Optimal irrigation strategy with limited water availability accounting for the risk from weather uncertainty

by

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B.Sc., Bogor Agricultural University, 2003
M.Ec., University of Malaya, 2007

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

Risk averse farmers face a substantial challenge managing irrigation water when they face limited water availability. The two primary reasons for limited water availability in the High Plains Aquifer region of the United States are limited well capacity (i.e., the rate at which groundwater can be extracted) or a constraint imposed by a policy. In this dissertation, I study how risk averse farmers optimally manage limited water availability in the face of weather uncertainty and also the impact of limited water availability on farmer welfare.

I use AquaCrop, a daily biophysical crop simulation model, to predict corn yield under alternative irrigation scenarios with historical weather. Since no simple functional form exists for the crop production function, I use discrete optimization and consider 234,256 potential irrigation strategies. I also account for risk preferences by using expected utility analysis to determine the optimal irrigation strategy. Using a daily biophysical model is important because water stress in a short period of the growing season can impact crop yield (even if average water availability throughout the growing season is sufficient) and well capacity is a constraint on daily water use. The daily biophysical crop simulation model accounts for the dynamic response of crop production to water availability.

First, I examine how optimal irrigation strategies change due to limited water availability. I find that it is never optimal for irrigators to apply less than a particular minimum instantaneous rate per irrigated acre. An optimal required instantaneous rate implies that a farmer with a low well capacity focuses on adjustment at the extensive margin. On the other hand, farmers who initially have a high well capacity should adjust at the intensive margin in response to well capacity declining. I also find that total water use increases as the degree of risk aversion increases. More risk averse farmers increase water use by increasing irrigation intensity to reduce

the variance in corn yields. Another important finding is that a higher well capacity could actually promote less water use because the higher well capacity allows a greater instantaneous rate of application that allows the farmer to decrease irrigation intensity while still maintaining or increasing corn yield. This finding may imply an accelerated rate of groundwater extraction when the groundwater depletion reaches a particular threshold.

Second, I analyze the welfare loss due to limited water availability. The relationship between welfare loss and well capacity due to a policy constraint differs by soil type. I found the welfare loss from a water constraint policy does not always increase as well capacity increases. Farmers with very high well capacity may make small or no adjustment at the extensive margin due to a higher instantaneous rate and higher soil water holding capacity. However, that is not the case for a farmer with land that has lower soil water holding capacity as the increase in well capacity results in greater welfare loss. I also investigate the effect of risk averse behavior on the magnitude of welfare loss. I found that the welfare loss per unit of reduced water use is lower for the farmer with more risk aversion. Thus, economic models that ignore risk aversion misestimate the cost of reducing water use.

Finally, I investigate the incentive for adopting drip irrigation and its effect on water use. I find that a decrease in well capacity increases the benefits of adopting drip irrigation but is not sufficient to overcome the high initial investment cost without government support. While subsidies of the magnitude offered by current U.S. programs are sufficient to induce drip irrigation adoption, I find that such subsidies have the unintended consequence of increasing total water use, particularly for small well capacities.

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Approved by:

Major Professor
Nathan P. Hendricks

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Dedication

To my beloved Father and Mother for their unconditional love and support. To my beloved wife, Rohazatulsima Binti Ahmad for her patience, sacrifice and love.

Chapter 1 - Introduction

Risk averse farmers face a substantial challenge in managing irrigation water when they face limited water availability. The two primary reasons for limited water availability in the High Plains Aquifer region of the United States are limited well capacity (i.e., the rate at which groundwater can be extracted) or policy constraint. Understanding optimal management of a limited amount of water requires an understanding of how risk aversion impacts behavior due to weather uncertainty. For example, a limited amount of water may still produce excellent crop yields with average rainfall, but in drought years producers suffer extreme losses, and this uncertainty results in a different management strategy under risk aversion. In this dissertation, I study how risk averse farmers optimally manage limited water availability in the face of weather uncertainty and the impact of limited water availability on farmer welfare.

Kansas has above average weather unpredictability (Silver and Fischer-baum 2014), so its weather volatility challenges a risk averse farmer to find an optimal irrigation strategy. This uncertainty is also likely to increase in the future due to climate change (Lobell et al. 2008; Lobell, Schlenker and Costa-Roberts 2011).

