IRRIGATION SCHEDULING, CROP CHOICES AND IMPACT OF AN IRRIGATION TECHNOLOGY UPGRADE ON THE KANSAS HIGH PLAINS AQUIFER

by

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B.Sc.(Agriculture), Acharya N.G. Ranga Agricultural University, Hyderabad, India, 2000

AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Agricultural Economics
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Abstract

The High Plains aquifer is a primary source of irrigation in western Kansas. Since World War II, producers increased irrigation and the irrigated acreage with the widespread adoption of newer irrigation technologies, causing a reduction in the saturated thickness of the High Plains aquifer. In an effort to conserve water and reduce further decline of the aquifer, the state of Kansas administered cost-share programs to producers who upgraded to an efficient irrigation system. But evidence suggests that the efforts to reduce water consumption have been undermined by producers, who under certain conditions have increased irrigation and irrigated acreage of high-valued and water-intensive crops. The state of Kansas is in a quandary to reduce water consumption and stabilize the saturated thickness of the aquifer while maintaining the economic viability of irrigated agriculture.

A producer is faced with the choice of crop, irrigation timing and irrigation technology at the start of the season. This research identifies the conditions for risk-efficient crop choices and estimates the effect of an irrigation technology upgrade on the aquifer. Simulation models based on data from Tribune, Kansas were executed under various scenarios, varying by crop (corn or sorghum), irrigation system (conventional center-pivot or center-pivot with drop nozzles) and well capacity (190, 285 or 570 gallons per minute). Each well capacity was associated with a pre-season soil moisture level (0.40, 0.60 or 0.80 of field capacity). Each scenario was simulated over weather data observed during the 36-year period (1971-2006).

Results indicate that producers with slower wells could maximize their net returns while conserving water by choosing less water-intensive crops like sorghum, while irrigating with a conventional center-pivot irrigation system. Producers with faster wells could maximize net returns by choosing water-intensive crops like corn and irrigate with the more efficient center-pivot with drop nozzle irrigation system. In order to reduce groundwater consumption and maintain the saturated thickness of the aquifer, water policies should internalize the interests of all stakeholders and be a combination of irrigation technology, economic factors, hydrological conditions, agronomic practices, conservation practices and local dynamics of the region.

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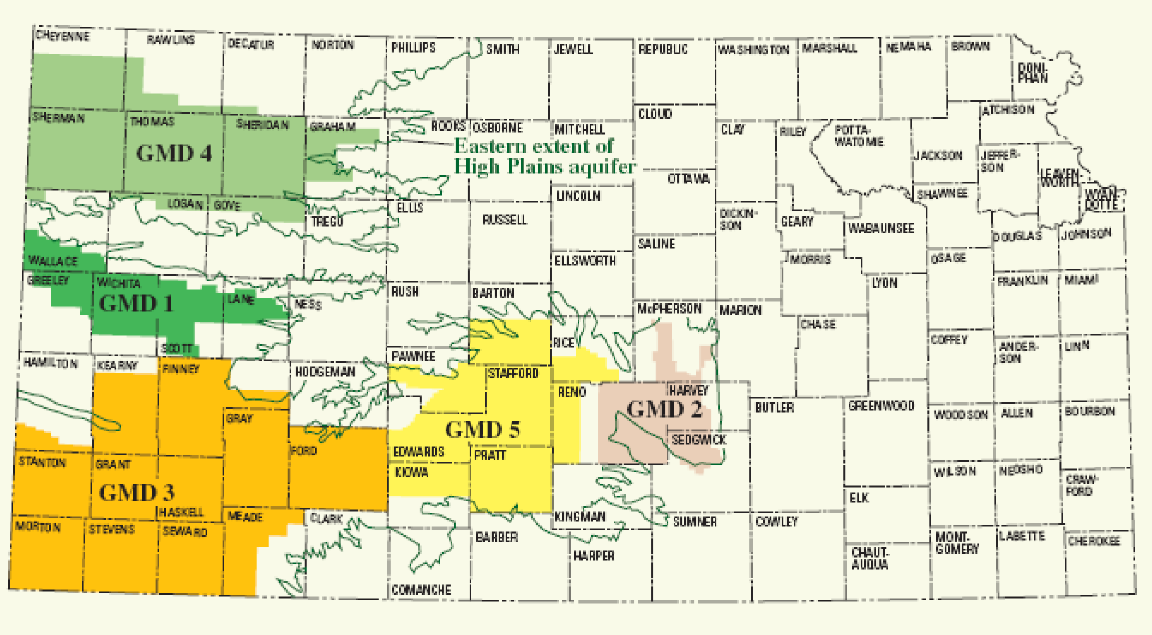
Dedication

I dedicate this dissertation to my brilliant wife, Priya. You have been my inspiration and stood by me through the thick and thin of my doctoral program. No words will do justice to the numerous sacrifices you made to realize this dream!

CHAPTER 1 - INTRODUCTION

The High Plains aquifer is spread over 174,000 square miles across eight states, underlying approximately 33,500 square miles of 46 counties in western and south-central Kansas. Groundwater from the High Plains aquifer is used for irrigation, drinking water, livestock, mining and industry. Irrigation accounts for the largest consumption (85%) of groundwater in the five Groundwater Management Districts (GMDs – Figure 1.1) in western Kansas (US Geological Survey). The value of irrigation is accentuated because of lack of surface water availability and low precipitation in western Kansas.

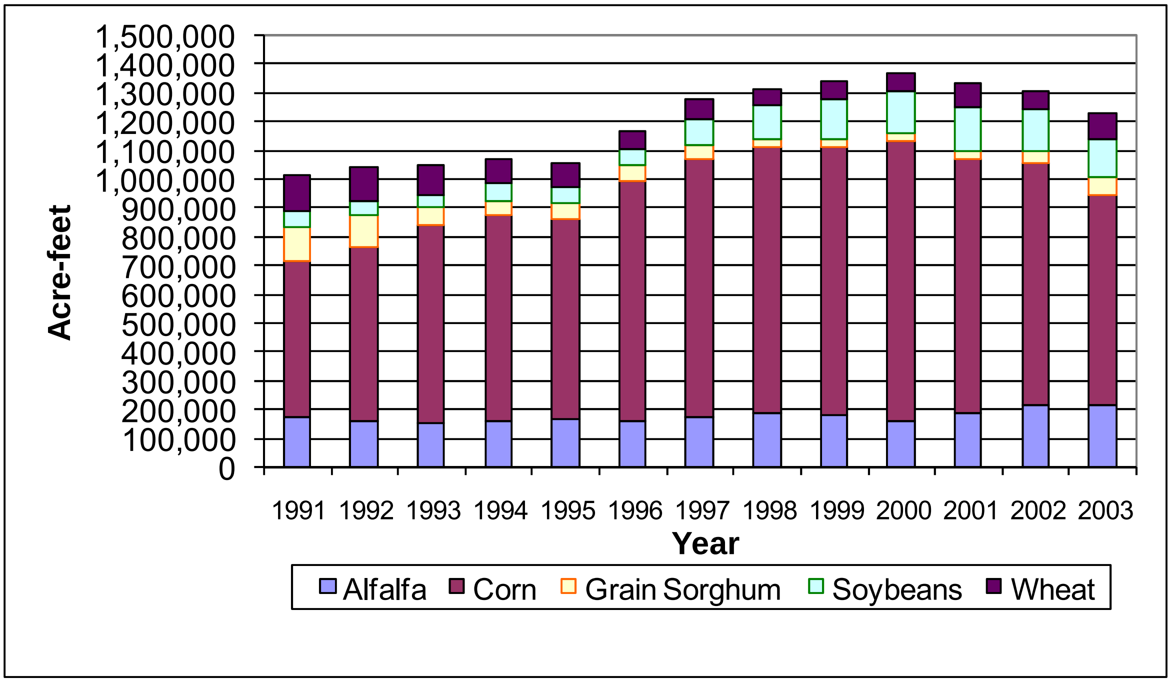
Figure 1.1. Groundwater Management Districts within the Kansas High Plains Aquifer.



Source: U.S. Geological Survey

In the post World War II era, irrigated acreage on the High Plains aquifer in Kansas expanded extensively, owing in part to the developments in irrigation technology. The increase in consumption of groundwater has led to withdrawals exceeding recharge rates, thereby causing a decline in water levels in the aquifer. During the 1990s, even though irrigated acreage continued to be less than that of 1980s, irrigated acres followed a steady upward trend. Further, the share of water intensive crops increased dramatically (Peterson, Ding and Roe, 2003). As shown in Figure 1.2, from 1991-2003, the total irrigation water applied to water-intensive crops like corn, alfalfa and soybeans increased, whereas the total irrigation water applied to less water-intensive grain sorghum and wheat decreased. Similarly, total water use across all irrigated crops increased steadily until about 2000 and then began to decline, a pattern which may be partially explained by the drought cycle in the region.

Figure 1.2. Total Irrigation Water Applied in the 5 GMD's Overlying the Kansas High Plains Aquifer, by Crop, 1991-2003.



Source of Data: Perry, 2006

A trend coinciding with the expansion of water-intensive crops was the rapid and widespread adoption of center-pivot[1] and center-pivot-with-drop-nozzle[2] irrigation systems. As shown in Figure 1.3, these systems replaced older flood systems and by the late 1990s center pivot with drops was the predominant irrigation technology. Compared to conventional center pivot systems, drop nozzle systems have higher application efficiency. A common technology upgrade during recent decades is to insert drop nozzles on a conventional center pivot system. These conversions are reflected in the steady decline of irrigated acreage under "conventional

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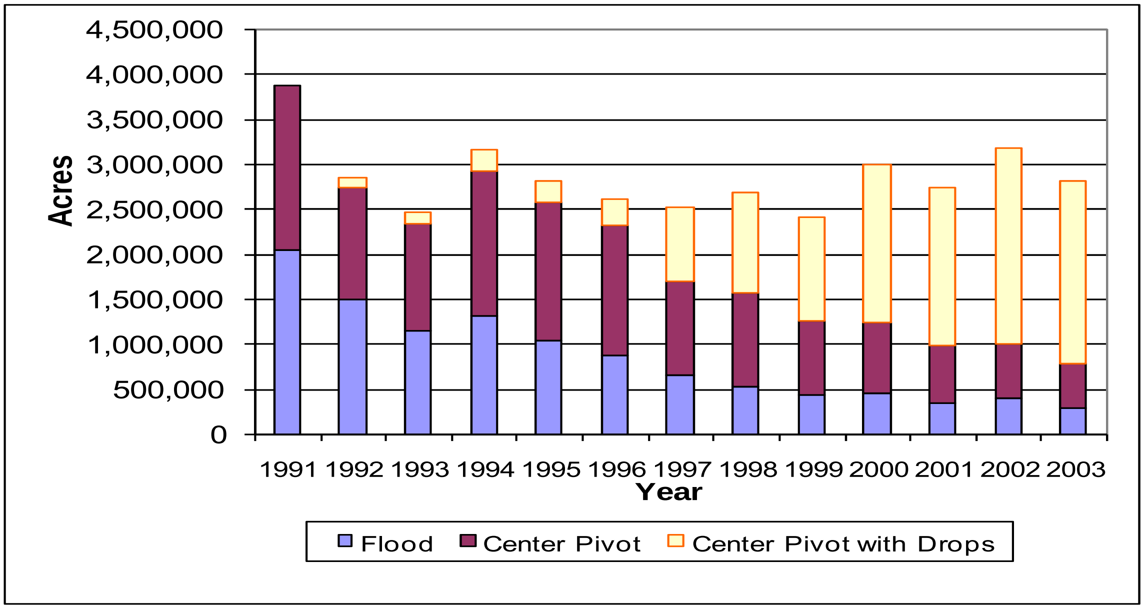
[1] A sprinkler irrigation lateral that is mounted on wheeled structures (towers), anchored at one end (pivot point), and which automatically rotates in a circle when irrigating.

[2] Flexible or rigid hoses or pipe that lower the discharge point of a nozzle below the main lateral of a center-pivot to distribute water usually at low pressure between crop rows in order to reduce evaporation.

center pivot" systems in Figure 1.3. Over the same period, the water used by flood and conventional center pivot systems decreased in the 5 GMDs, but the water used by "center pivot with drops" system increased (Figure 1.4). In the early 1990s, the water use per irrigated acre varied widely across irrigation system, but over the years on an average there is little variability across irrigation systems (Figure 1.5), suggesting that producers have not reduced the water use per acre after conversion to a more efficient irrigation system.

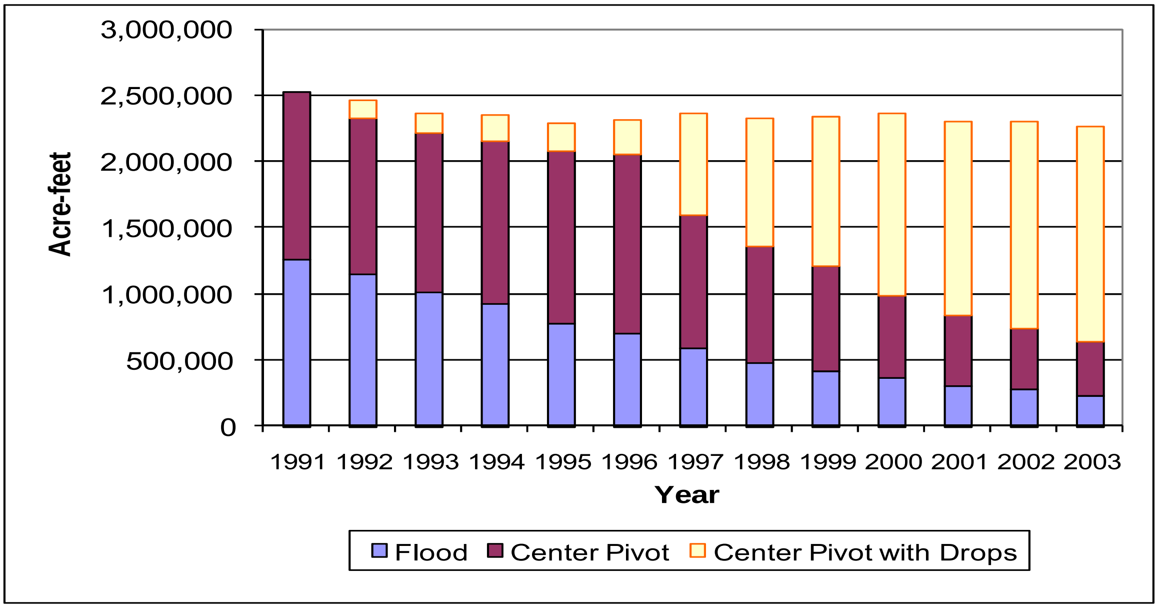
Figure 1.3. Irrigated Acreage in the 5 GMDs Overlying the Kansas High Plains Aquifer, by Irrigation System, 1991-2003.



Source of Data: Perry, 2006

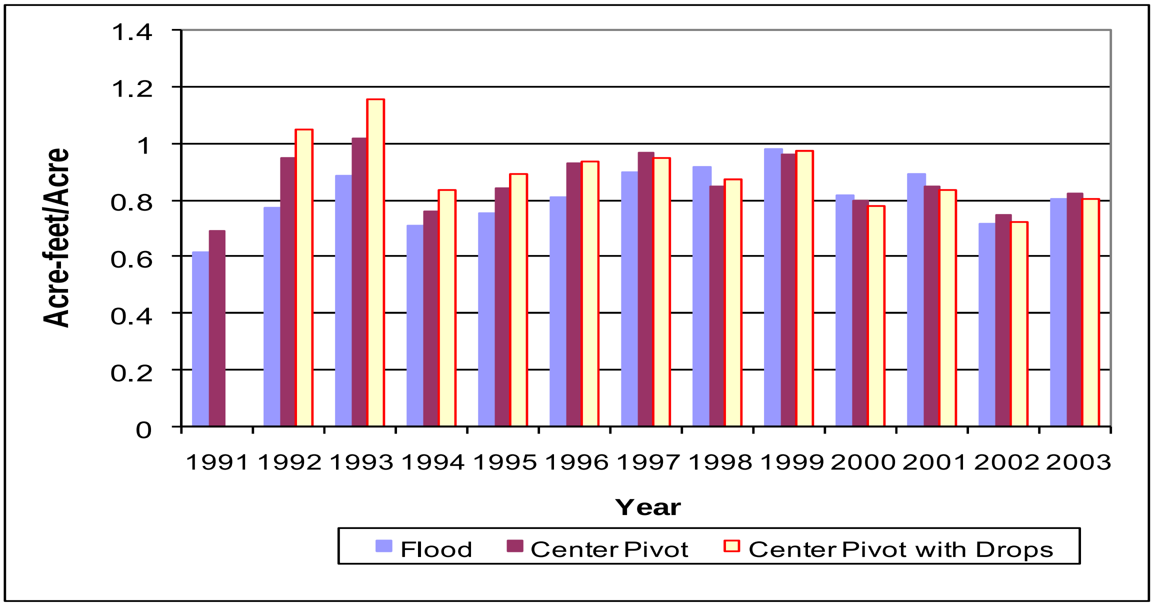
Newer irrigation technologies such as the drop nozzle system were introduced with the aim of increasing irrigation efficiency and reducing groundwater consumption. While they undoubtedly increased irrigation efficiency, the impact of new technologies on consumptive water use is a matter of some dispute (Whittlesey, 2003; Huffaker and Whittlesey 1995, 2003). Producers may respond to increased efficiency (and the associated reduction in the marginal cost of irrigation) by increasing water consumption and expanding the acreage of more water-intensive crops (Peterson and Ding, 2005; Perry, 2006). Moreover, the conversion to center pivot irrigation system changes the composition of water losses; more water is lost to evaporation than drainage (drainage is deep percolation of water that finally reaches the aquifer). Water lost as drainage, although in small quantity, contributes to aquifer recharge. Estimating the amount of aquifer recharged through drainage and the time taken by the water to reach the aquifer is a tremendous challenge that needs to be addressed with further research. All this implies that technological improvements and the profits from water-intensive crops may not have slowed aquifer decline rates.

Figure 1.4. Water Use in 5 GMDs Overlying the Kansas High Plains Aquifer, by Irrigation System, 1991- 2003



Source: Perry, 2006

Figure 1.5. Water Use by Irrigated Acre in the 5 GMDs Overlying the Kansas High Plains Aquifer, across Irrigation Systems, 1991-2003



Source: Perry, 2006

The state of Kansas has administered various programs including a cost-share program providing financial assistance to producers who adopt water conservation practices. Unfortunately, these efforts may have been undermined by the improvements in irrigation technology and returns from the high value of irrigated cropping (Golden and Peterson, 2006). The state of Kansas is in a quandary, in terms of reducing water consumption while maintaining the economic viability of irrigated agriculture on the region. In order to avoid undesirable effects of water conservation, the new laws should use proper accounting procedures for water use (Huffaker and Whittlesey, 1995). According to Huffaker and Whittlesey, in general, on-farm water conservation occurs when crops consume less water and water conservation should be assessed in terms of consumptive use.

Whether technological improvements have hastened the decline rate or not, the aquifer is nevertheless declining in most parts of western Kansas and irrigators increasingly find themselves in conditions of water scarcity. One method for producers to optimally manage limited water supplies during the growing season is irrigation scheduling[3] based on soil moisture. Irrigation scheduling techniques based on soil moisture optimally allocate the quantity and timing of irrigation events to maintain adequate soil moisture levels for crop growth. An irrigation event is triggered whenever the soil moisture level falls below a threshold level called the management allowed deficit (MAD).

MAD is the deficit level of soil moisture below the field capacity of the soil. In other words, the soil moisture level and MAD level add up to the field capacity of the soil. The benefits to irrigation scheduling are reduced water use, increased crop yields, reduced production costs and improved farm operating efficiencies (Dudek, Horner and English, 1981). Irrigation scheduling is dependent on water availability, soil moisture and the crop choice.

A producer is faced by the decision of the choice of irrigation technology, selection of irrigated crop and an MAD level for irrigation scheduling at the start of a season. In order to choose the appropriate irrigation technology, the producer considers the net returns, irrigation efficiency, costs and risk associated with each irrigation system. In choosing an irrigated crop, the producer will choose the irrigated crop and allocate irrigated land across crops based on the

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[3] Irrigation scheduling is a procedure used in determining when to irrigate and how much water to apply to meet specific management objectives.

availability of water, costs, returns to capital, crop prices and irrigation efficiency. A producer can make better choices if presented with risk-efficient crop choices. A producer can strategically choose the crop, irrigation system and MAD with the aim of maximizing net returns while ensuring the efficient use of available groundwater.

This study addresses the related issues of the impact of technology adoption on the High Plains aquifer and the farm-level impact of irrigation scheduling. The technology question is evaluated by comparing conventional center-pivot and center-pivot with drop nozzle irrigation systems in terms of water consumption. Risk-efficient crop choices are presented under conventional center-pivot and center-pivot with drop nozzle irrigation systems for corn and sorghum, providing information that producers could use to choose irrigated crops to efficiently use the resources.

1.1 Objectives

The goal of this study is to predict economically optimal irrigation schedules, crop choices and irrigation technologies under various policy scenarios and resource settings. The specific objectives are to:

1. Determine risk-efficient irrigation schedules and MAD level for corn and sorghum under various risk preferences, and compute farmers' willingness to accept payment to conserve water by increasing their MAD levels.
2. Present a risk-efficient crop choice considering corn and sorghum, while comparing conventional center-pivot and center-pivot with drop nozzles irrigation systems under varying levels of precipitation, soil moisture, well capacity, MAD and risk preference.
3. Determine the effect of a technology upgrade on the aquifer, specifically conventional center pivot to center-pivot with drops irrigation systems, in terms of gross irrigation consumptive use, season long irrigation efficiency, return flow, and reduction in irrigation.

To accomplish the goal, I developed a model that combines an irrigation scheduling program called *KanSched* (Clark and Rogers, 2000), a crop yield estimating program called the Kansas Water Budget (KWB) model (Stone *et al.,* 1995) and Stochastic Efficiency with respect to a function risk analysis using SIMETAR (Richardson, Schumann and Feldman, 2004).

The optimal irrigation schedules are devised using a strategy to select the irrigation dates based on the well capacity and the soil moisture level. The soil moisture level is updated every day based on a water balance equation. An irrigation event is triggered if the soil moisture falls below a predetermined deficit level. For the crop season, all the dates when an irrigation event was scheduled are recorded to develop an irrigation schedule. Based on the irrigation schedules, for a given well capacity, the optimal MAD is determined for corn and sorghum.

The risk-efficient crop choices (corn and sorghum) are presented for three well capacities and three levels of pre-plant soil moisture. The purpose of the risk analysis is to choose the crop based on the water availability and the risk preference of the producer. Four scenarios are compared, which include combinations of corn and sorghum irrigated with conventional center-pivot and center-pivot with drop nozzle irrigation systems.

The effect of a technology upgrade on the aquifer is determined using the measures of irrigation efficiency, consumptive use, non-beneficial use and change in soil water storage. These measures are obtained from the Kansas Water Budget model, which is also used to estimate the crop yields.

1.2 Organization of Remaining Chapters

Chapter two reviews literature on crop yield models, irrigation scheduling and irrigation systems. Chapter three describes the model and research procedures. Chapter four provides details on the sources of data for the dissertation. Chapter five expands on the simulations based on the research procedures and describes the results. Finally, in Chapter six, the summary, conclusions and the direction of future research are elucidated.

CHAPTER 2 - LITERATURE REVIEW

A vast literature exists on irrigation water management. For the purpose of this study, the literature in three broad categories will be reviewed:

1. Deterministic crop yield studies, which predict crop yields from different irrigation schedules.
2. Irrigation scheduling studies, which focus on determining irrigation schedules. The models developed in this literature can be classified into two groups:
    - Static experimentation models that estimate a crop-response function and use the crop-response to predict yields and choose an irrigation schedule in a static framework.
    - Dynamic optimization models that optimally schedule irrigation events as the season progresses based on soil moisture measurements.
3. Irrigation system choice studies, focusing on the choice of irrigation system and evaluating irrigation efficiency and the effect of water conservation policies.

2.1 Deterministic Crop Yield Models

There is a large literature available on crop yield models in relation to water availability. Here, two representative studies that developed such models are briefly reviewed; the models selected are those most directly related to this study. Interested readers are directed to the following sources for more comprehensive reviews: Kang *et al.* (2002), Ghahraman and Sepaskhah (1997), Bryant *et al.* (1992), Hill *et al.* (1984), and Jensen *et al.* (1970).

Minhas, Parikh and Srinivasan (1974) studied the interdependence of plant water use at different time points, available soil moisture, and the quantity of water used by crop plants in a unified framework. They estimated the evapo-transpiration (ET) function of water using soil moisture data from Delhi and Ohio over a six-year period (1960-1965). Using the ET function, or the functional relationship between ET and available soil moisture, the soil moisture was predicted. The crop production function with dated inputs was estimated by simulating yield with respect to water in two periods – 71 to 90 days and 91 to harvest days from planting. The two problems in irrigation scheduling were – the decision about timing of water release and allocation of water among crops. To estimate the optimal amounts of irrigation, it is important to know the marginal product of water at each growth stage. The study concluded that the ET function performed well in estimating actual ET. The ET function was very useful in estimating production function and yield; this study could be of considerable help to formulate irrigation policy in general and to prepare irrigation schedules.

Stone *et al.* (1995) developed a water balance model and investigated the interrelationships among irrigated water supply, drainage, ET, and crop yield. The core of this model is the water balance equation:

$$SoilWater_t = SoilWater_{t-1} - ET^a_{t-1} - Drain_{t-1} + Rain_{t-1} + Irrigation_{t-1} \qquad \textbf{(1.1)}$$

The total water in the soil profile on each day was calculated based on the previous day's soil water, actual ET, drainage, rainfall and irrigation. The ET was computed based on solar radiation, crop coefficients, and available soil water. The available soil water is bounded between the water content in the soil profile at permanent wilting point (the lower bound) and field capacity (the upper bound). Drainage is based on the water in the soil profile and drainage coefficients. The model was adapted to western Kansas based on weather data from Tribune, Kansas. After computing the soil water levels, yields were estimated for corn, sunflower, and winter wheat based on actual ET, maximum ET and weighting factors corresponding to crop growth stages. The study found that critical growth stages were flowering and early seed formation. Yields are sensitive to water stress occurring during the tasseling, silking and pollination stages. The yields estimated assume other factors such as soil nutrients, incidence of pests, diseases and severe weather conditions were non-limiting. However, the water budget model and software could be used to study drainage or ET, and to estimate crop yields in western Kansas as influenced by water conditions.

2.2 Static Experimentation Models

Dudek, Horner and English (1981) developed a method to assess the regional economic effects of irrigation scheduling and applied the method to develop a perspective on factors which affect the benefits and costs of irrigation scheduling. Water use and crop production coefficients under irrigation scheduling were estimated from a two-stage simulation process. The first stage of the process involved interaction of soil moisture and irrigation to simulate moisture stress and seasonal ET based on soil moisture, wind velocity, percolation depth, root zone, temperature, solar radiation and relative humidity. The second stage was comprised of the crop production model based on ET, soil moisture tension, quantity of irrigation, rainfall and number of irrigations applied to the field. Optimal water application was determined by maximizing net returns to land and management using linear programming. The regional economic model projected the amount of irrigation activity that would be scheduled as if a private company provided the service. The conclusions of this study were that irrigation scheduling could be an effective tool because the objective is to maintain soil moisture levels above the permanent wilting point and below field capacity levels with minimum irrigations. This resulted in minimizing drainage losses without reducing acreage or yields. Scheduling costs proved to be a significant factor in determining the aggregate amount of irrigated acreage.

Harris and Mapp (1986) compared the economic efficiency of alternative water conserving irrigation strategies. The authors studied the impacts of risk for alternative irrigation schedules using a stochastic dominance approach. Estimates from a crop growth simulation model were combined with crop price and input costs to estimate the net returns under different irrigation scenarios, which included up to one pre-plant and five post-plant irrigation events. The conclusions of the study were that several proposed water-conserving schedules were preferred to the intensive irrigation schedule because they provided higher expected net returns and reduced the risk of deviations from net returns. The study also identified efficient schedules with alternative risk preferences. The study found that irrigation is critical at grain filling and later stages of crop growth. The authors found that risk aversion does not explain the use of intensive irrigation policies.

Bernardo *et al.* (1987) presented a two-stage simulation model to determine optimal intraseasonal allocation of irrigation water under conditions of limited water supply. As water becomes scarce and irrigation costs increase, irrigation water management must be reoriented towards increasing precision of irrigation scheduling and application to maximize returns to scarce water resources. The authors found that the problems in intra-seasonal water allocation were computational intractability and unavailability of crop-water response information. Historically, the problems were focused on the timing and depth of irrigation events, but no study considered other management practices in conjunction with irrigation scheduling for efficient irrigation programs, such as crop substitution and reallocation of water among crops.

The two-stage simulation model included crop simulation using the soil-plant-air-water-irrigation model to analyze yield response to a specific irrigation schedule based on ET; the irrigation responses were then used in a mathematical programming model to maximize returns through efficient allocations of the available water supply. The conclusions of the study were that through conjunctive development and application of efficient irrigation programs, significant reductions in seasonal water application and consumptive use could be attained with small losses in producer returns. Water efficiency could be improved by employing high-frequency schedules, reducing depth of application and eliminating irrigation in non-critical stages.

Talpaz and Mjelde (1988) developed an *ex ante* method by optimizing irrigation scheduling via experimentation. The crop response to irrigation was obtained by a two-stage experimental procedure involving an estimated production function. In the first stage, crop growth was simulated using a quadratic response function, which can be interpreted as a second-order Taylor's series approximation of the underlying response relationship. The objective of the second stage was to take the crop growth responses into account to provide improved decision rules for the next set of trials with the experimental procedure. The initial decision rule to schedule irrigation events was to find the soil moisture threshold level that triggers irrigation. Two important attributes for *ex ante* strategies are to account for stochastic weather conditions and provide flexible decision rules. One critique of this method is that a quadratic response function may not accurately reflect the true response function, which could be highly non-linear and more complex. The conclusions of the study are that the producers should be more protective of the crop during later stages of crop growth. If rainfall can be predicted, then it can improve the irrigation scheduling greatly. *Ex ante* rules, in general, are easy to implement in stochastic environments and in many simulation models.

Jones (2004) reviewed irrigation scheduling methods to address the advantages and pitfalls of plant-based methods. The increasing costs of irrigation and shortage of water emphasize the importance of minimum water use and maximum water use efficiency. Irrigation scheduling is conventionally based either on soil water measurement or soil water balance calculations. A potential problem with all soil-water based approaches is that the plant's physiology responds directly to changes in water content in the plant tissues, rather than changes in soil water content. It has been suggested that use of plant stress sensing can bring greater precision in irrigation. Under the plant stress approach, irrigation scheduling is based on plant responses rather than direct measurements of soil water status. Plant stress can be identified by – tissue water status and physiological responses. Both methods require highly sophisticated equipment and are very labor-intensive.

2.3 Dynamic Optimization Models

Yaron *et al.* (1980) developed a dynamic programming model for optimal irrigation scheduling with varying salinity. The study answers two important questions under conditions of irrigation with saline water: (a) given initial soil salinity, should a pre-planting leaching be applied, and if so, at what quantity; and (b) what is the optimal irrigation schedule - i.e., the optimal combination of quantities and timing of irrigation events during the entire irrigation season. The method developed was applied to determine optimal irrigation schedules with saline water for sorghum. The authors extended dynamic programming to account for crop response to soil moisture as well as soil salinity in two steps. The first step was to estimate a soil potential function dependent on soil moisture and soil salinity levels. The second step involved dividing the crop season into sub-periods and obtaining a yield expression. Yield was expressed as a function of maximum obtainable yield and the reduction in yield during critical days of soil salinity and moisture. The objective was to maximize the cumulative net income for every crop price and soil salinity level subject to soil moisture and state of the system by applying a dynamic programming backward induction procedure. The conclusions of the study were that frequent applications of small quantities of water were preferable to large quantities at extended intervals. Under high soil salinity conditions, extra irrigation water for leaching is justified in the beginning of the season. The authors recommend extended irrigation over long periods under relatively low saline conditions and no irrigations under saline conditions. One critique of the article is that soil salinity level may not be constant throughout the growing season. However, this model could be used for detailed analysis of optimal irrigation with saline water.

Harris and Mapp (1980) evaluated the potential impact of alternative irrigation strategies to derive optimal time path strategies to conserve water while maintaining net returns to the producer. The objective of this study was to derive an irrigation strategy for the growing season that maximizes net returns to grain sorghum producers from water use. The authors analyzed three production scenarios, first, testing the sensitivity and validating the model; second, simulating irrigation practices by applying 15 inches of groundwater; and third, applying an optimal control procedure to derive irrigation sequences to maximize net returns. The amount of irrigation water applied in the optimal control and 15 acre-inch irrigation scenarios was substantially different but the grain sorghum yields were comparable. The results indicate that there is a high potential for irrigation producers to reduce irrigation water application while maintaining yields and increasing net returns.

Bras and Cordova (1981) studied the problem of optimal temporal allocation of irrigation water considering dynamics of soil moisture depletion and intraseasonal stochasticity. The optimization problem in this study was to maximize net benefits from irrigation subject to the stochastic process of soil moisture. The yield was estimated as a function of actual ET, potential ET and a crop sensitivity factor. The solution algorithm was obtained using a backward recursive formulation of a stochastic dynamic programming model. The probability distribution of soil moisture was used to obtain an optimal irrigation policy using dynamic programming. The mean and variance of irrigation net benefits for each case were computed. This study was one of the first to analytically include a physical model into a stochastic algorithm. The net benefits obtained under stochastic control were always greater than those obtained under a fixed date schedule. The expected value of net benefits increases and its variability was reduced when using stochastic control. One critique of the study is that it may be unrealistic to assume that the soil water availability is known without actually measuring it.

