30 percent level or 10.98 inches in the total profile.

During Periods 2 and 4, all crop irrigations are scheduled when available soil water falls below the 50 percent level of 12.5 inches. Once an initial irrigation has been applied, a higher priority block or crop will preempt lower priority blocks or crops only if available soil water falls below 30 percent or 10.98 inches.

During Period 3, corn is the top priority crop as it progresses through most of the late vegetative, silking and dough stages. Corn irrigations are scheduled when available soil water falls below 50 percent or 12.5 inches. Grain sorghum yields are not reduced substantially due to stress during this period of time if soil water is adequate during subsequent periods. Thus, grain sorghum irrigations are scheduled only if available soil water falls below 30 percent or 10.98 inches. The first block of corn may preempt water use from lower priority blocks and crops if available soil water falls below 30 percent or 10.98 inches. For grain sorghum, the first blocks may preempt water use from lower priority blocks if available soil water falls below ten percent or 9.45 inches.

Grain sorghum irrigations during Period 5 are scheduled whenever available soil water falls below 30 percent or 10.98 inches. Higher priority blocks may preempt water-use from lower priority blocks when available soil water falls to 9.45 inches. For the second priority crop, wheat preplant irrigation applications are scheduled if soil water falls below 50 percent or 12.5 inches. Block 1 preempts water-use from block 2 only if available soil water under block 1 falls below ten percent or 9.45 inches.

The above irrigation strategies are not intended to imply that the irrigation operator is capable of distinguishing between levels of available soil water to two decimal places. The decision rules are merely an attempt to simulate the decisions operators make based on feel of the soil and appearance of plants. Since these actions must be computerized, the rules are quite specific.

RESULTS

To demonstrate the general validity of the models, a series of 20-year simulation experiments was announced. Each experiment consisted of a series of runs designed to conducted ability of the model to simulate irrigated and dryland crop yields based on soil water and atmospheric stress, given the assumptions made regarding irrigation strategies and the organization of production. In the following sections, the results of 20 replications of each 20-year simulation run are summarized and discussed.

Grain Sorghum

A summary of irrigated grain sorghum yields for the first crop block, G1, is presented in Table 9. Grain sorghum yields range from a maximum of 142 bushels per acre to a minimum of 100 bushels per acre. Within a single 20-year simulation run, the greatest difference between maximum and minimum yields is 40 bushels. Mean values of each replication are uniform, ranging from 122 to 127 bushels per acre. The coefficient of variation, which is defined as the mean divided by the

Table 9. Irrigated Grain Sorghum Yields in Bushels Per Acre, Crop Block G1.

	Year																			
Replication	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	125.4	138.9	117.6	129.2	114.5	122.3	117.0	129.0	130.3	127.1	127.2	108.7	115.9	127.3	122.2	125.0	123.4	117.4	107.7	121.5
2	132.0	129.7	121.5	120.0	133.3	126.8	113.8	125.1	113.7	128.0	131.2	113.0	123.0	114.7	120.8	129.5	113.6	109.8	123.8	129.0
3	132.3	130.8	124.4	118.9	123.5	119.2	121.3	132.4	127.6	128.8	129.1	134.2	116.2	115.0	116.2	135.3	126.8	140.9	126.8	114.0
4	114.2	120.0	119.7	128.2	123.5	112.8	122.8	112.1	137.4	114.0	124.6	121.0	137.3	120.3	133.7	121.6	130.6	122.4	134.7	124.3
5	111.1	114.5	130.8	123.9	141.4	126.0	135.4	117.0	114.5	124.8	136.7	134.7	136.1	110.4	126.6	119.9	133.3	128.4	134.5	121.8
6	125.0	127.8	119.1	113.0	123.1	115.5	111.4	112.2	134.9	126.9	109.1	127.0	134.2	127.3	135.2	113.9	132.6	121.9	110.6	133.9
7	114.1	126.6	129.2	127.3	136.4	100.4	132.4	128.7	135.9	132.8	142.0	121.0	129.2	124.6	139.1	124.1	115.4	119.2	126.8	134.4
8	117.4	134.8	124.2	123.6	113.8	129.9	122.7	133.6	132.0	101.9	130.4	114.2	109.2	112.6	112.8	129.5	122.5	123.7	127.1	115.4
9	133.2	120.3	128.2	108.5	111.8	138.9	120.6	131.4	115.2	132.3	117.2	114.2	116.3	125.6	115.6	115.2	128.9	136.6	134.7	115.0
10	125.8	129.0	134.1	124.4	135.8	129.4	115.2	125.3	123.9	116.6	130.1	135.3	114.5	124.2	128.8	123.1	109.2	122.8	118.1	121.6
11	127.0	115.7	134.1	132.4	131.1	129.9	133.6	130.3	124.1	120.8	123.7	130.9	121.3	134.2	118.6	123.1	129.5	119.9	110.1	122.4
12	109.2	135.6	121.7	134.4	125.1	128.0	113.5	116.7	114.0	110.8	123.8	116.4	125.1	118.1	134.4	127.4	125.4	131.5	117.4	136.7
13	118.4	132.0	129.2	111.2	133.6	122.2	124.4	128.7	114.9	136.6	129.1	121.8	115.7	120.9	126.8	116.2	138.0	135.1	139.2	132.2
14	126.4	128.8	136.7	114.3	126.1	127.0	128.9	114.4	115.9	118.3	117.6	125.9	110.5	117.4	119.7	120.2	128.0	128.2	139.3	126.9
15	102.8	121.0	138.0	113.0	124.1	140.3	128.8	121.8	116.3	127.4	109.4	125.8	120.7	115.2	115.6	125.0	122.8	126.1	113.3	125.2
16	137.6	129.0	123.0	121.9	129.0	138.8	136.4	111.1	129.1	126.9	109.9	111.4	127.9	122.4	129.6	136.4	138.8	133.4	137.2	112.8
17	110.0	111.6	124.0	125.3	124.3	116.6	124.7	132.1	139.7	113.0	112.2	134.2	116.6	118.0	118.7	139.2	131.9	118.6	115.0	110.7
18	128.2	126.0	110.7	126.7	110.2	112.5	131.1	110.7	110.3	130.4	134.7	122.8	119.7	117.2	118.0	119.5	114.0	128.7	128.4	124.8
19	121.7	128.5	113.4	134.9	127.8	120.9	127.8	135.2	125.0	124.7	122.8	113.8	134.2	135.2	112.6	138.2	123.1	118.8	115.4	133.0
20	132.3	141.2	114.4	126.2	123.3	113.1	126.8	132.0	115.2	116.0	126.3	109.8	128.0	124.2	117.1	117.4	134.0	137.5	130.7	126.7
Mean	122.1	127.2	124.7	122.8	125.5	123.5	124.4	124.0	123.4	123.0	124.4	121.8	122.6	121.2	123.2	124.9	126.1	126.0	124.5	124.2
Std. Dev.	9.6	8.0	7.8	7.7	8.4	10.1	7.6	8.6	9.4	8.7	9.4	8.9	8.5	6.6	8.0	7.6	8.3	8.0	10.4	7.7
Max.	138	141	138	135	141	140	136	135	140	137	142	135	137	135	139	139	139	141	139	137
Min.	103	112	111	108	110	100	111	111	110	102	109	109	109	110	113	114	109	110	108	111
Range	35	29	27	27	31	40	25	24	30	35	33	26	28	25	26	25	30	31	31	26
Coef. of Var.	.07	.06	.06	.06	.07	.08	.06	.07	.08	.07	.08	.07	.07	.05	.06	.06	.07	.06	.08	.06

standard deviation, ranges from .05 to .08. Mean yields are higher and yield variability is lower on crop block G1 than on other blocks of grain sorghum. This uniformity reflects the fact that irrigation applications were more numerous and more timely on G1 than on the other grain sorghum blocks.