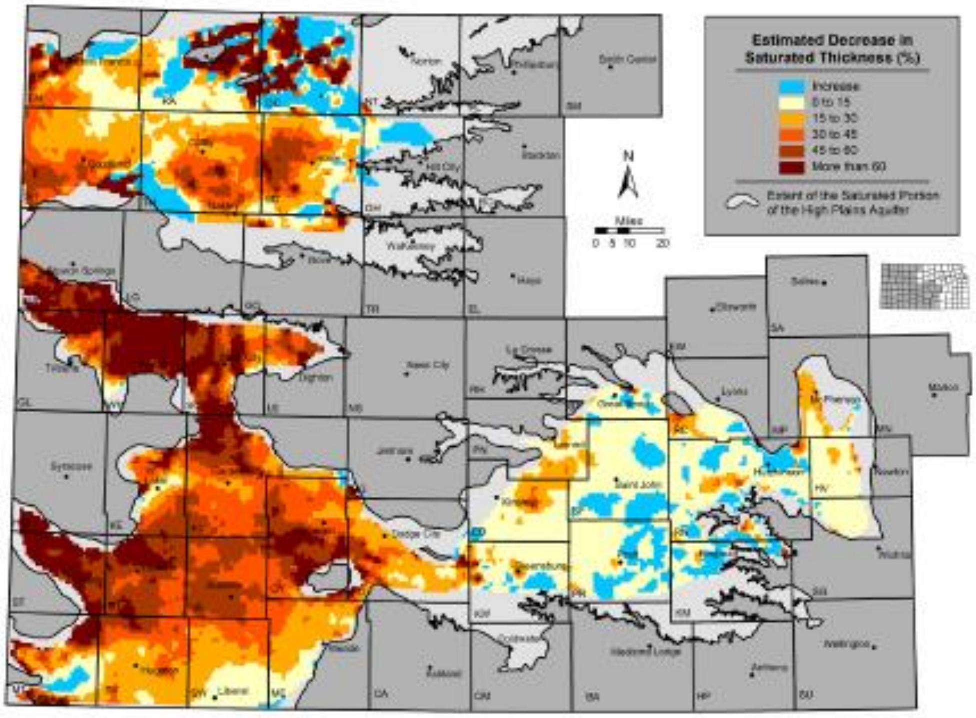
A farmer may apply groundwater irrigation to mitigate the risk in production associated with weather variability (Jain et al. 2015; Wood et al. 2014). However, due to the limited water availability, groundwater irrigation needs to be managed efficiently to gain maximum profit or risk-adjusted profit and conserve groundwater. Unfortunately, groundwater irrigation adjusted for limited water availability will not diminish risk completely as some uncertainty will remain (English 1990). Ultimately, the farmer will choose irrigation strategies that give optimum profitability relative to their risk behavior and risk preference.

Farmers in the high plains have historically pumped water from the aquifer at a rate that has resulted in severe aquifer depletion (Buchanan et al. 2001; Opie 2000), which in turn reduces the saturated thickness and subsequently decreases well capacity. The Ogallala Aquifer (or High Plains Aquifer), one of the main groundwater sources in Kansas, has depleted in some areas by 60% (see Figure 1.1). The extent of depletion differs across the aquifer region because of several factors such as historical pumping rate, natural discharge, physical aquifer properties, and natural and human-induced recharge rates (USGS 2016).

Nonetheless, the decrease in well capacity may become a major factor limiting irrigation water use since well capacity limits the instantaneous rate of irrigation water application and limits the soil moisture range that a farmer can effectively manage for a given water constraint (Foster, Brozović and Butler 2014; Upendram, Wibowo and Peterson 2015). Consequently, an important question is how do the welfare impacts of the decline in well capacity account for a farmer’s optimal adjustments to irrigation strategy?

To address this question, water constraint policies have been enacted to reduce the rate of saturated thickness affecting depletion and thereby extend the use of the aquifer for irrigation. However, lower water constraint will limit water irrigation even though the farmer has high well capacity (Foster et al. 2014; Peterson and Ding 2005). An important factor of water constraint policy is not only the quantity of quota but also the time range of the constraint. A longer time constraint may give the farmer more ability to adjust an irrigation strategy to minimize the risk in crop production from weather uncertainty.