Feinerman and Falkovitz (1997) developed a mathematical model to determine the economically optimal scheduling of fertilization and irrigation that maximizes a farmer’s profits. The state of soil-plant-nitrogen and the water system is defined by three state variables, a measure of plant size, plant available nitrogen in the root zone and relative soil moisture. The control variables are the rates of nitrogen and water application. The authors found that the maximum yield to the optimization problem is achieved when a predetermined level of nitrogen fertilizer is applied at the beginning of the season and irrigation water is applied continuously so that the soil moisture is maintained at field capacity. The results indicate that controlling nitrogen pollution via taxation becomes more effective at higher tax rates. The limitations of the study are that it is difficult to accurately estimate the pollution and that imposing a tax on the amount of nitrogen leached is likely to be impractical. It was found that the level of leaching is much more sensitive to changes in the fertilizer price than to changes in the tax levied on leached nitrogen.

2.4 Irrigation System Choice Studies

Zilberman (1984) analyzed the use of an exhaustible resource by an agricultural industry, considering agricultural policy and technological change. The author analyzed the use of water in a general equilibrium framework and states that an increase in irrigation effectiveness on actual water use is explained by the elasticity of marginal productivity (EMP) of water. A high EMP suggests a strong decline in the marginal productivity of water whereas a low EMP suggests a small decline in marginal productivity. An increase in irrigation effectiveness (also known as application efficiency) was shown to reduce the water use in cases with high EMP whereas it increases water use in cases with low EMP. An increase in irrigation effectiveness always increases crop yield but saves water only in cases with high EMP. The author also shows that the dynamics of water price, irrigation effectiveness and adoption cost affect the critical size of the farms directly and indirectly through their impacts on output price. The author suggests that the direct effect of higher irrigation cost is to reduce water use over time and the direct effect of technological change is to reduce water use over time in high EMP cases but increase it in low EMP cases. Price-increasing policies (an increase in water price) are more effective in mitigating the effect of technological improvements and output demand on water depletion.

Hornbaker and Mapp (1988) developed a model to study economic efficiency of different irrigation systems under optimized irrigation schedules. The crop growth simulation model was combined with an intra-seasonal recursive programming model and the recursive model developed optimal irrigation strategies at each growth stage, while maximizing expected net returns for the season. All the optimal irrigation schedules developed in the model were similar at the initial stages of crop growth. The low energy precision application (LEPA) system applied much less water than high pressure and low pressure conventional systems. LEPA produced higher yields and net returns with lower levels of irrigation water applied because it provided more water to the plant in the later stages of crop growth when soil and atmospheric conditions are most severe.

Letey *et al.* (1990) conducted an economic analysis of irrigation systems based on their performance and costs in relation to cotton production and drainage volumes. The objective of this study was to determine the economically optimal irrigation system among furrow, subsurface drip, hand-moved sprinkler, linear-moved sprinkler and low energy precise application (LEPA). The authors included management costs associated with irrigation systems, shifts in crop yield, drainage volumes associated with optimal management of the irrigation system, and costs associated with disposal of drainage waters. The crop-water production function depends on irrigation uniformity. Irrigation uniformity varies among irrigation systems and there is high degree of uncertainty in the measurements. The crop-water production function was superimposed with an irrigation uniformity distribution to obtain crop yield and drainage. The production function assumed that no excess water is applied during any irrigation event. The results indicate that maximum profits were achieved with furrow irrigation systems and profitability decreases as the cost of drainage water disposal increases. The rate of profit is strongly dependent on the irrigation uniformity assigned to each irrigation system. While the furrow irrigation system was found to be the most profitable, it would be economical to switch to other systems if significant costs were imposed. The differences in profitability for the various systems are related to both yield differences and drainage volumes.

Green *et al.* (1996) assessed the effect of three broad classes of factors affecting irrigation technology choice – economic variables, environmental characteristics and institutional variables on irrigation technology choices. This study is innovative in terms of using a multinomial logit model to examine switching between irrigation technologies; the empirical model includes a complete set of physical characteristics; both annual and perennial crops are included; and soil data variables are continuous. The authors present a model of the adoption decision in which the grower decides the irrigation technology based on estimating the expected profits. The results indicate that the adoption of irrigation technology is highly dependent on the choice of crop and water-saving technologies will be adopted as the cost of irrigation increases. The authors find that physical and agronomic characteristics appear to govern irrigation technology adoption more than the cost of irrigation. The authors noted that the heterogeneity of land quality is critical in the study of technology adoption.

Huffaker and Whittlesey (2003) formulated a conceptual model to study farm responses to economic policies with the aim of water conservation. The objective of this paper was to investigate the conceptual circumstances under which higher water prices and farm subsidies encourage water conservation. The authors use a profit maximization model to select optimal levels of water and investment in on-farm irrigation. The decision variables selected were applied water, investment in improved-on farm irrigation efficiency and farm acreage. The authors determined the optimal responses to policies intended to conserve water using comparative statics. The impact of an increase in the cost of applied water results in a reduction in the demand for water and acreage, thereby reducing consumptive water use. The impact of subsidies to improve irrigation efficiency is ambiguous. The farm ultimately adjusts its demand for applied water in a direction dictated by relative marginal adjustments in acreage and irrigation efficiency to satisfy the production constraint. The results indicate that increasing the cost of irrigation may be an effective water policy than subsidizing the cost of investing in improved irrigation efficiency.

2.5 Summary and Discussion

Deterministic crop models are the basis for the optimization and simulation models that evaluate irrigation schedules and irrigation systems. Optimization via experimentation is a two step iterative program of experimentation of crop response and optimization of irrigation for maximum returns. The lack of efficient methodology for validation and calibration for introduction and adaptation to a new location and its environment is a limitation to simulation models. Further, decision rules are developed in an *ex post* fashion and are not always implementable at the farm level.

Dynamic optimization is employed to obtain *ex ante* decision rules and has potential to increase water use efficiency. However, these models often employ simple approximations to the water response function instead of embedding an explicit crop model. The models so constructed are difficult to generalize or apply to new situations, as their results are specific to a location based on the empirical data used for the crop response function. Nevertheless, dynamic optimization has advantages over the static method because it accounts for the sequential nature of decision making during the growing season. Moreover, the response function can be changed to adapt the model to a new environment and stochastic elements can be included to model risk and observe the scheduling responses.

Irrigation systems choice and policy studies have focused around comparing alternative irrigation strategies and the circumstances under which there is a switch between irrigation technologies. The water conservation policy studies were centered around evaluating policies such as increasing irrigation costs, taxation and other policy instruments to mitigate water depletion and promote conservation for prolonged use of water.

CHAPTER 3 - MODEL AND PROCEDURES

This chapter explains the models and research procedures used in this study. Research procedures involved in the model are described including the steps involved in the analysis. The three models – KWB, *KanSched*, and Stochastic Efficiency with Respect to a Function (SERF) are explained in detail. The model assumptions under each irrigation systems are elucidated.

3.1 Research Procedure

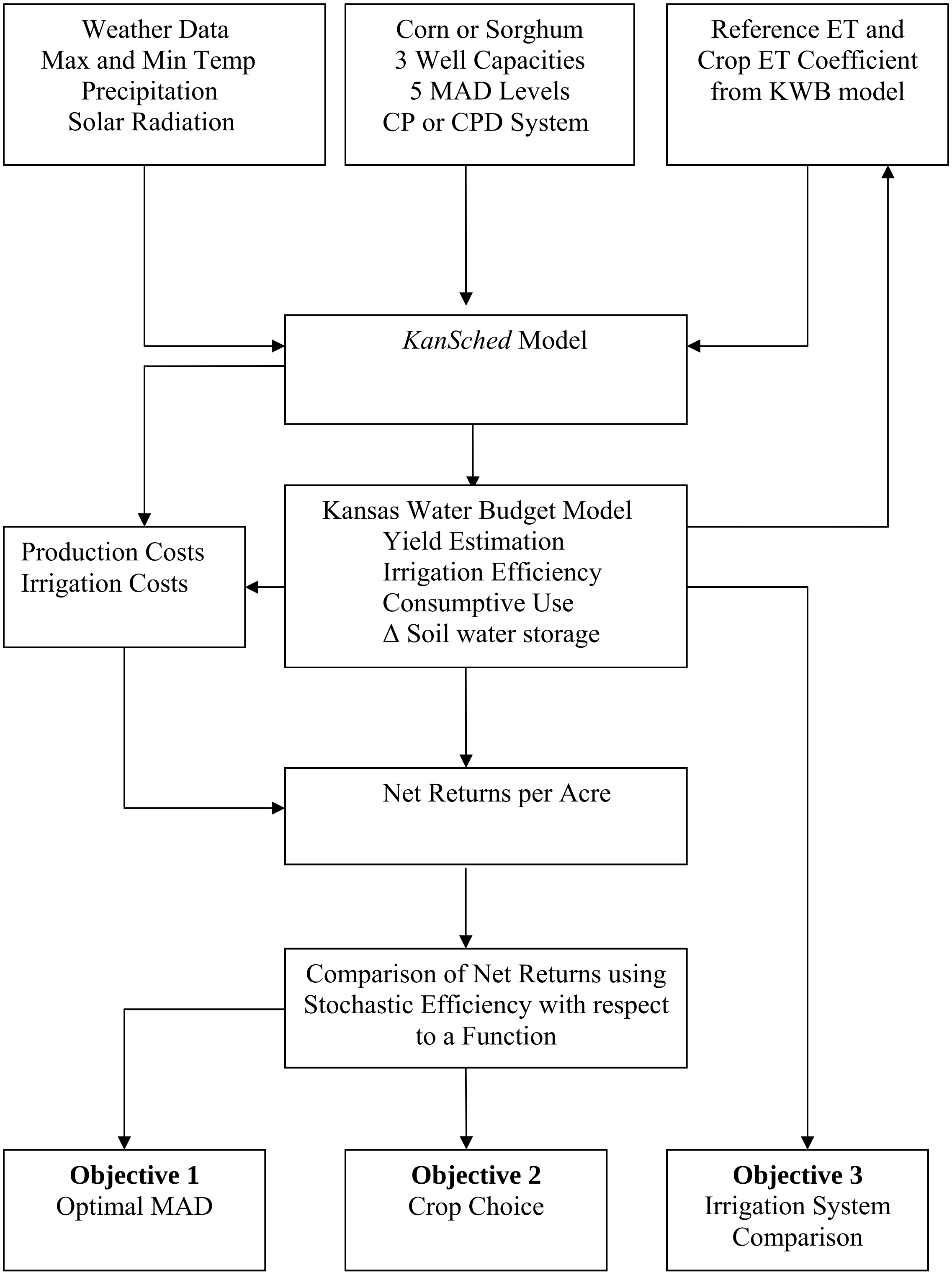
The following section describes the research analysis procedures to accomplish the objectives of the study.

The five steps involved in the analysis are:

1. Irrigation scheduling using the *KanSched* model.
2. Crop yield estimation using the KWB model.
3. Comparison of irrigation systems based on consumptive use, season long irrigation efficiency and change in soil water storage.
4. Compute costs of production, irrigation costs and net returns from crop budgets.
5. Comparison of net returns using stochastic efficiency with respect to a function.

The steps involved in the analysis are illustrated as a model flowchart in figure 3-1. Not all of these steps apply to each research objective. Evaluating the optimal MAD (objective 1) involves steps 1, 2, 4 and 5. Alternative irrigation schedules were developed for different MADs (step1), and each of them is entered in the KWB model to simulate yields for 36 years of weather data (step 2). In step 4, the yields were used in conjunction with crop budgets to compute net returns in each of the 36 weather years, generating an empirical distribution of income for each MAD level. The final step is to compare these distributions using the risk efficiency criteria in SIMETAR (step 5). Moreover, optimal MADs were selected only for center-pivot irrigated corn and sorghum, the situations where the benefits of irrigation scheduling were likely to be greatest due to the differences in the timing-sensitive nature of water deliveries to corn and sorghum.

Figure 3.1. Model Flowchart of Irrigation Scheduling, Yield Estimation and Comparison of Net Returns



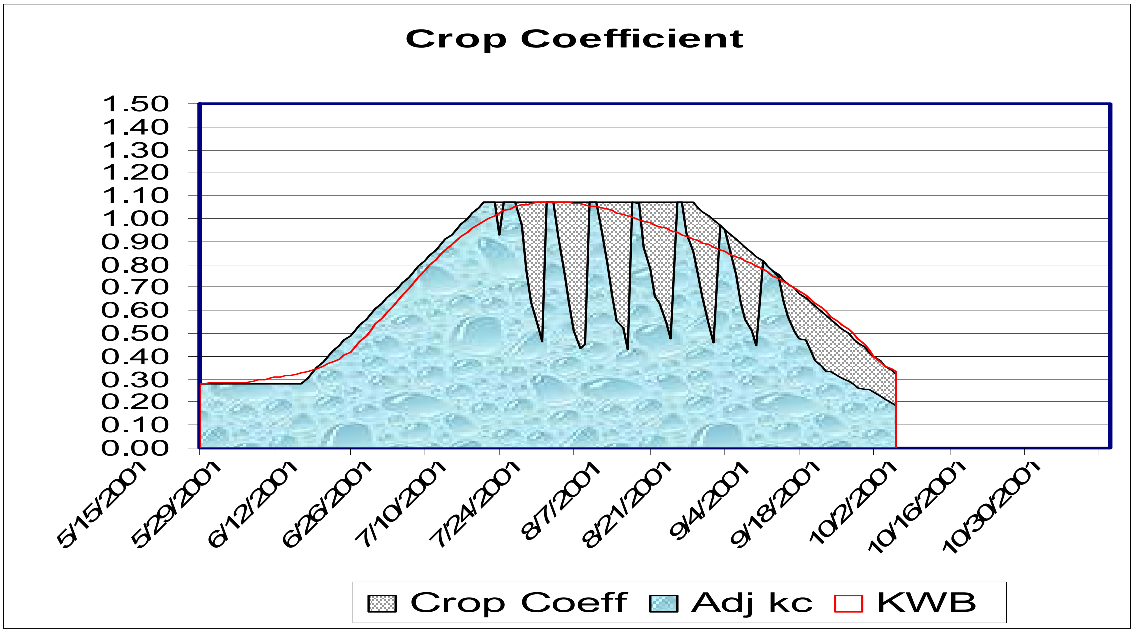
Presenting the risk-efficient crop choices (objective 2) also involves steps 1, 2, 4, and 5, except that in step 5 comparisons were made between different cropping scenarios for a given irrigation system. Irrigation schedules for corn and sorghum for both the irrigation systems were obtained as described above in steps 1 and 2, respectively, setting the MAD in each case at the optimal level determined in objective 1. Income distributions were generated as described above in step 4, for each crop-technology scenario and well capacity. Holding the irrigation system and well capacity fixed, the income distributions of different cropping schemes were then compared using SERF method in SIMETAR, which is described in the following section (step 5).

Determining the effect of a technology upgrade on the aquifer (objective 3) involves steps 1, 2, and 3. The irrigation schedules (step1) and yield estimation (step 2) were completed as described above, for each crop-technology combination (these are discussed below and presented in table 3.2), again setting the MAD at the optimal levels already obtained. In step 3, the water use (averaged over the 36 weather years) was compared across the crop-technology scenarios. The comparisons of interest are those involving a switch in technology, particularly, changes from conventional center pivot to center pivots with drops.

3.1.1 Irrigation Scheduling – KanSched Model

The *KanSched* model (Clark and Rogers, 2000) monitors the water balance in the soil and schedules irrigation based on daily values of rainfall and ET. The first step involved in irrigation scheduling was to calculate the reference ET for each day based on weather data. The second step was to calculate the maximum crop ET based on weather conditions, irrigation and crop characteristics. This calculation requires date-specific values of the ratio of reference ET and maximum ET for the crop being modeled. This ratio, known as the crop coefficient, changes throughout the growing season; the changing values of the crop coefficient over time form the crop coefficient curve (Doorenbos and Pruitt, 1975). *KanSched* approximates the crop coefficient curve as a piece-wise linear function of time elapsed from planting. The nodes (or "kinks") in this function and the slopes of the lines between them were set to fit the actual crop coefficient curve from the KWB model as closely as possible (Figure 3.2). After computing maximum ET for each day, the model can compute actual ET based on the amount of water available in the soil profile.

Figure 3.2. Crop coefficient, Adjusted Crop Coefficient (Adj K_c) and KWB Crop Coefficient for Corn During the Crop Season.



The final step was to identify the start date of each irrigation event. *KanSched* triggers an irrigation event whenever the soil moisture depletion exceeds the user-specified MAD level. However, in this study, irrigation events also constrained by well capacity, which limits irrigation frequency. The *KanSched* model was modified so that it could not trigger irrigation events more frequently than the values reported in table 3.1 for each well capacity. Irrigation schedules corresponding to three well capacities (190, 285 and 570 gallons per minute) and five MAD values[4] (0, 0.15, 0.3, 0.45 and 0.6) were computed using the *KanSched* model. The irrigation schedules for each scenario were then entered into the KWB model to estimate crop yields, described in the next sub-section.

One of the difficulties in modeling center-pivot irrigation system is that water is delivered to different parts of the field as the tower gradually pivots around the field. Thus, there is a time lag between irrigating the first portion of the field and the last portion of the field (figure 3.3). The last portion of the field is water-stressed for a longer period of time before it receives irrigation than the first portion of the field. Martin et al. (1991) pointed out that to avoid water stress, irrigation schedules should take into account the time taken to irrigate the field and the

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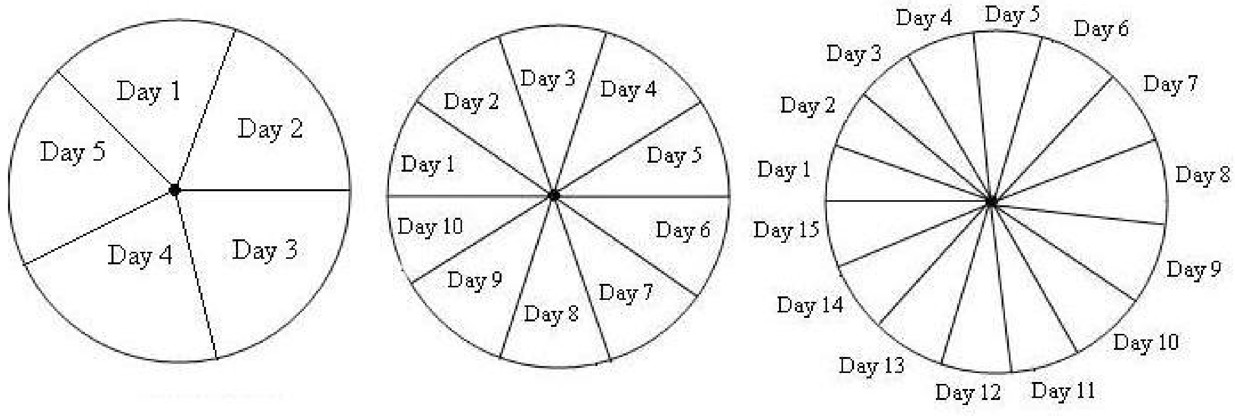
[4] Only for objective 1, and for center-pivot with drop nozzles system. For objectives 2 and 3, MAD was held fixed at a single value as discussed below.

depletion time for the latter parts of the field. The time that is taken to irrigate the entire field before the occurrence of water stress is referred to as the irrigation frequency or cycle time. The irrigation frequencies for a 190, 285 and 570 gpm well are 15, 10 and 5 days, respectively as represented in table 3.1.

Figure 3.3. Time-lags in Center-pivot Irrigation



570 GPM - 5 Days

285 GPM - 10 Days

190 GPM - 15 Days

To capture the time lag in irrigation, the 126 acre field is divided into a number of sections (figure 3.3) corresponding to the capacity of the well. Irrigation schedules were computed for the first section using *KanSched* and are lagged by successive days for the remaining sections of the field. The yield, ET and drainage were estimated using the KWB model for each section and were then averaged over all the sections.

Table 3-1. Irrigation Capacity, Frequency, Flow-rate and Initial Soil Water Availability for a Standard Seven Tower Center Pivot 1.2” Net Irrigation to Make a Complete Revolution Irrigating 126 acres at Various Well Capacities.

Irrigation Capacity Inches per day	Frequency and Amount Applied	Flow-rate in GPM	Initial Soil Water Availability in Inches
0.067”	1.2” in 15 days	190	0.40
0.100”	1.2” in 10 days	285	0.60
0.200”	1.2” in 5 days	570	0.80

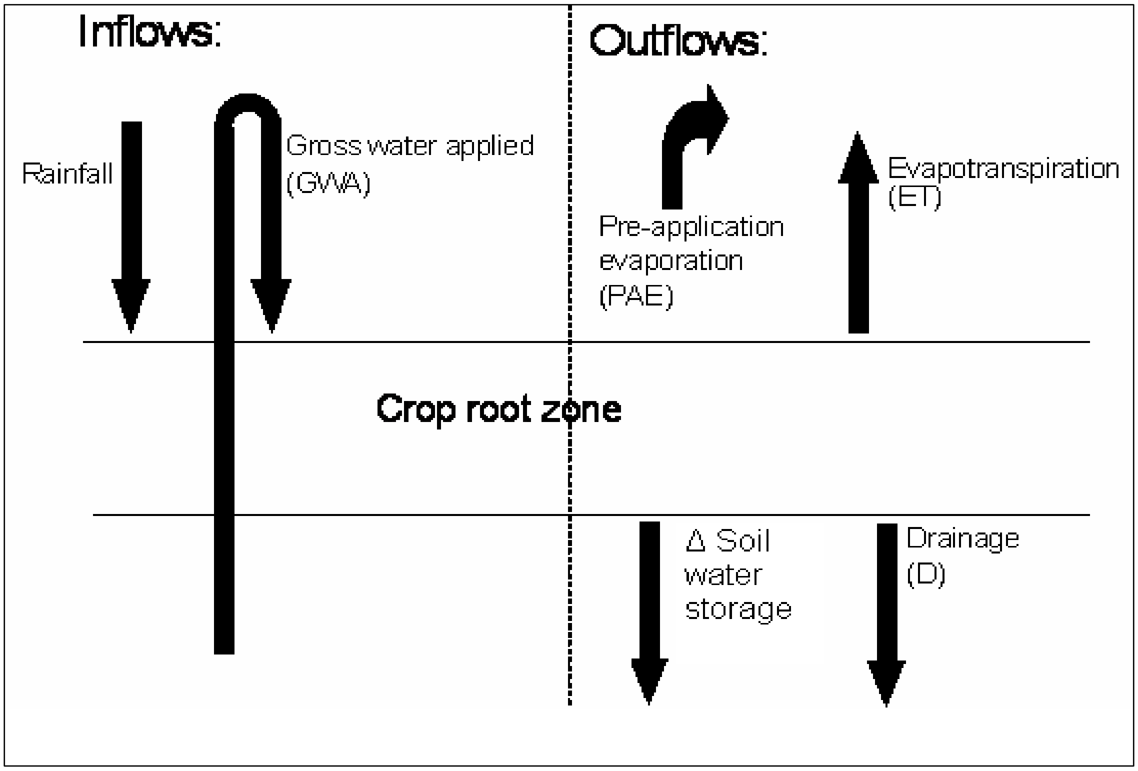
3.1.2 Crop Yield Estimation – Kansas Water Budget (KWB) Model

The yields for corn were simulated using the KWB model. In particular, the KWB model predicted yields from each irrigation schedule using daily observations of rainfall, irrigation, temperature and solar radiation based on the soil water balance equation (equation (1.1)) on page 9). As discussed above this equation calculates the total water in the soil profile each day of the year. To run the model, the irrigation schedule obtained from *KanSched* and the corresponding weather data were entered as user inputs. The model then executes on a daily cycle, updating the soil water balance and computing daily values of ET and drainage. Yield was finally calculated based on accumulated ET during various stages of the growing season. The KWB model generates a detailed report of ET, drainage and yields which were recorded for each model run.

3.1.3 Comparisons of Irrigation Systems

The soil water balance equation at the field level is represented by water flows in figure 3.4. Rainfall and irrigation (gross water applied) constitute the inflows, whereas ET, pre-application evaporation, change in soil water storage (Δ SW) and drainage (D) constitute the outflows.

Figure 3.4. Water Flows at the Field Level



The inflows and outflows at the field level are related by the following equation

$$Rain + GWA = PAE + ET + D + \Delta SW. \qquad \textbf{(3.1)}$$

Consumptive Use (*CU*) is defined as

$$CU = PAE + ET, \qquad \textbf{(3.2)}$$

as PAE and ET are both ‘escape outflows’ from the system. However, only a portion of CU is beneficially used to produce the crop, namely ET. Another way of categorizing the flows in figure 3.4 is to identify beneficial and non-beneficial outflows. Non-Beneficial Use (*NBU*) is defined as

$$NBU = PAE + D + \Delta SW. \qquad \textbf{(3.3)}$$

Season long irrigation efficiency (*SIE)* is calculated as:

$$SIE = \frac{ET}{Rain + GWA - \Delta SW} \quad . \qquad \textbf{(3.4)}$$

Note that *SIE* is not directly determined by the level of pre-application evaporative losses, which is assumed to be 15% of GWA for conventional center pivot systems and 5% of GWA for center pivot with drop nozzle systems. For the conventional center-pivot system, for example, SIE can be equivalently expressed by substituting (3.3) into (3.1), yielding

$$SIE = \frac{Rain + GWA - NBU}{Rain + GWA - \Delta SW} \quad . \qquad \textbf{(3.5)}$$

Because *PAE* is only one component of *NBU*, *SIE* may differ from 85% (=100%-15%) depending on the value of *D* and *ΔSW*. The latter two variables are computed in the KWB model and will differ across weather conditions, irrigation scheduling practices, and the crop grown.

The irrigation systems were compared based on ET, consumptive use, non-beneficial use season long irrigation efficiency, and reduction in irrigation water for each well capacity. The purpose of comparing the irrigation systems was to evaluate the effect of an irrigation technology upgrade on the aquifer and determine the best alternative irrigation strategy given the well capacity.

3.1.4 Crop Budgeting and Irrigation Costs

The production costs for irrigated corn and irrigated sorghum in western Kansas were computed based on the K-State Research and Extension Crop Budgets (Dumler *et al.*, 2006; Dumler and Thompson, 2006) as presented in detail in the next chapter.

The irrigation costs were computed based on the irrigation cost equation in the Irrigation Economics Evaluation System (IEES – Williams *et al.*, 1996):

*Irrcost=NGprice*Energy*Pumplift*Irrseas+Pumprepair***,** **(3.6)**

where *Irrcost* ($/acre) is the cost of irrigation over the season, *NGprice* ($7.50/mcf[5]) is the price of natural gas, *Energy* (0.00186 mcf) is the amount of energy required to lift one unit of water one feet assuming the efficiency of the pump to be 75%, *Pumplift* (250+20*2.31=296.2) is the sum of depth to water table and an adjustment factor to account for system operating pressure,[6] *Irrseas* is the amount of irrigation applied during the crop season (acre inches per acre) and *Pumprepair* is the product of number of irrigations in the season, estimated cost of repair per irrigation ($ 0.30) and maintenance of the irrigation pump ($ 12.00).

3.1.5 Comparison of Net Returns

The simulated yield and K-State Extension projected crop budgets were used to compute net returns for each year in the weather dataset, the specified MAD, and the specified well capacity. Finally, the simulated net returns across all weather conditions under a fixed combination of MAD, crop-technology scheme, and well capacity were gathered together to form a probability distribution. Depending on the research objective, several distributions were selected for analysis and compared using SERF (stochastic efficiency with respect to a function) in *SIMETAR*.

SERF belongs to a larger family of criteria for ranking probability distributions of risky alternatives (e.g., choices with uncertain net returns) known as stochastic dominance rules. Stochastic dominance rules were introduced to economic decision problems by Hadar and Russell (1969) and Hanoch and Levy (1969) and are based on the preferences, or utility functions, of decision makers under specified conditions. The utility function $u(x)$ is assumed to be increasing, continuous and twice differentiable, where x represents the decision-maker's wealth. More assumptions on the utility function result in a more refined and discerning criteria

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[5] mcf=1000 cubic feet

[6] Depth to the water table is assumed to be 250 feet, while the operating pressures of the conventional center pivot and center pivot with drop nozzle systems are assumed to be 75 and 20 pounds per square inch, respectively. *Pumplift* is computed as 250 + *Pressure**2.31, where Pressure is either 20 or 75 psi depending n the system and 2.31 is the conversion factor that translates pressures in psi to an equivalent distance of vertical lift.

to select between risky alternatives. Stochastic dominance is of three types, First-degree Stochastic Dominance (FSD), Second-degree Stochastic Dominance (SSD) and Third-degree Stochastic Dominance (TSD). The three types of stochastic dominance differ in the number of assumptions on the utility function and the bounds on the absolute risk aversion coefficients (ARAC) (Pratt, 1964; Arrow, 1965). The absolute risk aversion coefficient, denoted $r_a(x)$, is defined as

$$r_a(x) = \frac{-u''(x)}{u'(x)}. \qquad \textbf{(3.7)}$$

Stochastic dominance orders alternatives for decision makers facing uncertain outcomes by setting lower bounds (r_L) and upper bounds (r_U) on the absolute risk aversion coefficient

$$r_L \le r_a \le r_U. \qquad \textbf{(3.8)}$$

One advantage of the SERF method is that it allows the researcher to specify the lower and upper bounds on the absolute risk aversion coefficient. As explained in more detail below, other stochastic dominance methods simply assume that r_a lies in a predetermined interval. As such, SERF is a more discerning method because it allows for narrower limits on the risk aversion coefficient.

FSD assumes only that the decision maker has positive marginal utility of wealth ($u'(x) > 0$, where x represents current wealth), i.e. more is preferred to less. However, it makes no assumption about the degree of risk aversion; the RAC is assumed to lie anywhere in the range $(-\infty, \infty)$. Consider two alternatives, A and B, with cumulative distribution functions (CDFs) $F(x)$ and $G(x)$, respectively. By FSD, A dominates B for all x, if $F(x) \le G(x)$, with at least one strong inequality. Geometrically, this means that the CDF of A should lie below and to the right of the CDF of B (Hardaker *et al.,* 2004). If A dominates B by FSD, then the expected utility of alternative A is greater, under the maintained assumption that $u'(x) > 0$ (Hadar and Russell, 1969).

SSD assumes the decision maker to be risk averse ($u''(x) < 0$), in addition to having a positive marginal utility function. With SSD, the absolute risk aversion coefficient is assumed to lie in the interval $[0, \infty)$. By SSD, A dominates B if $\int_{-\infty}^{y} F(x)dx \le \int_{-\infty}^{y} G(x)dx,$ for all values of y, with at least one strong inequality. If A dominates B by SSD, then

$E[u(x) \mid F(x)] > E[u(x) \mid G(x)]$, assuming the utility function satisfies conditions specified above (Hadar and Russell, 1969). That is, SSD is equivalent to higher expected utility under the assumption that utility function is increasing in net returns (higher utility for higher net returns) and the producer is risk averse. Geometrically, SSD compares probability distributions by the area under alternative cumulative distribution functions. Dominated distributions are inefficient in that they would never be preferred by risk-averse utility maximizing decision makers.

TSD requires the decision maker to be risk averse, have a positive marginal utility function and meet the additional assumption that the coefficient of absolute risk aversion decreases with respect to net returns ($u'''(x) > 0$). This implies that with an increase in net returns the risk aversion of the decision maker should decrease. With TSD, the absolute risk aversion coefficient is assumed to be bounded within the range $[0, \infty)$, but to decrease monotonically in wealth. TSD has only a slight advantage over SSD in terms of discrimination between distributions (Hardaker *et al.,* 1997).

These stochastic dominance methods have a few limitations. Often, in practice, no distribution is preferred to the other by any criteria and it becomes very difficult to make a choice among the two distributions. Additionally, when alternative strategies are not mutually exclusive, it is difficult to use stochastic dominance. Stochastic dominance generally can be useful in obtaining an efficient set but not a uniquely optimal choice.

Stochastic dominance with respect to a function (SDRF), introduced by Meyer (1977), is more flexible and has a stronger discriminatory power than any of the three degrees of stochastic dominance. At the same time, SDRF is simply a more general version of FSD and SSD (Cochran *et al.,* 1985). By SDRF, cumulative distribution $F(x)$ stochastically dominates cumulative distribution $G(x)$ with respect to utility function $q(x)$ if and only if

$$\int_0^y [G(x) - F(x)]\, dq(x) \ \geq 0 \quad \forall y \in [0,1], \qquad \textbf{(3.9)}$$

where wealth has been normalized so that the support of both distributions $F(x)$ and $G(x)$ are the [0, 1] interval. The function $q(x)$ can be thought of as a utility function that defines a lower bound of the risk aversion coefficient. That is, if the actual risk aversion coefficient of the decision maker's true, but unknown, utility function satisfies $-u''(x)/u'(x) \geq -q''(x)/q'(x)$, then it can be shown that $E[u(x) \mid F(x)] > E[u(x) \mid G(x)]$ (Meyer, 1977). This result is a basis for a computational procedure (now referred to as SDRF) that allows the analyst to find preferred alternatives for all decision makers with risk aversion coefficients lying in some range. This gives SDRF stronger discriminatory power than the other forms of stochastic dominance.