Mean yields and water-use rates indicate the accuracy with which the "average" situation is being represented. Mean yields ranging from 122 to 127 bushels per acre are associated with mean acre inches pumped ranging from 24 to 26 acre inches per acre. It should be emphasized that the number of acre inches pumped per acre for grain sorghum does not account for water that is lost in the application process. An irrigation efficiency of two-thirds was assumed so that mean acre inches pumped per acre actually ranged from 16 to 17 acre inches. These figures are slightly lower than the 18 acre inch per acre usually recommended for the study area. However, the 18 acre inch figure is based on assumptions of water requirements by months of the growing season. Irrigation applications based on soil moisture relative to critical stages of plant development would be expected to result in similar yields with a slightly lower total water application rate.[9]

Table 10 presents a summary of irrigated grain sorghum yields in bushels per acre for crop block G2. G2 is the second priority block of grain sorghum and, as such, receives irrigation water only if soil water under crop block G1 is adequate during a given stage of plant development. Grain sorghum yields range from a maximum of 141 bushels per acre to a minimum of 78 bushels per acre. The greatest range between maximum and minimum yield per acre is 63 bushels. Coefficients of variation, reflecting relative variability across replications range from .10 to .16. Yield variability is substantially greater here than for grain sorghum crop block G1. Mean yields across replications are from 6 to 13 bushels per acre less than on crop block G1. Mean yields range from about 108 to 121 bushels per acre with mean acre inches pumped ranging from about 20 to 23 acre inches per acre. Assuming an irrigation efficiency of two-thirds, actual water application rates range from 13.3 to 15.3 acre inches per acre. These yields and water use rates are compatable with those experienced in the study area.

A summary of irrigated grain sorghum yield per acre for crop block G3, the third priority grain sorghum block, is presented in Table 11. Yield per acre ranges from a maximum of 140 bushels per acre to a minimum of 61 bushels per acre. The greatest range, the difference between a maximum of 136 and a minimum of 61 bushels per acre, is 75

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[9] Water-use rates were obtained for each crop block and for every replication of the simulation runs. Although they will not be presented in tabular form, the water-use rates were judged to be realistic by those who analyzed them and representative of pumping rates existing in the study area.

Table 10. Irrigated Grain Sorghum Yields in Bushels Per Acre, Crop Block G2.

	Year																			
Replication	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	110.6	132.2	103.0	106.7	87.4	110.6	118.3	116.9	116.6	119.3	127.4	81.8	101.1	113.0	106.6	125.8	112.6	104.8	80.1	113.6
2	136.2	128.8	111.1	117.6	137.8	118.8	105.5	115.3	89.8	128.6	112.0	83.7	105.4	85.4	112.0	108.6	91.2	82.0	132.4	123.5
3	123.6	133.2	110.9	104.6	119.7	109.8	115.0	121.4	124.7	124.6	133.5	129.4	102.6	101.3	120.9	120.9	123.0	140.3	133.2	93.6
4	84.0	99.8	102.1	129.0	126.2	88.4	103.3	99.2	131.2	105.1	107.6	104.8	133.1	100.0	126.0	120.1	133.4	107.5	130.5	122.8
5	107.9	94.8	124.9	128.4	139.4	118.2	131.8	95.1	99.6	131.8	129.2	125.1	130.4	89.2	122.3	116.9	132.1	130.8	135.1	110.5
6	129.0	120.6	110.6	95.0	111.9	108.6	80.2	83.2	130.3	123.0	92.0	111.9	126.7	126.6	132.6	113.3	133.0	118.3	91.1	119.1
7	90.0	131.8	123.1	129.9	127.5	97.8	125.3	92.6	131.0	130.0	134.8	93.9	129.0	127.9	135.8	115.4	93.0	99.5	128.1	129.4
8	102.3	125.0	109.5	127.7	82.6	122.9	126.3	124.2	132.5	92.9	125.0	93.5	80.1	84.5	97.5	129.3	128.6	107.7	105.1	96.6
9	132.4	115.4	118.7	92.9	87.1	130.9	122.9	131.1	78.5	121.8	90.2	106.0	118.9	122.8	96.8	88.8	131.5	136.2	131.2	90.7
10	127.2	125.5	123.8	107.6	128.1	130.4	101.2	108.4	109.3	84.0	132.6	129.0	103.1	128.6	112.1	109.6	89.1	122.5	105.6	116.2
11	129.7	93.2	138.4	133.4	124.2	119.4	138.5	133.4	123.7	114.7	111.7	125.3	119.2	130.1	103.8	123.4	127.3	107.9	91.6	115.8
12	99.9	131.6	121.0	128.0	124.8	98.1	111.7	95.7	93.5	99.4	110.7	92.6	116.3	106.2	131.8	105.8	128.9	124.7	103.3	137.2
13	95.0	124.8	126.4	93.9	131.0	127.6	120.3	125.8	99.5	133.6	128.1	113.6	109.4	117.4	112.8	111.8	132.8	135.7	129.4	126.3
14	118.1	114.3	125.6	81.7	119.3	121.4	132.3	97.6	102.1	111.8	120.1	115.7	86.1	91.4	109.0	94.3	122.5	119.4	137.0	114.1
15	109.3	123.6	136.3	93.1	126.2	130.4	119.6	117.5	102.1	130.7	82.5	117.7	125.2	91.7	104.4	118.4	114.8	125.8	80.4	131.6
16	131.8	121.2	117.9	105.5	127.2	136.8	136.5	100.0	118.5	115.9	89.9	81.7	126.4	122.8	110.3	121.2	131.1	129.4	130.8	83.4
17	98.3	96.2	128.8	120.0	125.4	101.7	108.3	128.3	141.3	81.5	90.1	135.2	98.8	105.7	113.9	135.6	123.1	103.9	118.0	97.3
18	123.1	132.2	89.0	123.8	107.8	92.5	129.7	90.1	90.9	122.4	128.9	133.9	115.2	116.5	107.7	108.7	82.8	121.7	127.6	121.7
19	113.2	132.3	84.6	134.0	123.7	115.9	119.3	111.2	104.2	105.4	103.8	94.2	134.8	125.5	92.2	131.7	103.7	113.3	102.8	130.9
20	124.5	139.3	91.9	128.2	127.0	94.5	112.9	122.7	100.6	86.8	113.1	91.3	133.3	122.4	110.2	105.1	128.5	137.1	116.2	115.8
Mean	114.2	120.8	114.9	114.2	119.2	113.8	117.8	110.4	110.0	113.2	113.2	108.1	114.6	110.4	113.0	115.2	118.2	118.5	115.4	114.6
Std. Dev.	15.5	14.2	14.9	16.3	16.1	14.3	13.9	15.2	17.4	16.8	17.0	18.0	15.9	15.9	12.2	11.8	16.8	14.9	18.9	15.0
Max.	136	140	138	134	139	137	138	133	141	134	135	135	135	130	136	136	133	140	137	137
Min.	84	93	85	82	83	88	80	83	78	81	83	82	80	85	92	89	83	82	80	83
Range	52	47	53	52	56	49	58	50	63	53	52	53	55	45	44	47	50	58	57	54
Coef. of Var.	.14	.12	.13	.14	.13	.13	.12	.14	.16	.15	.15	.17	.14	.14	.11	.10	.14	.13	.16	.13

Table 11. Irrigated Grain Sorghum Yields in Bushels Per Acre, Crop Block G3.