Figure 1.1 Change in saturated thickness for the High Plains Aquifer in Kansas



Source: Buchanan et al. (2001)

The Walnut Creek IGUCA (Intensive Groundwater Use Control Area) and the Sheridan 6 Local Enhanced Management Area (Sheridan 6 LEMA) are two examples of water constraint policies in Kansas that allow time range flexibility in irrigation water allocation over a particular period. Both policies enable the farmer to extend the irrigation limit to a five-year account with limited restriction on the amount pumped in a given year. Such flexibility in water constraint policy will give the farmer a more efficient tool to adapt to weather variability. Moreover, afarmer may bring an “unused quota” of irrigation from a previous year to the next year to address unfavorable precipitation. Additionally, flexibility in water constraint policy may help the farmer to meet the crop water demand with more efficiency but still reduce average total irrigation. The extent of the impact of the change in quantity and flexibility of water constraint on the welfare and on water use is critical for determining future policies.

The most common irrigation strategies that a farmer can implement in response to weather variability and limited water availability are to change the irrigated acreage (extensive margin of adjustment), to change the water intensity per acre (intensive margin of adjustment), and/or to change irrigation technology (English 1990; Pfeiffer and Lin 2014; Peterson and Ding 2005; Wang and Nair 2013; Wolff and Stein 1999). Accordingly, a farmer with particular water availability, well capacity, and water policy constraint, may adjust irrigated acreage to prevent crop yield loss during drought. First, the adjustment in irrigated acreage would give the farmer more flexibility in choosing the optimum water intensity per acre for a particular weather condition. Regarding low well capacity, Foster et al. (2014) found that the farmer is likely to focus strategy on changing irrigated acreage in response to weather uncertainty. Next, in the case of low well capacity and low soil quality, the farmer may more likely maximize profit by adopting more efficient irrigation technology (Caswell and Zilberman 1986).

The optimal adjustment in the intensive margin can best be thought of as the optimal irrigation schedule. One method to achieve it is to set different soil moisture levels for different crop growth stages. Consequently, a water optimization analysis may use a daily biophysical crop simulation model to predict the crop yield instead of using an economic water production function. A crop simulation model gives an advantage to the robustness of yield estimation by accounting for the effect of dynamic response of a crop to water, which is not accounted for by the economic water production function (Moore 1961). Hexem and Heady (1978) mentioned that an economic water production function may suffer from multicollinearity, and so they do not consider the effect of irrigation timing on crop yield. However earlier, Moore (1961) stated that estimating water production function may have little meaning if we do not consider the final soil moisture level for each irrigation cycle.

My study will use AquaCrop, a daily biophysical crop simulation model, for crop yield prediction based on soil moisture and Management Allowed Depletion (MAD) as farmer input choices. The seasonal irrigation water use is dependent on MAD settings for each crop growth stage and specified weather conditions. Crop water productivity is different for each growth stage, so using MAD for the irrigation schedule is better than using total seasonal water use to illustrate a farmer’s demand for water.

The effectiveness of an irrigation schedule depends on the range of soil moisture that a farmer can manage. Thus, a farmer may set a higher soil moisture level in a critical crop growth stage to obtain both higher yield and better water use efficiency (Panda, Behera and Kashyap 2004). The effectiveness of an irrigation schedule is also affected by soil characteristics (Panda et al. 2004). Considering different soil characteristics may prompt a more effective irrigation schedule. Another important factor in the intensive margin of adjustment is well capacity. A farmer with a low well capacity will have a narrow soil moisture range with which to efficiently attain optimal yield (Foster et al. 2014). Thus, a farm with low well capacity is exposed to higher production risk.

Adopting modern and more efficient irrigation technology could also address weather variability and groundwater depletion (Wolff and Stein 1999; Negri and Hanchar 1989). Ultimately, modern irrigation technology is expected to increase irrigation efficiency, which may lower the variation in crop yield affected by weather variability. However, the impact of more modern irrigation technology on water use is ambiguous (Huffaker and Whittlesey 2003; Peterson and Ding 2005). A farmer will likely increase irrigation water use when upgrading the irrigation technology if the marginal productivity of water is low (Caswell and Zilberman 1986). Modern irrigation technology also may induce the farmer to use more water by planting a more water intensive crop or to increase the irrigated acreage (Pfeiffer and Lin 2014). Pfeiffer and Lin (2014) also found that adopting modern irrigation technology has encouraged the farmer to increase water use by decreasing the probability of leaving the field unirrigated. All the same, modern and more efficient irrigation technology does not always offer higher profitability than existing less efficient irrigation technology (Peterson and Ding 2005) and thus may be an inefficient use of public funds.