The SERF method, developed by Hardaker *et al.* (2004), is closely related to SDRF and identifies utility efficient sets by ordering alternative sets in terms of certainty equivalents[7] (CE) over a range of risk aversion coefficients. Suppose there are p states of nature, each occurring with probability $1/p$, and that the wealth level if state i occurs is x_i. Expected utility is then

$$E[u(x)] = \int u(x)dF(x) = \sum_{i=1}^{p} u(x_i)\frac{1}{p}. \tag{3.10}$$

If utility takes the form of a negative exponential ($u(x) = 1 - e^{-rx}$), then the risk aversion coefficient is constant and equal to r. Let $EU(r)$ denote the expected utility of the observed distribution, $\{x_i\}$, assuming a negative exponential utility function with a risk aversion coefficient of r. Expected utility can then be computed as

$$EU(r) = \sum_{i=1}^{p}\left(\frac{1}{p}\right)\left[1 - e^{-rx_i}\right]. \tag{3.11}$$

The certainty equivalent of income at this RAC level, $CE(r)$, can be found by setting the computed value of $EU(r)$ equal to the utility function evaluated at $CE(r)$:

$$EU(r) = 1 - e^{-r \cdot CE(r)}. \tag{3.12}$$

Solving for $CE(r)$ yields

$$CE(r) = \ln\left(1 - EU(r)\right)^{-1/r}. \tag{3.13}$$

For a risk-averse decision maker, the certainty equivalent is always less than expected income. A will be preferred to B by the SERF criterion, for a range of absolute risk aversion coefficients, $[r_L, r_U]$, if $CE(r)$ under distribution A is greater than $CE(r)$ under distribution B for all $r \in [r_L, r_U]$. Hardaker *et al.* (2004) established that if the above condition holds, then the expected utility of A will exceed that of B for any utility function with an absolute risk aversion coefficient in the range $[r_L, r_U]$. Since the conditions are derived with a negative exponential utility function, the SERF method assumes that the decision makers' utility is of that form. SERF is more advantageous than SDRF because it identifies a much smaller efficient set than SDRF by comparing each with all other alternatives simultaneously (Hardaker *et al.,* 2004).

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[7] The certainty equivalent is an income level that a decision maker is indifferent between receiving versus the (uncertain) income generated by taking the risky decision.

To illustrate, consider one of the comparisons needed for objective 2, identifying the most risk-efficient cropping scheme under a flood irrigation system. For a given well capacity, 4 distributions of income were generated, corresponding to scenarios 1-4 from table 3.2 below. One of these was arbitrarily selected as the base alternative and a range of risk aversion coefficients was chosen using the McCarl and Bessler method, as described in the next sub-section. The most risk-efficient cropping alternative was then identified as the one with the largest $CE(r)$ value over the chosen RAC range. This process was then repeated for all three well capacities – 280 gpm, 400 gpm and 699 gpm – to determine the most risk-efficient alternative in each case.

3.1.6 Estimation of Risk Aversion Coefficients

Several authors (King and Robison, 1981; King and Oamek, 1983; Raskin *et al.*, 1986; McCarl *et al.*, 1987) have developed methods to determine limits to the risk aversion coefficient that are consistent with agents' observed behavior in risky situations. The first method limits the bounds by relaxing the assumption of non-negativity of wealth. In this method, the risk premium is restricted to be less than the mean. In the second method, the risk premium is restricted by a confidence interval. In the third method, the risk premium is bound to be less than the value of five divided by the variance for each probability distribution. The bounds are tighter in progression from the first to the third method. The upper bounds (r_U) determined by these methods are found to be better than the maximum RAC at which rankings occurred in many studies (McCarl and Bessler, 1989).The lower bounds (r_L) in all the three methods is assumed to be zero, since we are assuming risk-averse decision makers. In this study, the second method described by McCarl and Bessler was used to determine the upper bounds.

3.2 Model Assumptions

For the purpose of analysis I assume that a producer owns a 160-acre square field (quarter section), part of which will be planted to an irrigated crop (corn or sorghum). The producer is assumed to own the machinery and irrigation equipment. The risk preferences of the producer are unknown. Four combinations of irrigation technology and crop selection were modeled as shown in table 3.2. These scenarios include two irrigation systems (conventional center-pivot and center-pivot with drop nozzles) and two irrigated crops (corn and grain sorghum). Both irrigation systems irrigate a 126-acre crop circle in the quarter-section, leaving

34 acres of non-irrigated land in the "corners" of the field, which is not modeled here. The irrigation systems and the assumptions about their water delivery are discussed in more detail below. The two crops chosen are commonly grown in western Kansas and differ in their water requirements. Corn is a water-intensive crop that is highly sensitive to water stress at critical stages of the growing season, while grain sorghum requires less water overall and also is less sensitive to the timing of water stress. Costs and prices were assumed to be non-random but randomness in yields is introduced by fluctuations in rainfall.

Irrigation water is assumed to be supplied from a single well. For each crop technology scenario, three irrigation well capacities were examined, 190, 285 and 570 gallons per minute (gpm). Soil water availability (SWA) at the beginning of the season (referred to as initial soil water availability in what follows) was assumed to vary depending on the well capacity. In particular, the initial SWA (measured as a proportion of water holding capacity of the soil) was 0.40, 0.60 and 0.80 for the three well capacities, respectively[8]. The number of irrigations during the crop season cannot exceed 18 due to a limitation inherent to the KWB model[9]. Additionally, water regulations in western Kansas typically limit the total amount of irrigation to 24 inches during the crop season.

Table 3-2. Crop-technology Scenarios

Scenario	Irrigation System	Irrigated Corn	Irrigated Sorghum
1	Conventional Center-Pivot	126	0
2	Conventional Center-Pivot	0	126
3	Center-Pivot with Drop Nozzles	126	0
4	Center-Pivot with Drop Nozzles	0	126

3.2.1 Assumptions for Conventional Center-Pivot and Center-Pivot with Drop Nozzle Irrigation Systems

As noted above, both the conventional center-pivot and center-pivot with drop nozzle systems are similar in that they irrigate a fixed acreage of 126 acres. However, the two irrigation

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[8] The initial soil water availability levels are taken from Fredrickson (2004). The water availability at the start of a cropping season in a well is directly proportional to the capacity of the well. A higher well capacity ends up with more water in the soil profile and a lower capacity well ends up with less water in the soil profile. This was validated by running the KWB model for corn and sorghum.

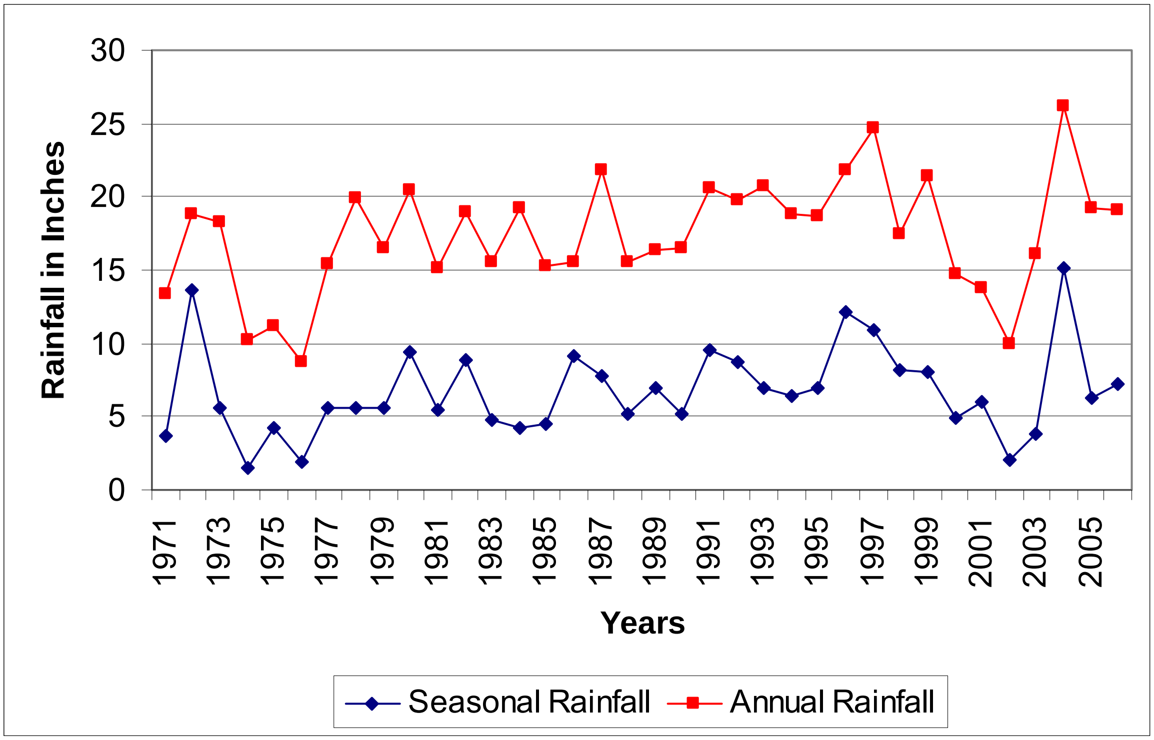
[9] The limitation on the number of irrigations per growing season can be relaxed in the spreadsheet version of the KWB model.

systems differ in the pre-application evaporation losses. The pre-evaporation loss for the conventional center-pivot irrigation system was assumed to be 15% and that of center-pivot with drop nozzles was assumed to be 5% (Rogers *et al.,* 1997). The producer was assumed to schedule irrigations by choosing one of the management allowed deficit (MAD) levels of 0, 0.15, 0.30, 0.45 and 0.60 at the beginning of the crop season to trigger irrigation events as the season progresses. As discussed earlier, one of the objectives of the research was to determine which of these levels is optimal from a risk management point of view. The gross amount of water applied per irrigation event was set so at 1.2 inches, reflecting typical irrigation management practices in the region. The amount of irrigation water reaching the soil profile after evaporation losses was 1.02 inches (85% of 1.2 inches) and 1.14 inches (95% of 1.2 inches) for conventional center-pivot and center-pivot with drop nozzles, respectively.

CHAPTER 4 - DATA

Long-run weather data from the Kansas Weather Data Library were obtained for Tribune, Kansas. The dataset includes daily observations of temperature, rainfall, and solar radiation over the 36-year period 1971-2006. Figure 4.1 shows the variation of annual and seasonal (May 15 – September 5) precipitation over the observed period. The cumulative distribution function of the seasonal rainfall is illustrated in Figure 4.2.

Figure 4.1. Seasonal and Annual Rainfall Distribution in Tribune, KS.



Long-run ET values and crop coefficients for the crop season (May 15 - September 5) were obtained from the KWB model. The cost of production was taken from the 2006 crop enterprise budgets developed by K-State Research and Extension. Three yield levels were set, corresponding to the three well capacities. The prices paid for the crop, government payments and the production costs excluding irrigation, were computed for corn and sorghum as shown in tables 4.1 and 4.2, respectively. Harvest costs were included in non-machinery labor for both corn and sorghum.

Table 4-1. Irrigated Corn Budget in Western Kansas, 2006

Item	--------------Cost ($/acre)--------------		
	190 gpm	285 gpm	570 gpm
A. Yield per acre	--------Simulated by KWB Model--------		
B. Price per bushel	$2.99	$2.99	$2.99
C. Net government payment	$29.92	$32.53	$35.13
D. Net Returns/acre	(A*B)+C	(A*B)+C	(A*B)+C
Nonland Costs			
Seed	$43.94	$50.70	$57.46
Herbicide	$30.96	$30.96	$30.96
Pesticide	$37.43	$37.43	$37.43
Fertilizer	$70.17	$84.10	$100.39
Crop consulting	$6.50	$6.50	$6.50
Miscellaneous	$10.00	$10.00	$10.00
Non-machinery labor	$12.51	$13.49	$14.64
Sub Total	$211.51	$233.18	$257.38
Interest on 1/2 Nonland Costs	$18.14	$20.24	$22.51
Total Non-irrigation Costs	$229.65	$253.42	$279.89

Source: K-State Research and Extension Crop Budgets

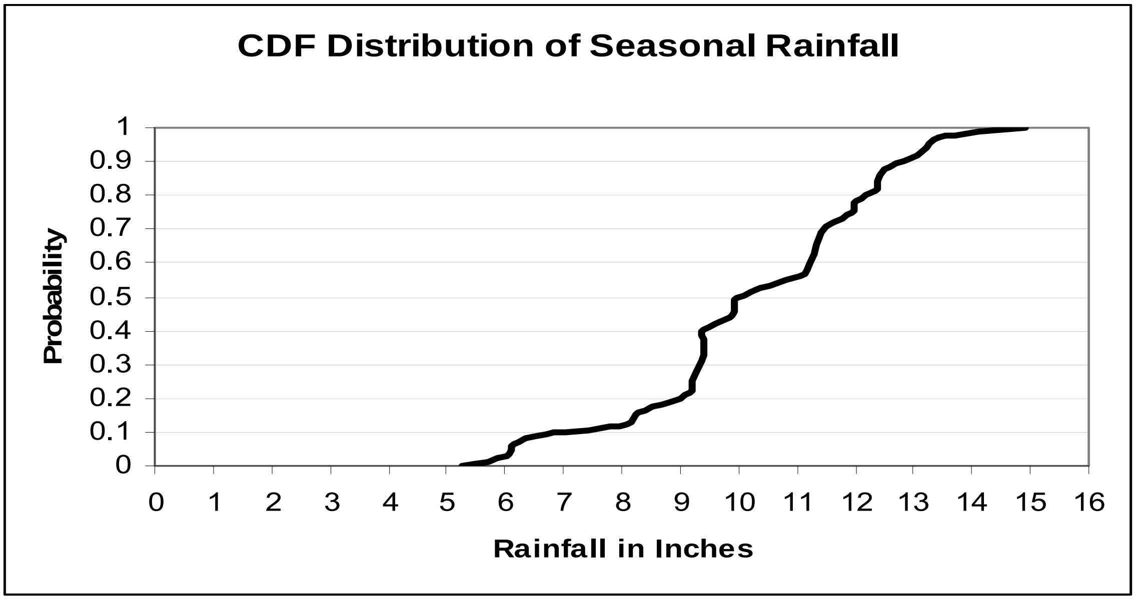
Table 4-2. Irrigated Sorghum Budget in Western Kansas, 2006

Item	---------------Cost ($/acre)---------------		
	190 gpm	285 gpm	570 gpm
A. Yield per acre	------Simulated by KWB Model----------		
B. Price per bushel	$2.65	$2.65	$2.65
C. Net government payment	$29.92	$32.53	$35.13
D. Net Returns/acre	(A*B)+C	(A*B)+C	(A*B)+C
Nonland Costs			
Seed	$16.38	$17.75	$17.75
Herbicide	$28.04	$28.04	$28.04
Pesticide	$0.00	$0.00	$0.00
Fertilizer	$40.19	$45.46	$53.33
Crop consulting	$6.25	$6.25	$6.25
Miscellaneous	$10.00	$10.00	$10.00
Non-machinery labor	$10.39	$10.90	$11.41
Sub Total	$111.25	$118.40	$126.78
Interest on 1/2 Nonland Costs	$11.81	$13.31	$14.38
Total Non-irrigation Costs	$123.06	$131.71	$141.16

Source: K-State Research and Extension Crop Budgets

The cost of irrigation was computed based on the irrigation cost equation from the Irrigation Economics Evaluation System (IEES – Williams *et al.*, 1996*).* The price of natural gas was obtained from the Department of Energy and crop prices were obtained from Ag Outlook for the year 2006. The average cost of irrigation per inch for conventional center-pivot irrigation and center-pivot with drop nozzles irrigation system was $5.94 and $4.17, respectively. Irrigation was scheduled using the *KanSched* model.

Figure 4.2. CDF Distribution of Seasonal Rainfall



Various other parameters were required to run the *KanSched* model, which are presented in Table 4.3. The soil water holding capacity was set to 0.15 inches of water/inch of soil depth, and the permanent wilting point to 0.13 inches of water/inch of soil depth representing the Ulysses silty loam soil type in Tribune, Kansas. The emergence date, water budget dates were set in accordance with typical irrigated and dryland crops in western Kansas. The depth of the roots on the start date was set at 6 inches and the maximum root zone depth that would be able to pull water from the soil profile was set at 60 inches. The crop growth dates correspond to irrigated crops in western Kansas. The crop coefficients were adjusted to fit the crop coefficients from the KWB model as closely as possible.

Table 4-3. General Input Information for *KanSched* model

General Input Information	Data
Soil Available Water Holding Capacity (inches of water/inch of soil depth)…………	0.15
Enter the Permanent Wilting Point (PWP) water content of the soil (in./in.)………….	0.13
Emergence Date (for example, enter June 1 as 6/1)……………………………	15-May
Enter the Date To Start The Water Budget for the crop.	15-Jun
Enter the root depth (inches) on the start date (for example 6 inches and must be >1)	6
Enter the maximum managed root zone depth in inches (the range is from 12 to 48 inches)	60
Enter the date that the crop canopy cover exceeds 10% of the field area (e.g. 6/15/00) [This is the date that rapid growth begins]	4-Jun
Enter the date that the crop canopy cover is at 70% to 80% of the field area (e.g. 6/25/00)	8-Jul
Enter the date when the crop is at initial maturation (water use is declining, e.g. 8/1/00)	16-Aug
Enter the date of the end of the growing season (e.g. 8/25/00)…………..	22-Sep
Enter the initial crop coefficient (0.25 is the default)………………………	0.28
Enter the maximum crop coefficient (1.00 is the default)………………………	1.07
Enter the final crop coefficient (0.6 is the default)………………………………	0.34

Source: *KanSched* Model

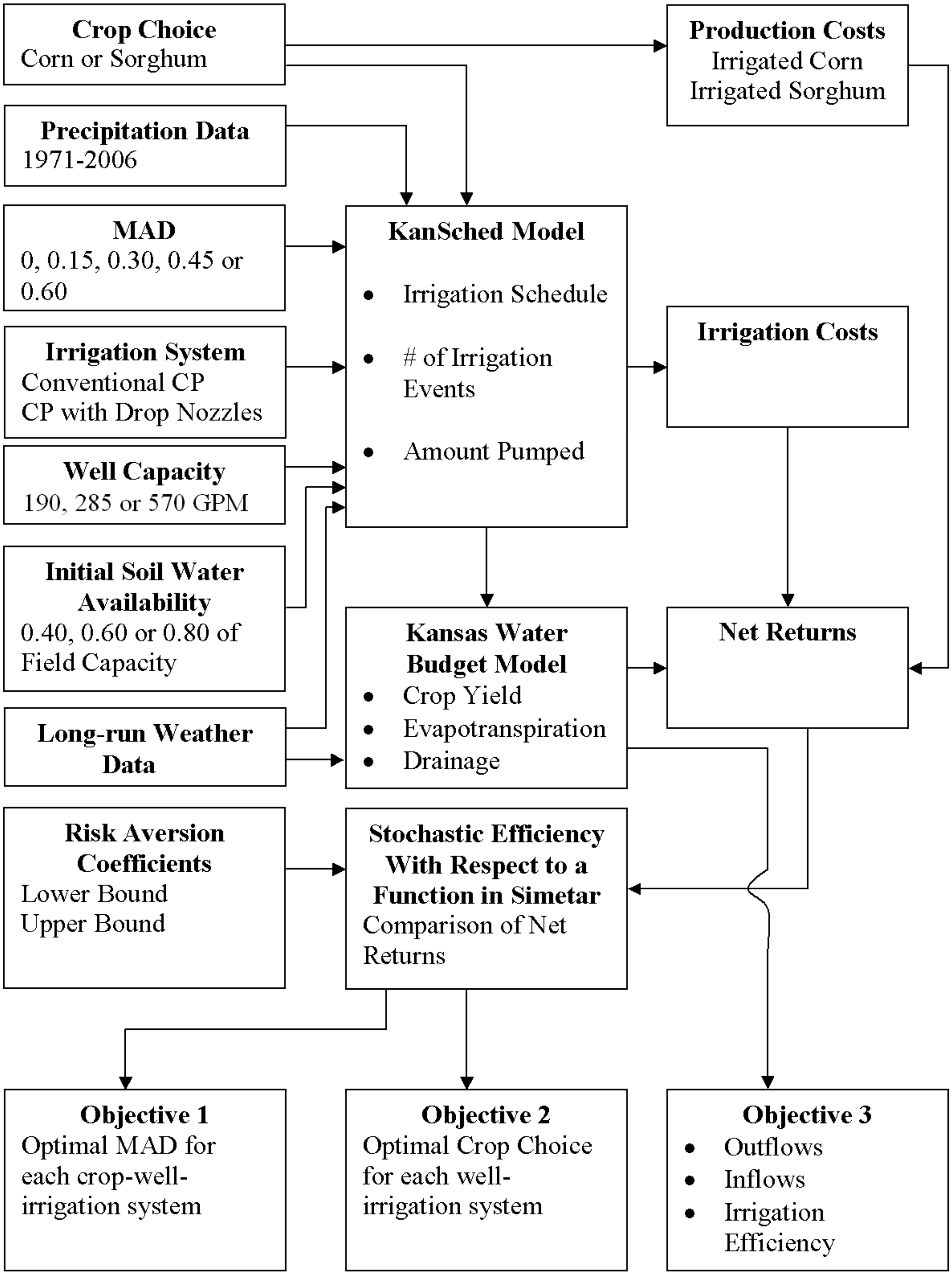
CHAPTER 5 - SIMULATIONS AND RESULTS

The purpose of this chapter is to describe the simulations of irrigated corn and sorghum production using methods described in the previous chapter. The objective of carrying out simulations were three fold – first, to find the conditions that maximize the benefit of irrigation; second, to choose a risk-efficient crop; and third, to evaluate alternative irrigation systems.

Crop yields and irrigation schedules were modeled under limited irrigation conditions in Tribune, KS. Each scenario was a combination of a crop choice (corn or sorghum), irrigation system (conventional center-pivot or center-pivot with drop nozzles), well capacity (190, 285 or 570 gpm) with a corresponding initial soil water availability (0.40, 0.60 or 0.80 of field capacity), an MAD level (0, 0.15, 0.30, 0.45 or 0.60), all across 36 years of weather data (1971-2006). In selecting the most preferred MAD (objective 1), crop choice (objective 2) and irrigation technology (objective 3), a total of 2,160 simulations were carried out.

Figure 5.1 presents the data flow diagram for the simulations. The first step in setting up the simulations in the *KanSched* model was to choose the well capacity by adjusting the frequency of irrigation (cycle time), for example, for a lower well capacity like 190 gpm, the frequency of irrigations was set to 15 days, i.e., it would take 15 days for the center-pivot arm to complete one revolution and irrigate the entire area of the 126 acre crop circle. Similarly, the frequency of irrigation for the 285 and 570 gpm wells was set to 10 days and 5 days, respectively. The initial soil water availability for 190, 285, and 570 gpm wells was set to 0.40, 0.60 and 0.80, respectively, following Fredrickson (2004). Five levels of MAD were investigated in this study for each well – 0, 0.15, 0.30, 0.45 and 0.60.

Figure 5.1. Model Flowchart



The precipitation for the crop season period (May 21 – September 5) for each year was summed and averaged across 36 years. The ratio of the total precipitation to the average precipitation across 36 years was then used as a factor to scale the long-run weather data (obtained from the KWB model). The scaling of the long-run weather data created a seasonal rainfall distribution with the same fluctuations as the annual rainfall distribution. This seasonal rainfall distribution across 36 years was then used as an input in the *KanSched* model to generate an irrigation schedule.

In the *KanSched* model, an irrigation event was triggered if two conditions were satisfied – first, the soil moisture was below a threshold level, and second, an irrigation event was not called for in the previous 5, 10, or 15 days corresponding to 285, 400 or 570 gpm wells. The threshold level was determined by subtracting the MAD level from 1. For example, the threshold level for a 0.30 MAD level was 0.70. Other constraints to scheduling irrigation included a 24 inch gross irrigation limit due to the regulations set by the state of Kansas and no more than 18 irrigation events per season due to an inherent limitation within the KWB model. The irrigation schedules were assembled for each of the 36 years given the annual precipitation patterns. A 36-year array of irrigation schedules was constructed for each section of the field (5, 10 or 15), for all MAD levels (0, 0.15, 0.30, 0.45 and 0.60), and all well capacities (corresponding to irrigation frequencies of 5, 10 or 15 days).

In the KWB model, irrigation schedule was used as an input to determine crop yield, ET and drainage measures. Based on the irrigation schedule, the days of the year during which the irrigation was applied were determined. The total amount of irrigation during the crop season was calculated by adding the amounts of irrigation for all the events in the crop season. The average annual precipitation for each year was calculated based on annual precipitation for the year being simulated. The KWB model estimated yield, ET and drainage based on the crop, total amount of irrigation, application efficiency and average annual precipitation in the year. The crop yields[10] were then adjusted by the following equation:

$$Adjusted\ Yield = Yield * (Yield_{\text{producer's maximum}} / Yield_{\text{maximum}}), \qquad \textbf{(5.1)}$$

---

[10] The yield adjustment is made following Stone *et al.* (2006)

Where $Yield_{\text{producer's maximum}}$ is the maximum obtainable yield in the site being studied, and $Yield_{\text{maximum}}$ is the maximum yield embedded in the KWB model's response functions. This adjustment reflects the fact that corn hybrids have improved from the time the yield-ET relationships in the KWB model were estimated. For corn, the producer's maximum yields were set at 240 bushels each, following recent yields in western Kansas, while $Yield_{\text{maximum}}$ was set at 215 bushels for corn. No yield adjustments were made for sorghum as actual sorghum yields have not increased appreciably since the development of the KWB model. The simulated crop yields for corn and sorghum are presented in appendix tables: A1-A12. Net returns were computed from the simulated yield, the costs and prices in Extension crop budgets (tables 4.1-4.2), and the pumping cost formula (equation (3.6)). Seasonal water-use measures were computed based on precipitation, ET, drainage and irrigation. The measures of interest were consumptive use, season-long irrigation efficiency and return flows. These net returns were then compared using the stochastic efficiency approach to find the most optimal MAD. After choosing the MAD level, crop selection was made based on net returns and risk characteristics.

5.1 Net Returns Distributions

The net returns for corn and sorghum were simulated for each well capacity, crop, MAD level and section of the field. The section with the average net returns closest to the overall mean of net returns for that model were chosen as representative sections. The representative sections are the sections with the least deviation from the average net returns across all the sections. As a result, the 8th, 6th and 3rd sections were chosen as the representative sections of the field for the 190 gpm (15 sections), 285 gpm (10 sections) and 570 gpm (5 sections) wells, respectively. For a given well capacity, crop, and MAD level, the simulated net returns over the 36 years of weather can be regarded as the producer's probability distribution of profits. As there are 2 crops, 3 well capacities, 5 MAD levels and 2 irrigation systems, a total of 60 probability distributions were generated. These probability distributions are presented graphically in this section as cumulative distribution functions (CDFs); and as the tabular results in appendix tables: B1-B12. Each of the figures below presents the CDFs of the five MAD levels, for a given crop and irrigation system.

Figure 5.2. CDF of Net Returns for Conventional CP Irrigated Corn on 190 gpm Well

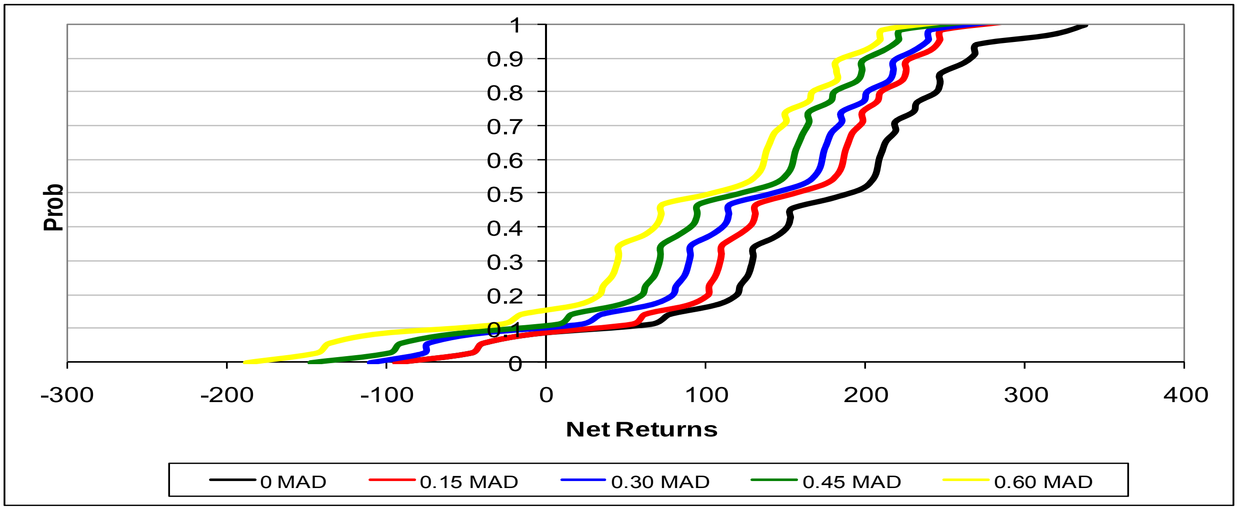


Figure 5.3. CDF of Net Returns for Conventional CP Irrigated Corn on 285 gpm Well

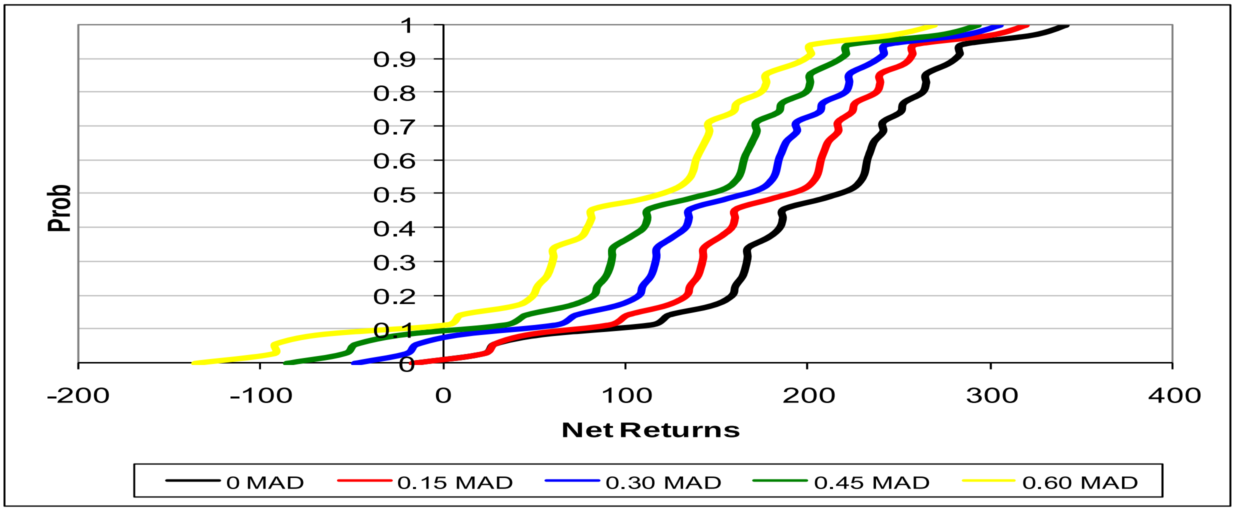
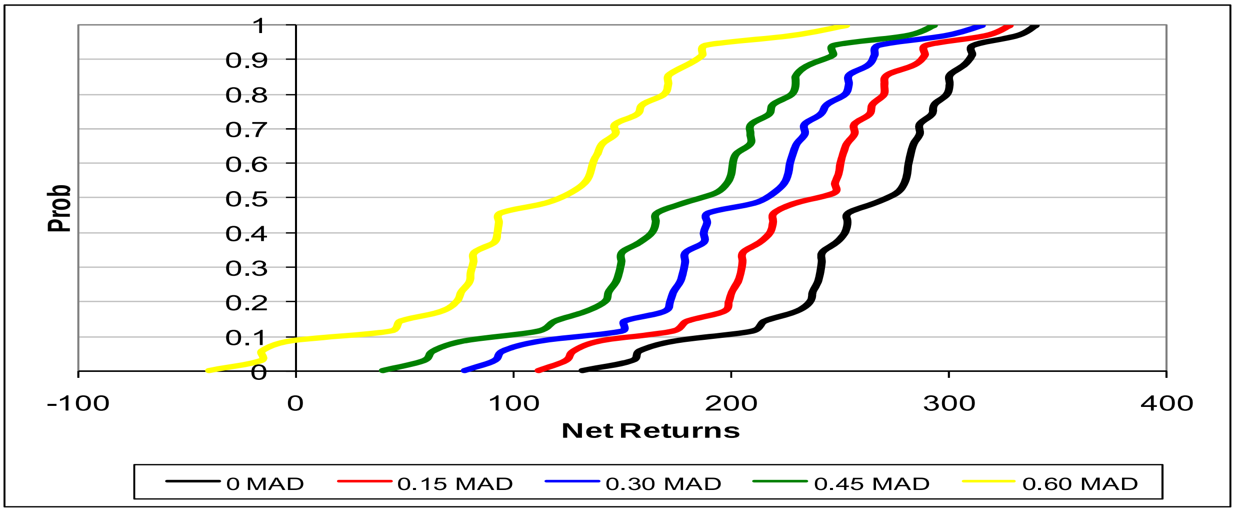


Figure 5.4. CDF of Net Returns for Conventional CP Irrigated Corn on 570 gpm Well



The CDFs of net returns of conventional center-pivot irrigated corn on 190, 285, and 570 gpm wells are presented in figures 5.2, 5.3, and 5.4, respectively. The poorest weather years were reflected in the lower tails of the distribution where net returns are lowest. The distributions corresponding to the 0 and 0.15 MAD levels nearly coincide in their lower tails, meaning that they provide the same level of income in poor weather years. However, in better weather years, the 0 MAD level produced higher net returns and, in fact, was the most preferred among all MAD levels. While the net return distribution under the highest MAD of 0.6 was similar across the three well capacities, the distributions at lower MADs shifted further to the right as well capacity increases. Producers with faster wells had the opportunity to increase net returns substantially by lowering their MADs, while producers with slower wells could increase net returns only modestly.