	Year																			
Replication	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	106.7	131.4	91.0	110.0	78.8	118.3	108.7	108.7	119.8	129.6	109.0	81.2	89.1	127.2	109.0	112.8	85.1	111.2	60.9	107.3
2	121.8	121.1	111.7	116.3	135.4	99.4	93.4	88.7	112.0	131.7	131.7	84.4	113.7	83.6	117.4	87.0	91.6	75.1	131.1	120.2
3	105.5	121.7	88.6	81.6	119.5	85.9	120.3	119.3	113.8	127.1	127.1	127.7	94.6	81.2	101.4	132.9	113.6	139.7	118.5	78.6
4	76.7	81.7	86.1	124.5	128.0	66.5	116.3	130.4	95.1	103.0	103.0	106.3	103.3	87.6	123.8	112.2	130.6	102.4	125.3	114.8
5	108.0	76.1	127.0	119.1	139.4	115.7	135.1	91.9	91.4	125.4	112.4	115.0	131.7	71.2	124.0	106.2	133.1	125.9	133.9	121.4
6	124.3	99.9	114.2	82.6	115.3	91.8	77.2	72.4	132.4	117.8	73.2	98.5	139.5	112.7	124.2	103.9	128.9	115.2	71.0	116.4
7	83.4	128.5	120.3	128.2	126.1	93.2	128.4	86.3	127.3	124.8	137.1	97.5	134.6	129.4	139.4	128.5	83.7	85.1	118.1	135.7
8	81.4	108.2	121.7	114.6	75.7	127.0	116.7	122.5	128.7	81.0	112.2	86.0	66.9	93.2	82.7	133.9	98.7	125.5	115.4	78.7
9	128.0	122.8	96.7	84.8	97.6	135.9	113.0	123.3	73.7	119.6	85.8	94.3	111.5	111.8	89.9	71.5	119.8	128.3	131.4	74.8
10	121.0	114.5	119.5	85.1	135.8	128.4	92.7	98.9	100.6	94.6	129.9	129.4	79.4	120.7	112.2	109.1	81.5	119.3	105.9	118.8
11	123.9	74.0	130.2	137.1	118.5	110.2	133.8	135.1	122.1	106.8	114.5	118.8	92.0	130.5	107.1	119.0	102.9	95.4	73.3	95.7
12	83.3	137.1	99.7	126.9	126.7	94.0	105.3	72.6	67.7	74.1	107.1	93.2	101.4	117.2	129.4	93.9	130.0	111.2	81.9	132.2
13	94.1	126.1	115.2	91.8	128.9	113.9	124.3	119.9	82.8	129.6	129.8	104.4	86.5	113.2	111.4	108.4	134.6	122.2	125.9	118.3
14	116.3	113.1	131.9	80.9	122.1	127.7	104.9	76.4	76.9	109.9	122.0	98.2	62.7	95.4	98.2	78.0	123.0	106.0	135.8	119.4
15	100.5	98.7	132.9	94.0	117.4	128.2	127.6	115.0	81.5	128.7	63.3	116.1	123.7	82.8	92.0	115.2	127.5	125.3	89.6	125.1
16	129.0	114.8	81.5	97.9	126.2	131.0	133.6	84.4	111.8	100.5	68.7	84.7	136.2	107.0	106.6	117.6	133.0	130.9	131.4	86.3
17	79.1	81.6	124.2	118.9	118.1	92.3	100.1	111.1	137.0	76.4	80.7	130.3	104.4	107.8	114.1	138.5	122.0	106.5	92.8	81.2
18	125.2	133.3	97.6	116.6	84.7	70.8	122.9	93.1	98.6	116.5	127.9	135.4	86.4	91.8	91.1	91.6	88.2	126.6	124.0	128.1
19	120.4	116.5	79.8	127.8	99.8	113.8	103.2	107.5	99.9	91.8	107.0	104.2	138.3	137.0	83.4	126.9	102.2	116.1	79.1	124.8
20	122.1	139.7	88.6	117.9	118.0	87.8	113.9	133.1	90.5	89.2	107.6	75.5	115.2	125.2	115.3	111.4	126.2	130.8	103.5	78.6
Mean	107.4	112.0	108.0	107.9	115.7	106.6	113.6	103.0	104.0	108.0	107.5	104.0	105.5	106.3	108.5	110.0	113.0	109.8	107.4	107.8
Std. Dev.	18.4	20.4	17.9	18.4	18.5	20.7	15.6	19.9	21.9	19.1	22.3	17.9	23.7	19.2	15.6	18.3	19.0	24.4	24.1	20.6
Max.	129	140	133	137	139	136	135	135	137	134	137	135	140	137	139	138	135	140	136	136
Min.	77	74	80	81	76	66	77	72	68	74	63	75	63	71	83	72	82	75	61	75
Range	52	66	53	56	63	70	58	63	69	60	74	60	77	66	56	66	53	65	75	61
Coef. of Var.	.17	.18	.17	.17	.16	.19	.14	.19	.21	.18	.21	.17	.22	.18	.15	.17	.17	.22	.22	.19

bushels. Relative yield variability is greater than for crop block G3. Coefficients of variation range from .14 to .22. Mean yields across replications vary from 103 to 115 bushels per acre. These mean yields on crop block G3 are 4 to 9 bushels per acre less than mean yields on crop block G2. Mean yields computed across replications of the simulation run, range from 103 to 116 bushels per acre. These yields are associated with mean water-use rates ranging from 19 to 21 acre inches per acre. Again, assuming an irrigation efficiency of about two-thirds, actual water-use rates range from 12 to 14 acre inches per acre.

A summary of irrigated grain sorghum yields per acre for the final block of irrigated grain sorghum, G4, is presented in Table 12. This block of grain sorghum receives irrigation water only after crop blocks G1, G2 and G3 are assured of adequate soil water. The maximum yield produced on crop block G4 is 141 bushels per acre and the minimum is 56 bushels per acre. The greatest range between maximum and minimum yields is 80 bushels per acre. This range widened from about 40 bushels per acre for G1 to 80 bushels per acre for G4.

Relative yield variability, as measured by the coefficient of variation, has increased also and ranges from .14 to .32. Mean yields range from 86 to 109 bushels per acre. These mean yields are from 1 to 17 bushels per acre less than mean yields on crop block G3. Mean yields, computed across replications of the simulation run, range from 87 to about 109 bushels per acre. These mean yields are associated with mean water-use rates ranging from 16 to 19 acre inches per acre. Actual water-use rates are reduced to between 10 and 12 acre inches per acre when an irrigation efficiency of two-thirds is assumed. These average yields are considered consistent with those expected in the study area, given the average irrigation application rate.

In addition to the four blocks of irrigated grain sorghum, the representative study area farm operation contained 30 acres of dryland grain sorghum in crop block G5. This crop block received no irrigation water and was subjected to the same soil water and atmospheric stress conditions as the irrigated crop blocks. A summary of dryland grain sorghum yields is presented in Table 13. As expected, variation in dryland yields was much greater than variation in irrigated yields. The maximum dryland grain sorghum yield simulated was almost 92 bushels per acre. The minimum dryland yield was zero. When soil moisture is inadequate at planting time, no stand is achieved. Often farm operators plant the crop in hopes of adequate rainfall shortly after planting. However, a dryland grain sorghum crop failure occurs about 1 year in 5, or 4 years in 20. Examination of the yields generated by the simulation model reveals that crop failures occurred on the average, between 3 and 4 times in 20 years. Mean yields computed across replications ranged from 11 to 20 bushels

Table 12. Irrigated Grain Sorghum Yields in Bushels Per Acre, Crop Block G4.

	Year																			
Replication	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	72.9	130.3	82.4	89.2	86.5	79.7	106.6	111.0	119.9	112.8	108.3	87.5	59.8	116.3	107.2	108.6	70.8	92.6	57.9	93.3
2	129.0	111.1	119.0	103.7	133.5	92.4	91.0	86.2	72.6	86.8	118.1	71.0	99.2	89.2	112.5	81.3	60.3	94.1	114.7	88.9
3	105.4	120.7	64.5	75.7	86.5	95.7	102.3	125.5	99.0	132.0	122.9	125.8	76.2	81.0	103.1	133.9	99.8	140.7	114.8	74.8
4	61.9	103.9	60.2	126.0	106.9	63.2	111.4	84.2	127.9	107.7	117.1	98.1	104.3	92.1	119.8	105.5	103.9	105.3	127.4	105.2
5	105.2	62.2	122.5	108.2	140.2	97.3	134.5	88.3	97.7	99.6	111.4	121.3	127.4	67.3	118.7	110.5	127.6	121.4	127.3	105.7
6	121.2	83.9	110.5	85.1	116.9	92.0	57.6	74.0	123.7	123.7	79.8	82.3	130.8	105.8	121.3	92.9	125.7	115.6	68.9	131.7
7	72.4	120.0	123.0	126.5	95.9	86.4	134.1	82.1	131.3	91.5	136.7	81.4	133.0	116.1	137.8	102.6	83.3	95.7	116.2	135.1
8	75.9	97.9	117.5	115.8	68.4	129.1	104.6	125.4	127.0	61.2	112.3	75.2	59.5	78.2	63.1	126.6	93.1	101.7	82.7	58.2
9	129.9	86.3	73.7	74.0	93.0	131.5	100.6	128.4	58.5	115.0	90.7	92.2	83.3	98.8	78.8	75.0	104.2	126.9	126.4	64.2
10	116.3	124.2	81.6	92.3	129.3	114.6	66.1	102.6	61.2	61.7	116.8	126.4	58.0	105.8	111.9	128.9	75.7	104.4	109.6	122.7
11	115.7	68.8	130.7	134.7	106.4	101.9	137.7	129.0	106.0	73.3	98.6	100.7	84.7	128.7	101.6	120.2	77.5	99.6	56.0	86.3
12	93.2	127.4	78.8	125.3	111.0	80.6	81.7	68.4	62.7	69.4	92.9	76.4	84.2	122.8	128.6	80.5	131.7	90.5	74.2	128.0
13	87.2	106.4	80.8	70.8	126.7	92.8	107.3	121.8	79.6	132.3	127.8	83.6	69.7	111.9	125.3	108.3	131.3	117.2	123.8	118.9
14	88.8	115.0	119.2	69.6	102.0	97.0	77.0	58.6	71.4	125.2	110.7	94.5	60.4	87.9	88.3	88.7	124.8	93.3	134.4	129.5
15	102.1	76.8	132.1	100.3	104.4	131.1	121.7	110.8	99.2	135.1	58.7	85.6	112.6	63.3	80.8	112.7	130.0	113.0	70.4	96.1
16	122.5	120.2	67.6	89.8	136.1	129.7	132.3	58.0	91.8	84.1	59.4	70.3	121.4	105.9	110.2	118.7	129.9	125.8	126.7	72.1
17	72.7	70.5	120.2	88.3	117.1	78.8	100.4	97.4	136.8	69.4	61.7	130.8	102.3	91.9	102.2	137.6	108.2	89.2	75.8	72.4
18	131.4	129.1	76.5	115.7	81.3	58.2	104.9	81.0	95.1	108.4	116.9	125.3	91.3	70.5	90.8	92.4	83.5	108.0	130.2	115.1
19	111.9	116.5	69.0	133.9	81.1	96.5	109.8	107.6	98.0	73.5	93.0	71.8	133.5	124.6	92.7	125.0	120.0	101.8	104.0	124.8
20	114.9	139.6	61.8	116.9	116.8	74.2	89.2	115.5	83.6	65.4	107.0	67.5	102.3	101.7	109.2	103.8	121.0	134.1	76.1	72.9
Mean	101.6	105.5	94.6	102.2	107.0	96.2	103.6	97.8	97.2	96.4	102.1	86.8	94.6	98.0	105.2	107.8	106.6	108.6	100.9	99.8
Std. Dev.	21.9	23.2	26.1	21.6	20.4	21.9	22.3	23.3	24.9	25.8	22.6	28.0	26.1	19.5	18.6	18.4	24.0	15.2	27.1	25.2
Max.	131	140	132	135	140	132	138	129	138	135	137	126	134	129	138	138	132	141	134	135
Min.	62	62	60	70	68	58	58	58	58	61	59	67	58	63	63	75	60	89	56	58
Range	69	78	72	65	72	74	80	71	80	74	78	59	76	66	75	63	72	52	78	77
Coef. of Var.	.22	.22	.28	.21	.19	.23	.21	.24	.26	.27	.22	.32	.28	.20	.18	.17	.23	.14	.27	.25