Most studies analyze the adoption of more efficient irrigation technology based on its relationship to factors such as water price, labor cost, agronomic and physical characteristics, farm size, and weather characteristics (Caswell and Zilberman 1985; Frisvold and Bai 2016; Green et al. 1996; Negri and Brooks 1996). However, the high investment in more efficient irrigation technology could generate a sufficient barrier to its adoption even for farms with limited water availability. The research on the effect of limited water availability to adoption of more efficient irrigation technology is still somewhat limited. O'Brien et al. (1998) examine the economic comparison between center pivot and drip irrigation assuming full irrigation. Additionally, Peterson and Ding (2005) analyze the consequences of converting to irrigation technology including the limitation in well capacity (e.g. 300 and 500 GPM) and assuming fixed irrigated acreage.

Modern irrigation technology does have a higher irrigation efficiency, but it also requires a higher investment. Thus, newer technology does not always provide greater profitability, although in general, investment in irrigation technology has caused the average farm to produce larger crop yield and to plant larger irrigated acreage. However, for the region with more limited water availability, this option may not be economically feasible, instead generating too high off-farm cost. Thus, the impact of higher irrigation efficiency from modern technology may not offset the high investment cost in the case of too low water availability. Moreover, perhaps modern irrigation technologies are more appealing in a region with limited water availability. The important question is to what extent of limited water availability will the farmer invest in more efficient irrigation technology?

The total production and marginal productivity of water on crop yield may be affected by soil texture and soil water holding capacity. Zhao et al. (2007) stated that soil properties have significant impact on crop biomass productivity, which later will affect crop growth and crop production. Zhao et al. (2007) also mentioned that when the difference in soil property is greater between lands, the effect of irrigation on crop productivity will vary greatly. Thus, a farmer with different soil properties may have different optimal irrigation strategies, for both intensive and extensive margins of adjustment, in response to limited water availability and weather uncertainty. However, a farmer with less preferred soil characteristic may have greater change in irrigation strategy in response to more limited water availability. Thus, a model that does not account for the spatial difference in soil characteristics may be a poor predictor of optimal irrigation strategy and water use.

Some previous studies consider only the intensive margin of adjustment in their irrigation strategy choice to cope with scarce water and weather variability (Boggess et al. 1983; English 1990; Heeren et al. 2011). For example, Peterson and Ding (2005) and Upendram et al. (2015) use the intensive margin of adjustment and irrigation technology but without an extensive margin of adjustment as possible strategies for the farmer. An irrigation choice that uses both intensive and extensive margins of adjustment in response to limited water availability better represent the farmer’s choice (Baumhardt et al. 2009; Foster et al. 2014; O’Brien et al. 1998; O’Brien et al. 2001; D. L. Martin, Gilley and Supalla 1989). Additionally, the “Pac-Man” shape of a corn farm may prove that the farmer uses an extensive margin of adjustment as part of the irrigation strategy (see Figure 1.2). Broadening the traditional approach, this research considers extensive and intensive margins of adjustment and irrigation technology choice as possible strategies for optimizing water use and crop yield.

Figure 1.2 The Pac-Man shape of center pivot irrigation system

Source: Earthobservatory (2015)

The degree of risk aversion has an impact on a farmer's irrigation strategy with respect to weather variability (Bernardo 1988; Boggess et al. 1983; Foster et al. 2014; Peterson and Ding 2005). This means deficit irrigation affected by weather variability may produce more variability in crop yield compared to full irrigation. However, deficit irrigation may allow the farmer to apply a limited amount of water over a larger area. Nevertheless, a risk averse farmer may prefer an irrigation strategy that offers lower profit variability. Evidence shows that a risk averse attitude induces the farmer to decrease optimal irrigated acreage (Foster et al. 2014) to reduce the variability in crop yield by focusing available water on a smaller irrigated acreage.

1.1 Objectives and Main Findings

The primary objective of this study is to analyze the effect of a limited well capacity—due to groundwater depletion—and a water constraint policy on a farmer's optimal irrigation strategy (extensive adjustment, intensive adjustment, and irrigation technology). Thus, the study focuses on the following six specific objectives:

I. Estimate how limited well capacities affect the optimal irrigation strategy and net return.
II. Examine the effect of soil characteristics on the optimal irrigation strategy with limited water availability.
III. Analyze how different degrees of risk aversion affect the optimal strategy with limited water availability.
IV. Analyze how the optimal strategy changes when government enforces a water constraint policy.
V. Quantify the welfare loss from a limited well capacity or policy constraint.
VI. Analyze how limited well capacities and policy contraints affect the incentives to adopt a more efficient irrigation technology.