The CDFs of net returns of center-pivot with drops irrigated corn on 190, 285, and 570 gpm wells are presented in figures 5.5, 5.6 and 5.7, respectively. Similar to the standard center pivot results, the highest net returns for corn under the slower wells was ambiguous in the lower tails of the distributions, beyond which corn under 0 MAD level produced the highest net returns. Unlike the standard center pivot distributions, however, the variance of net returns decreased substantially as well capacity increased (the CDFs became more vertical). The additional efficiency in application under the center-pivot with drops system allowed producers with faster wells to reduce production risk substantially, most likely because more net irrigation could be delivered to the crop during critical growth periods.

Figure 5.5. CDF of Net Returns for CP with Drops Irrigated Corn on 190 gpm Well

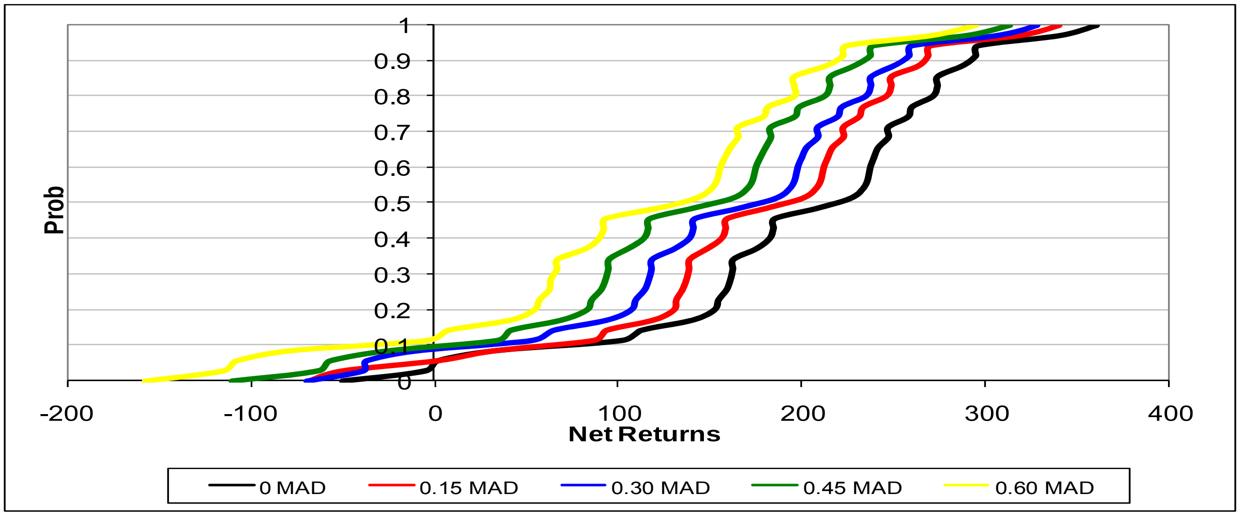


Figure 5.6. CDF of Net Returns for CP with Drops Irrigated Corn on 285 gpm Well

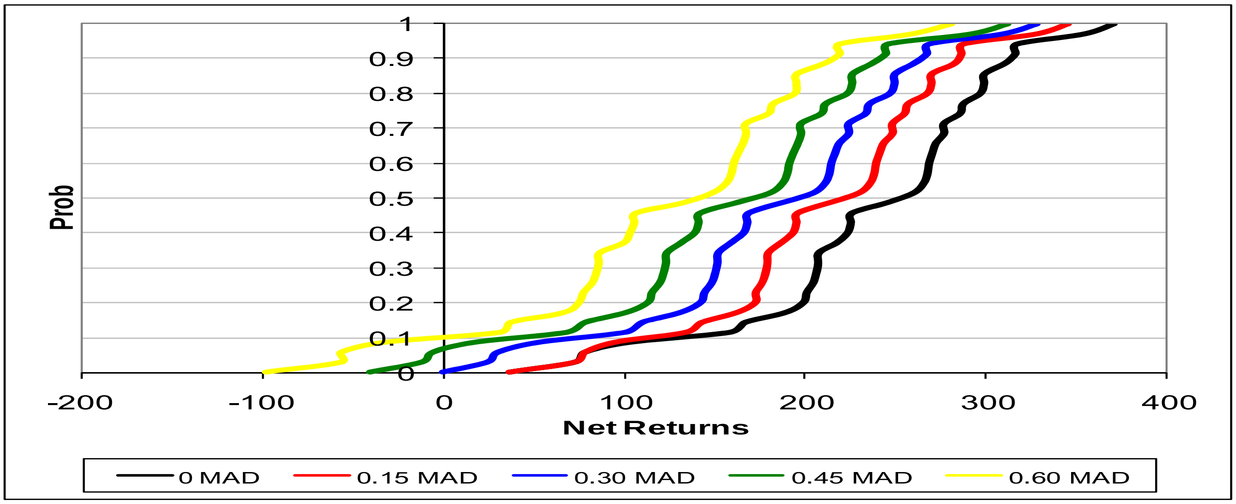


Figure 5.7. CDF of Net Returns for CP with Drops Irrigated Corn on 570 gpm Well

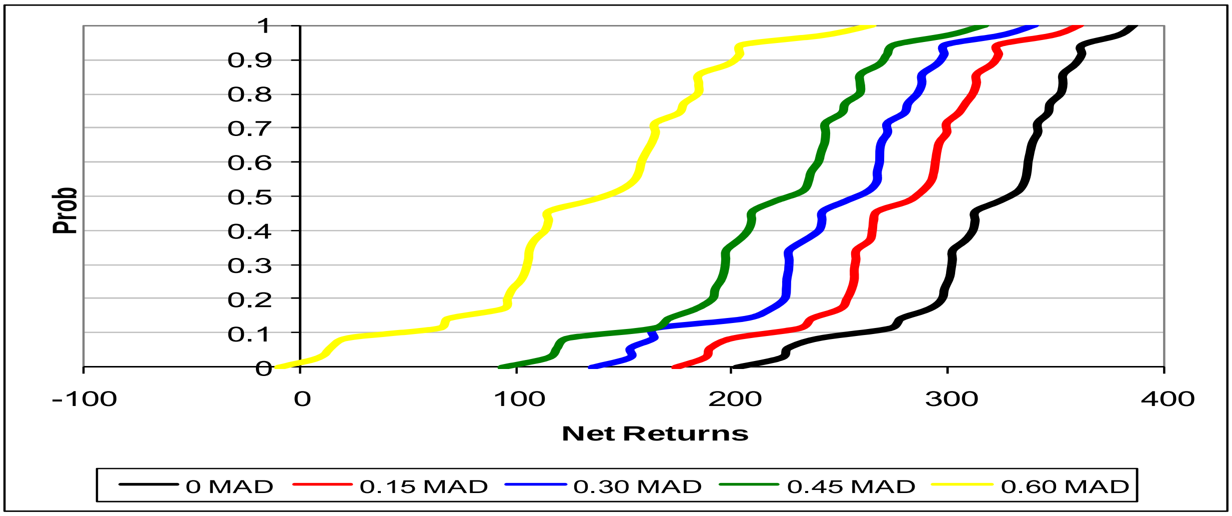


Figure 5.8. CDF of Net Returns for Conventional CP Irrigated Sorghum on 190 gpm Well

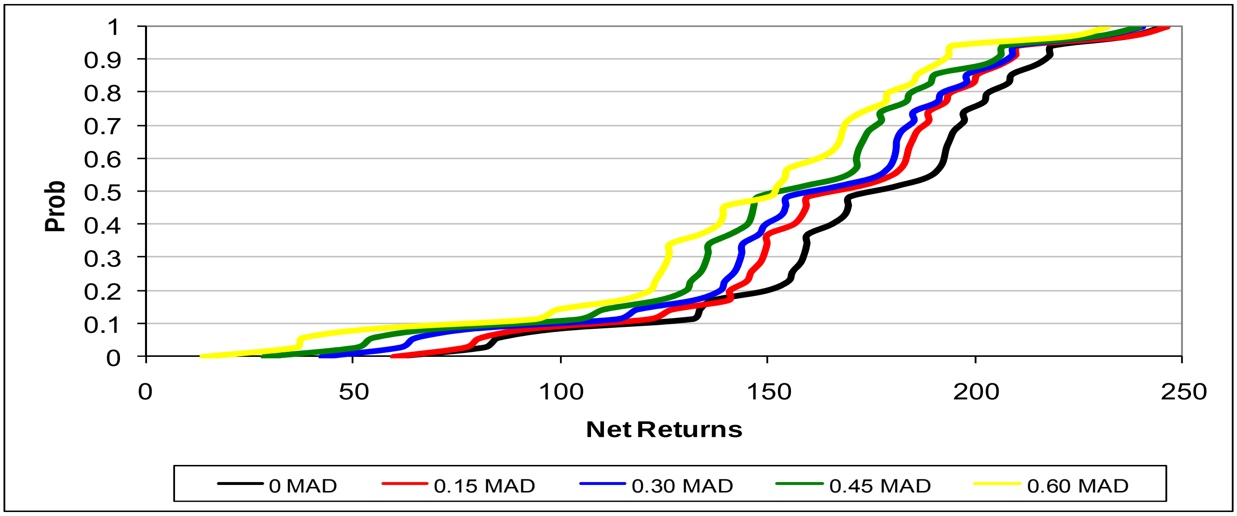


Figure 5.9. CDF of Net Returns for Conventional CP Irrigated Sorghum on 285 gpm Well

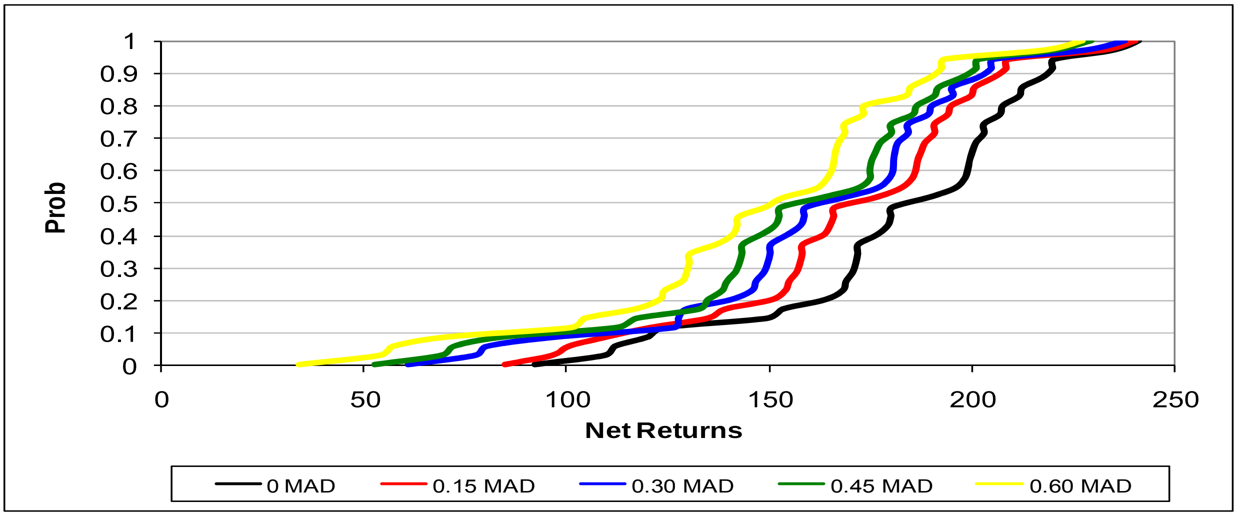
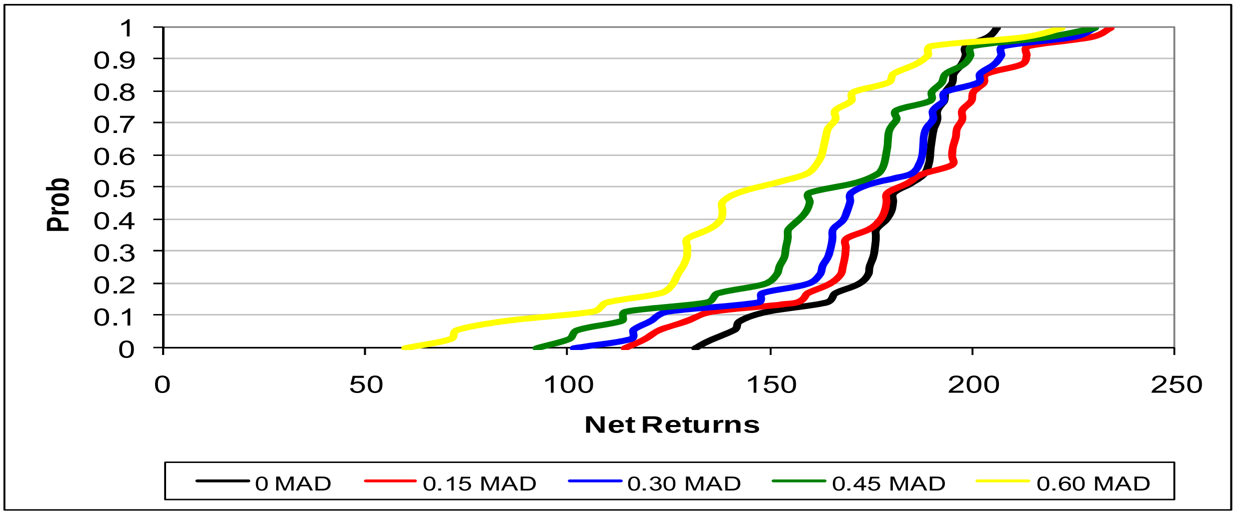


Figure 5.10. CDF of Net Returns for Conventional CP Irrigated Sorghum on 570 gpm Well



The CDFs of net returns for conventional center-pivot irrigated sorghum under 190, 285 and 570 gpm wells are presented in figures 5.8, 5.9 and 5.10, respectively. In some years, at higher well capacities, the net returns for 0.15, 0.30, 0.45 and 0.60 MAD level were higher than 0 MAD level, particularly with a 570 gpm well beyond a ARAC of 0.54. For the most part, the highest net returns for sorghum under 190 and 285 gpm wells were produced under the 0 MAD level. The highest net returns for sorghum under a 570 gpm well was produced under the 0 MAD level until an ARAC of 0.54, beyond which, the highest net returns were produced under 0.15 MAD level.

The CDFs of net returns for center-pivot with drops irrigated sorghum under 190, 285 and 570 gpm wells are presented in figure 5.11, 5.12 and 5.13, respectively. In some years, the net returns at higher wells were higher for 0.15 and 0.30 MAD levels than 0 MAD level, a little less drastic as compared to the conventional center-pivot system. For the most part, the highest net returns for center-pivot with drops irrigated sorghum under the three wells were produced under the 0 MAD level. The variance of net returns for center-pivot with drops irrigated sorghum was lower than conventional center-pivot irrigated sorghum at all well capacities.

In summary, the net returns increased for higher well capacities and the net returns for 0 MAD level were predominantly higher than any other MAD level for corn and sorghum under all the three well capacities and both irrigation systems. The net returns for sorghum were always positive, while net returns for corn were negative with a nonzero probability in several simulations. At the same time, the highest corn net returns were larger than the highest sorghum net returns. The average net returns were larger at higher well capacities, as more water that was pumped into the soil profile translated to higher yields and eventually to higher net returns. The average net returns decreased across all wells as the level of MAD increased. The decrease in net returns was because fewer irrigation events were scheduled and as a result less water was available to the crop. The lowest MAD gave the highest net returns, but to determine whether this condition holds definitely, risk analysis was performed.

Figure 5.11. CDF of Net Returns for CP with Drops Irrigated Sorghum on 190 gpm Well

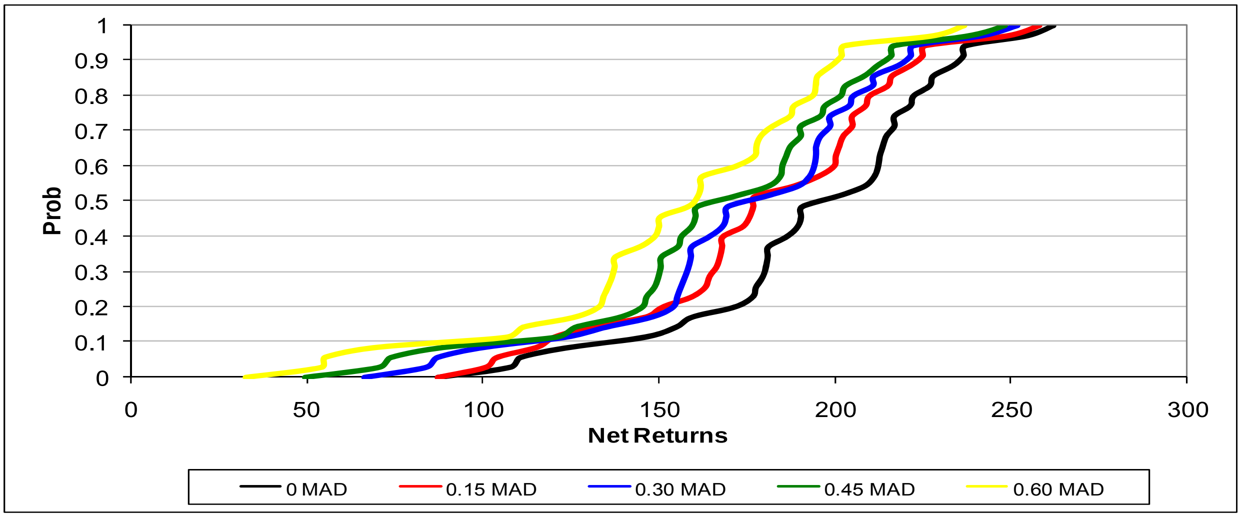


Figure 5.12. CDF of Net Returns for CP with Drops Irrigated Sorghum on 285 gpm Well

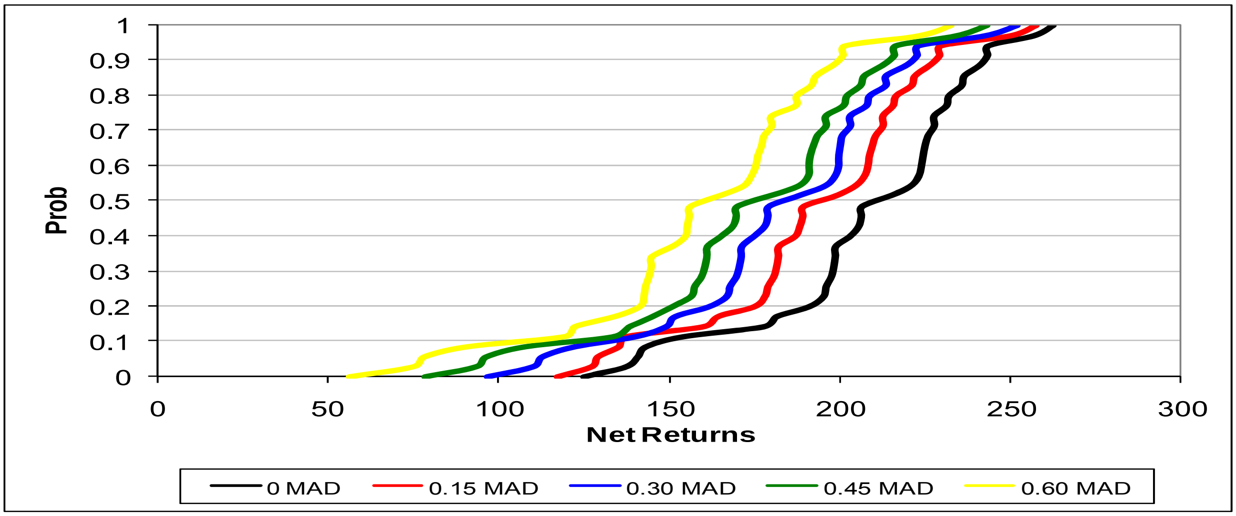
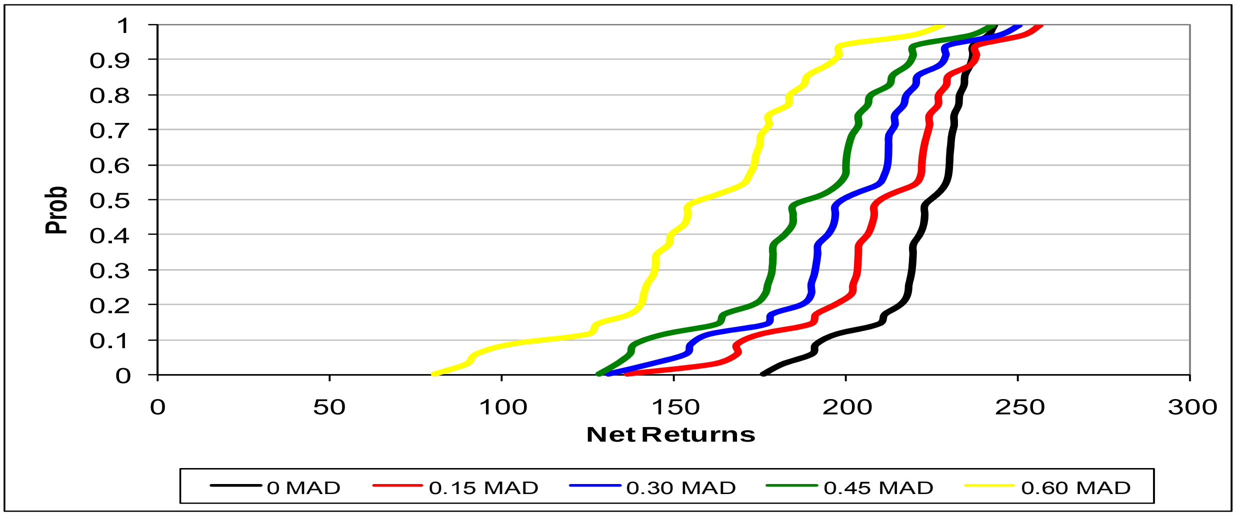


Figure 5.13. CDF of Net Returns for CP with Drops Irrigated Sorghum on 570 gpm Well



5.2 Optimal MAD Choice

For each crop and irrigation system, the optimal MAD was determined by comparing net return distributions using the SERF method. The figures below depict the certainty equivalents (CE) of each distribution as a function of the absolute risk aversion coefficient (ARAC) in the range [0, 0.1] following Raskin and Cochran (1986). An upper bound of 0.1 was considered for this objective as there was little variation in the optimal choice of MAD beyond an ARAC of 0.1.

Figure 5.14 illustrates the CE relationships for the case of corn irrigated with a 190 gpm well under a conventional center-pivot irrigation system. The 0 MAD level has the highest (or is tied for the highest) CE throughout the entire ARAC range, making it the only alternative not dominated by another alternative. The 0 MAD level was the most preferred MAD level for a very narrow ARAC range of [0, 0.0542]. For ARACs above 0.0542, the CEs from 0 and 0.15 MAD levels coincided, indicating that producers within the ARAC range would be indifferent between either alternative. The preference ordering of MAD levels followed the progression from the most preferred at 0 to least preferred at 0.60.

The distance between the CE for a 0 MAD and another MAD level for an ARAC=0 represents the difference in mean net returns from the two irrigation strategies; any ARAC above 0 represents the amount, called willingness to accept (WTA), a producer would need to be compensated to switch from 0 MAD to another level. As the graph shows, the WTA varies by the risk aversion level (ARAC). Because the other MAD levels result in lesser irrigation, they can be regarded as “water conserving” irrigation practices. At an ARAC of 0.1, for instance, the WTA is $93.18/acre for the 0.6 MAD level. The WTA payments are discussed in Section 5.3.

Figures 5.15 and 5.16 show the certainty equivalents of the five MAD levels for corn irrigated by a standard center pivot system with well capacities of 285 and 570 gpm, respectively. Figure 5.15 shows the same qualitative pattern as the 190 gpm well. For a 285 gpm well (figure 5.15), decision makers with ARACs above about 0.095 would be indifferent between MAD =0 and MAD = 0.15, while MAD=0 is superior for farmers with ARACs below 0.095. For a 570 gpm well, MAD=0 is the unequivocal best choice across all ARACs. The MAD levels have the same preference ordering in all three figures, with lower MAD levels being preferred over higher ones. An increase in well capacity shifts all the CE curves upward, reflecting the extra income generating potential; farmers with a faster well can apply more water throughout the season and can also prevent water stress during critical stages of plant growth.

Figure 5.14. Corn CP 190 gpm Well Certainty Equivalents against ARAC

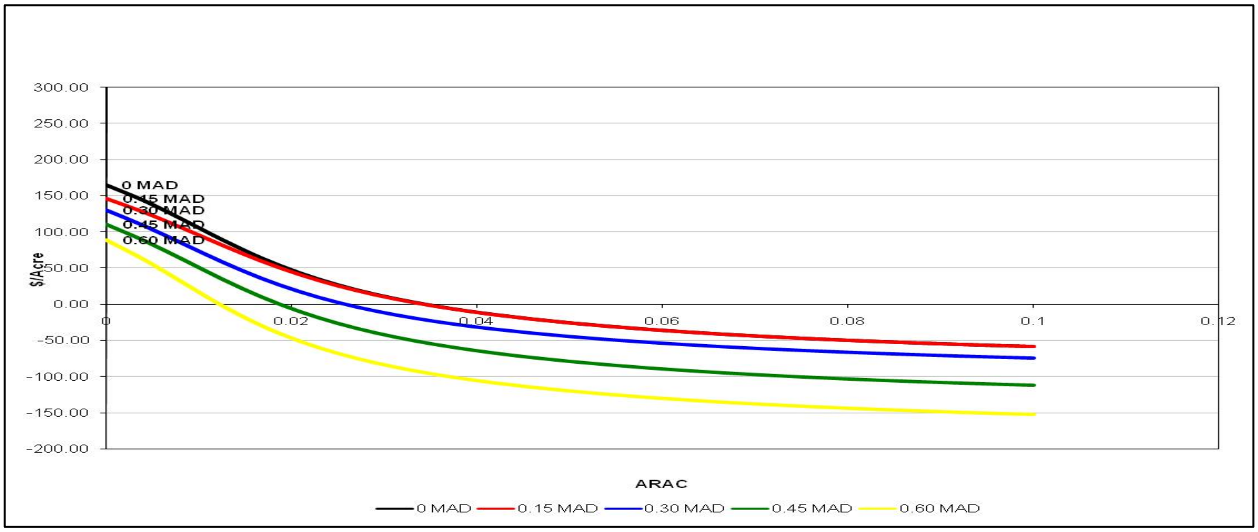


Figure 5.15. Corn CP 285 gpm Well Certainty Equivalents against ARAC

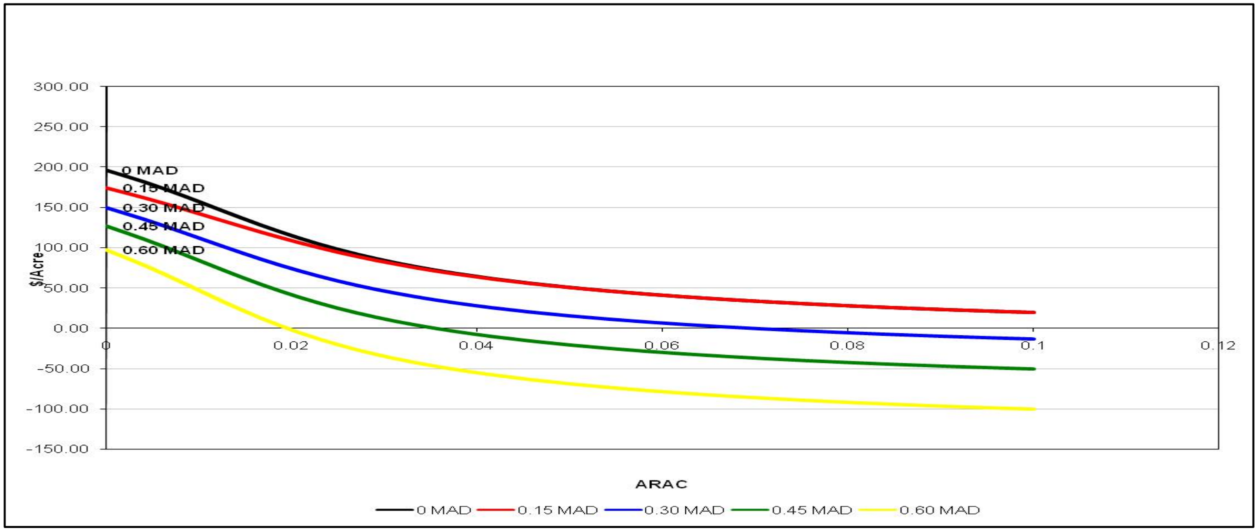


Figure 5.16. Corn CP 570 gpm Well Certainty Equivalents against ARAC

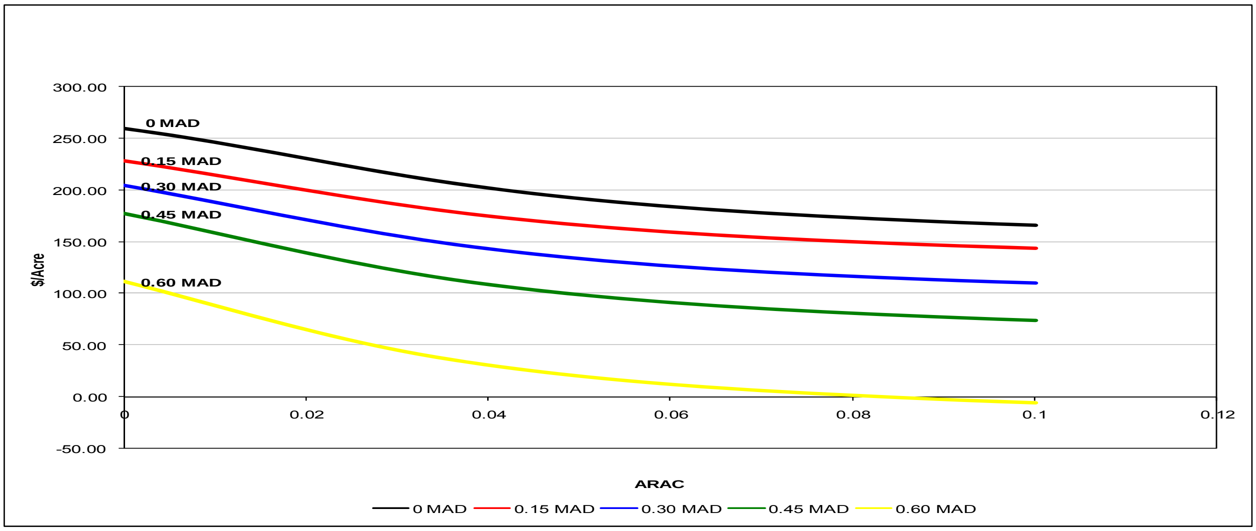


Figure 5.17. Corn CPD 190 gpm Well Certainty Equivalents against ARAC

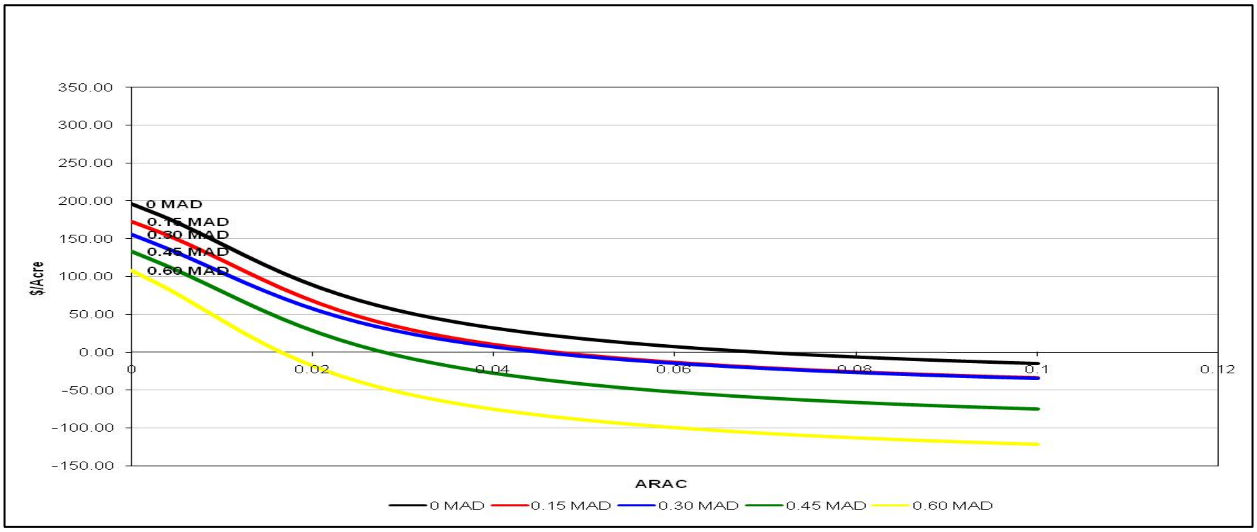


Figure 5.18. Corn CPD 285 gpm Well Certainty Equivalents against ARAC

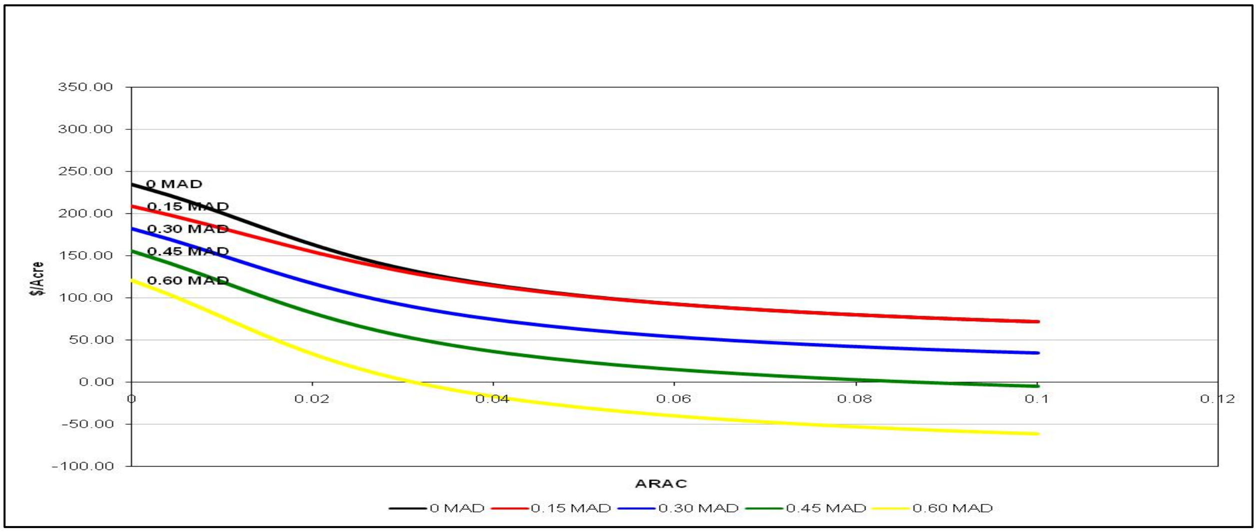
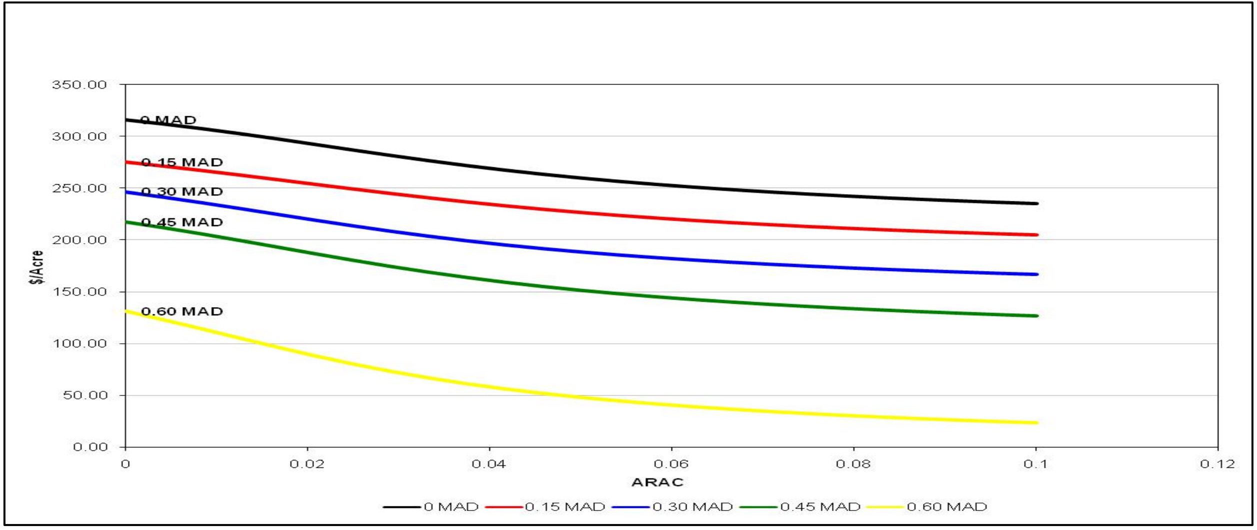


Figure 5.19. Corn CPD 570 gpm Well Certainty Equivalents against ARAC



The CE relationships for corn irrigated with center-pivot with drop nozzles (CPD) systems, with well capacities of 190, 285, and 570 gpm, are presented in figure 5.17, 5.18, and 5.19, respectively. Similar to the conventional center-pivot (CP) system, the 0 MAD level was the most risk-efficient choice at all well capacities; it has the highest CE (or is tied for the highest) across all ARACs in all three figures. Compared to the CP irrigated corn, the CPD systems shift the CE curves upward, reflecting the additional yields and lower pumping costs of the more efficient irrigation technology.