Table 13. Dryland Grain Sorghum Yields in Bushels Per Acre, Crop Block G5.

	Year																			
Replication	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	11.2	63.2	--	19.0	--	9.4	16.6	11.9	12.4	23.9	9.7	7.7	--	18.7	28.5	15.8	9.2	13.8	--	12.2
2	12.6	21.0	18.6	--	21.2	8.0	9.4	--	--	11.3	--	9.1	11.9	--	--	13.5	--	--	15.2	16.1
3	12.5	18.8	12.1	13.9	9.3	--	--	22.5	--	19.5	21.6	33.5	--	--	12.0	43.9	12.9	92.2	13.6	10.9
4	10.1	13.1	7.8	14.8	15.7	--	11.7	9.8	--	17.5	11.1	9.2	75.2	13.6	39.2	11.0	--	18.7	16.4	9.7
5	74.4	9.1	14.8	13.2	80.4	10.6	24.4	14.4	10.2	14.0	22.4	25.6	35.2	--	11.1	19.5	20.0	12.0	23.3	13.7
6	11.8	14.8	13.6	7.0	--	8.0	8.0	8.0	30.3	23.4	8.5	13.1	--	10.6	20.0	8.4	29.5	15.7	--	32.1
7	--	--	9.9	11.4	20.7	--	--	16.2	43.8	23.6	59.5	12.8	29.6	13.9	67.2	13.4	10.2	9.4	--	48.7
8	9.8	14.4	--	12.3	--	36.1	13.2	25.2	43.0	14.3	32.2	9.1	--	7.6	7.7	26.2	10.4	14.5	13.6	8.2
9	18.7	--	10.4	16.6	10.4	38.3	8.5	32.8	7.9	17.2	--	10.4	10.6	30.1	14.6	--	10.7	23.8	36.0	8.9
10	16.3	25.0	14.1	9.1	20.5	15.7	9.6	--	8.3	9.6	14.1	20.5	8.5	15.5	17.5	--	11.1	12.6	--	24.8
11	15.6	10.0	36.4	50.4	11.6	15.1	--	19.3	--	13.9	18.0	13.6	--	21.9	8.9	--	13.0	--	5.8	13.5
12	22.8	40.9	15.9	32.0	--	18.6	9.0	5.2	--	6.3	13.6	13.2	11.2	10.5	35.7	12.6	13.3	21.1	11.5	49.6
13	--	15.3	9.6	--	25.0	11.6	13.1	19.9	9.5	52.4	17.4	12.0	10.7	--	13.2	--	70.5	15.3	19.7	19.9
14	13.9	13.9	17.9	--	8.3	10.0	11.1	6.4	8.4	12.4	--	10.6	8.2	13.2	9.3	16.6	14.6	10.1	46.9	30.8
15	23.1	8.5	55.7	--	8.0	43.1	25.2	12.1	13.7	--	5.7	13.7	14.2	--	14.6	16.0	12.5	31.4	6.2	11.5
16	30.7	14.0	8.5	20.2	--	71.8	37.7	--	--	9.6	6.5	8.2	36.4	14.3	9.7	17.2	41.4	31.7	25.9	8.1
17	--	7.3	21.3	8.6	10.1	--	--	13.1	91.5	7.4	6.7	29.8	18.1	13.0	--	73.4	16.0	7.6	8.3	5.3
18	12.2	13.8	--	20.8	--	7.5	11.3	--	--	43.4	29.6	9.9	10.2	9.8	56.1	61.4	8.4	17.6	12.3	13.1
19	19.0	21.9	6.7	24.1	10.4	12.6	9.0	25.7	13.3	12.9	17.8	10.8	40.4	25.7	--	17.9	--	11.5	--	46.6
20	22.9	79.4	10.3	14.2	13.4	9.4	10.0	18.9	--	9.2	9.6	6.1	11.4	--	--	12.2	35.4	22.0	12.8	11.0
Mean	17.0	20.2	14.3	14.4	13.2	16.4	11.4	13.0	14.6	17.0	15.3	14.0	16.5	11.0	18.4	18.9	16.9	19.2	13.4	19.8
Std. Dev.	15.6	19.7	12.8	12.0	17.9	18.0	9.3	9.6	22.7	12.2	13.9	7.5	18.6	9.1	18.5	19.4	16.6	19.1	12.5	14.4
Max.	74	79	56	50	81	72	38	33	92	52	60	33	75	30	67	73	71	92	47	50
Min.	0	0	0	0	0	0	0	0	0	0	0	6	0	0	0	0	0	0	0	5
Range	74	79	56	50	81	72	38	33	92	52	60	27	75	30	67	73	71	92	47	45
Coef. of Var.	.92	.97	.90	.84	1.35	1.10	.82	.74	1.55	.72	.91	.54	1.13	.83	1.01	1.03	.98	1.00	.94	.73

per acre. Yield variability was much greater for the dryland block than for any of the irrigated crop blocks with coefficients of variation ranging from .72 to 1.55 on crop block G5.

Wheat

Crop yields were simulated for two blocks of irrigated wheat. A summary of wheat yields in bushels per acre for crop block W1 is presented in Table 14. The maximum yield produced during any simulation run was 72 bushels per acre while the minimum was 41 bushels per acre. The greatest range is 22 bushels per acre, the difference between a maximum yield of 66 and a minimum yield of 44 bushels per acre. Relative yield variability, as measured by the coefficient of variation, is very small, ranging from .03 to .09 across replications. The high mean yields, ranging from 58 to 61 bushels per acre, and small yield variability, reflect adequate and timely irrigation applications on this top priority block of irrigated wheat. These mean wheat yields are associated with mean water-use rates ranging from 17 to 20 acre inches per acre. Assuming an irrigation efficiency of two-thirds, actual water-use rates range from 11 to 13 acre inches per acre. Irrigation recommendations for the clay loam soils of the Oklahoma Panhandle range from 12 to 18 acre inches per acre. These recommendations assume applications are necessary to meet specified water requirements by the month.

A summary of irrigated wheat yields in bushels per acre for crop block W2 is contained in Table 15. The maximum yield produced in any replication is just over 70 bushels per acre and the minimum is just over 24 bushels per acre. The greatest range is 43 bushels per acre, the difference between a maximum of 69 and a minimum of 26 bushels per acre. The coefficient of variation is fairly stable ranging from .15 to .20, however, variation is substantially greater than for crop block W1. Mean yields range from 47 to 54 bushels per acre, from 7 to 12 bushels per acre less than on W1. Maximum yields of 60 to 70 bushels per acre are associated with water-use rates of about 12 acre inches per acre while minimum yields of 24 to 25 bushels per acre are associated with water-use rates of about 6 acre inches per acre. These relationships are very similar to those found for crop block W1.