The main contribution of my study is the analysis of aquifer depletion impact on optimal irrigation strategy and welfare. To that end, this study addresses intensive margin of adjustment with non-uniform soil moisture level as one possible strategy that a farmer may choose. I believe this type of deficit irrigation has not been analyzed in previous studies (Foster et al. 2014; Foster, Brozović and Butler 2015a; Upendram et al. 2015). The variable of non-uniform soil moisture level in irrigation schedule affects crop-water productivity at each growth stage and is therefore important in analyzing water use and conservation strategies. My study will also contribute to the literature by investigating the effect of different soil characteristics on intensive and extensive margins of adjustment, which, to my knowledge has not been analyzed in previous research (Foster et al. 2014; Upendram et al. 2015). The combination of different soil characteristics and optimal irrigation technology will generate a more specific understanding of irrigation efficiency. This study explains how the farmer with limited well capacity may choose a strategy based on irrigation efficiency and total water quota. Another contribution of this study is that I impose the water constraint on total water use with a 5-year average time constraint whereas previous literature has imposed the constraint on water use per irrigated acre on annual basis (Nair, Wang, et al. 2013; Peterson and Ding 2005; Upendram et al. 2015). My study will give insight into how groundwater depletion may affect the adoption rate of more efficient irrigation technology, which is still not fully understood with regard to limited water availability.

There are four key findings in this dissertation. First, my study finds a counterintuitive result that water use does not increase monotonically with well capacity. Instead, my results show that water use is greatest with a well capacity of roughly 600-700 GPM and decreases with smaller and larger well capacities. This counterintuitive result occurs because the well capacity of 600-700 GPM has a smaller instantaneous rate of application, so farmers find it optimal to apply water more frequently to maintain higher soil moisture to avoid the risk of severely depleted soil moisture in a long dry period when the small instantaneous rate cannot maintain soil moisture. Including the effect of non-uniform soil moisture level in adjustment at the intensive margin in the analysis might cause the difference in findings between my study and previous studies (Foster et al. 2014). Accommodating the non-uniform soil moisture level also might cause a higher instantaneous rate to generate less average water use because of more efficiency in irrigation scheduling especially during unfavorable weather conditions. This counterintuitive result also implies a faster rate of groundwater extraction when depletion in groundwater resources causes well capacity reduction at a particular level. The groundwater depletion pattern is consistent with data on actual depletion rates from the High Plains Aquifer that show a peak in groundwater demand rather than groundwater demand always declining over time (Steward and Allen 2016). Specifically, the well capacities that result in the greatest groundwater extraction differ by soil type and depend on capacity threshold.

The well capacity threshold is the point at which a farmer changes from adjustment in the intensive margin to adjustment in the extensive margin. The adjustment in the extensive margin occurs at a constant return to scale production. The threshold also shows when the reduction in well capacity results in rapid decline of farmer welfare. The well capacity threshold differs by soil characteristic. Identifying the threshold accounting the spatial variability in soil is critical for policy maker monitoring the impact of groundwater depletion to welfare loss.

The second important finding of this dissertation is that risk aversion induces farmers to significantly increase water use. For example, I find that optimal water use under plausible levels of risk aversion is roughly 30% larger than under risk neutrality with Richfield soils with a 600 GPM well capacity. My study simulates the sensible range of risk averse behavior using the Babcock, Choi and Feinerman (1993) method, which is different from methods used in previous studies (Foster et al. 2014; Peterson and Ding 2005; Upendram et al. 2015). The impact of risk averse behavior on the change in water use differs by well capacity, and it is the highest at medium well capacity due to the small instantaneous rate typical of medium well capacities that reduces the ability to mitigate risk.

The third key finding is that the impact of water policy constraints on farmer welfare differs substantially by well capacity and soil type. For example, the welfare loss of Valent-Vona soil is 106% higher than for Richfield soil at 900 GPM wells, and the welfare loss of 500 GPM wells is 108% higher than for 600 GPM wells for land with Richfield soil. Surprisingly, the impact of a water constraint policy on welfare loss is smaller for large well capacities than for medium well capacities for soils with high soil water holding capacity. For example, the welfare loss of 1200 GPM wells is 26% lower than for 900 GPM wells for land with Richfield soil. The greater soil water holding capacity enables farmers with higher well capacities to focus on adjustment at the intensive margin instead of at the extensive margin in response to policy constraint, resulting in less welfare loss. Therefore, models that do not account for different soil types and well capacities when predicting the impact on farmer welfare of policy constraints are misleading.