The CE relationships for CP-irrigated sorghum are displayed in figures 5.20-5.22, and those for CPD-irrigated sorghum are in figures 5.23-5.25. The 0 MAD level again has the highest (or is tied for the highest) CE, making it the most preferred MAD level in all scenarios. The preference ordering of the MAD levels also follows the same pattern as corn, following the progression from the most preferred at 0 to least preferred at 0.60. The sorghum CE functions display somewhat less curvature than those for corn, with a smaller gap in the CE calculated at an ARAC of 0 compared to an ARAC of 0.60. This implies that, for a given well capacity, the CE functions for corn and sorghum may intersect, making the risk-efficient crop choice dependent on the farmer's risk tolerance. The question of crop selection is addressed in Section 5.4.

In summary, based on stochastic efficiency with respect to a negative exponential utility function, the results indicated that 0 MAD level was the most preferred for conventional center-pivot and center-pivot with drops irrigated corn and sorghum with 190, 285 and 570 gpm wells. The preference of MAD levels followed the progression from the most preferred at 0 to least preferred at 0.60 for both corn and sorghum under both conventional center-pivot and center-pivot with drop nozzles irrigation system.

Figure 5.20. Sorghum CP 190 gpm Well Certainty Equivalents against ARAC

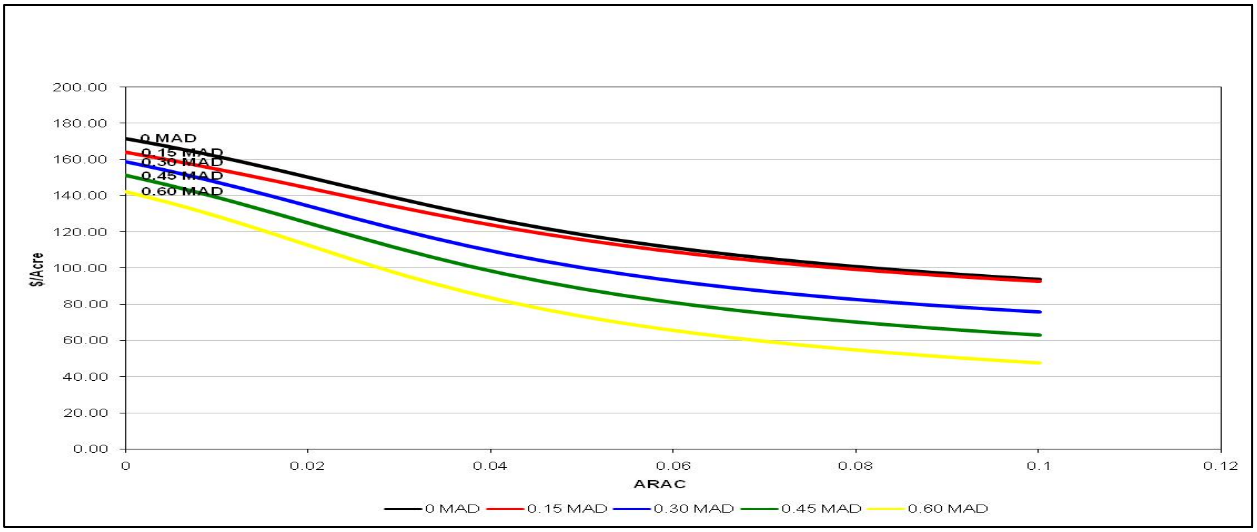


Figure 5.21. Sorghum CP 285 gpm Well Certainty Equivalents against ARAC

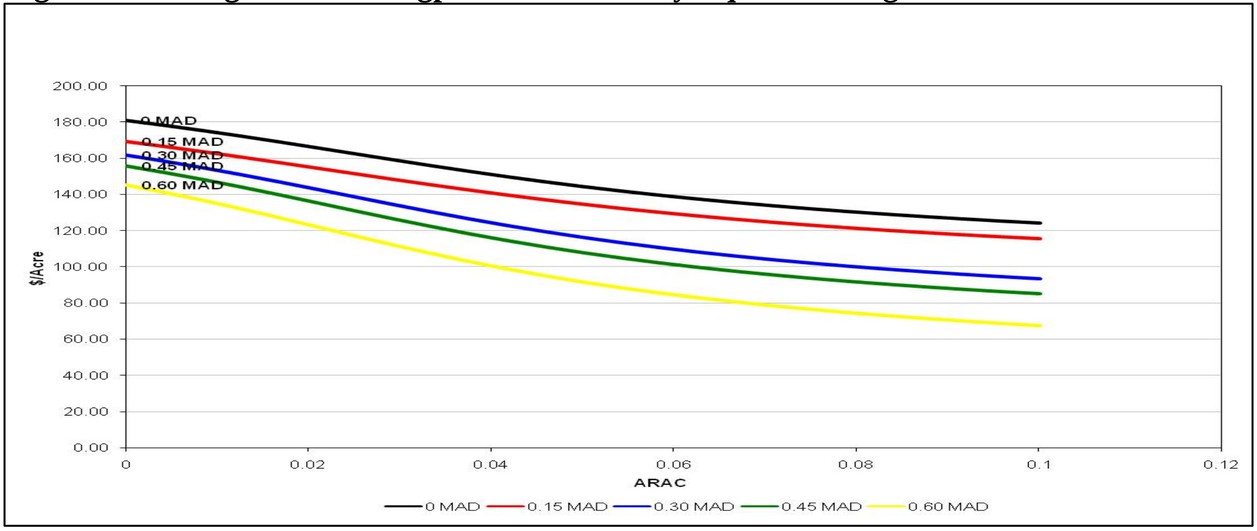


Figure 5.22. Sorghum CP 570 gpm Well Certainty Equivalents against ARAC

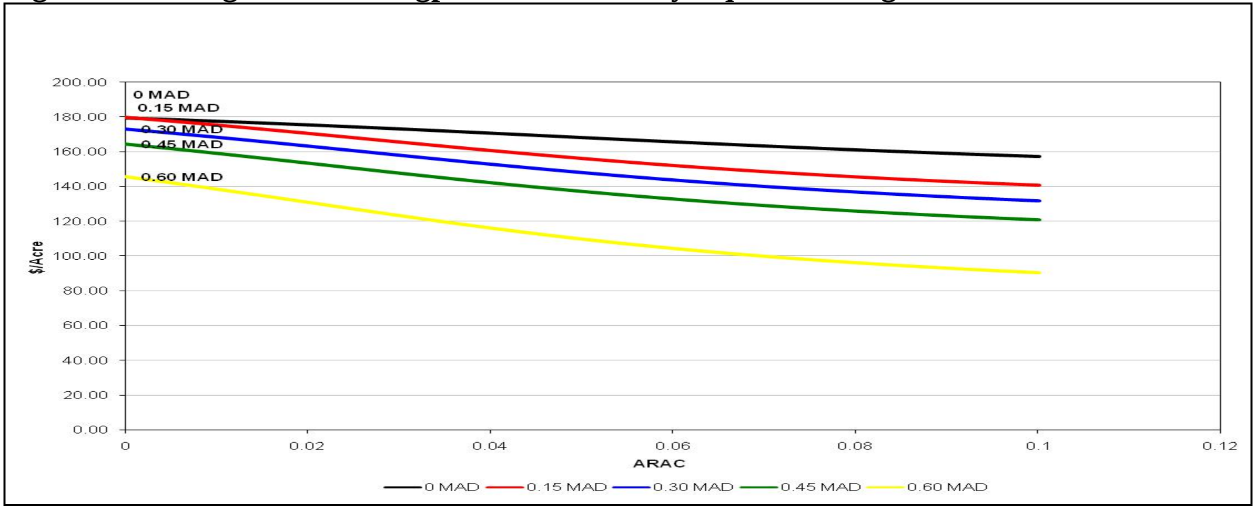


Figure 5.23. Sorghum CPD 190 gpm Well Certainty Equivalents against ARAC

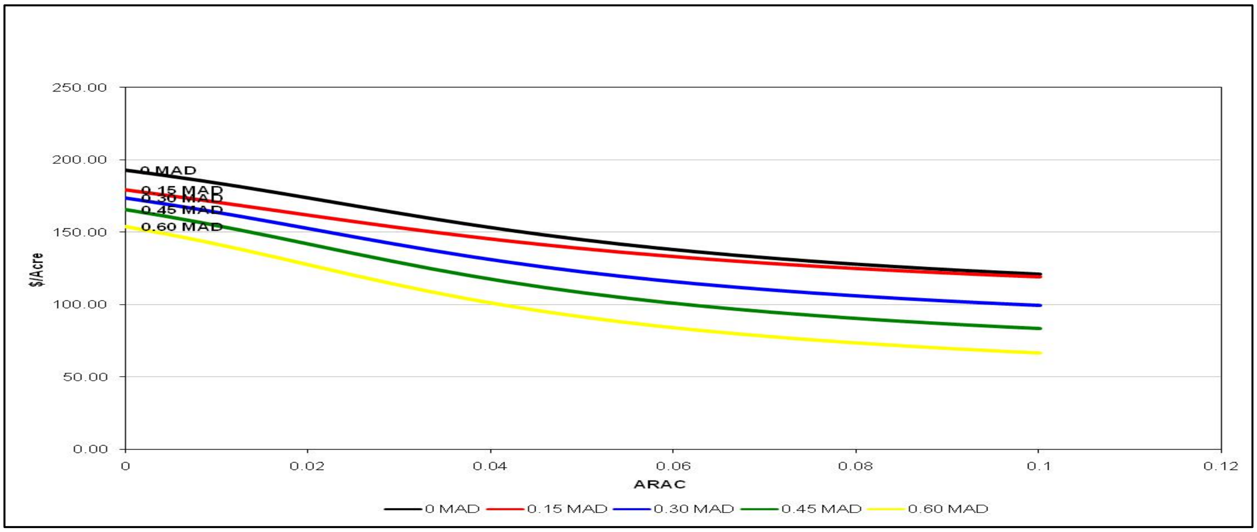


Figure 5.24. Sorghum CPD 285 gpm Well Certainty Equivalents against ARAC

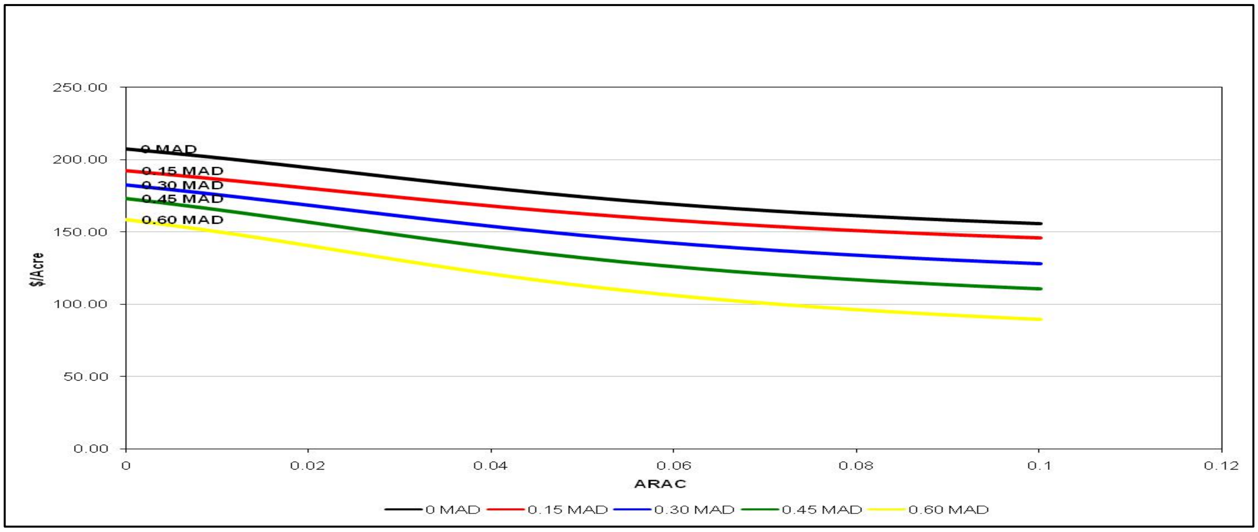
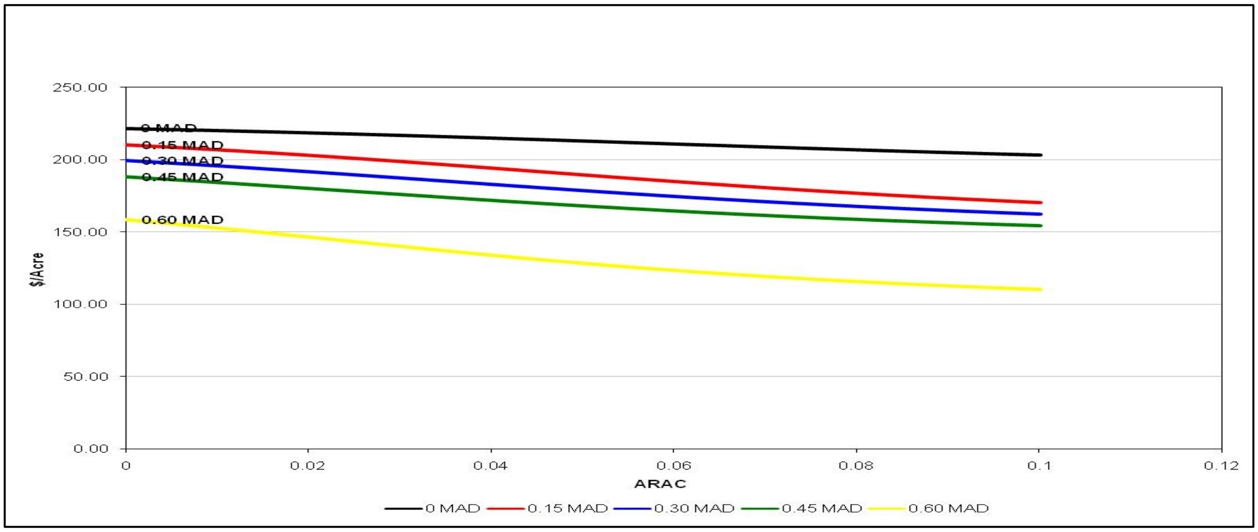


Figure 5.25. Sorghum CPD 570 gpm Well Certainty Equivalents against ARAC



5.3 Willingness to Accept (WTA) Payments

Willingness to accept payment is the amount a producer needs to give up or be compensated in order to switch from a preferred MAD to another MAD level. Table 5.1 and 5.2 present the WTA payments to switch from 0 MAD level to other levels for corn and sorghum irrigated by a conventional center-pivot irrigation system and center-pivot with drop nozzles irrigation system, respectively. In switching to a higher MAD level a producer would reduce irrigation and this amount is reported in the tables. The WTA payments have policy significance because they are an estimate of the minimum government payments farmers would need to implement water conservation through reduced irrigation. The WTA per inch of water savings is reported to compare the unit cost of conserving water through contract payments to farmers in different situations.

If such a government policy were enacted, a method of computing appropriate contract payments to offer farmers would need to be found. One possibility would be to offer a contract price equal to the estimate the gap in mean net returns between the MAD=0 level and the alternative being considered. However, if a farmer is risk averse and the new alternative creates significantly more risk, then the actual WTA payment he needs will be larger than the gap in mean net returns. The amount that the actual WTA exceeds the gap in mean net returns is known as the risk premium. To determine whether the risk premiums are significant, the gap in mean net returns also is reported in the tables.

Table 5-1. Willingness to Accept Payments to Change from 0 MAD to Other MAD Levels When ARAC is 0.1 for Conventional Center-Pivot Irrigated System, by Crop and Well Capacity

	Corn			Sorghum		
Item	190 gpm	285 gpm	570 gpm	190 gpm	285 gpm	570 gpm
MAD = 0.15						
Willingness to accept payment ($/acre)	0.00	0.01	22.10	1.00	8.90	16.37
Gap in mean net returns at ARAC=0	18.02	22.61	30.55	7.75	11.87	-0.59
Reduction in irrigation (acre-inches/acre)	1.07	0.93	3.10	1.23	1.20	6.20
Premium per inch of water savings	0.00	0.01	7.13	0.81	7.42	2.64
MAD = 0.30						
Willingness to accept payment ($/acre)	15.91	32.75	55.79	17.94	30.73	25.59
Gap in mean net returns at ARAC=0	34.17	46.58	55.10	13.11	19.18	6.19
Reduction in irrigation (acre-inches/acre)	1.53	1.53	4.53	2.27	2.37	7.77
Premium per inch of water savings	10.40	21.41	12.32	7.90	12.97	3.29
MAD = 0.45						
Willingness to accept payment ($/acre)	53.05	69.73	91.87	30.90	39.15	36.31
Gap in mean net returns at ARAC=0	53.79	69.91	82.26	20.42	25.43	14.91
Reduction in irrigation (acre-inches/acre)	2.27	2.37	6.17	2.57	3.40	9.17
Premium per inch of water savings	23.37	29.42	14.89	12.02	11.51	3.96
MAD = 0.60						
Willingness to accept payment ($/acre)	93.18	119.91	171.66	45.99	56.77	66.99
Gap in mean net returns at ARAC=0	75.97	99.13	147.75	29.32	35.74	33.67
Reduction in irrigation (acre-inches/acre)	2.80	3.77	11.93	3.57	4.83	13.87
Premium per inch of water savings	33.28	31.81	14.39	12.88	11.75	4.83

Table 5-2. Willingness to Accept Payments to Change from 0 MAD to Other MAD Levels When ARAC is 0.1 for Center-Pivot with Drop Nozzles Irrigated System, by Crop and Well Capacity

	Corn			Sorghum		
Item	190 gpm	285 gpm	570 gpm	190 gpm	285 gpm	570 gpm
MAD = 0.15						
Willingness to accept payment ($/acre)	19.54	0.02	30.43	2.20	9.54	32.69
Gap in mean net returns at ARAC=0	23.38	25.94	40.88	13.42	15.04	11.69
Reduction in irrigation (acre-inches/acre)	1.07	0.93	4.33	1.23	1.20	7.63
Premium per inch of water savings	18.26	0.02	7.03	1.79	7.95	4.28
MAD = 0.30						
Willingness to accept payment ($/acre)	20.10	37.08	68.25	21.84	27.62	40.86
Gap in mean net returns at ARAC=0	40.07	52.77	69.52	19.17	24.83	22.36
Reduction in irrigation (acre-inches/acre)	1.53	1.53	5.80	2.27	2.37	8.87
Premium per inch of water savings	13.14	24.24	11.77	9.62	11.65	4.61
MAD = 0.45						
Willingness to accept payment ($/acre)	60.05	77.04	108.28	37.92	44.89	48.65
Gap in mean net returns at ARAC=0	62.94	79.51	98.98	26.88	34.21	33.60
Reduction in irrigation (acre-inches/acre)	2.27	2.37	7.23	2.53	3.40	10.27
Premium per inch of water savings	26.45	32.51	14.98	14.99	13.20	4.74
MAD = 0.60						
Willingness to accept payment ($/acre)	107.01	133.58	211.96	54.68	65.99	92.80
Gap in mean net returns at ARAC=0	88.20	113.90	184.60	38.89	48.95	63.10
Reduction in irrigation (acre-inches/acre)	2.83	3.77	12.60	3.53	4.97	14.30
Premium per inch of water savings	37.81	35.43	16.82	15.49	13.28	6.49

The WTA payments were typically higher for corn as compared to sorghum and the WTA payments for center-pivot with drop nozzles irrigation system were higher than the conventional center-pivot irrigation systems. The WTA payments increased from a lower to higher well capacity, indicating that with more water being available for irrigation, the needed incentives were higher to switch to a water-saving irrigation regime. This pattern was much more dramatic for corn, however, indicating that the public cost of obtaining water savings would be much smaller if obtained from sorghum producers than corn producers. Thus, it is important to understand which crop farmers are likely to select in different production settings is addressed in the next section. The risk premiums existed for sorghum production in all categories and for corn in the case of a 570gpm well and an MAD of 0.6. In these cases, offering farmers a payment equal to their loss in mean net returns would not be sufficient to induce their participation. However, for corn producers with slow wells and if the target MAD level is less than 0.6, a payment equal to the mean net returns would be sufficient.

5.4 Choice of Crop

The most preferred crop was determined by comparing net return distributions of corn and sorghum using the SERF method. The figures below describe the CE relationship as a function of ARAC.

Figures 5.26 and 5.27 illustrate the CE relationships in the case of corn and sorghum irrigated by a CP system with a 190 gpm well. Both 0 and 0.15 MAD levels were considered for the choice of crop, as they were both optimal for certain ARAC values. Under both MAD levels, the CE for sorghum is higher than corn throughout the entire range of ARAC, making sorghum the most preferred crop irrigated with a 190 gpm well under conventional center-pivot irrigation system.

Figure 5.26. Corn vs Sorghum Certainty Equivalents against Absolute Risk Aversion Coefficients for a CP 190 gpm Well and 0 MAD

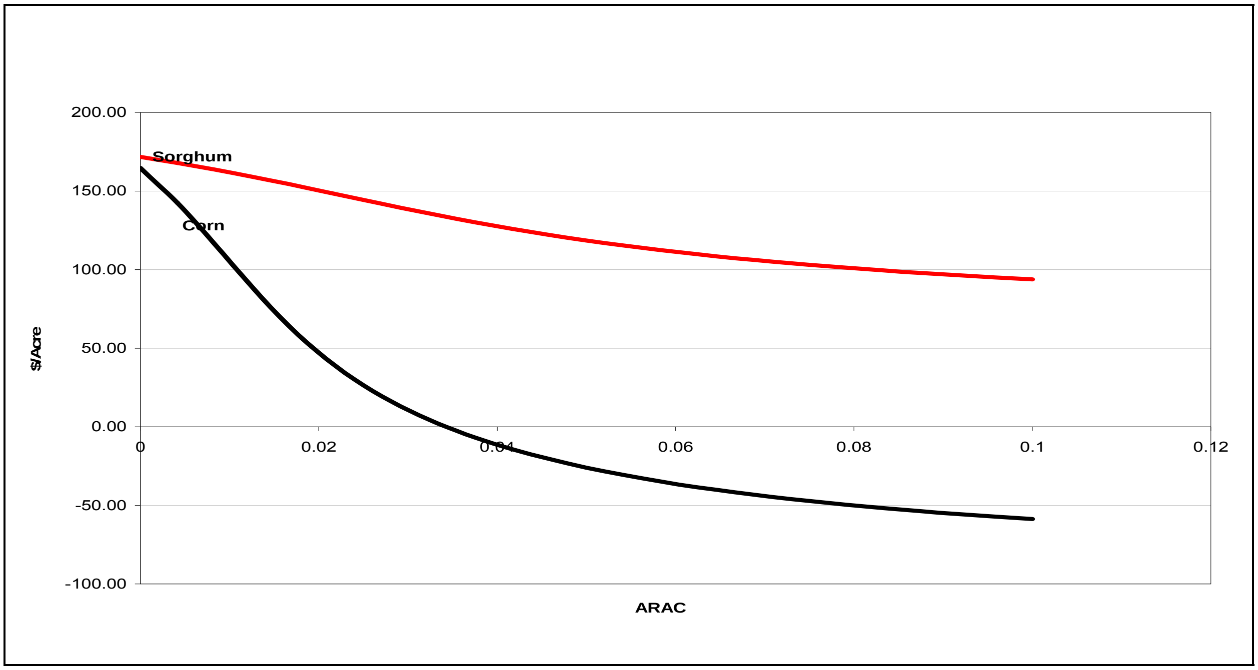
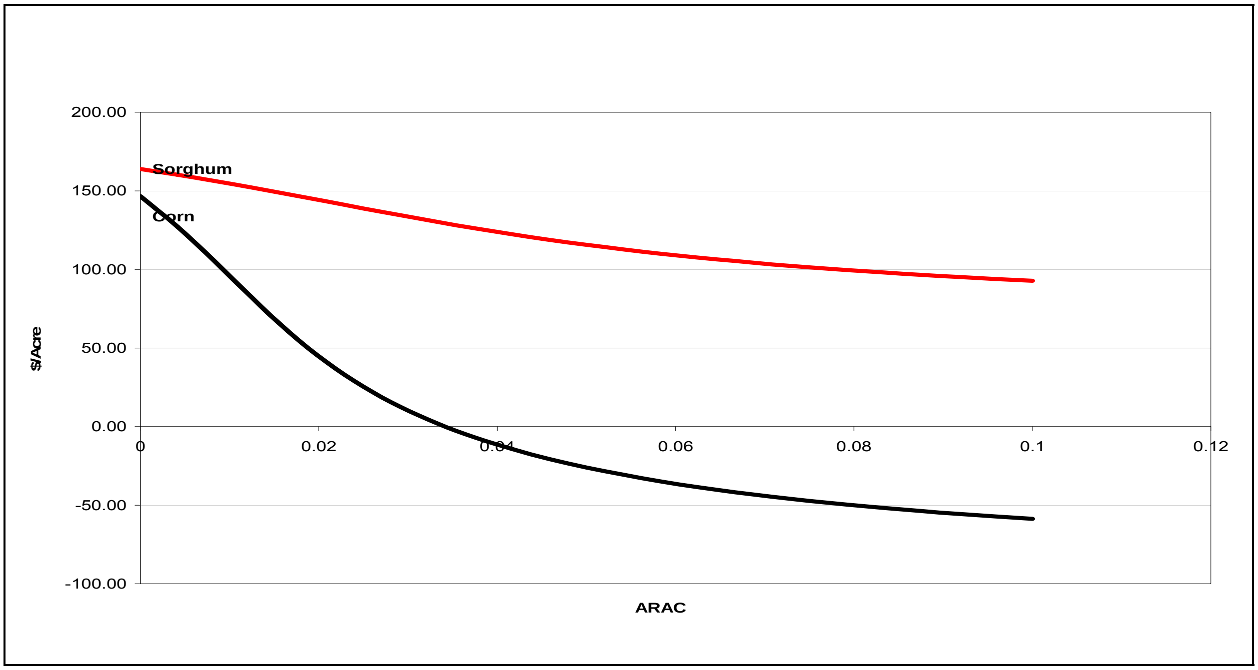


Figure 5.27. Corn vs Sorghum Certainty Equivalents against Absolute Risk Aversion Coefficients for a CP 190 gpm Well and 0.15 MAD



Figures 5.28 and 5.29 illustrate the CE relationships for the case of corn and sorghum irrigated by a CP irrigation system with a 285 gpm well. Once again, 0 and 0.15 MAD were considered, and under both the MAD levels, the CEs for corn was higher than sorghum for a

Figure 5.28. Corn vs Sorghum Certainty Equivalents against Absolute Risk Aversion Coefficients for a CP 285 gpm Well and 0 MAD

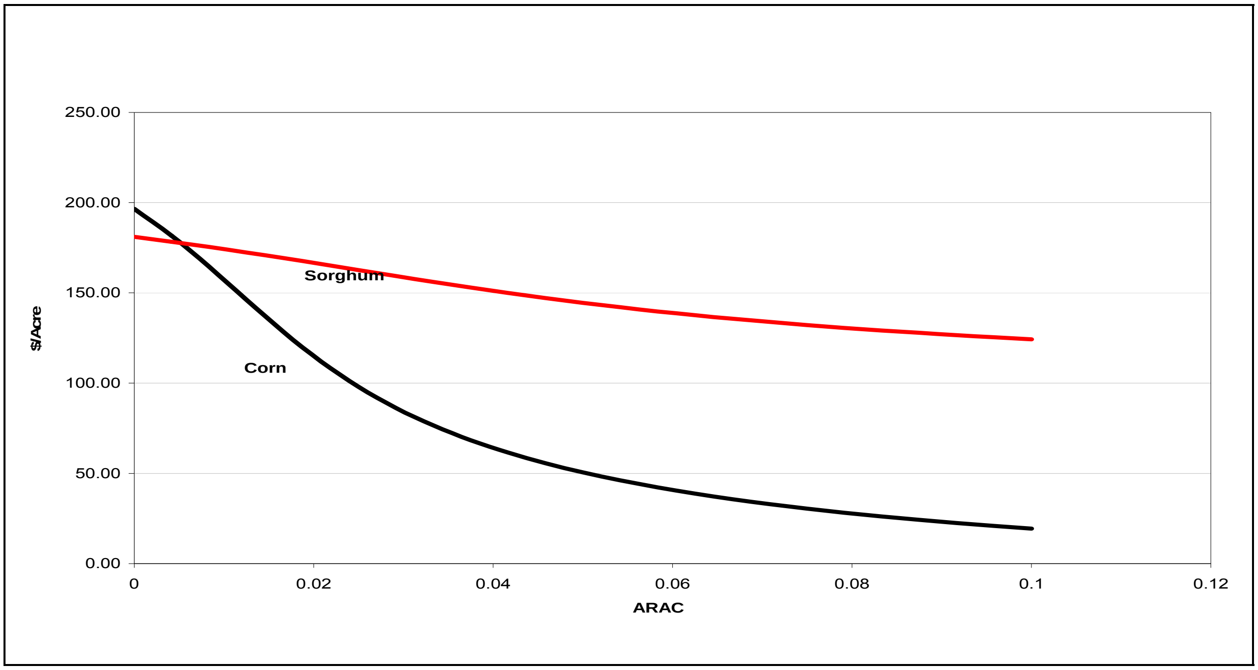
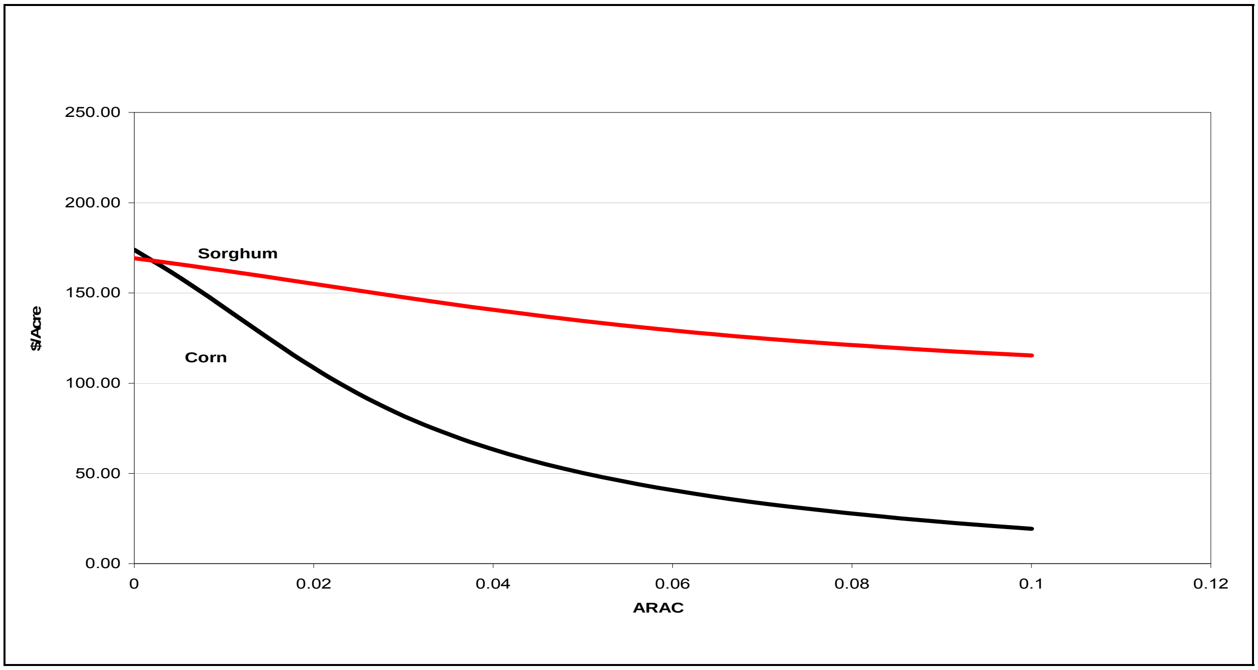