In addition to the two blocks of irrigated wheat, one block of dryland wheat is contained on the representative farm of the study area. This crop block, W3, received no irrigation water, and was subjected to the same rainfall and evapotranspiration conditions as all other crops, including dryland grain sorghum. A summary of dryland wheat yields is presented in Table 16. The maximum dryland wheat yield simulated was almost 49 bushels per acre. The minimum dryland yield

Table 14. Irrigated Wheat Yield in Bushels Per Acre, Crop Block W1.

	Year																			
Replication	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	63.1	63.5	55.6	56.3	52.9	51.9	44.7	35.7	58.4	55.0	53.9	38.4	59.2	58.7	43.8	53.6	48.2	59.0	42.0	54.9
2	41.2	41.2	39.2	39.5	53.4	56.0	38.5	54.8	52.8	55.4	56.6	34.7	40.6	44.8	43.4	64.0	46.9	25.6	52.3	57.8
3	55.0	63.5	53.5	46.2	53.9	53.9	54.6	42.6	55.4	54.0	58.6	54.2	57.7	42.1	54.5	56.5	45.6	40.1	40.3	52.8
4	36.7	41.3	61.2	54.9	54.6	40.3	52.6	40.3	61.4	40.8	52.6	43.5	65.0	65.0	58.7	55.3	45.4	55.9	53.3	54.0
5	68.3	38.7	47.9	60.5	54.2	61.7	54.7	56.0	52.3	47.3	57.2	61.2	61.7	51.7	60.1	50.3	53.3	46.3	56.5	54.8
6	54.0	55.2	44.2	51.1	39.9	50.0	26.8	49.8	36.9	40.6	29.0	57.1	43.3	52.9	53.6	56.3	57.5	41.2	40.0	43.8
7	52.3	38.8	55.3	56.2	57.0	66.5	39.6	69.1	58.0	66.9	54.7	41.0	53.4	55.2	40.2	51.0	43.6	44.9	58.6	55.1
8	53.2	63.1	51.6	55.0	38.2	38.9	51.8	58.0	59.7	68.6	56.9	43.1	49.8	53.6	46.3	56.1	43.5	32.6	45.3	65.2
9	55.0	52.0	42.3	65.4	41.2	52.2	54.4	55.1	51.5	52.8	44.2	43.3	59.7	60.0	58.1	24.9	51.7	57.8	53.8	44.1
10	59.5	63.9	69.1	55.4	41.9	57.2	58.0	40.8	48.0	53.8	54.8	57.4	46.9	59.2	44.2	44.8	44.1	54.4	43.0	41.0
11	54.5	44.2	41.1	55.2	55.1	68.4	39.7	53.8	54.1	55.1	60.5	39.0	39.4	43.3	53.7	56.7	61.4	41.3	38.8	55.7
12	70.2	63.8	54.6	43.2	42.6	55.4	41.1	32.4	29.7	29.7	40.4	54.5	52.7	51.4	42.0	64.3	59.6	60.3	53.6	45.7
13	39.1	57.1	46.0	53.9	56.8	55.2	46.9	62.1	43.9	52.1	57.3	55.0	26.9	51.3	54.1	41.1	54.0	45.9	53.4	53.8
14	50.4	53.0	53.0	38.4	43.7	38.8	56.0	47.5	54.0	55.1	43.2	37.0	26.5	42.5	56.2	50.8	46.0	60.8	55.8	54.4
15	66.3	55.1	47.2	37.0	56.5	57.5	62.9	28.1	52.5	41.1	41.2	54.2	54.0	26.0	43.8	40.6	44.3	56.1	46.9	42.9
16	49.4	55.3	50.6	55.2	39.4	40.7	54.4	41.4	58.0	44.4	26.6	52.9	39.3	40.7	27.4	53.5	48.5	53.7	58.5	27.0
17	40.0	45.2	61.9	58.5	41.7	50.6	37.7	57.9	39.3	42.0	44.9	62.8	46.8	43.3	39.4	55.5	58.5	54.0	34.3	52.9
18	54.0	40.7	54.7	61.5	58.8	37.4	55.0	43.3	39.4	67.6	42.2	47.4	45.7	57.5	52.9	57.2	24.1	42.8	40.2	55.0
19	56.0	57.8	26.1	45.6	53.4	53.4	48.3	62.3	49.7	55.8	53.8	53.7	41.2	53.8	41.9	53.4	50.8	45.8	52.9	59.5
20	53.1	43.0	56.0	53.4	40.8	40.9	61.5	63.6	49.6	42.6	53.4	53.3	41.1	40.3	38.5	41.9	61.1	52.4	44.4	61.6
Mean	53.5	51.8	50.6	52.0	48.8	51.4	49.0	49.7	50.2	52.0	49.1	49.1	47.6	49.7	47.6	51.4	49.4	48.6	48.2	51.7
Std. Dev.	9.3	9.3	9.5	7.9	7.4	9.2	9.2	11.4	8.4	10.5	9.7	8.5	10.7	9.3	8.6	9.0	8.6	9.4	7.6	8.7
Max.	70	64	69	65	59	68	63	69	61	69	60	63	65	65	60	64	61	61	59	65
Min.	37	39	26	37	38	37	27	28	30	30	27	35	27	26	27	25	24	26	34	27
Range	33	25	43	28	21	31	36	41	31	39	33	28	38	39	33	33	39	37	25	38
Coef. of Var.	.17	.18	.19	.15	.15	.18	.19	.23	.17	.20	.20	.17	.22	.19	.18	.18	.17	.19	.16	.17

Table 15. Irrigated Wheat Yield in Bushels Per Acre, Crop Block W2.

	Year																			
Replication	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	64.5	65.0	59.1	62.8	60.1	58.9	60.6	58.7	65.0	59.5	60.9	58.6	60.6	62.3	59.7	59.3	66.5	59.1	58.5	63.8
2	56.6	58.7	51.7	58.0	58.2	63.7	59.8	58.6	61.6	59.3	60.8	59.8	55.0	59.0	59.5	65.4	63.2	55.5	57.6	62.1
3	58.7	64.9	59.2	61.1	60.4	55.7	57.5	59.5	58.4	60.9	62.9	57.0	60.6	57.5	57.8	59.8	57.9	40.9	64.5	58.0
4	57.4	56.7	64.1	59.3	60.0	58.8	57.9	55.4	63.2	50.7	55.3	59.6	68.9	64.7	66.2	60.7	59.5	59.4	59.2	61.2
5	68.3	58.6	57.9	62.8	56.6	67.8	57.2	61.5	62.8	63.2	64.1	63.1	68.5	54.5	65.8	53.4	55.7	61.0	61.4	55.2
6	59.7	59.8	60.3	59.1	54.5	59.6	58.8	60.6	57.7	56.0	58.9	62.0	58.6	59.0	60.4	60.8	60.7	56.7	56.0	59.5
7	59.8	55.6	55.9	57.7	63.0	67.7	54.1	70.2	62.2	65.5	57.0	58.7	55.8	61.3	43.9	60.3	59.1	58.9	64.4	56.8
8	57.4	66.7	59.1	61.0	58.2	54.3	61.1	61.9	60.1	71.4	57.4	58.8	60.2	60.7	59.9	60.7	64.9	58.0	59.4	65.8
9	60.3	60.1	60.5	71.8	59.3	57.8	65.6	57.5	57.9	64.4	58.9	57.4	62.8	66.4	60.9	55.7	62.0	61.2	56.0	59.4
10	63.2	62.6	69.7	58.1	60.6	65.7	63.6	58.6	60.2	55.9	60.0	59.7	65.4	60.7	59.8	60.7	59.2	58.5	59.4	58.2
11	57.4	59.5	56.1	57.7	57.1	70.0	56.9	58.7	58.6	60.5	65.4	59.7	56.2	59.4	58.5	60.4	61.7	53.1	58.9	63.2
12	71.9	63.9	61.9	58.7	59.6	72.2	59.0	60.4	59.6	59.3	56.6	57.4	55.1	57.0	59.4	65.3	60.4	63.1	54.5	59.6
13	55.5	62.5	61.0	56.7	61.9	61.2	60.2	60.9	57.9	59.1	64.0	59.1	58.8	58.6	56.5	58.0	62.6	60.1	59.3	56.8
14	58.7	55.0	58.5	56.0	60.6	54.1	62.4	60.3	56.4	60.6	58.2	59.5	56.7	58.2	62.9	57.3	60.5	63.1	58.2	56.9
15	68.1	58.9	60.9	59.2	64.1	62.8	67.3	59.1	59.0	59.8	58.3	58.5	59.3	54.8	58.4	51.7	59.7	61.3	59.7	59.7
16	60.0	57.4	59.0	64.7	58.5	55.4	60.0	62.7	64.5	59.2	58.2	59.0	53.6	56.4	55.1	59.4	45.5	58.9	65.1	60.6
17	55.8	59.7	65.5	65.3	59.0	57.2	57.8	64.0	44.2	57.9	62.5	64.0	56.2	59.0	54.4	59.2	65.1	56.2	59.9	60.0
18	60.0	55.4	60.0	61.4	65.4	56.1	57.7	58.6	52.2	70.7	58.0	61.1	60.4	61.5	56.1	61.4	55.5	59.2	57.5	60.6
19	58.8	65.8	56.8	60.3	60.0	59.4	57.2	67.7	60.3	60.7	61.3	58.4	58.9	59.6	59.2	59.7	58.1	61.9	54.6	66.5
20	61.9	48.0	58.6	60.2	56.9	53.1	65.2	63.2	59.3	58.4	58.1	58.7	59.3	58.4	53.1	57.6	64.9	63.2	61.1	64.3
Mean	60.7	59.9	59.9	60.6	59.6	60.6	60.0	60.9	59.0	60.9	59.8	59.6	59.6	59.5	58.4	59.3	60.1	58.4	59.2	60.4
Std. Dev.	4.4	4.6	3.8	3.6	2.6	5.7	3.4	3.5	4.6	4.2	2.8	1.9	4.2	2.9	4.8	3.2	4.6	4.8	2.8	3.2
Max.	72	67	70	72	65	72	67	70	65	71	65	64	69	66	66	65	66	63	65	67
Min.	56	48	52	56	54	53	54	55	44	56	55	57	54	55	44	52	45	41	55	55
Range	16	19	18	16	11	19	13	15	21	15	10	7	15	11	22	13	21	22	10	12
Coef. of Var.	.07	.08	.06	.06	.04	.09	.06	.06	.08	.07	.05	.03	.07	.05	.08	.05	.08	.08	.05	.05