The final key finding is that current government subsidies for drip irrigation are large enough to induce adoption in locations with a policy constraint, and adoption is more likely to occur for medium well capacity. However, the adoption of drip irrigation under a policy constraint is likely to increase water use, especially in the case of smaller well capacity. A farmer who adopts drip irrigation might decrease water use from historical use but actually increase water use relative to what they would use with center pivot irrigation and constraint policy. Thus, the government subsidy might not reduce water use. My model allows farmer to make changes to irrigated acreage and deficit irrigation application, which is more specific and different than research based on previous study model assumptions (O’Brien et al. 1998; Peterson and Ding 2005). In addition, the policy constraint considers a flexible time range application, the 5-year time constraint, which is motivated by LEMA and Walnut Greek IGUCA implementation.

1.2 Organization of the remaining chapters

Chapter two presents the literature review on the crop water production model, irrigation strategy, and farmer decision under risk and uncertainty, while Chapter three addresses the methods and research procedure. Chapter four addresses objectives one to four. The analysis on welfare loss as an impact of groundwater depletion and water constraint policy (objective five) is addressed in Chapter five, and Chapter six analyzes the impact of limited well capacity and government policy on adoption of modern irrigation technology (objective six). The final chapter presents the summary, conclusions, and potential future research.

Chapter 2 - Literature review

Many studies have addressed how crop producers choose the optimal irrigation strategy under limited water availability and uncertainty. To address the most significant studies, the literature review will be divided into six sections: (1) water optimization analysis that previous studies used and the benefit of using daily biophysical crop simulation models in the analysis; (2) a review of the importance of using management allowed deficit (MAD) for the irrigation schedule as the input choice for optimization analysis; (3) limited water availability caused by groundwater depletion and water constraint policy and studies that discuss the effect of limited water availability on optimal irrigation strategy; (4) review of irrigation strategy with respect to adjustment in extensive and intensive margins and discussion of how farmers tradeoff between those two irrigation strategies in response to limited water availability; (5) factors that affect the adoption of more efficient irrigation technology, and the effect of those factors on total water use; and (6) objectives that previous studies used for optimal irrigation management under risk and uncertainty. In addition, this final section will also review the use of the absolute risk aversion coefficient to represent the farmer's risk preference.

2.1 Crop-water production function and AquaCrop

Crop-water production function shows the relation between crop yields to water received by the crop. This function is used not only as a crop-yield predictor (Kallitsari, Georgiou and Babajimopoulos 2011; Martin, Watts and Gilley 1984; Moore, Gollehon and Negri 1989) but also as a tool to find optimal irrigation strategies for both unlimited water availability and also for limited water availability (Dinar and Knapp 1986; English 1990; D. Martin, Brocklin and Wilmes 1989; Peterson and Ding 2005; Wang and Nair 2013). The optimization analysis using the crop-water production function is to evaluate water allocation by the economic value it generates (Harou et al. 2009). The function is estimated by assuming a particular production model, for example the Translog production model (Peterson and Ding 2005), or one of several models such as the quadratic and the power function (Cobb-Douglas) production model (Dinar and Knapp 1986; Wang and Nair 2013), Square root, Mitscherlich-Baule, Linear Von Liebig, and nonlinear Von Liebig (Llewelyn and Featherstone 1997). The most widely chosen input variable in crop-water production function is total water use, which can be determined based on crop growth stages (Peterson and Ding 2005) or annual/seasonal (Dinar and Knapp 1986; Llewelyn and Featherstone 1997).

Using the crop-water production function in optimization analysis is not restricted only to using water as an input choice. Other inputs such as soil moisture level (Limaye et al. 2004; Paudel et al. 2005; Shani, Tsur and Zemel 2004; Shani et al. 2007), well capacity (O’Brien et al. 2001), and irrigation capacity (Lamm, Stone and O’Brien 2007) are regularly used to find the most optimal water allocation, irrigation technology choices, or crop acreage allocation.