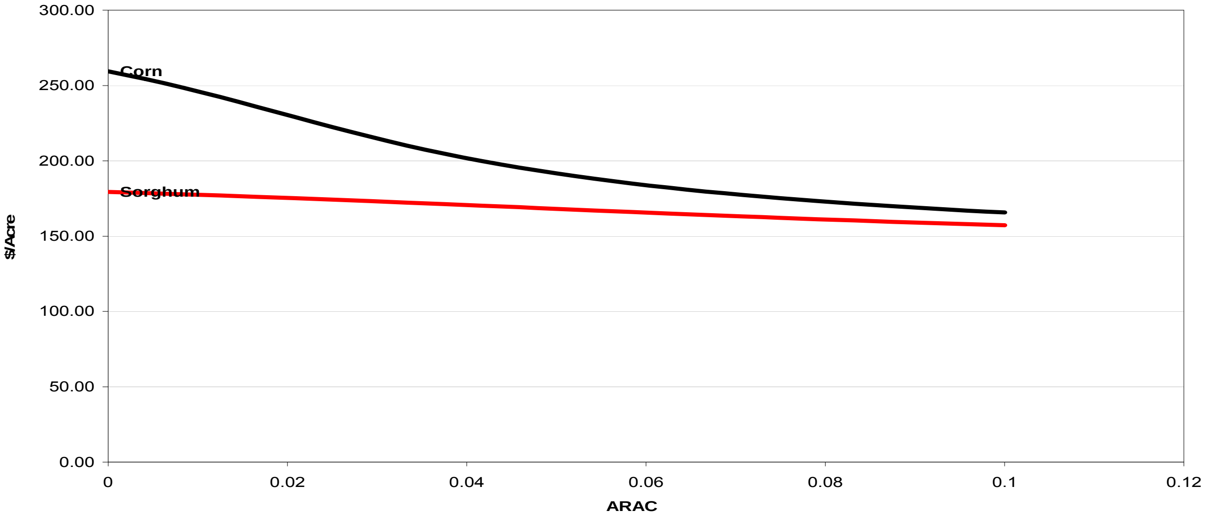
Figure 5.29. Corn vs Sorghum Certainty Equivalents against Absolute Risk Aversion Coefficients for a CP 285 gpm Well and 0.15 MAD



very narrow range of ARAC below 0.0083 and 0.042 for 0 and 0.15 MAD, respectively. For an ARAC above the 0.0083 for 0 MAD and 0.0042 for 0.15 MAD, the CE for sorghum was higher than corn

Figure 5.30 illustrates the CE relationship for the case of corn and sorghum irrigated by a CP system with a 570 gpm well. Here, only an MAD level of 0 was considered, as it was the unequivocal best choice for both crops. In contrast to 190 and 285 gpm wells, the CEs for corn were higher than sorghum for the whole range of ARAC [0, 0.1], making it the most preferred crop irrigated by conventional center-pivot irrigation system with a 570 gpm well.

Figure 5.30. Corn vs Sorghum Certainty Equivalents against Absolute Risk Aversion Coefficients for a CP 570 gpm Well and 0 MAD



Now, turning to the CPD system, figure 5.31 and 5.32 show the CE relationship for the case of CPD-irrigated corn and CPD-irrigated sorghum with a 190 gpm well. As above, both the 0 and 0.15 MAD levels were considered, and under the 0 MAD level, the CEs for corn were higher than sorghum for a very narrow range of ARAC [0, 0.0042] but above an ARAC of 0.0042, the CEs for sorghum were higher than corn. For the 0.15 MAD level, the CEs for sorghum were higher than corn throughout the entire range of ARACs. Figures 5.31

Figure 5.31. **Corn vs Sorghum Certainty Equivalents against Absolute Risk Aversion Coefficients for a CPD 190 gpm Well and 0 MAD**

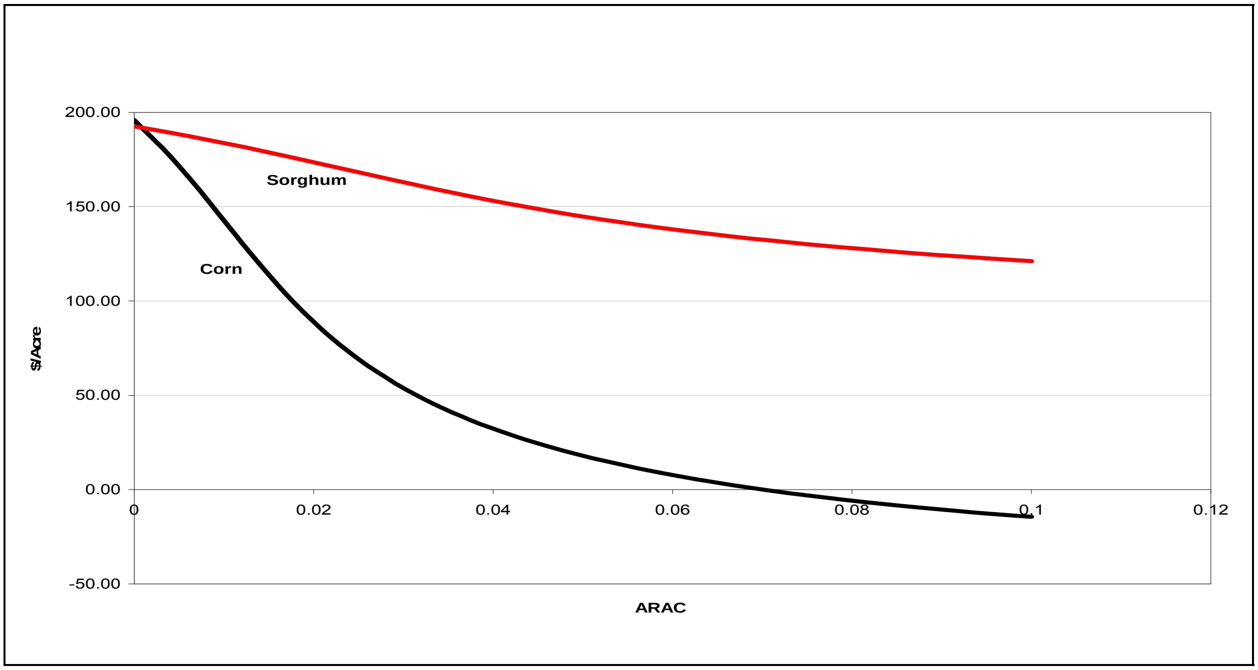
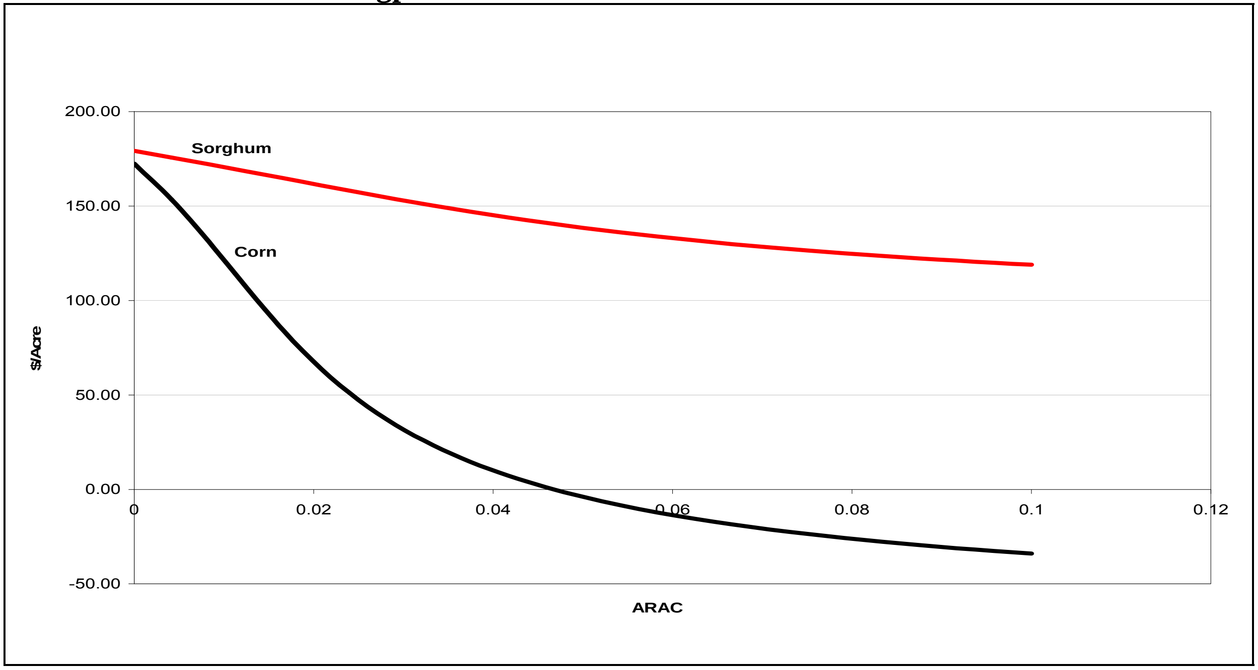


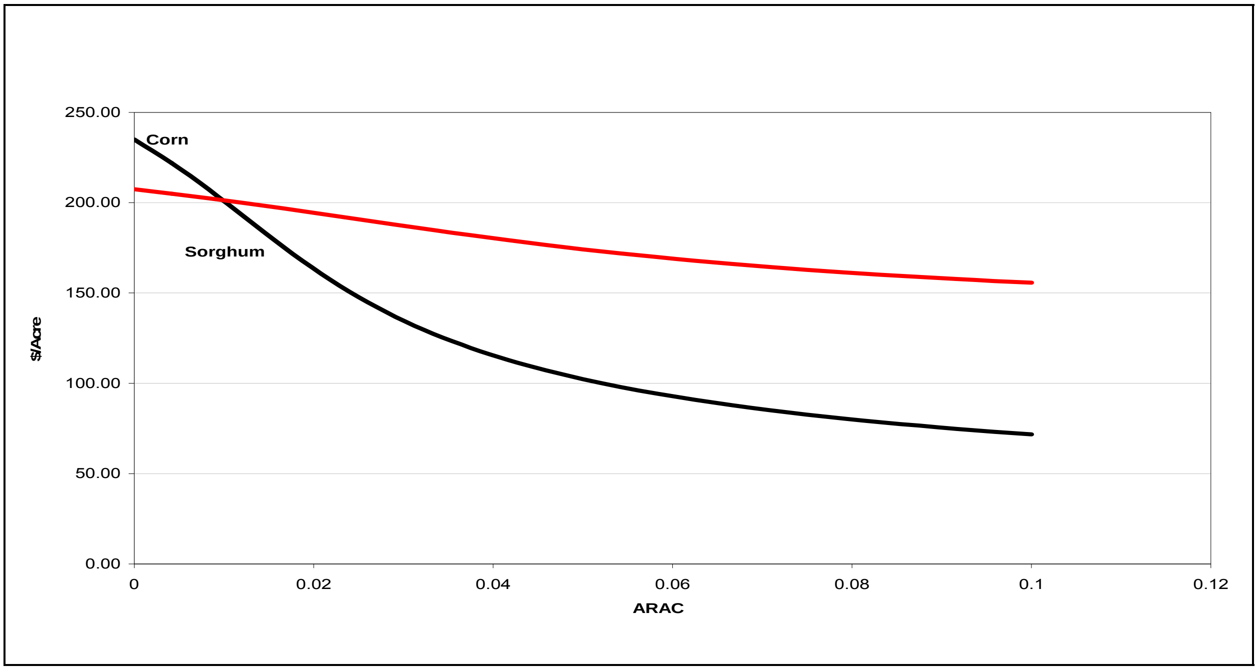
Figure 5.32. Corn vs Sorghum Certainty Equivalents against Absolute Risk Aversion Coefficients for a CPD 190 gpm Well and 0.15 MAD



differ from Figures 5.26 (which represented the CP system at 190gpm), in that the preference ordering of crops changed for very mildly risk averse producers and also both the corn and sorghum CE relationships have shifted upward due to the more efficient irrigation technology.

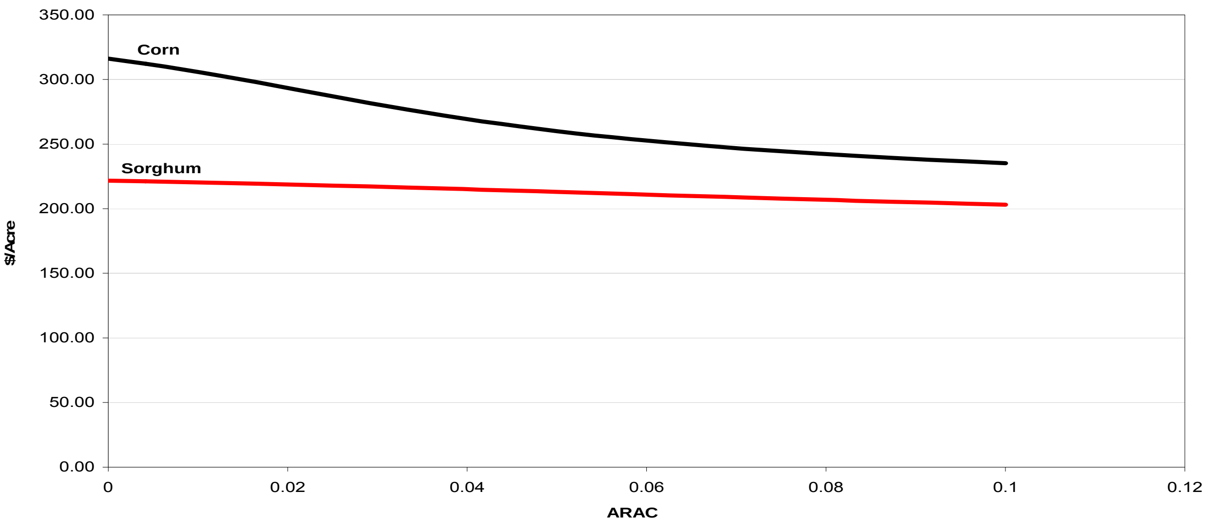
Figure 5.33 displays the CE relationship in the case of corn and sorghum irrigated by a center-pivot with drop nozzles irrigation system with a 285 gpm well. Only a 0 MAD level is considered here because it was the only optimal choice in both cases. The CEs for corn were higher than sorghum for a range of ARACs [0, 0.0125] but above an ARAC of 0.0125, the CEs for sorghum were higher than corn. Although the difference in mean net returns is $27.54/acre at an ARAC of 0, the corn CE function falls quickly as the ARAC level increases, making it soundly dominated by sorghum at higher ARACs.

Figure 5.33. Corn vs Sorghum Certainty Equivalents against Absolute Risk Aversion Coefficients for a CPD 285 gpm Well and 0 MAD



Finally, figure 5.34 shows the CE relationship for CPD-irrigated corn and sorghum with a 570 gpm well. Unlike the CP system results (Figure 5.30), the CE for corn was higher than sorghum throughout the range of ARAC range of [0, 0.1]. Corn is the unequivocal risk-efficient crop. However the CE's remain apart from each other as compared to the conventional center-pivot system results.

Figure 5.34. Corn vs Sorghum Certainty Equivalents against Absolute Risk Aversion Coefficients for a CPD 570 gpm Well and 0 MAD



In summary the SERF analysis results indicated that sorghum was the most preferred crop at 190 gpm well irrigated with both conventional center-pivot and center-pivot with drop nozzles irrigation system. For producers with a 285 gpm well under both irrigation systems, corn was the most preferred crop at very low ARACs while sorghum was preferred at higher ARACs. For a producer with a conventional center-pivot irrigation system or a center-pivot with drop nozzles system with a 570 gpm, corn was the most preferred crop at all ARACs

Sorghum, when irrigated with slower wells, uses water efficiently and translates it to higher net returns than corn. Corn, on the other hand, is relatively water-intensive and generates a higher return when water is abundantly available. As a result, corn generates negative net returns in poor weather years, but also generates net returns higher than sorghum in good weather years or when water is abundantly available. With an increase in well capacity, the WTA payments to switch between corn and sorghum decreased, indicating that it is remunerative both in terms of net returns and saving water to switch from corn to sorghum. So far, we have determined the optimal MAD and the crop choice but the choice of irrigation system still remains. The next step is to determine the choice of irrigation system for corn and sorghum irrigated with 190, 285 and 570 gpm wells.

5.5 Choice of Irrigation System

Field-level water inflows, outflows, and efficiency measures were compared for conventional center-pivot and center-pivot with drop nozzles irrigation system across crops. For the most preferred MAD level (0) and most preferred crop (sorghum), the irrigation system that maximizes net returns subject to limited water use was determined to be the most preferred irrigation technology. Table 5.3, 5.4 and 5.5 compares the water characteristics for corn and sorghum irrigated by conventional center-pivot and center-pivot with drop nozzles irrigation system under a 190, 285 and 570 gpm wells, respectively.

Table 5-3. Comparison of CP and CPD Water Characteristics for Corn and Sorghum Irrigated with 190 gpm Well

	Sorghum		Corn	
	190 GPM		190 GPM	
	CP	CPD	CP	CPD
In Inches				
Inflows (inches)				
Rainfall (seasonal)	6.71	6.71	6.71	6.71
Gross irrigation	7.20	7.20	7.20	7.2
Total inflows	13.91	13.91	13.91	13.91
Outflows (inches)				
Consumptive use				
Evapotranspiration (ET)	16.59	16.83	18.48	18.78
Pre-application Evaporation (PAE)	1.08	0.36	1.08	0.36
Return Flows				
Drainage (D)	0.11	0.13	0.07	0.07
Change in soil water (Δ SW)	-3.87	-3.40	-5.71	-5.30
Total outflows	13.91	13.91	13.91	13.91
Season long Irrigation Efficiency (SIE)	0.68	0.69	0.76	0.77
Net Returns ($/Irrigated Area)				
Mean	171.73	192.64	164.62	195.90
Standard Deviation	42.65	40.60	99.12	94.19
Maximum	244.99	262.22	337.44	360.66
Minimum	59.87	87.59	-94.44	-50.10
Field-level net returns, mean($)	21,638.27	24,272.65	20,742.16	24,683.28

The inflows – rainfall (constant at 6.71 inches) and gross irrigation applied equals the outflows – consumptive use (evapotranspiration, pre-application evaporation loss) and return flows (drainage and change in soil water storage) as described in equation 3.1 on page 23. Season long irrigation efficiency (SIE) was computed based on equation 3.4 and 3.5 on page 23.

Other measures, such as the net returns per irrigated area and net returns for 126 acres were computed for comparison across irrigation systems. The water characteristics were computed for a crop circle of 126 acres to determine the extent of water inflows and outflows at the field level for a typical center-pivot irrigation system.

In terms of outflows, corn and sorghum irrigated with 190 and 285 gpm wells using a CPD system generated more evapotranspiration (ET) and less pre-application evaporation (PAE) losses compared to the CP system. The additional ET was more than offset by the reduction in PAE, with the result that consumptive use was smaller under the CPD. For example, for sorghum with a 190 gpm well, consumptive use (ET + PAE) is 17.67 inches under the CP system and 17.19 inches with the CPD system. For corn with a 285 gpm well, consumptive use was 18.87 inches and 18.19 inches under the CP and CPD systems, respectively. Thus, converting from a CP to a CPD system provides water savings, on the order of 0.5 acre inches per irrigated acre, or about 6% of gross irrigation. The two irrigation systems result in very similar amounts of drainage but the CPD system depletes less water from the soil profile. In addition, the season long irrigation efficiency increased by 1% for the 190 gpm well and by 2% for the 285 gpm well. In summary, based on water characteristics, the most preferred irrigation system for corn and sorghum irrigated with 190 and 285 gpm wells was center-pivot with drop nozzles irrigation system. Sorghum under center-pivot with drop nozzles irrigation system used water more efficiently than conventional center-pivot irrigation system as the PAE losses are down from 15% to 5% and there was less water depleted from the soil profile from -3.87 to -3.40 inches per acre, and from -2.76 to -2.13 inches per acre for 190 and 285 gpm wells, respectively. Corn, although relatively water-intensive, displayed a similar pattern as sorghum by depleting less water with a center-pivot with drop nozzles irrigation system.

In terms of net returns, the additional ET under the CPD system translated into an economic gain, with average net returns 12.17% and 14.57% higher for sorghum with a 190 and 285 gpm well, respectively. Similarly, with the conversion from CP to CPD, corn produced 19% and 19.56% higher net returns, with a 190 and 285, gpm well, respectively. This increase in average income was also accompanied by a reduction in income variation. For an individual producer, the management question is whether the annual economic gains justify the investment cost of converting from a CP to a CPD system. Williams, Llewelyn, Delano and others performed some studies on this issue for Kansas between 1996 and 1998 (Williams et al, 1996;

DeLano et al, 1997; Strickland and Williams, 1998; Williams and DeLano, 1996; Williams, 1998) . Based on historical records (Golden and Peterson, 2006), it appears this conversion was economically feasible for many producers who made precisely this investment between 1991 and 2004. From a public policy point of view, these conversions were desirable, as they generated private benefits to farmers and also translated to real water savings.

Table 5-4. Comparison of CP and CPD Water Characteristics for Corn and Sorghum Irrigated with 285 gpm Well

	----------Sorghum------		-----------Corn-----------	
	-----------285 GPM------		-----------285 GPM------	
	CP	**CPD**	**CP**	**CPD**
In Inches				
Inflows (inches)				
Rainfall (seasonal)	6.71	6.71	6.71	6.71
Gross irrigation	9.60	9.60	9.60	9.6
Total inflows	16.31	16.31	16.31	16.31
Outflows (inches)				
Consumptive use				
Evapotranspiration (ET)	17.43	17.71	19.56	19.91
Pre-application Evaporation (PAE)	1.44	0.48	1.44	0.48
Return Flows				
Drainage (D)	0.20	0.25	0.09	0.10
Change in soil water (Δ SW)	-2.76	-2.13	-4.78	-4.18
Total outflows	16.31	16.31	16.31	16.31
Season long Irrigation Efficiency (SIE)	0.65	0.67	0.73	0.75
Net Returns ($/Irrigated Area)				
Mean	181.03	207.40	196.51	234.94
Standard Deviation	35.72	33.88	81.84	76.66
Maximum	240.92	262.89	340.88	370.44
Minimum	92.04	125.26	-16.13	36.36
Field-level net returns, mean($)	22,809.47	26,132.71	24,760.35	29,602.97

Table 5.5 compares the water characteristics for corn and sorghum irrigated by conventional center-pivot and center-pivot with drop nozzles irrigation system with a 570 gpm well. Similar to the results above, the CPD generated a more ET and less PAE than the CP system for both crops under 285 and 570 gpm wells. As above, the extra ET from the CPD system was more than offset by the reduction in PAE, so that consumptive use was smaller under the CPD system for a given crop. For sorghum irrigated with a 570 gpm well, consumptive use was 22.14 inches under the CP system and 20.47 inches with the CPD system. Consumptive use

on corn irrigated with a 570 gpm well was 24.78 and 23.22 inches for CP and CPD system, respectively. Thus, holding the crop constant, converting from a CP to a CPD system with a 570 gpm well would reduce consumptive use by about 1.6 inches, or about 8% of gross irrigation. The return flows to the soil profile (ΔSW) for both corn and sorghum were larger under the CPD system compared to the CP system. The season long irrigation efficiency was about 1% higher under the CPD system for both sorghum and corn.

Table 5-5. Comparison of CP and CPD Water Characteristics for Corn and Sorghum Irrigated with 570 gpm Well

	----------Sorghum-----		-----------Corn------------	
	-----------570 GPM------		----------570 GPM-------	
	CP	**CPD**	**CP**	**CPD**
In Inches				
Inflows (inches)				
Rainfall (seasonal)	6.71	6.71	6.71	6.71
Gross irrigation	19.20	19.20	19.20	19.20
Total inflows	25.91	25.91	25.91	25.91
Outflows (inches)				
Consumptive use				
Evapotranspiration (ET)	19.26	19.51	21.90	22.26
Pre-application Evaporation (PAE)	2.88	0.96	2.88	0.96
Return Flows				
Drainage (D)	2.04	3.16	0.88	1.60
Change in soil water (Δ SW)	1.73	2.29	0.25	1.09
Total outflows	25.91	25.91	25.91	25.91
Season long Irrigation Efficiency (SIE)	0.53	0.54	0.60	0.61
Net Returns ($/Irrigated Area)				
Mean	179.32	221.69	259.46	316.13
Standard Deviation	18.91	16.29	49.01	43.24
Maximum	205.82	243.28	340.49	385.10
Minimum	131.62	176.19	131.60	201.58
Field-level net returns, mean($)	22,594.72	27,933.27	32,691.38	39,832.99

Based on water characteristics, the most preferred irrigation system for both corn and sorghum irrigated with a 570 gpm well is the CPD system. Corn and sorghum under center-pivot with drop nozzles irrigation system used water more efficiently than conventional center-pivot system as the PAE losses were reduced from 15% to 5% and there were increased return flows to the soil profile from 1.73 to 2.29 inches per acre and from 0.25 to 1.09 inches per acre for sorghum and corn, respectively.

As expected, the CPD system also results in higher economic returns for a given crop with a 570 gpm well. For sorghum, mean net returns are about $42/acre higher with the CPD system, while the standard deviation was about $2/acre lower. For corn, the CPD has an advantage of nearly $56/acre in mean returns, accompanied by a standard deviation that was nearly $5/acre lower than under the CP system. From an individual producer's point of view, the conversion from a CP to a CPD system was even more advantageous with a 570 gpm well than for lower capacity wells. As long as the same crop was grown after the conversion as before, such a technology upgrade would again be desirable from a public policy point of view; farmers receive an economic benefit while reduced demand was placed on publicly managed water supplies.

If the technology upgrade was accompanied by a switch in crops, however, private and public interests may diverge. In particular, if a producer with a 285 gpm well initially has a CP system and grows sorghum, and then converts to the CPD system and henceforth produces corn, then consumptive use will in fact increase by about 1.52 inches per acre, from 18.87 inches to 20.39 inches, or about 16% of gross irrigation. The analysis in Section 5.4 suggests that such a scenario was plausible. Under the CP system and a 285 gpm well, sorghum is the optimal crop for all producers with an ARAC above 0.0083 (Figure 5.29). Under the CPD system, corn was the optimal crop for all producers with an ARAC in the range of [0, 0.0125] (Figure 5.33). Thus, for producers who have a risk aversion parameter in the range of [0.0083, 0.0125] with a 285 gpm well, sorghum would be optimal before the conversion while corn would be optimal after. Similarly, for producers with an ARAC in the range of [0, 0.0042] with a 190 gpm well, sorghum would be optimal before the conversion while corn will be optimal after the conversion to CPD system.

Within each irrigation system, the consumptive use, return flows and season long irrigation efficiency showed an upward trend with an improvement in irrigation technology. As more water was applied, an increasing amount of water was utilized and more water was discharged into the soil profile as return flows.

5.6 Chapter Summary

The simulation results indicated that for all the well capacities studied, setting the MAD level at zero and irrigating as frequently as possible yielded the maximum expected utility. In terms of crop choice, sorghum was preferred for risk-averse producers while corn was preferred for risk-neutral producers. For wells of moderate capacity (285 gpm), corn was preferred by risk neutral or mildly risk averse farmers, while sorghum was preferred by more risk-averse farmers. For wells of moderately high capacity (570 gpm), corn was the preferred crop. In terms of irrigation systems, for both corn and sorghum, the CPD system was a “water saving” technology, in that consumptive use was smaller than under the CP system. Within each irrigation system, the consumptive use, return flows and season long irrigation efficiency showed an upward trend with an improvement in irrigation technology. As more water was applied, an increasing amount of water was utilized and more water was discharged into the soil profile as return flows. In addition, the CPD system generated higher crop yields and higher mean net returns while reducing income variability across years. Thus, in most cases, upgrading technology was economically beneficial to the producer while indirectly contributing towards the recharge of the aquifer. However, under certain conditions, for all the three wells, farmers with a risk aversion coefficient within a certain range may switch crops following the technology upgrade, generating negative water savings.

CHAPTER 6 – SUMMARY AND CONCLUSIONS

The purpose of this research was three-fold, first, to present the producer with optimal management allowed deficit (MAD) levels for corn and sorghum. This goal was accomplished by comparing net return distributions across various MAD levels for corn and sorghum. The second objective was to present the producer with risk-efficient crop choice to choose between corn and sorghum. This goal was accomplished by comparing risk premiums of corn and sorghum for a chosen optimal MAD level. Lastly, from a policy maker's perspective, the third objective was to validate the effect of irrigation technology upgrade on the aquifer in terms of water characteristics. This goal was accomplished by comparing conventional center-pivot and center-pivot with drop nozzle irrigation systems in terms of inflows, outflows and season long irrigation efficiency for a given MAD level and crop choice.

The main finding from the net returns distribution was that net returns for corn and sorghum increased with increase in well capacities but decreased under a tighter water regime (i.e., a larger MAD). The variance in net returns for corn was greater than sorghum for wells slower than 570 gpm but corn produced higher net returns than sorghum for faster wells such as 570 gpm. However, sorghum produced positive net returns and used less water than corn for all the three wells – 190, 285 and 570 gpm. To make the choices easy for the producer, the optimal MAD was evaluated for corn and sorghum under three wells (190,285 and 570 gpm) and two irrigation systems (conventional center-pivot and center-pivot with drop nozzles).

The main finding from the optimal MAD choice is that 0 MAD was the most preferred MAD level for corn and sorghum for wells slower than 570 gpm well and the preference of MAD levels followed the progression of most preferred at 0 to least preferred at 0.60. For wells slower than 570 gpm, a higher MAD (i.e., a stricter water regime), such as 0.60, might conserve water but the producer's willingness to accept payments on an average would be as high as \$120.30/acre for corn and \$60.34/acre for sorghum, making the switch infeasible. Producers with a faster well have an opportunity to switch to a stricter water regime or switch to a less water-intensive crop to save water.

The main finding form the risk-efficient crop choice was that for the most part, sorghum was the preferred crop with 190 and 285 gpm wells. Corn was the preferred crop with a 285 gpm well for risk neutral or mildly risk averse producers and by producers with a 570 gpm well. Corn, which is relatively water intensive, displayed positive net returns with faster wells, whereas sorghum, which is relatively less water intensive, displayed positive net returns with all wells. It was remunerative both in terms of net returns and water savings to switch from corn to sorghum with 190 and 285 gpm wells. However, it was remunerative to switch from sorghum to corn under 190 and 285 gpm wells capacities for a certain range of absolute risk aversion coefficients (ARACs) as corn translated the additional water available to higher net returns with lower risk aversion coefficients.

The main finding from the irrigation system choice was that center-pivot with drop nozzles (CPD) irrigation system was preferred to the conventional center pivot (CP) system, both in terms of water characteristics and producer income, for low-capacity (190 and 285 gpm) wells. For moderate capacity (570 gpm) wells, the CPD system was also preferred assuming the crop choice stays constant. However, a technology upgrade from a CP to a CPD system would likely be accompanied by a switch in crops from sorghum to corn for producers with ARACs in a particular range. In these cases, water saving will actually be negative (consumptive use increases), creating a divergence between private economic interest and any public interest in preserving the aquifer. Over time, if unchecked, pumping water from the aquifer will no longer be feasible and this will lead to a decline in income of producers. The economic impact of a decline in income of producers in the local economy would be a reduced demand for goods and services linked to agriculture, loss of jobs, less money circulating and eventually a slowdown in the regional economy.