Table 16. Dryland Wheat Yield in Bushels Per Acre, Crop Block W3.

	Year																			
Replication	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	18.4	34.4	13.9	18.6	11.4	11.1	13.8	12.7	26.7	15.9	13.0	13.8	--	15.3	12.9	17.9	28.3	15.4	--	19.2
2	--	11.6	9.1	10.6	12.0	--	11.5	--	12.8	--	--	15.6	9.5	10.9	11.4	21.7	17.5	--	11.5	19.2
3	12.9	--	12.6	13.0	15.7	11.9	13.3	--	15.4	16.4	--	12.8	16.7	11.0	12.2	--	11.2	12.8	--	11.3
4	11.1	11.1	20.1	14.4	14.7	--	12.4	10.2	--	10.6	12.0	13.1	38.2	26.3	24.2	17.2	--	14.0	16.6	12.9
5	--	--	15.3	--	14.9	25.9	14.9	--	19.8	28.8	--	18.0	25.9	11.0	20.2	10.7	16.0	12.4	15.5	12.7
6	16.5	14.1	12.9	11.3	10.2	--	--	17.8	--	9.9	10.4	--	11.3	--	12.4	--	16.0	11.2	10.5	12.8
7	12.3	10.6	14.3	15.1	--	--	9.7	35.9	24.0	30.9	14.4	11.2	11.7	22.8	14.1	18.3	11.8	--	17.0	14.6
8	12.0	20.6	10.9	17.8	10.6	9.9	--	--	20.6	48.6	18.5	--	12.1	20.7	12.4	15.6	20.2	15.3	15.5	33.5
9	18.2	11.6	11.6	41.6	10.8	12.5	26.6	13.2	--	--	11.1	11.6	16.4	25.0	16.7	9.7	--	16.7	12.5	12.2
10	15.7	--	36.4	13.4	11.9	21.9	20.7	10.8	19.9	12.5	--	16.4	19.2	--	11.7	12.0	12.8	13.5	--	10.9
11	20.0	--	10.0	--	13.4	38.4	9.8	15.6	13.6	19.5	26.3	--	10.4	12.5	12.4	15.1	26.2	--	--	--
12	34.5	30.4	22.3	23.4	--	--	--	--	--	11.6	10.2	13.3	12.1	--	--	--	25.2	21.4	13.3	13.7
13	10.4	15.3	11.9	12.1	15.0	15.6	12.3	--	10.8	11.7	24.8	13.7	11.4	11.0	--	--	22.1	14.7	17.4	12.1
14	11.3	12.0	11.5	--	--	12.1	16.7	17.8	12.4	--	10.9	--	--	11.9	19.6	10.7	14.9	17.3	--	13.8
15	32.9	13.1	18.8	11.3	22.1	27.9	27.6	--	12.2	11.1	11.2	15.7	--	9.5	12.8	9.7	12.9	11.4	--	11.9
16	18.1	14.2	19.0	19.6	10.2	10.3	14.1	14.5	17.2	--	11.1	--	10.3	11.1	14.0	11.8	15.3	12.5	18.4	13.9
17	--	--	19.5	24.1	11.8	10.5	--	19.1	18.0	12.1	--	--	10.7	12.8	9.9	15.0	18.1	--	--	--
18	13.0	--	11.9	--	18.5	12.9	13.4	10.8	9.0	40.9	11.4	12.6	12.6	23.7	12.0	16.2	--	11.9	10.1	--
19	14.3	22.6	--	12.2	11.9	15.7	15.7	27.3	15.4	17.0	19.2	--	--	13.2	10.9	13.1	10.7	14.4	10.9	--
20	19.4	17.4	14.6	11.9	--	9.7	--	28.2	11.8	11.6	11.9	12.5	12.5	10.6	9.6	12.2	24.3	20.3	16.8	22.8
Mean	14.6	12.0	14.9	13.5	10.8	12.4	11.4	11.8	13.0	15.6	10.8	9.0	12.0	13.0	12.4	11.4	15.1	12.0	9.2	12.4
Std. Dev.	9.3	10.0	7.0	9.9	6.3	10.2	8.0	10.8	8.0	13.2	7.8	7.0	9.1	7.8	5.6	6.6	8.2	6.6	7.4	8.3
Max.	37	34	36	42	22	38	28	36	27	49	26	18	38	26	24	22	28	21	18	34
Min.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Range	37	34	36	42	22	38	28	36	27	49	26	18	38	26	24	22	28	21	18	34
Coef. of Var.	.64	.84	.47	.73	.58	.83	.70	.92	.62	.85	.73	.77	.76	.59	.45	.58	.54	.55	.80	.66

was zero. Zero wheat yields result when, due to insufficient soil moisture at planting time, no stand is achieved. In the study area, wheat crop failures occur about 20 percent of the time, or about 4 years in 20. The average for the simulation runs in Table 16 is between 4 and 5 years in 20. Mean wheat yields range from about 9 to 16 bushels per acre. Yield variability is high, as expected, for dryland wheat. The coefficient of variation ranges from .45 to .92.

Corn

Four blocks of irrigated corn are included in the model. Two crop blocks, C1 and C2, contain corn grown for grain. The other two blocks, CS1 and CS2, contain corn grown for silage. Within the study area, irrigation operators increasingly are growing grain-type corn varieties for silage production. Consequently, as previously explained, corn silage yields are computed based on corn grain yields for a given crop block. That is, corn silage yield on crop block CS1 is computed as a linear function of corn grain yield on crop block C1. Likewise, yield on CS2 is computed directly from yield on C2. Consequently, only corn grain yields for crop blocks C1 and C2 are presented in tabular form.

A summary of corn grain yield in bushels per acre for crop block C1 is presented in Table 17. Maximum corn yield is slightly less than 145 bushels per acre. Minimum yield is about 102 bushels per acre. Irrigated corn yields demonstrate limited variability. The coefficient of variation ranges from .04 to .07. The corresponding corn silage yields range from a maximum of 26 tons to a minimum of 18 tons per acre. Mean corn grain yields on C1 range from about 127 to 132 bushels per acre. Mean corn silage yields range from 23 to 27 tons per acre. Mean water-use rates range from 27 to 31 acre inches per acre. If an irrigation efficiency of two-thirds is assumed, mean water-use rates range from 18 to 20 acre inches per acre. Irrigation recommendations for corn grain and silage in the study area range from 16 to 22 acre inches per acre.