However, using annual or seasonal water as an input choice for crop production in optimization analysis may cause problems. Moore (1961) stated that relating crop yield to total water applied during growing season may have little meaning when the final soil moisture condition for each irrigation cycle is not taken into account. Thus, researchers may misuse the crop-water production function for an irrigation experiment, which could cause the function to not represent the farmer’s demand for water (Moore 1961). Moore (1961) also stressed the crop-water production function for each irrigation cycle, which means estimating total crop yield must take into account the plant-soil-water relationship. Other setbacks of using the crop-water production function are that it does not consider the dynamic response of crop to water, and the multicollinearity among the independent variables (Hexem and Heady 1978). The crop-water production function also does not account for the timing effect of water application on crop yield.

Moreover, other studies did not use the crop-water production function; instead, they used a daily biophysical crop simulation model for water optimization analysis (Baumhardt et al. 2009; Foster et al. 2014; Heeren et al. 2011; Nair, Wang, et al. 2013; Upendram et al. 2015). Specifically, those studies used soil moisture level, denoted as Management Allowed Depletion (MAD), as a farmer input choice. The daily biophysical crop simulation model predicts the crop yield based on the water retained in the soil for each irrigation cycle. Other advantages of the daily biophysical crop simulation model are it accounts for the dynamic response of crop to water and also for the effect of water stress on crop yield. Thus, it will better predict the effect of water application on crop yield. Also, an important factor of daily biophysical crop simulation model reliability is the robustness of yield estimation. The daily biophysical crop simulation model with MAD as an input choice may enable optimal water use for varied conditions, which is not the case with optimization analysis using the crop-water production function.

Foster et al. (2014) mentioned that the reliability of integrated modelling that uses a daily biophysical crop simulation model to improve water management is dependent on the capability of the model to capture the structures and variables that determine the farmer’s decision. Thus, the integrated modelling for water management should have a link between agricultural production and the hydrological system. Foster et al. (2014) also stated that using soil moisture to examine farmer actual decision and demand of water is more realistic than the use of crop-water production function.

In pursuit of water optimization practice, engineers have developed computer software that uses the daily biophysical crop simulation model. Given weather characteristics, soil characteristics, and irrigation water supply, the software can predict crop yield. My study will use the programming software AquaCrop developed by Food and Agricultural Organization (FAO) for estimating crop yield.

The AquaCrop model incorporates the practical empirical production function for estimating crop yield response to water (Raes et al. 2009). Raes et al. (2009) mentioned that AquaCrop model offers better accuracy, simplicity, and robustness than other crop yield simulation models. Moreover, AquaCrop requires less parameter and input data to simulate the crop yield response to the water supply (Steduto et al. 2009). Araya, Kisekka and Holman (2016) mentioned that AquaCrop uses fewer inputs than other crop yield simulation models such as DSSAT and APSIM. Also, the normalization of biomass water productivity estimation made AquaCrop applicable in diverse locations and seasons (Steduto et al. 2009). Steduto et al. (2009) also mentioned that another distinguishing feature of AquaCrop is that it uses canopy grown cover (CC) instead of leaf area index (LAI) as the basis to differentiate between evaporation and transpiration.

Steduto et al. (2009) stated that the main growth engine for AquaCrop to predict the crop yield is the water-driven growth model that calculates the transpiration in the 1st stage and translates it into biomass in the 2nd stage, using conservative crop specific parameters and climate parameters. The fundamental implication of such a water driven growth approach is that it improves the robustness and generality of the model (Steduto et al. 2009). In fact, Stricevic et al. (2011) found that AquaCrop can be used with a high degree of reliability in water management and estimation of yield with regard to climate change.

The AquaCrop model emphasizes the fundamental processes of crop growth productivity and crop water stress caused by water deficit. Consequently, AquaCrop has been successfully applied to various crops in different geographical locations for economic assessment or yield estimation (Foster et al. 2014; Foster, Brozović and Butler 2015b; Zhang et al. 2013). Ultimately, the suitability and flexibility of AquaCrop for various crops and geographical locations has been a major motivation for my using the model in this study (A. Araya et al. 2016; Heng et al. 2009; Mebane et al. 2013; Stricevic et al. 2011).

2.2 Irrigation schedule and Management Allowed Deficit (MAD)

The supply of water for irrigated farms essentially comes from rainfall and groundwater irrigation. The groundwater irrigation application is affected by many factors such as weather, crop, water availability, irrigation system, soil characteristics, climate settings and economics (Stegman 1983). Additionally, applying groundwater irrigation can be managed by irrigation schedule, which determines the amount of water applied to the field at different times throughout the growing season (Broner 2005).