The latter result has policy significance, in that public funds have been devoted to irrigation technology upgrades of precisely the kind analyzed. These programs provided cost-sharing for “water conserving” technology improvements may have had undesirable effects, as some producers may have exploited the efficiency gains in irrigation technology to increase both net irrigation and the acreage of highly water-intensive crops. Such cases would have exacerbated the decline of the water table in the High Plains aquifer over the years.

To guard against these uncertainties, this study suggests that the state should instead devote funds to encourage producers of all well capacities to irrigate less-water intensive crops and reduce the pumping of water from an already declining aquifer. The life of the aquifer can be extended in the long term if producers with faster wells are given incentives to tighten the irrigation regime or choose a less water-intensive crop and reduce their irrigated acreage. Rather than providing a blanket subsidy to upgrade irrigation technology, irrigation policies would ideally consider a broader set of localized factors in a more dynamic framework. Any subsidies for technology changes should be conditioned on hydrological factors, agronomic practices, other conservation practices, and local dynamics of the region. Further, care should be taken to prevent the producers from taking advantage of any loopholes in the policy.

Some broader measures to consider that might help mitigate the further decline in the aquifer are adoption of water harvesting techniques and directing storm water drainage towards aquifer recharge as well as invest towards storm water storage methods. Introduction of a water pumping surcharge across the aquifer could discourage volume pumping for irrigation. The state of Kansas could extend cost-share programs only to producers if they display water savings over time and set up critical limits to withdrawals of water across the High Plains aquifer.

This study has limited forecasting abilities and is an *ex post* method. The model ignores the soil moisture and weather conditions outside the crop season. The model excludes the occurrence of pests and diseases on crops. The model calculates returns to irrigation capital but does not directly analyze the investment decision to purchase or upgrade irrigation equipment. Further, there is lack of data on consumptive and non-beneficial use of water, which makes it difficult to understand the relationship between consumptive use, non-beneficial use and other uses. Limitations on water application per season in western Kansas to 24 inches and the number of irrigation events to 18 excludes the evaluation of faster wells.

This unique contribution of this thesis to the literature is that it provides producers with decision making choices in scheduling irrigation, crops and irrigation system to maintain economic viability while facing limited irrigation conditions. Policy makers are also afforded alternative methods to reduce the further decline of the High Plains aquifer. This thesis can be extended to include other crops of economic importance to Kansas such as winter wheat, soybeans and alfalfa. This model can be extended to evaluate wells faster than 570 gpm by relaxing the 24 inch water application and the 18 irrigation events limitations. Also, the impact of recent adoption of sub-surface irrigation technology can be investigated by extending this model.

It remains to be investigated whether the water lost into the soil profile eventually recharges the aquifer. There is scope for further research to evaluate alternative methods to decrease irrigated acreage such as cutting down on the irrigated crop circle or partial irrigation of the crop circle. Better weather forecasting abilities can enhance the predictability of this model.

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Appendix A - Corn and Sorghum Yields

Table A-1.Corn Yields with a Conventional CP Irrigation System for a 190 gpm Well

Well Capacity	**190GPM**	**190GPM**	**190GPM**	**190GPM**	**190GPM**
MAD	0 MAD	0.15 MAD	0.30 MAD	0.45 MAD	0.60 MAD
Initial SWA	0.40	0.40	0.40	0.40	0.40
Section	8	8	8	8	8
1	92.37	86.68	77.31	70.68	60.19
2	135.07	126.57	122.64	115.00	109.65
3	131.78	123.03	119.02	111.13	105.66
4	60.69	60.69	48.46	43.18	27.73
5	70.66	70.66	57.48	53.33	37.05
6	44.36	44.36	37.60	26.33	12.19
7	110.44	102.29	96.54	88.61	80.84
8	142.30	133.49	128.83	122.53	116.43
9	118.78	110.10	105.22	97.05	90.41
10	145.75	137.23	132.71	126.62	120.72
11	108.31	101.11	94.22	86.17	78.29
12	135.73	127.28	123.36	115.77	110.46
13	111.09	102.97	97.25	89.35	81.61
14	138.20	129.94	126.08	117.68	111.34
15	109.05	100.82	95.03	87.01	79.17
16	111.49	103.40	97.69	89.81	82.10
17	153.12	144.46	140.21	134.48	128.99
18	111.65	103.57	97.86	90.00	82.29
19	117.79	109.04	104.13	95.90	89.21
20	118.48	109.78	104.89	96.70	90.04
21	146.58	138.13	133.64	127.60	120.79
22	141.55	132.68	127.99	121.65	115.50
23	146.70	138.26	133.77	127.74	120.94
24	134.74	126.21	122.27	114.61	109.25
25	133.94	125.35	121.39	113.67	108.28
26	153.55	144.94	140.70	135.01	129.53
27	167.55	160.00	155.31	150.71	144.11
28	125.96	116.78	112.64	104.31	99.07
29	150.79	142.69	137.57	131.70	126.07
30	104.55	97.16	90.13	81.86	74.24
31	95.73	89.04	80.96	73.13	63.77
32	58.51	58.51	47.70	40.99	25.34
33	115.46	106.56	101.59	93.20	86.86
34	173.76	166.61	161.93	157.97	151.50
35	138.20	129.94	126.08	117.68	111.34
36	136.49	128.10	124.20	116.66	111.38
Average	**121.98**	**114.68**	**109.01**	**101.83**	**94.23**
Std Dev	29.70	27.60	29.43	29.99	32.57
Variance	881.85	761.65	866.27	899.50	1061.00
Correlation	0.96	0.97	0.98	0.99	0.99
Minimum	44.36	44.36	37.60	26.33	12.19
Maximum	173.76	166.61	161.93	157.97	151.50

Table A-2. Corn Yields with a Conventional CP Irrigation System for a 285 gpm Well

Well Capacity	**285GPM**	**285GPM**	**285GPM**	**285GPM**	**285GPM**
MAD	0 MAD	0.15 MAD	0.30 MAD	0.45 MAD	0.60 MAD
Initial SWA	0.60	0.60	0.60	0.60	0.60
Section	6	6	6	6	6
1	117.65	110.74	99.89	89.34	77.65
2	152.87	143.09	136.24	128.31	118.37
3	150.11	140.08	133.07	124.93	114.69
4	91.85	91.85	76.96	66.91	51.42
5	99.98	97.53	84.37	72.86	59.16
6	78.43	78.43	66.66	55.50	38.22
7	132.44	122.93	115.23	105.72	93.88
8	158.93	148.84	141.49	134.74	125.28
9	139.32	129.33	121.83	112.84	101.58
10	161.83	152.05	144.91	138.35	128.89
11	130.69	123.21	113.26	103.61	91.59
12	153.42	143.69	136.88	128.99	119.11
13	132.97	123.51	115.83	106.36	94.57
14	155.49	145.95	139.27	130.47	120.63
15	131.30	121.71	113.94	104.34	92.39
16	133.30	123.86	116.21	106.76	95.01
17	168.04	158.12	151.41	145.12	135.20
18	133.44	124.01	116.36	106.92	95.18
19	138.50	128.44	120.89	111.84	100.49
20	139.07	129.06	121.54	112.54	101.25
21	162.53	152.82	145.74	139.22	127.84
22	158.30	148.15	140.75	133.96	124.43
23	162.63	152.93	145.85	139.35	127.98
24	152.59	142.78	135.92	127.97	118.00
25	151.92	142.05	135.15	127.15	117.11
26	168.41	158.54	151.85	145.59	135.30
27	180.21	171.22	164.62	158.37	146.52
28	145.27	134.80	127.49	118.98	109.46
29	166.08	156.75	149.06	142.64	132.47
30	127.60	119.96	109.78	99.90	88.97
31	120.39	113.60	102.95	92.59	79.70
32	90.07	90.07	75.06	64.94	51.17
33	136.58	126.36	118.71	109.51	99.29
34	185.40	176.66	170.47	164.62	153.26
35	155.49	145.95	139.27	130.47	120.63
36	154.06	144.39	137.61	129.78	119.96
Average	**142.14**	**133.71**	**125.46**	**116.99**	**105.74**
Std Dev	24.52	22.19	24.15	25.58	26.92
Variance	601.19	492.23	583.13	654.08	724.81
Correlation	0.90	0.92	0.95	0.97	0.99
Minimum	78.43	78.43	66.66	55.50	38.22
Maximum	185.40	176.66	170.47	164.62	153.26

Table A-3. Corn Yields with a Conventional CP Irrigation System for a 570 gpm Well

Well Capacity	**570GPM**	**570GPM**	**570GPM**	**570GPM**	**570GPM**
MAD	0 MAD	0.15 MAD	0.30 MAD	0.45 MAD	0.60 MAD
Initial SWA	0.80	0.80	0.80	0.80	0.80
Section	3	3	3	3	3
1	170.36	155.26	146.03	132.45	101.38
2	191.94	176.10	167.04	157.09	127.11
3	190.28	175.20	164.77	154.68	123.98
4	154.85	143.82	131.88	118.04	85.75
5	159.69	147.37	134.89	122.21	89.62
6	146.93	138.98	126.56	113.22	80.59
7	179.44	164.19	154.06	143.15	112.24
8	195.54	180.53	170.02	160.52	131.90
9	183.68	169.19	157.99	146.72	114.48
10	197.23	182.57	172.44	163.02	134.78
11	178.36	162.95	152.68	141.65	110.47
12	192.27	176.50	167.45	157.61	127.79
13	179.77	164.58	154.49	143.61	112.43
14	193.51	178.04	169.08	157.39	128.10
15	178.74	163.37	153.16	142.17	111.15
16	179.98	164.82	154.75	143.90	112.80
17	200.73	185.55	177.15	166.60	140.11
18	180.06	164.92	154.85	144.01	112.95
19	183.18	168.58	157.32	145.99	113.50
20	183.53	169.00	157.78	146.49	114.18
21	197.63	182.07	173.00	163.61	135.39
22	195.17	180.10	171.25	159.92	131.10
23	197.68	182.15	173.09	163.70	135.52
24	191.78	175.89	166.80	156.91	126.77
25	191.37	175.37	166.23	156.29	125.94
26	200.93	185.78	176.54	166.78	140.60
27	207.06	191.93	184.33	174.80	150.51
28	187.33	172.17	162.19	150.37	120.66
29	199.64	184.10	175.70	165.43	138.01
30	176.46	162.26	151.90	139.00	108.34
31	172.04	157.19	146.39	134.73	102.67
32	153.79	142.68	130.63	116.69	85.60
33	181.99	167.18	157.31	144.28	113.96
34	209.52	195.07	187.03	178.36	155.67
35	193.51	178.04	169.08	157.39	128.10
36	192.66	176.99	167.99	157.52	126.30
Average	**185.24**	**170.57**	**160.66**	**149.62**	**119.73**
Std Dev	14.68	13.49	14.52	15.70	17.60
Variance	215.59	182.08	210.89	246.48	309.76
Correlation	0.85	0.74	0.79	0.82	0.97
Minimum	146.93	138.98	126.56	113.22	80.59
Maximum	209.52	195.07	187.03	178.36	155.67

Table A-4. Corn Yields with a CP with Drops Irrigation System for a 190 gpm Well

Well Capacity	**190GPM**	**190GPM**	**190GPM**	**190GPM**	**190GPM**
MAD	0 MAD	0.15 MAD	0.30 MAD	0.45 MAD	0.60 MAD
Initial SWA	0.40	0.40	0.40	0.40	0.40
Section	8	8	8	8	8
1	99.39	93.36	83.29	76.15	64.84
2	139.94	130.83	126.57	118.33	112.54
3	136.80	127.43	123.08	114.59	108.65
4	69.37	69.37	56.27	50.38	33.76
5	78.83	78.83	64.76	60.06	42.64
6	53.82	53.82	46.50	34.32	18.78
7	116.52	107.83	101.63	93.10	84.70
8	146.83	137.37	132.37	125.52	118.94
9	124.44	115.17	109.89	101.11	93.91
10	150.13	140.98	136.12	129.49	123.13
11	114.50	106.83	99.41	90.75	82.23
12	140.57	131.51	127.27	119.08	113.32
13	117.14	108.48	102.31	93.82	83.42
14	142.92	134.06	129.88	120.82	113.99
15	115.21	106.42	100.18	91.57	83.09
16	117.52	108.89	102.73	94.26	85.92
17	157.16	147.86	143.27	137.04	131.08
18	117.67	109.05	102.90	94.44	86.11
19	123.50	114.15	108.84	100.00	92.75
20	124.15	114.85	109.57	100.77	93.55
21	150.92	141.84	137.02	130.45	123.08
22	146.12	136.60	131.56	124.67	118.04
23	151.03	141.97	137.15	130.58	123.22
24	139.62	130.49	126.22	117.95	112.15
25	138.86	129.66	125.37	117.05	111.20
26	157.58	148.32	143.75	137.55	131.62
27	170.96	162.83	157.75	152.74	145.51
28	131.26	121.44	116.95	107.99	102.31
29	154.94	146.24	140.71	134.33	128.23
30	110.94	103.06	95.49	86.60	78.38
31	102.58	95.47	86.78	78.35	68.24
32	67.30	48.37	55.70	48.37	31.44
33	121.29	111.78	106.41	97.39	90.54
34	176.89	169.21	164.13	159.80	152.71
35	142.92	134.06	129.88	120.82	113.99
36	141.29	132.30	128.07	119.95	114.22
Average	**127.53**	**119.19**	**113.60**	**105.84**	**97.56**
Std Dev	28.22	27.22	27.92	28.54	31.34
Variance	796.36	740.95	779.63	814.44	982.30
Correlation	0.94	0.91	0.98	0.97	0.98
Minimum	53.82	48.37	46.50	34.32	18.78
Maximum	176.89	169.21	164.13	159.80	152.71

Table A-5. Corn Yields with a CP with Drops Irrigation System for a 285 gpm Well

Well Capacity	**285GPM**	**285GPM**	**285GPM**	**285GPM**	**285GPM**
MAD	0 MAD	0.15 MAD	0.30 MAD	0.45 MAD	0.60 MAD
Initial SWA	0.60	0.60	0.60	0.60	0.60
Section	6	6	6	6	6
1	125.57	118.24	106.79	95.59	83.16
2	158.59	148.22	140.88	132.42	121.75
3	156.00	145.36	137.85	129.17	118.18
4	101.54	101.54	85.82	75.01	58.45
5	109.11	106.51	92.62	80.45	65.65
6	89.06	89.06	76.72	64.62	46.01
7	139.40	129.38	121.15	111.04	98.40
8	164.30	153.59	145.75	138.48	128.31
9	145.85	135.29	127.27	117.71	105.66
10	167.04	156.65	149.03	141.96	131.79
11	137.76	129.81	119.28	109.03	96.20
12	159.11	148.79	141.49	133.08	122.46
13	139.90	129.92	121.72	111.65	99.07
14	161.06	150.94	143.77	134.36	123.80
15	138.33	128.23	119.93	109.73	96.96
16	140.21	130.26	122.08	112.04	99.48
17	172.89	162.35	155.16	148.37	137.75
18	140.34	130.39	122.22	112.19	99.65
19	145.08	134.45	126.38	116.76	104.62
20	145.62	135.03	127.00	117.42	105.34
21	167.70	157.38	149.82	142.80	130.61
22	163.71	152.93	145.04	137.73	127.49
23	167.79	157.49	149.93	142.92	130.74
24	158.33	147.93	140.58	132.09	121.39
25	157.70	147.24	139.84	131.30	120.52
26	173.24	162.74	155.58	148.82	137.79
27	184.31	174.79	167.71	160.97	148.16
28	151.45	140.35	132.53	123.47	113.27
29	171.04	161.13	152.91	145.98	135.09
30	134.87	126.75	115.98	105.49	93.84
31	128.13	120.92	109.67	98.68	84.94
32	99.89	99.89	84.03	73.15	58.45
33	143.28	132.49	124.30	114.53	103.60
34	189.16	179.93	173.27	166.95	154.64
35	161.06	150.94	143.77	134.36	123.80
36	159.71	149.45	142.19	133.83	123.29
Average	**148.56**	**139.62**	**130.84**	**121.78**	**109.73**
Std Dev	22.97	20.50	22.53	24.04	25.46
Variance	527.48	420.37	507.45	577.85	648.20
Correlation	0.87	0.90	0.94	0.96	0.98
Minimum	89.06	89.06	76.72	64.62	46.01
Maximum	189.16	179.93	173.27	166.95	154.64

Table A-6. Corn Yields with a CP with Drops Irrigation System for a 570 gpm Well

Well Capacity	**570GPM**	**570GPM**	**570GPM**	**570GPM**	**570GPM**
MAD	0 MAD	0.15 MAD	0.30 MAD	0.45 MAD	0.60 MAD
Initial SWA	0.80	0.80	0.80	0.80	0.80
Section	3	3	3	3	3
1	178.95	163.38	138.88	138.88	103.01
2	198.07	179.21	170.41	158.72	128.02
3	196.63	177.33	168.49	157.94	124.66
4	164.89	151.78	138.48	126.95	89.52
5	169.29	154.19	141.81	128.46	90.30
6	157.70	147.73	134.74	120.78	82.33
7	187.10	169.11	158.43	148.25	112.92
8	201.13	181.90	172.61	162.49	133.95
9	190.86	172.15	162.35	151.17	116.68
10	202.56	182.92	173.92	164.44	136.13
11	186.14	169.46	158.71	146.99	110.98
12	198.35	179.43	169.77	159.11	128.70
13	187.39	169.47	158.77	148.69	113.52
14	199.41	180.79	171.26	159.75	129.97
15	186.47	168.46	159.09	147.39	111.66
16	187.58	169.70	159.02	148.85	113.89
17	205.48	186.49	177.62	168.27	140.52
18	187.65	169.80	159.12	148.96	114.03
19	190.42	172.78	161.71	150.46	116.17
20	190.73	171.97	162.16	150.95	116.83
21	202.90	183.40	174.52	164.54	135.83
22	200.82	182.42	172.08	161.98	133.17
23	202.95	183.48	174.61	164.64	135.95
24	197.92	179.00	170.18	159.23	127.68
25	197.58	178.58	169.83	158.83	126.87
26	205.65	186.47	177.85	167.86	140.12
27	210.68	192.73	184.32	175.48	150.62
28	194.07	175.42	165.41	154.23	120.64
29	204.58	185.55	176.59	167.21	138.53
30	184.44	167.53	156.58	144.74	110.39
31	180.46	165.10	153.11	140.95	102.81
32	163.93	152.56	140.10	125.71	87.90
33	189.37	171.61	161.23	149.12	114.72
34	212.69	194.69	187.16	178.84	156.92
35	199.41	180.79	171.26	159.75	129.97
36	198.68	179.77	170.15	159.61	129.48
Average	**192.03**	**174.37**	**163.95**	**153.34**	**120.98**
Std Dev	12.96	11.04	12.89	13.47	17.27
Variance	167.84	121.92	166.06	181.35	298.33
Correlation	0.80	0.66	0.72	0.80	0.97
Minimum	157.70	147.73	134.74	120.78	82.33
Maximum	212.69	194.69	187.16	178.84	156.92

Table A-7. Sorghum Yields with a Conventional CP Irrigation System for a 190 gpm Well

Well Capacity	**190GPM**	**190GPM**	**190GPM**	**190GPM**	**190GPM**
MAD	0 MAD	0.15 MAD	0.30 MAD	0.45 MAD	0.60 MAD
Initial SWA	0.40	0.40	0.40	0.40	0.40
Section	8	8	8	8	8
1	101.06	94.44	88.82	85.37	78.67
2	124.10	117.94	114.17	110.79	106.60
3	122.34	116.00	112.11	109.16	104.31
4	83.36	79.04	73.13	66.64	60.17
5	89.02	83.79	78.52	72.69	64.19
6	73.88	73.88	64.63	56.78	51.14
7	110.89	104.49	99.47	96.44	90.12
8	127.92	121.75	118.34	115.50	110.47
9	115.39	108.86	104.33	101.27	95.98
10	129.73	123.79	120.49	117.29	112.89
11	109.74	103.24	98.13	95.06	89.04
12	124.45	118.33	114.24	111.23	107.06
13	111.24	104.87	99.88	96.86	90.58
14	125.76	119.79	115.79	112.84	108.43
15	110.14	103.67	98.59	95.54	89.56
16	111.46	105.11	100.13	97.12	90.86
17	133.55	127.71	124.76	121.03	116.29
18	111.55	105.20	100.23	97.23	90.98
19	114.86	108.27	103.71	100.62	95.28
20	115.23	108.68	104.14	101.07	95.77
21	130.16	124.27	120.69	117.83	113.47
22	127.53	121.31	117.88	115.02	110.76
23	101.70	101.70	101.70	101.70	101.70
24	123.92	117.75	113.96	110.58	106.37
25	123.50	117.28	113.46	110.56	105.82
26	133.78	127.97	125.03	121.32	116.60
27	140.78	135.35	132.77	129.76	124.64
28	119.24	113.08	108.47	105.37	100.62
29	132.35	126.34	123.31	119.48	115.07
30	107.70	101.60	95.75	92.62	86.39
31	102.90	96.43	90.57	87.55	80.61
32	82.12	77.72	71.77	65.21	59.65
33	113.60	107.44	102.25	99.11	93.65
34	143.74	138.76	136.60	133.58	128.02
35	125.76	119.79	115.79	112.84	101.37
36	124.85	118.78	114.72	111.72	100.01
Average	**116.09**	**110.40**	**106.06**	**102.63**	**97.03**
Std Dev	16.10	15.44	16.58	17.42	17.93
Variance	259.08	238.46	274.74	303.37	321.59
Correlation	0.96	0.97	0.98	0.99	0.99
Minimum	73.88	73.88	64.63	56.78	51.14
Maximum	143.74	138.76	136.60	133.58	128.02

Table A-8. Sorghum Yields with a Conventional CP Irrigation System for a 285 gpm Well

Well Capacity	**285GPM**	**285GPM**	**285GPM**	**285GPM**	**285GPM**
MAD	0 MAD	0.15 MAD	0.30 MAD	0.45 MAD	0.60 MAD
Initial SWA	0.60	0.60	0.60	0.60	0.60
Section	6	6	6	6	6
1	115.27	107.03	101.31	95.91	89.03
2	134.11	126.61	121.90	116.95	110.79
3	132.67	124.94	120.10	115.53	109.06
4	101.16	94.15	86.61	80.80	72.52
5	105.64	97.69	90.52	85.46	77.62
6	93.68	90.84	79.21	73.39	63.71
7	123.26	115.34	109.69	104.28	96.66
8	137.25	129.79	125.37	121.20	113.49
9	126.94	118.94	113.60	108.52	101.96
10	138.73	131.56	127.27	122.77	114.69
11	122.32	114.29	108.55	103.06	97.25
12	134.40	126.94	121.76	117.34	111.22
13	123.54	115.66	110.04	104.65	97.08
14	135.47	128.20	123.12	118.79	111.79
15	122.64	114.65	108.95	103.48	97.71
16	123.72	115.86	110.25	104.88	97.33
17	141.84	134.87	130.87	126.68	118.10
18	123.79	115.94	110.34	104.98	97.44
19	126.50	118.44	113.06	107.94	101.33
20	126.81	118.79	113.43	108.34	101.77
21	139.09	131.98	127.25	123.26	115.26
22	136.93	129.41	124.96	120.76	113.65
23	104.23	101.70	101.70	101.70	101.70
24	133.96	126.44	121.72	116.76	110.57
25	133.61	126.03	121.28	116.79	110.06
26	142.03	135.09	131.11	126.94	118.40
27	147.59	141.35	137.09	134.05	125.10
28	130.11	122.53	116.94	112.14	105.96
29	140.87	133.67	129.58	125.30	117.00
30	120.66	113.01	106.54	100.89	94.93
31	116.76	108.68	102.46	97.78	90.30
32	100.17	95.25	85.45	79.60	71.23
33	125.48	117.83	111.81	106.60	99.85
34	149.86	144.20	140.60	137.39	128.51
35	135.47	128.20	123.12	118.79	111.79
36	134.73	127.33	122.18	117.79	110.93
Average	**127.26**	**120.09**	**114.72**	**110.04**	**102.94**
Std Dev	13.48	13.07	14.25	14.73	14.71
Variance	181.67	170.88	203.14	217.00	216.36
Correlation	0.90	0.92	0.95	0.97	0.99
Minimum	93.68	90.84	79.21	73.39	63.71
Maximum	149.86	144.20	140.60	137.39	128.51

Table A-9. Sorghum Yields with a Conventional CP Irrigation System for a 570 gpm Well

Well Capacity	**570GPM**	**570GPM**	**570GPM**	**570GPM**	**570GPM**
MAD	0 MAD	0.15 MAD	0.30 MAD	0.45 MAD	0.60 MAD
Initial SWA	0.80	0.80	0.80	0.80	0.80
Section	3	3	3	3	3
1	144.89	131.30	125.05	117.66	96.19
2	154.58	140.49	135.04	129.12	112.33
3	153.93	140.28	133.78	128.15	110.64
4	136.92	123.86	115.90	108.37	86.27
5	139.45	126.13	119.34	110.14	88.21
6	132.72	120.65	113.29	104.51	81.41
7	149.24	135.80	128.86	122.22	101.94
8	155.95	142.40	137.10	130.56	114.90
9	151.15	137.10	131.05	124.58	105.60
10	156.57	143.37	137.40	131.47	115.63
11	148.74	135.36	128.07	121.46	100.96
12	154.71	140.75	135.06	129.18	112.75
13	149.39	135.88	129.12	122.35	102.32
14	155.19	141.36	135.94	129.98	113.44
15	148.92	135.62	128.36	121.78	101.39
16	149.49	135.98	129.28	122.53	102.28
17	157.80	144.68	139.59	134.16	119.38
18	149.52	135.37	129.34	122.60	102.37
19	150.93	136.82	130.64	124.27	105.42
20	151.08	136.99	130.92	124.58	105.63
21	156.71	143.67	137.63	131.89	116.18
22	155.81	142.20	136.91	130.36	115.14
23	134.34	111.78	107.04	101.70	101.70
24	154.52	140.37	134.90	128.96	112.12
25	154.36	140.41	134.60	128.76	111.61
26	157.87	144.83	139.79	134.35	119.67
27	159.91	148.07	143.62	138.72	125.77
28	152.72	138.91	132.96	125.92	107.61
29	157.42	144.19	138.92	133.52	118.17
30	147.85	134.33	126.89	120.32	99.80
31	145.71	132.32	125.41	118.69	97.51
32	136.36	123.92	116.16	107.54	85.64
33	150.40	136.38	130.26	123.53	104.33
34	160.72	149.82	145.61	140.38	129.14
35	155.19	141.36	135.94	129.98	113.44
36	154.86	140.88	135.30	129.36	112.53
Average	**150.72**	**137.04**	**130.97**	**124.55**	**106.93**
Std Dev	7.13	7.85	8.40	9.08	10.90
Variance	50.91	61.58	70.52	82.49	118.78
Correlation	0.85	0.74	0.79	0.82	0.97
Minimum	132.72	111.78	107.04	101.70	81.41
Maximum	160.72	149.82	145.61	140.38	129.14

Table A-10. Sorghum Yields with a CP with Drops Irrigation System for a 190 gpm Well

Well Capacity	**190GPM**	**190GPM**	**190GPM**	**190GPM**	**190GPM**
MAD	0 MAD	0.15 MAD	0.30 MAD	0.45 MAD	0.60 MAD
Initial SWA	0.40	0.40	0.40	0.40	0.40
Section	8	8	8	8	8
1	105.03	93.95	89.29	88.28	81.16
2	126.84	120.24	116.19	112.53	108.00
3	125.18	118.38	114.21	111.00	105.76
4	88.41	83.99	77.52	70.64	63.61
5	93.71	88.25	82.55	76.34	67.33
6	79.52	79.52	69.64	61.37	55.10
7	114.32	107.48	102.14	98.85	92.07
8	130.47	123.85	120.19	117.10	111.64
9	118.58	111.59	106.76	103.43	97.75
10	132.19	125.82	122.27	118.78	114.01
11	113.23	106.29	100.86	97.52	91.07
12	127.17	120.62	116.22	112.94	108.45
13	114.65	107.85	102.53	99.25	92.51
14	128.42	122.02	117.71	114.51	109.74
15	113.61	106.71	101.30	97.98	91.58
16	114.86	108.07	102.78	99.50	92.78
17	135.82	129.56	126.37	122.34	117.14
18	114.94	108.16	102.87	99.60	92.89
19	118.07	111.03	106.16	102.81	97.07
20	118.42	111.42	106.58	103.24	97.54
21	132.60	126.29	122.42	119.31	114.58
22	130.10	123.43	119.74	116.63	112.02
23	101.70	101.70	101.70	101.70	101.70
24	126.67	120.06	115.99	112.32	107.77
25	126.27	90.11	115.51	123.24	116.24
26	136.03	129.81	126.63	122.62	117.45
27	142.65	136.86	134.05	130.78	125.17
28	122.23	115.63	110.70	107.33	102.21
29	134.68	128.23	124.96	120.83	115.99
30	111.30	104.80	98.58	95.16	88.51
31	106.77	99.88	93.68	90.37	82.97
32	87.24	82.75	76.23	69.27	63.20
33	116.88	110.30	104.76	101.35	95.49
34	145.42	140.14	137.79	134.50	128.39
35	128.42	122.02	117.71	114.51	102.04
36	127.56	121.05	116.68	113.43	100.70
Average	**119.17**	**112.16**	**108.37**	**105.04**	**98.93**
Std Dev	15.32	15.13	15.83	16.83	17.31
Variance	234.72	228.83	250.53	283.26	299.77
Correlation	0.94	0.91	0.98	0.97	0.98
Minimum	79.52	79.52	69.64	61.37	55.10
Maximum	145.42	140.14	137.79	134.50	128.39

Table A-11. Sorghum Yields with a CP with Drops Irrigation System for a 285 gpm Well

Well Capacity	**285GPM**	**285GPM**	**285GPM**	**285GPM**	**285GPM**
MAD	0 MAD	0.15 MAD	0.30 MAD	0.45 MAD	0.60 MAD
Initial SWA	0.60	0.60	0.60	0.60	0.60
Section	6	6	6	6	6
1	119.76	111.07	105.05	99.25	91.95
2	137.33	129.39	124.37	119.08	111.38
3	135.98	127.81	122.65	117.77	109.79
4	106.68	99.38	93.22	85.21	76.45
5	110.82	102.49	94.97	89.52	81.22
6	99.79	96.77	87.12	78.43	68.17
7	127.21	118.83	112.84	107.11	98.98
8	140.24	132.37	127.65	123.18	113.68
9	130.64	122.17	116.50	111.10	104.00
10	141.62	134.05	129.48	124.64	115.40
11	126.33	117.84	111.76	105.94	98.36
12	137.60	129.71	124.18	119.45	111.80
13	127.47	119.14	113.17	107.46	99.37
14	138.60	130.90	125.49	120.85	112.94
15	126.63	118.18	112.14	106.34	98.81
16	127.64	119.33	113.38	107.69	99.62
17	144.48	137.15	132.88	128.38	118.91
18	127.71	119.40	113.46	107.77	99.72
19	130.23	121.70	115.99	110.54	103.39
20	130.52	122.03	116.34	110.93	103.81
21	141.95	134.45	129.40	125.11	115.95
22	139.95	132.00	127.26	122.76	113.81
23	104.48	101.70	101.70	101.70	101.70
24	137.19	129.23	124.20	118.89	111.17
25	136.87	128.85	123.78	118.98	110.65
26	144.65	137.37	133.12	128.63	119.21
27	149.70	143.25	138.69	135.39	125.60
28	133.60	125.58	119.62	114.50	107.03
29	143.59	136.01	131.64	127.03	117.74
30	124.78	116.70	109.85	103.87	97.44
31	121.15	112.63	106.06	101.03	93.07
32	105.77	100.54	92.18	84.08	75.23
33	129.28	121.19	114.79	109.25	101.96
34	151.73	145.92	142.08	138.60	128.93
35	138.60	130.90	125.49	120.85	112.94
36	137.90	130.08	124.59	119.88	112.07
Average	**130.79**	**123.23**	**117.70**	**112.53**	**104.51**
Std Dev	12.78	12.33	13.10	13.93	13.64
Variance	163.46	152.11	171.52	194.07	186.07
Correlation	0.87	0.90	0.94	0.96	0.98
Minimum	99.79	96.77	87.12	78.43	68.17
Maximum	151.73	145.92	142.08	138.60	128.93

Table A-12. Sorghum Yields with a CP with Drops Irrigation System for a 570 gpm Well