A summary of corn grain yield for crop block C2 is presented in Table 18. Maximum corn grain yield produced was slightly over 142 bushels per acre. Minimum yield was only about 75 bushels per acre. Yield variability was greater on block C2, the second priority corn grain block. The coefficient of variation ranged from .04 to .11. Corn silage yield ranged from a maximum of 26 to a minimum of 13 tons per acre. Mean corn grain yields ranged from 121 to 130 bushels per acre across replications. Corn silage mean yields ranged from 22 to 23 tons per acre. Mean irrigation water-use rates ranged from 26 to 29 acre inches per acre. Assuming an irrigation efficiency of two-thirds, actual water-use rates ranged from 17 to 20 acre inches per acre.

Table 17. Irrigated Corn Grain Yield in Bushels Per Acre, Crop Block C1.

	Year																			
Replication	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	132.7	140.5	131.2	119.1	110.4	122.2	128.3	136.8	130.7	131.2	123.2	118.9	132.6	128.6	122.4	125.7	122.4	136.1	118.2	133.5
2	128.3	120.4	122.7	120.0	135.5	121.9	121.7	136.8	119.5	132.4	126.0	119.5	125.9	126.4	130.0	137.0	131.0	121.2	128.5	115.6
3	134.2	132.8	131.8	121.1	114.7	129.0	124.6	137.1	133.3	131.3	137.0	132.2	135.6	128.5	130.4	140.3	131.3	140.6	137.9	123.5
4	125.9	121.0	128.4	131.2	128.8	130.8	124.8	126.9	134.9	119.3	121.1	127.0	141.5	136.7	142.7	135.7	140.6	132.6	132.0	121.5
5	143.2	119.8	135.9	128.6	140.9	139.1	138.1	124.2	130.8	129.6	141.1	128.4	139.3	123.5	124.2	136.7	137.0	137.2	138.2	126.2
6	120.0	135.3	136.4	120.5	124.6	120.9	118.0	112.1	137.7	132.8	114.7	137.9	135.2	137.7	136.0	130.4	139.1	127.3	129.5	134.6
7	127.3	131.4	133.0	135.8	124.4	126.4	129.9	142.1	140.8	135.8	133.8	127.5	128.5	137.2	134.3	128.9	118.7	127.6	131.8	138.3
8	136.2	131.2	129.2	126.8	126.6	135.5	126.9	135.6	136.5	140.0	126.2	122.1	119.7	131.8	126.2	136.0	129.3	135.1	126.2	135.6
9	134.3	118.2	130.9	129.0	127.4	133.5	131.3	131.3	129.3	129.1	125.9	119.8	120.0	125.7	122.8	116.2	123.8	136.9	140.6	123.9
10	117.5	138.8	131.0	135.4	133.9	130.4	122.0	119.7	131.3	130.9	138.7	138.9	122.3	132.9	123.7	131.2	117.6	122.9	122.7	128.0
11	129.4	128.7	135.4	134.9	120.3	133.1	134.6	138.2	137.3	119.2	133.5	121.2	122.7	132.3	128.2	132.4	130.4	122.2	115.6	121.8
12	137.5	138.6	134.5	137.3	135.1	141.4	128.1	124.2	125.1	121.3	130.5	122.8	132.4	132.9	131.2	132.9	133.0	125.4	132.7	135.5
13	130.5	138.9	119.8	127.9	138.2	120.3	122.5	135.3	127.8	141.6	131.2	132.9	130.8	124.7	125.1	123.5	137.9	137.5	135.4	124.5
14	137.2	132.2	131.3	125.3	136.0	128.4	118.7	127.9	130.0	122.5	112.6	133.5	120.8	122.7	127.9	129.5	133.5	131.6	138.2	136.0
15	124.5	134.1	130.9	120.9	118.1	140.4	136.6	122.9	133.9	133.8	122.8	114.7	126.2	102.5	120.2	131.7	126.3	139.0	125.7	124.1
16	132.9	138.8	114.9	110.9	123.0	134.2	142.8	115.8	133.8	128.1	119.0	127.7	129.8	115.2	134.9	123.6	133.2	135.0	136.1	130.0
17	104.9	116.9	136.1	127.5	125.7	132.5	126.5	132.1	140.4	114.7	116.8	125.3	121.3	123.1	125.2	140.2	135.6	133.5	120.9	131.0
18	135.0	127.0	128.4	136.5	124.1	118.3	130.0	127.9	120.3	136.0	132.2	131.8	128.5	132.6	124.9	125.4	116.0	125.8	131.1	131.7
19	125.4	129.1	119.7	128.8	131.2	126.9	121.4	128.1	132.5	131.6	130.2	120.1	135.9	134.2	118.3	118.6	127.1	130.5	135.2	137.7
20	134.3	132.1	120.1	125.5	128.1	122.7	134.8	132.1	132.8	120.9	128.9	127.8	112.7	121.5	126.3	126.7	141.6	132.7	127.8	139.6
Mean	129.5	130.2	129.0	127.2	127.4	129.3	128.2	129.4	132.0	129.3	128.0	126.6	128.2	127.6	127.6	130.2	130.2	131.6	130.2	129.8
Std. Dev.	8.5	7.6	6.2	6.9	7.9	6.9	6.8	7.9	5.8	7.6	7.5	6.6	7.5	8.5	6.0	6.7	7.6	5.9	7.0	6.7
Max.	143	140	136	137	141	141	143	142	141	145	141	139	142	138	143	140	142	141	141	140
Min.	105	117	115	111	110	118	118	112	119	115	113	115	113	102	118	116	116	121	116	116
Range	38	23	21	26	31	23	25	30	22	30	28	24	29	36	25	24	26	20	25	24
Coef. of Var.	.07	.06	.05	.05	.06	.05	.05	.06	.04	.06	.06	.05	.06	.07	.05	.05	.06	.04	.05	.05

Table 18. Irrigated Corn Grain Yield in Bushels Per Acre, Crop Block C2.