Well Capacity	**570GPM**	**570GPM**	**570GPM**	**570GPM**	**570GPM**
MAD	0 MAD	0.15 MAD	0.30 MAD	0.45 MAD	0.60 MAD
Initial SWA	0.80	0.80	0.80	0.80	0.80
Section	3	3	3	3	3
1	149.32	132.31	125.65	118.34	96.66
2	157.14	140.87	135.27	128.84	113.14
3	156.63	139.92	134.08	127.84	111.61
4	142.47	126.21	119.29	111.27	86.34
5	144.68	128.74	121.29	112.59	90.13
6	138.78	125.49	116.72	107.35	83.66
7	152.90	135.53	129.04	122.45	103.12
8	158.21	142.61	137.26	131.47	114.73
9	154.44	137.51	131.35	124.98	105.87
10	158.69	143.44	138.25	131.57	116.43
11	152.50	134.91	128.70	121.75	102.75
12	157.24	141.04	135.30	129.05	113.55
13	153.03	135.64	129.24	122.58	101.93
14	157.62	141.61	135.99	130.12	114.55
15	152.64	135.13	128.69	122.07	102.46
16	153.10	135.78	129.40	122.64	102.17
17	159.66	144.85	139.69	134.22	120.32
18	153.13	135.71	129.46	122.71	102.27
19	154.26	137.19	131.15	124.76	105.27
20	154.38	137.44	131.43	124.84	105.69
21	158.81	143.77	138.57	131.99	116.97
22	158.11	142.54	136.93	131.11	114.95
23	136.69	108.53	104.60	101.70	101.70
24	157.09	140.74	135.18	128.68	112.94
25	156.97	140.66	134.84	128.73	112.44
26	159.72	144.92	139.89	134.45	120.61
27	161.35	148.04	143.58	138.60	126.35
28	155.68	139.11	133.19	126.15	108.83
29	159.37	144.18	138.99	133.59	119.03
30	151.77	135.11	127.73	120.58	101.19
31	150.01	132.96	126.26	119.18	97.63
32	141.99	126.19	118.73	110.72	85.24
33	153.84	136.72	130.53	123.93	103.88
34	162.01	149.89	145.80	141.01	129.63
35	157.62	141.61	135.99	130.12	114.55
36	157.36	141.33	135.36	129.42	113.69
Average	**153.87**	**137.45**	**131.48**	**125.04**	**107.56**
Std Dev	6.15	7.64	8.09	8.52	10.89
Variance	37.80	58.32	65.46	72.63	118.55
Correlation	0.80	0.66	0.72	0.80	0.97
Minimum	136.69	108.53	104.60	101.70	83.66
Maximum	162.01	149.89	145.80	141.01	129.63

Appendix B - Corn and Sorghum Net Returns

Table B-1. Corn Net Returns with a Conventional CP Irrigation System for a 190 gpm Well

Well Capacity	**190GPM**	**190GPM**	**190GPM**	**190GPM**	**190GPM**
MAD	0 MAD	0.15 MAD	0.30 MAD	0.45 MAD	0.60 MAD
Initial SWA	0.40	0.40	0.40	0.40	0.40
Section	8	8	8	8	8
1	65.78	53.94	22.66	7.65	-27.36
2	208.32	187.08	173.96	155.58	137.75
3	197.32	175.25	161.87	142.67	124.40
4	-39.94	-39.94	-73.64	-91.25	-135.70
5	-6.67	-6.67	-43.51	-57.37	-104.58
6	-94.44	-94.44	-109.87	-147.50	-187.57
7	126.12	106.03	86.85	67.49	41.56
8	232.44	210.16	201.73	180.71	167.49
9	153.96	132.11	115.81	95.69	73.50
10	243.97	222.66	214.69	194.37	181.82
11	119.01	102.10	79.11	59.35	33.06
12	210.52	189.45	176.38	158.16	140.43
13	128.28	108.32	89.21	69.98	44.15
14	218.78	198.32	185.45	164.53	150.50
15	121.49	101.13	81.80	62.18	36.02
16	129.63	109.75	90.68	71.52	45.76
17	268.55	246.79	239.72	220.62	209.40
18	130.17	110.32	91.27	72.14	46.41
19	150.64	128.57	112.19	91.84	69.50
20	152.94	131.03	114.70	94.51	72.27
21	246.74	225.67	217.80	197.64	182.06
22	229.96	207.47	198.95	177.78	164.40
23	247.14	226.09	218.24	198.11	182.55
24	207.21	185.89	172.74	154.28	136.40
25	204.54	183.02	169.80	151.14	133.16
26	270.01	248.38	241.37	222.36	211.23
27	316.73	298.64	290.12	274.77	259.86
28	177.92	154.39	140.59	119.90	102.42
29	260.78	240.90	230.90	211.33	199.65
30	106.45	88.92	65.44	44.98	19.54
31	77.01	61.82	34.83	15.85	-15.39
32	-47.22	-47.22	-76.18	-98.56	-143.65
33	142.88	120.30	103.71	82.83	61.67
34	337.44	320.72	312.24	299.00	284.53
35	218.78	198.32	185.45	164.53	150.50
36	213.06	192.18	179.17	161.14	143.51
Average	**164.62**	**146.60**	**130.45**	**110.83**	**88.65**
Std Dev	99.12	93.78	100.36	101.77	111.04
Variance	9,823.82	8,795.22	10,072.07	10,356.69	12,329.46
Minimum	-94.44	-94.44	-109.87	-147.50	-187.57
Maximum	337.44	320.72	312.24	299.00	284.53

Table B-2. Corn Net Returns with a Conventional CP Irrigation System for a 285 gpm Well

Well Capacity	**285GPM**	**285GPM**	**285GPM**	**285GPM**	**285GPM**
MAD	0 MAD	0.15 MAD	0.30 MAD	0.45 MAD	0.60 MAD
Initial SWA	0.60	0.60	0.60	0.60	0.60
Section	6	6	6	6	6
1	114.75	91.70	62.62	34.53	2.65
2	232.30	206.78	183.94	164.60	138.56
3	223.11	196.75	173.34	153.31	126.26
4	28.66	28.66	-13.91	-47.47	-92.05
5	55.79	47.61	10.82	-20.47	-66.19
6	-16.13	-16.13	-48.29	-85.54	-136.10
7	164.12	139.52	113.81	89.19	56.80
8	252.53	225.99	208.58	186.05	161.60
9	187.08	160.87	135.83	112.97	82.52
10	262.23	236.71	220.01	198.12	173.67
11	158.28	133.31	107.23	82.16	49.17
12	234.15	208.80	186.06	166.87	141.02
13	165.90	141.43	115.82	91.33	59.12
14	241.06	216.35	194.03	171.80	146.09
15	160.31	135.44	109.52	84.60	51.82
16	167.01	142.63	117.07	92.66	60.57
17	282.95	256.97	241.69	220.71	201.86
18	167.45	143.10	117.57	93.20	61.15
19	184.34	157.90	132.71	109.63	78.88
20	186.24	159.96	134.87	111.95	81.40
21	264.56	239.28	222.76	201.02	177.28
22	250.45	223.69	206.13	183.46	158.78
23	264.89	239.65	223.15	201.43	177.74
24	231.38	205.77	182.87	163.47	137.32
25	229.14	203.33	180.29	160.72	134.33
26	284.18	258.35	243.16	222.26	202.18
27	323.56	300.68	285.80	272.06	246.77
28	206.95	179.12	154.75	133.45	108.81
29	276.39	252.40	233.87	212.43	192.74
30	147.98	122.47	95.62	69.78	40.42
31	123.91	101.24	72.81	45.38	9.48
32	22.72	22.72	-20.26	-54.03	-92.88
33	177.93	150.97	125.41	101.85	74.86
34	340.88	318.84	305.30	292.91	269.26
35	241.06	216.35	194.03	171.80	146.09
36	236.27	211.12	188.51	169.49	143.87
Average	**196.51**	**173.90**	**149.93**	**126.60**	**97.39**
Std Dev	81.84	76.32	82.76	87.39	93.91
Variance	6,697.32	5,824.59	6,848.62	7,637.22	8,818.29
Minimum	-16.13	-16.13	-48.29	-85.54	-136.10
Maximum	340.88	318.84	305.30	292.91	269.26

Table B-3. Corn Net Returns with a Conventional CP Irrigation System for a 570 gpm Well

Well Capacity	**570GPM**	**570GPM**	**570GPM**	**570GPM**	**570GPM**
MAD	0 MAD	0.15 MAD	0.30 MAD	0.45 MAD	0.60 MAD
Initial SWA	0.80	0.80	0.80	0.80	0.80
Section	3	3	3	3	3
1	209.80	173.66	149.98	111.79	43.72
2	281.83	250.35	227.21	201.15	136.73
3	276.29	247.34	219.64	193.11	126.27
4	158.01	128.32	95.60	63.67	-15.58
5	174.17	140.20	112.78	77.59	-2.67
6	131.60	112.19	77.87	40.46	-39.93
7	240.11	203.47	176.79	147.50	79.97
8	293.83	265.10	244.31	219.73	159.82
9	254.25	220.13	189.89	166.53	94.55
10	299.46	271.93	252.39	228.08	169.46
11	236.51	199.31	172.18	142.47	74.05
12	282.93	251.66	228.58	202.87	139.00
13	241.20	204.76	178.20	149.03	80.59
14	287.06	256.83	234.04	209.26	147.17
15	237.76	200.71	173.78	144.21	76.31
16	241.89	205.57	179.07	149.99	81.83
17	311.15	289.00	268.11	247.14	187.24
18	242.16	205.89	179.42	150.37	82.32
19	252.57	218.12	187.66	164.08	91.31
20	253.74	219.51	189.20	165.77	93.56
21	300.80	270.25	254.25	230.02	171.50
22	292.61	263.68	241.29	217.73	157.17
23	300.99	270.52	254.54	230.34	171.92
24	281.27	249.63	226.43	200.55	135.59
25	279.93	247.91	224.54	198.48	132.83
26	311.82	289.78	266.07	247.75	188.87
27	332.28	317.42	299.19	281.64	229.07
28	266.45	230.07	211.03	178.70	115.20
29	307.51	284.16	263.25	236.11	180.23
30	230.16	197.01	169.57	133.63	66.93
31	215.39	180.08	151.16	119.39	48.02
32	154.49	124.54	91.45	59.17	-16.08
33	248.62	213.44	187.63	158.38	92.82
34	340.49	327.92	315.34	293.52	253.44
35	287.06	256.83	234.04	209.26	147.17
36	284.21	253.30	230.38	209.72	141.14
Average	**259.46**	**228.91**	**204.36**	**177.20**	**111.71**
Std Dev	49.01	51.70	55.88	60.05	67.23
Variance	2,401.65	2,672.44	3,122.26	3,605.44	4,520.47
Minimum	131.60	112.19	77.87	40.46	-39.93
Maximum	340.49	327.92	315.34	293.52	253.44

Table B-4. Corn Net Returns with a CP with Drops Irrigation System for a 190 gpm Well

Well Capacity	**190GPM**	**190GPM**	**190GPM**	**190GPM**	**190GPM**
MAD	0 MAD	0.15 MAD	0.30 MAD	0.45 MAD	0.60 MAD
Initial SWA	0.40	0.40	0.40	0.40	0.40
Section	8	8	8	8	8
1	102.01	86.88	53.26	34.42	-3.32
2	237.32	211.93	197.70	175.22	155.88
3	226.85	200.58	186.07	162.72	142.91
4	1.80	1.80	-36.93	-56.58	-107.06
5	33.38	33.38	-8.58	-24.29	-77.40
6	-50.10	-50.10	-69.54	-110.18	-157.06
7	159.18	135.15	114.48	91.01	62.96
8	260.33	233.77	222.07	199.21	182.26
9	185.60	159.65	142.03	117.74	93.71
10	271.34	245.80	234.58	212.47	196.23
11	152.44	131.82	107.06	83.16	54.73
12	239.42	214.20	200.03	177.72	158.48
13	161.23	137.33	116.74	93.40	63.70
14	247.29	222.72	208.78	183.51	165.72
15	154.78	130.47	109.64	85.89	57.59
16	162.51	138.69	118.14	94.89	67.03
17	294.82	268.76	258.44	237.66	222.77
18	163.02	139.23	118.71	95.48	67.66
19	182.45	156.26	138.55	114.02	89.84
20	184.64	158.61	140.96	116.60	92.52
21	273.98	248.69	237.58	215.65	196.06
22	257.96	231.18	219.38	196.36	179.26
23	274.35	249.10	238.01	216.10	196.54
24	236.27	210.78	196.53	173.96	154.57
25	233.72	208.03	193.71	170.92	151.42
26	296.21	270.30	260.04	239.36	224.56
27	340.88	318.75	306.78	290.05	270.94
28	208.38	180.58	165.61	140.69	121.75
29	287.39	263.37	249.91	228.62	213.25
30	140.53	119.26	93.97	69.31	41.86
31	112.64	93.91	64.91	41.77	8.04
32	-5.11	-68.30	-38.84	-63.30	-114.80
33	175.08	148.35	130.42	105.33	82.44
34	360.66	340.02	328.07	313.62	294.95
35	247.29	222.72	208.78	183.51	165.72
36	241.84	216.82	202.72	180.61	161.48
Average	**195.90**	**172.51**	**155.83**	**132.96**	**107.70**
Std Dev	94.19	92.05	94.68	96.41	106.17
Variance	8,871.51	8,472.75	8,964.75	9,295.07	11,271.85
Minimum	-50.10	-68.30	-69.54	-110.18	-157.06
Maximum	360.66	340.02	328.07	313.62	294.95

Table B-5. Corn Net Returns with a CP with Drops Irrigation System for a 285 gpm Well

Well Capacity	**285GPM**	**285GPM**	**285GPM**	**285GPM**	**285GPM**
MAD	0 MAD	0.15 MAD	0.30 MAD	0.45 MAD	0.60 MAD
Initial SWA	0.60	0.60	0.60	0.60	0.60
Section	6	6	6	6	6
1	158.20	133.73	100.52	68.14	31.66
2	268.43	238.80	214.31	191.08	160.45
3	259.78	229.27	204.20	180.23	148.56
4	78.02	78.02	30.54	-5.53	-55.83
5	103.26	94.58	53.24	17.62	-31.77
6	36.36	36.36	0.17	-40.22	-97.32
7	204.38	175.94	148.47	119.72	82.52
8	287.49	256.72	235.56	211.29	182.35
9	225.91	195.66	168.89	141.99	106.78
10	296.63	266.93	246.51	222.92	193.99
11	198.91	172.37	142.22	113.02	75.18
12	270.17	240.72	216.35	193.26	162.84
13	206.05	177.74	150.37	121.77	84.75
14	276.68	247.90	223.97	197.57	167.31
15	200.81	172.08	144.39	115.35	77.73
16	207.08	178.86	151.56	123.04	86.15
17	316.14	285.96	266.98	244.33	218.86
18	207.50	179.31	152.03	123.55	86.70
19	223.34	192.85	165.92	138.80	103.28
20	225.12	194.80	167.98	141.01	105.70
21	298.82	269.39	249.14	225.72	195.04
22	285.52	254.53	233.21	208.79	179.62
23	299.13	269.74	249.52	226.11	195.49
24	267.56	237.84	213.29	189.99	159.25
25	265.46	235.52	210.83	187.35	156.36
26	317.30	287.28	268.39	245.83	219.02
27	354.28	327.50	308.86	291.35	258.61
28	244.58	212.54	186.44	161.19	132.15
29	309.97	281.90	259.46	236.33	209.98
30	189.26	162.16	131.22	101.21	67.31
31	166.75	142.69	110.15	78.46	37.61
32	72.49	72.49	24.57	-11.75	-55.83
33	217.32	186.30	158.98	131.35	99.90
34	370.44	344.66	327.43	311.34	280.25
35	276.68	247.90	223.97	197.57	167.31
36	272.17	242.92	218.69	195.78	165.59
Average	**234.94**	**209.00**	**182.18**	**155.43**	**121.04**
Std Dev	76.66	70.01	76.70	81.65	87.81
Variance	5,876.16	4,901.27	5,883.17	6,666.87	7,709.98
Minimum	36.36	36.36	0.17	-40.22	-97.32
Maximum	370.44	344.66	327.43	311.34	280.25

Table B-6. Corn Net Returns with a CP with Drops Irrigation System for a 570 gpm Well

Well Capacity	**570GPM**	**570GPM**	**570GPM**	**570GPM**	**570GPM**
MAD	0 MAD	0.15 MAD	0.30 MAD	0.45 MAD	0.60 MAD
Initial SWA	0.80	0.80	0.80	0.80	0.80
Section	3	3	3	3	3
1	272.49	230.53	163.75	163.75	64.04
2	336.29	293.36	269.00	239.98	157.53
3	331.51	287.09	262.60	232.36	146.30
4	225.56	186.82	152.43	118.93	14.01
5	240.23	199.86	163.52	123.96	21.61
6	201.58	173.30	134.95	93.33	-9.97
7	299.70	254.64	224.02	195.03	102.14
8	346.54	307.33	281.34	252.57	177.30
9	312.25	264.80	242.10	209.77	114.66
10	351.29	310.74	285.70	259.08	184.58
11	296.49	255.84	224.94	190.83	95.66
12	337.24	294.12	266.86	241.27	159.79
13	300.68	255.87	225.14	196.50	104.11
14	340.78	298.62	271.85	243.41	164.03
15	297.61	252.50	226.21	192.15	97.91
16	301.29	256.64	225.98	197.03	105.35
17	361.06	322.67	298.05	271.85	204.25
18	301.53	256.94	226.32	197.39	105.84
19	310.76	266.90	239.97	207.43	112.97
20	311.79	264.20	241.45	209.05	115.17
21	352.42	312.34	287.73	259.41	183.57
22	345.50	304.08	279.56	250.86	174.71
23	352.58	312.60	288.02	259.73	184.00
24	335.81	292.67	268.24	236.68	156.40
25	334.66	291.25	267.06	235.36	153.67
26	361.62	322.59	298.84	275.50	202.90
27	378.40	348.51	325.41	300.92	242.95
28	322.96	280.73	252.30	219.98	132.89
29	358.03	319.53	294.63	268.33	197.61
30	290.81	249.37	217.82	183.30	93.69
31	277.54	236.26	206.24	170.68	68.36
32	222.37	189.43	152.83	114.80	8.62
33	307.27	262.99	233.35	202.95	108.13
34	385.10	360.05	339.92	317.15	263.98
35	340.78	298.62	271.85	243.41	164.03
36	338.33	295.23	268.12	242.94	162.39
Average	**316.13**	**275.25**	**246.61**	**217.16**	**131.53**
Std Dev	43.24	43.45	48.69	51.16	63.39
Variance	1,869.79	1,888.15	2,370.43	2,617.71	4,018.03
Minimum	201.58	173.30	134.95	93.33	-9.97
Maximum	385.10	360.05	339.92	317.15	263.98

Table B-7. Sorghum Net Returns with a Conventional CP Irrigation system for a 190 gpm Well

Well Capacity	**190GPM**	**190GPM**	**190GPM**	**190GPM**	**190GPM**
MAD	0 MAD	0.15 MAD	0.30 MAD	0.45 MAD	0.60 MAD
Initial SWA	0.40	0.40	0.40	0.40	0.40
Section	8	8	8	8	8
1	131.90	121.49	113.72	104.57	93.96
2	192.95	183.77	180.89	171.95	167.97
3	188.30	178.62	175.44	167.62	161.89
4	85.00	80.68	65.01	54.94	37.81
5	99.99	93.27	79.31	70.97	55.58
6	59.87	59.87	42.48	28.82	13.87
7	157.96	148.12	141.94	133.92	124.30
8	203.07	193.85	191.95	184.43	178.22
9	169.88	159.69	154.83	146.71	139.82
10	207.87	199.25	197.65	189.16	184.63
11	154.91	144.80	138.39	130.26	121.44
12	193.87	184.80	181.09	173.09	169.19
13	158.89	149.13	143.02	135.03	125.51
14	197.34	188.65	185.18	177.37	172.82
15	155.97	145.96	139.62	131.53	122.82
16	159.46	149.75	143.69	135.72	126.26
17	218.00	209.65	208.95	206.20	193.64
18	159.70	150.01	143.96	136.00	126.56
19	168.46	158.14	153.18	145.00	137.98
20	169.44	159.22	154.32	146.18	139.26
21	209.02	200.55	198.18	190.59	186.17
22	202.03	192.69	190.73	183.15	179.00
23	133.61	140.73	147.86	147.86	154.99
24	192.48	183.25	180.34	171.38	167.36
25	191.35	182.00	179.02	171.34	165.89
26	218.59	210.34	209.67	206.96	194.47
27	237.17	237.02	230.19	229.33	222.89
28	180.08	170.88	165.80	157.59	152.12
29	214.81	206.01	205.12	202.11	190.41
30	149.50	140.46	132.09	123.78	114.42
31	136.77	126.75	118.34	110.35	99.09
32	81.70	77.18	61.42	51.16	36.42
33	165.14	155.93	149.30	140.98	133.66
34	244.99	246.06	240.34	239.46	231.86
35	197.34	188.65	185.18	177.37	154.09
36	194.94	185.98	182.35	174.41	150.51
Average	**171.73**	**163.98**	**158.63**	**151.31**	**142.41**
Std Dev	42.65	42.14	45.62	47.51	49.58
Variance	1,819.39	1,775.89	2,081.58	2,257.59	2,458.53
Minimum	59.87	59.87	42.48	28.82	13.87
Maximum	244.99	246.06	240.34	239.46	231.86

Table B-8. Sorghum Net Returns with a Conventional CP Irrigation System for a 285 gpm Well

Well Capacity	**285GPM**	**285GPM**	**285GPM**	**285GPM**	**285GPM**
MAD	0 MAD	0.15 MAD	0.30 MAD	0.45 MAD	0.60 MAD
Initial SWA	0.60	0.60	0.60	0.60	0.60
Section	6	6	6	6	6
1	149.27	134.55	126.52	112.20	101.11
2	199.18	186.43	181.08	175.10	165.90
3	195.36	182.01	176.32	171.33	161.33
4	111.86	100.41	80.43	72.16	57.35
5	123.73	109.80	97.92	84.51	70.86
6	92.04	84.53	60.82	52.54	34.02
7	170.43	156.57	148.73	141.52	128.47
8	207.51	194.86	190.29	186.36	173.07
9	180.19	166.11	159.09	152.75	142.51
10	211.44	199.55	195.32	190.51	183.37
11	167.93	153.78	145.72	138.28	122.90
12	199.95	187.32	180.72	176.13	167.03
13	171.19	157.42	149.65	142.51	129.56
14	202.80	190.64	184.32	179.98	168.54
15	168.80	154.75	146.76	139.40	124.11
16	171.66	157.95	150.22	143.12	130.24
17	219.68	208.32	204.86	200.88	192.40
18	171.85	158.16	150.45	143.37	130.51
19	179.03	164.79	157.67	151.23	140.83
20	179.83	165.71	158.65	152.29	141.99
21	212.38	200.67	195.26	191.81	184.86
22	206.65	193.86	189.20	185.20	173.47
23	120.00	120.44	127.57	134.69	148.95
24	198.80	185.99	180.61	174.59	165.33
25	197.87	184.91	179.45	174.68	163.96
26	220.16	208.92	205.50	201.57	193.20
27	234.91	232.63	228.47	220.40	218.07
28	188.58	175.64	167.94	162.34	153.11
29	217.10	205.15	201.44	197.21	189.50
30	163.53	150.39	140.39	132.55	116.75
31	153.20	138.92	129.57	117.17	104.46
32	109.25	96.21	77.37	68.99	53.94
33	176.31	163.16	154.35	147.66	136.92
34	240.92	240.18	237.78	229.25	227.11
35	202.80	190.64	184.32	179.98	168.54
36	200.83	188.34	181.83	177.32	166.26
Average	**181.03**	**169.16**	**161.85**	**155.60**	**145.29**
Std Dev	35.72	36.24	39.83	41.11	43.76
Variance	1,275.80	1,313.16	1,586.14	1,690.15	1,914.52
Minimum	92.04	84.53	60.82	52.54	34.02
Maximum	240.92	240.18	237.78	229.25	227.11

Table B-9. Sorghum Net Returns with a Conventional CP Irrigation System for a 570 gpm Well

Well Capacity	**570GPM**	**570GPM**	**570GPM**	**570GPM**	**570GPM**
MAD	0 MAD	0.15 MAD	0.30 MAD	0.45 MAD	0.60 MAD
Initial SWA	0.80	0.80	0.80	0.80	0.80
Section	3	3	3	3	3
1	163.86	156.36	146.93	134.49	106.11
2	189.56	194.99	187.67	179.11	163.13
3	187.82	187.29	184.33	176.53	158.65
4	142.75	129.52	115.57	102.73	72.70
5	149.46	135.53	124.69	114.55	84.95
6	131.62	113.89	101.52	92.50	59.81
7	175.40	168.31	164.17	153.69	128.47
8	193.19	200.05	193.12	190.06	169.95
9	180.46	178.88	169.96	159.96	138.17
10	194.82	202.62	201.06	192.46	178.99
11	174.08	167.14	162.08	151.67	125.87
12	189.90	195.67	187.71	179.26	164.23
13	175.81	168.51	164.85	154.05	129.48
14	191.17	197.30	190.05	181.38	166.07
15	174.54	167.82	162.85	152.52	127.02
16	176.05	168.77	165.27	154.52	129.37
17	198.08	213.21	206.86	199.61	188.93
18	176.15	174.29	165.44	154.70	129.62
19	179.87	178.14	168.89	159.13	137.69
20	180.28	178.59	169.63	159.95	138.24
21	195.20	203.40	201.66	193.57	180.47
22	192.83	199.53	192.61	189.53	170.59
23	135.91	118.90	120.60	113.59	142.10
24	189.39	194.65	187.29	178.69	162.57
25	188.97	194.77	186.49	178.16	161.23
26	198.27	213.61	207.40	200.10	189.71
27	203.68	229.34	224.67	218.80	213.00
28	184.62	183.66	175.02	170.62	150.61
29	197.08	211.92	205.08	197.90	185.73
30	171.71	164.40	158.96	148.65	122.80
31	166.06	159.06	147.89	137.22	109.60
32	141.27	122.56	116.26	100.53	71.02
33	178.48	176.95	167.88	157.17	134.81
34	205.82	233.96	229.94	230.34	221.94
35	191.17	197.30	190.05	181.38	166.07
36	190.29	196.01	188.36	179.76	163.67
Average	**179.32**	**179.91**	**173.13**	**164.41**	**145.65**
Std Dev	18.91	29.37	30.33	32.31	37.53
Variance	357.48	862.58	919.87	1,043.93	1,408.51
Minimum	131.62	113.89	101.52	92.50	59.81
Maximum	205.82	233.96	229.94	230.34	221.94

Table B-10. Sorghum Net Returns with a CP with Drop Nozzle Irrigation System for a 190 gpm Well

Well Capacity	**190GPM**	**190GPM**	**190GPM**	**190GPM**	**190GPM**
MAD	0 MAD	0.15 MAD	0.30 MAD	0.45 MAD	0.60 MAD
Initial SWA	0.40	0.40	0.40	0.40	0.40
Section	8	8	8	8	8
1	155.19	130.83	123.47	120.80	106.94
2	212.98	200.50	194.76	185.05	178.05
3	208.57	195.56	189.50	181.00	172.12
4	111.15	104.43	87.27	74.04	55.42
5	125.19	115.70	100.60	89.16	70.29
6	87.59	87.59	66.40	49.49	32.86
7	179.80	166.68	157.53	148.79	135.83
8	222.59	210.06	205.35	197.16	187.70
9	191.08	177.57	169.77	160.94	150.89
10	227.16	215.27	210.86	201.63	193.98
11	176.91	163.52	154.13	145.27	133.20
12	213.86	201.49	194.84	186.16	179.24
13	180.67	167.65	158.57	149.87	137.00
14	217.16	205.20	198.80	190.31	182.67
15	177.91	164.62	155.31	146.50	134.53
16	181.22	168.25	159.21	150.53	137.73
17	236.77	225.18	221.72	216.05	202.28
18	181.44	168.49	159.47	150.80	138.02
19	189.74	176.09	168.18	159.29	149.10
20	190.67	177.12	169.28	160.44	150.34
21	228.25	216.52	211.27	203.02	195.48
22	221.61	208.94	204.16	195.92	188.71
23	146.37	151.37	156.37	156.37	161.37
24	212.53	200.00	194.23	184.49	177.46
25	211.46	120.63	192.95	208.43	194.89
26	237.33	225.84	222.42	216.79	203.09
27	254.87	249.54	242.10	238.42	228.55
28	200.76	188.28	180.20	171.29	162.72
29	233.75	221.66	218.00	212.05	199.24
30	171.80	159.57	148.10	139.04	126.40
31	159.79	146.53	135.10	126.35	111.73
32	108.05	101.14	83.86	70.42	54.34
33	186.60	174.14	164.46	155.42	144.91
34	262.22	258.22	251.99	248.28	237.10
35	217.16	205.20	198.80	190.31	162.26
36	214.87	202.63	196.06	187.43	158.72
Average	**192.64**	**179.22**	**173.47**	**165.76**	**153.75**
Std Dev	40.60	40.91	43.11	45.38	47.17
Variance	1,648.33	1,673.69	1,858.46	2,059.55	2,225.46
Minimum	87.59	87.59	66.40	49.49	32.86
Maximum	262.22	258.22	251.99	248.28	237.10

Table B-11. Sorghum Net Returns with a CP with Drop Nozzle Irrigation System for a 285 gpm Well

Well Capacity	**285GPM**	**285GPM**	**285GPM**	**285GPM**	**285GPM**
MAD	0 MAD	0.15 MAD	0.30 MAD	0.45 MAD	0.60 MAD
Initial SWA	0.60	0.60	0.60	0.60	0.60
Section	6	6	6	6	6
1	178.18	160.16	149.20	133.82	119.49
2	224.72	208.70	200.40	191.37	175.97
3	221.16	204.49	195.84	187.89	171.76
4	143.52	129.17	112.85	96.63	78.42
5	154.49	137.42	122.48	108.04	91.05
6	125.26	117.25	96.66	78.66	56.45
7	197.90	180.72	169.85	159.65	143.10
8	232.45	216.58	209.08	202.23	187.06
9	207.02	189.57	179.53	170.22	156.42
10	236.09	221.04	213.92	206.10	191.61
11	195.58	178.08	166.98	156.55	141.46
12	225.43	209.54	199.90	192.36	177.09
13	198.61	181.52	170.72	160.59	144.15
14	228.09	212.71	203.35	196.08	180.12
15	196.39	179.00	167.98	157.62	142.65
16	199.05	182.02	171.27	161.18	144.81
17	243.68	229.27	222.95	216.01	200.93
18	199.23	182.22	171.48	161.41	145.07
19	205.93	188.32	178.18	168.75	154.80
20	206.68	189.19	179.12	169.77	155.92
21	236.96	222.11	213.71	207.36	193.08
22	231.66	215.62	208.04	201.11	187.42
23	137.67	135.33	140.33	145.33	155.33
24	224.37	208.28	199.94	190.87	175.41
25	223.50	207.25	198.83	191.12	174.05
26	244.12	229.84	223.57	216.68	201.72
27	257.51	250.41	243.34	234.59	223.66
28	214.85	198.61	187.81	179.25	164.44
29	241.31	226.24	219.66	212.45	197.83
30	191.47	175.07	161.92	151.07	134.04
31	181.85	164.27	151.87	138.55	122.46
32	141.11	127.24	110.08	93.63	75.17
33	203.39	186.95	175.01	165.33	151.02
34	262.89	257.49	252.33	243.09	232.48
35	228.09	212.71	203.35	196.08	180.12
36	226.25	210.52	200.96	193.50	177.79
Average	**207.40**	**192.36**	**182.57**	**173.19**	**158.45**
Std Dev	33.88	33.77	36.10	38.35	39.55
Variance	1,147.87	1,140.65	1,303.47	1,470.73	1,564.52
Minimum	125.26	117.25	96.66	78.66	56.45
Maximum	262.89	257.49	252.33	243.09	232.48

Table B-12. Sorghum Net Returns with a CP with Drop Nozzle Irrigation System for a 570 gpm Well

Well Capacity	**570GPM**	**570GPM**	**570GPM**	**570GPM**	**570GPM**
MAD	0 MAD	0.15 MAD	0.30 MAD	0.45 MAD	0.60 MAD
Initial SWA	0.80	0.80	0.80	0.80	0.80
Section	3	3	3	3	3
1	209.64	189.58	176.93	162.56	125.11
2	230.37	222.26	212.43	200.39	173.79
3	229.01	219.75	209.27	197.73	169.72
4	191.50	168.39	155.08	138.83	92.75
5	197.35	175.13	160.37	147.32	102.80
6	181.70	161.51	143.25	128.44	80.67
7	219.14	203.10	190.91	178.45	142.23
8	233.21	226.86	217.69	207.37	183.01
9	223.20	208.35	197.03	185.15	154.51
10	234.49	229.07	220.31	212.62	187.49
11	218.07	201.47	190.00	176.60	141.24
12	230.64	222.71	212.49	200.95	174.88
13	219.47	203.39	191.44	178.81	144.09
14	231.63	224.22	214.32	203.76	177.52
15	218.44	202.05	189.98	177.44	140.47
16	219.67	203.77	191.87	178.96	144.72
17	237.05	237.82	229.14	219.65	197.81
18	219.75	203.59	192.03	179.15	144.98
19	222.73	207.52	196.51	184.58	152.93
20	223.06	208.17	197.24	184.79	154.03
21	234.79	229.94	221.18	213.74	188.94
22	232.93	226.68	216.82	206.40	183.59
23	176.19	136.55	131.14	133.48	148.48
24	230.24	221.93	212.19	199.97	173.24
25	229.91	221.72	211.28	200.10	171.92
26	237.20	238.00	229.68	220.25	198.57
27	241.52	251.27	244.44	236.24	218.79
28	226.49	212.59	201.91	193.24	162.36
29	236.26	236.04	227.28	217.96	194.39
30	216.14	196.99	187.45	173.50	137.12
31	211.47	191.30	178.54	164.79	127.67
32	190.21	168.34	153.59	137.36	89.85
33	221.62	206.26	194.87	182.37	149.24
34	243.28	256.17	250.32	242.63	227.49
35	231.63	224.22	214.32	203.76	177.52
36	230.95	223.48	212.65	201.92	175.24
Average	**221.69**	**210.01**	**199.33**	**188.09**	**158.80**
Std Dev	16.29	25.28	26.76	27.70	34.84
Variance	265.48	639.20	716.11	767.16	1,213.62
Minimum	176.19	136.55	131.14	128.44	80.67
Maximum	243.28	256.17	250.32	242.63	227.49