	Year																			
Replication	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	128.3	135.6	131.8	112.5	118.0	109.0	115.6	137.2	130.8	130.2	120.2	118.6	116.8	133.0	129.1	114.8	117.7	134.7	102.8	134.4
2	124.7	122.4	106.2	110.0	131.3	127.5	114.6	137.0	122.2	121.0	128.8	125.8	125.2	125.8	127.4	133.3	124.2	116.4	103.8	118.3
3	123.4	136.6	130.0	116.6	110.5	125.9	102.9	127.5	126.9	129.4	133.3	129.8	133.6	122.1	129.6	137.4	123.7	140.6	134.5	127.1
4	117.1	125.3	123.9	129.5	127.2	123.0	122.6	125.3	130.4	129.5	116.1	130.9	135.2	135.3	138.5	137.5	131.0	129.5	125.7	127.8
5	140.3	115.4	136.7	121.7	140.2	133.8	133.8	109.8	116.0	120.7	137.5	128.4	137.1	119.4	114.7	130.9	135.4	133.8	135.7	124.6
6	125.1	132.3	134.8	113.1	122.2	111.4	121.4	108.3	135.2	129.2	104.9	127.7	129.6	124.7	130.7	130.9	130.2	126.8	107.7	130.4
7	114.3	114.8	123.0	134.0	120.9	128.7	124.5	135.5	132.6	134.0	137.4	128.6	124.4	134.5	125.7	124.7	108.6	152.6	124.6	137.8
8	117.1	124.0	132.0	109.3	115.9	125.4	121.2	128.7	140.7	126.9	121.6	115.7	119.9	131.7	106.9	132.1	127.3	128.4	123.8	123.1
9	131.9	122.9	111.6	134.0	114.3	125.1	133.8	129.3	125.8	129.5	127.9	112.5	126.1	124.0	111.7	116.9	136.6	128.3	139.2	130.6
10	107.1	136.7	127.7	125.1	134.0	128.3	124.0	131.9	121.8	126.9	127.7	133.0	119.5	117.9	128.5	133.0	116.6	127.0	121.8	127.3
11	117.8	128.5	129.4	130.6	126.1	133.6	129.1	130.6	136.1	122.4	129.8	122.8	123.5	113.8	130.0	120.9	127.7	126.4	120.8	113.8
12	122.0	133.5	133.8	133.6	125.9	132.3	113.4	131.8	120.3	114.2	122.6	116.7	127.9	119.9	133.5	121.1	129.5	135.3	127.4	133.1
13	117.4	126.8	121.8	122.3	133.0	121.4	131.4	131.3	126.5	142.4	124.2	131.7	129.6	112.9	121.8	121.2	134.5	127.5	129.7	122.9
14	135.5	134.2	125.9	125.4	120.1	118.6	114.2	123.7	127.3	109.5	119.0	112.2	125.0	119.0	125.9	115.0	135.0	126.6	133.9	128.2
15	118.8	121.6	128.2	120.0	113.2	134.9	131.6	118.2	124.2	132.6	121.2	109.4	121.3	86.1	117.9	114.9	125.2	132.6	111.6	120.2
16	133.2	135.4	116.3	104.9	120.8	131.1	142.2	127.9	130.0	131.5	115.5	117.2	126.1	125.7	124.0	119.8	129.9	131.9	137.7	122.5
17	75.2	112.2	132.7	134.7	121.1	121.7	122.8	132.7	138.1	121.8	102.5	119.9	121.3	128.7	111.7	134.9	130.0	129.9	115.1	128.3
18	128.4	127.0	115.5	132.3	122.0	113.6	123.8	126.9	123.0	141.8	132.3	130.2	131.2	125.1	114.1	123.6	124.3	122.7	131.3	130.3
19	125.8	125.1	122.4	128.0	118.0	120.6	118.4	120.5	129.6	128.4	127.5	114.2	130.0	135.3	126.6	113.9	133.3	130.2	136.2	138.6
20	129.6	127.7	119.4	113.6	118.2	127.8	122.8	129.8	127.0	125.8	127.4	119.6	107.6	124.8	125.4	126.2	137.8	130.5	124.7	125.4
Mean	121.6	127.0	125.2	122.6	122.6	124.8	123.2	127.3	128.2	127.4	123.9	122.4	125.6	123.0	123.8	125.2	128.0	129.6	124.5	127.2
Std. Dev.	13.5	7.5	8.3	9.6	7.5	7.4	8.9	7.9	6.3	8.0	9.3	7.6	6.8	10.3	8.3	8.0	7.3	5.2	11.1	6.3
Max.	140	137	137	135	140	135	142	137	141	142	138	133	137	135	139	138	138	141	139	139
Min.	75	112	106	105	111	109	103	108	116	109	102	109	108	86	107	114	109	116	103	114
Range	65	25	31	30	29	26	39	29	25	33	36	24	29	49	32	24	29	25	36	25
Coef. of Var.	.11	.06	.07	.08	.06	.06	.07	.06	.05	.06	.08	.06	.05	.09	.07	.06	.06	.04	.09	.05

POTENTIAL APPLICATIONS

The results presented in previous sections illustrate that the model described herein is capable of simulating weather conditions in the study area and of computing crop yields as a function of soil water and atmospheric stress. This section discusses potential applicability of the model, as well as useful extensions for future research.

A form of the model has been applied to the problem of evaluating water-use regulation alternatives in the central basin in the Ogallala Formation [49]. In that study, three water-use regulatory alternatives are evaluated. The soil water-crop yield simulation model is used to determine water-use rates and crop yields for all of the irrigated and dryland crops for a representative farm in the study area. The yield and water-use information is then used in a farm firm simulator which performs the capital management operations, determines levels of inputs required for the specified organization of production, adjusts inventory of capital assets to meet the requirements and prepares a financial summary of the firm's operation. The economic impact of each regulatory alternative is evaluated.

Further applications of the model in its present form are possible. However, the usefulness and applicability of the model would be greatly expanded if all crops in the study area, including barley, alfalfa and native pasture, could be incorporated into the simulation process. This would require additional study designed specifically to isolate critical stages of plant development and to determine the effect of water and atmospheric stress during each stage of plant development on final crop yield.

Additional study of the crops currently incorporated into the model would also be valuable. Refinement of the yield reduction coefficients and soil water-atmospheric stress relationships could lead to development of a better approximation of reality. The existence of a model that predicts more accurately for the full range of atmospheric and soil water conditions would open many research possibilities. For example, the sensitivity of each crop to stress at each stage of plant development could be evaluated. Knowledge of these relationships would improve the farmer's ability to make irrigation applications based on better technical and economic information. Given sufficient data, the model could be utilized to evaluate irrigation strategies for farm operators. The production subset might be used in combination with linear programming, dynamic programming or statistical decision theory techniques to isolate optimum irrigation strategies.

The possibilities for additional research using either this model or an improved version of it appear promising. However, the use of more sophisticated models must be undertaken with discretion. The marginal benefits of a more sophisticated model should be weighed against the marginal cost. The results are likely to be only as good as the weakest link in the chain of data required for successful construction of the model.

SUMMARY AND CONCLUSIONS

The objectives of this study were to construct a soil water prediction model for a commonly irrigated soil in the study area using daily rainfall, evaporation and irrigation data; to identify the critical stages of plant development of the major dryland and irrigated crops in the study area; to simulate the effects of available soil water and atmospheric stress during critical stages of plant development on yield for the major dryland and irrigated crops in the study area; to combine the models for the individual crops; to develop a model for a farm firm, and, to illustrate the potential of such a model for analyzing agronomic and economic problems.

A soil water balance was developed for the Richfield clay loam soil of the Oklahoma Panhandle. The balance provides daily adjustments to soil water to reflect additions through rainfall and subtractions through estimates of evapotranspiration. Rainfall, which is very low and highly variable throughout the study area, is generated daily throughout the growing season from a series of discrete rainfall probability distributions. Pan evaporation, from which the estimates of actual evapotranspiration are derived, is generated daily from a series of lognormal pan evaporation distributions. The rainfall and evapotranspiration components are linked by a series of equations which permit the balance to compute daily estimates of soil water throughout the growing season.

Next, the soil-water balance and final crop yield are integrated. Under adequate soil water and atmospheric conditions, some maximum yield can be produced for each crop. However, crop yield reductions occur as a function of soil water and atmospheric stress. Yield reductions may occur when soil moisture is inadequate, even though atmospheric conditions may be ideal. Also, even when soil water is adequate, severe atmospheric conditions may cause crop yield reductions. The effect of soil water and atmospheric stress on final yield varies with stage of plant development. Critical stages of plant development are developed for irrigated and dryland grain sorghum, irrigated and dryland wheat and irrigated corn. Coefficients relating yield reduction to soil water and atmospheric stress by stage of plant development are developed for each crop.

A representative farm and organization of production for the study area are developed. The organization of production is divided into a series of crop blocks—four for irrigated grain sorghum, one for dryland grain sorghum, two for irrigated wheat, one for dryland wheat, two for irrigated corn grain and two for irrigated corn silage. Then, the crop year is divided into five critical stages, and irrigation priorities and irrigation strategies are developed for each period. Timing of irrigation applications is governed by the level of soil water in the entire soil profile. The use of crop blocks permits the farm operator to reduce irrigation application rates on a portion of a crop and thus maintain adequate moisture on a previously irrigated portion of the crop.

To test the ability of the model to simulate crop yields, a series of simulation runs was conducted. Yield for each crop block was simulated over a 20 year period and each simulation run was replicated 20 times. The results of these simulation runs were presented in tabular form and discussed in some detail.

Based upon the tabular results and the opinions of agronomists, agricultural engineers and irrigation and farm management specialists, it was concluded that the model does a satisfactory job of simulating the arid and variable weather conditions of the study area and crop yield as a function of soil water and atmospheric stress. Crop yields and water-use rates simulated appear realistic when compared with those experienced in the study area.

The model described in this bulletin has been used to evaluate the effect of water-use regulation alternatives in the study area. Unrestricted pumping, a quantity limitation and a water taxing arrangement were evaluated. The effects of each alternative on the amount of water used, farm income and the quantity of products produced were estimated at the farm and the area levels. A forthcoming Oklahoma Agricultural Experiment Station technical bulletin will report the results of this analysis.

Potential applications for the current model include the evaluation of irrigation strategies. The yield-stress model can be used jointly with a farm-firm simulator to evaluate the effect of alternative irrigation strategies on yield levels and profitability of the business. The usefulness and applicability of the model in evaluating irrigation strategies could be greatly enhanced by incorporating additional irrigated and dryland crops of the study area and refining the estimates of soil water and atmospheric stress coefficients. The refined model would be used to provide the basic data on response of crops to alternative levels and timing of stress, and hence, the basic response data required to search for an optimal annual irrigation strategy. Many of the concepts developed in the model may be transferable to similar semi-arid regions in this country and other parts of the world. The possibility for additional research using this model or an improved version appear promising.

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