The irrigation schedule emphasizes the timing criteria of irrigation water application, and the allowable root zone soil water depletion is the most popular method for the irrigation schedule (Stegman 1983). Such a schedule may preclude the farmer from experiencing crop yield loss due to over-irrigating or under-irrigating. Broner (2005) stated that over-irrigation would drain away of soil nutrition to below the root zone, waste energy, and labor, fail to use water effectively, reduce soil aeration and decrease crop yields. Meanwhile, under-irrigation could cause water-stress to the crop that would severely reduce crop productivity.

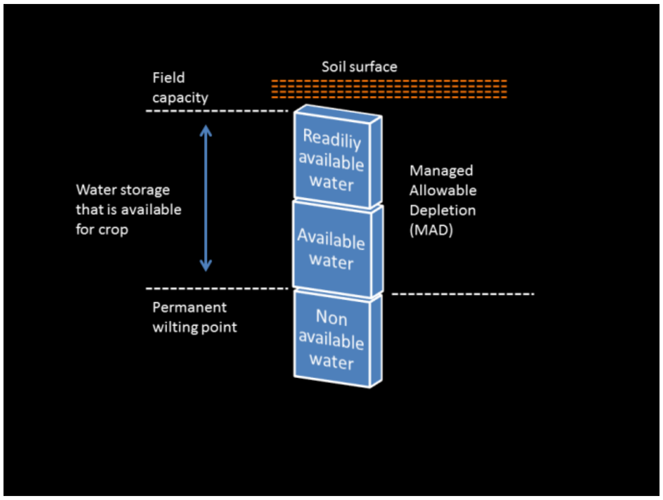
An appropriate irrigation schedule is imperative as each crop has different needs water and response to the quantity of water for each growth stages. For example, corn is more responsive to water during its development stage rather than its initial stage. In addition, corn is a water sensitive crop, so if water is not sufficiently delivered at the right time and in sufficient quantity; it will severely affect the corn yield as crop water stress occurs.

Bras and Cordova (1981) stated that the decision for water irrigation is made at each crop growth stage by comparing its benefit with cost in terms of yield increasing. For example, applying more water during growing season may not always give a positive result. Indeed, application of water for a given growth stage may depend on water demand and application in other growth stages. Thus, holding water irrigation application constant for other crop growth stages but over-irrigating during the vegetative stage in the dry season would reduce crop yield (Peterson and Ding 2005). Therefore, water as an input that increases yield variability may not hold if it is not applied with suitable timing and in sufficient quantity. Thus, sufficient timing and quantity of irrigation water are imperative in maximizing net crop returns.

The irrigation schedule criterion most widely used is based on setting the soil moisture content. The management of soil moisture will enable a crop to retain sufficient water and avoid crop water stress. Another advantage of maintaining soil moisture level is to avoid costly over-water use and reduce the risk of nutrient leaching (Broner 2005). The irrigation schedule method can be used to predict optimal water use for water allocation analysis. Specifically, previous studies (Foster et al. 2014; Foster et al. 2015b; Upendram et al. 2015; Heeren et al. 2011; Igbadun et al. 2008) have used an irrigation schedule based on soil moisture management, MAD, to find the optimal water allocation.

Irrigation keeps the soil moisture content suitable for crop growth by setting the management allowed deficit (MAD) to a specific level depending on soil and crop characteristics. MAD is the level of water content available in the soil that allows depletion until the next irrigation (Tariq and Usman 2009). In particular, MAD shows the available water that can be extracted from the soil until the permanent wilting point (see figure 2.1). Ultimately, the magnitude of crop yield losses due to water shortages is equivalent to the effect of soil moisture deficiency (Bras and Cordova 1981), which is why irrigation keeps the soil moisture above the given allowable depletion level. However, maintaining soil moisture at optimum MAD depends on water availability to avoid severe crop yield loss.

Figure 2.1 Management Allowed Deficit (MAD)



Computer programming has brought the water balance method of the irrigation schedule to the front line of irrigation management (Stegman 1983). This is because computer software can more carefully adjust the daily biophysical crop simulation model to predict the growth of plants, the crop's need for water, and crop yield. My study uses AquaCrop to schedule a hypothetical irrigation program based on setting the MAD level for each crop growth stage. AquaCrop estimates the soil water content by calculating for evapotranspiration (ET) (Steduto et al. 2009) to allow us to estimate the irrigation schedule for a given MAD using the weather forecast. Using such crop predicting software as a tool for irrigation scheduling seems very reliable for use with an automated irrigation system. The automated irrigation system uses soil water measurement tools (tensiometer, psychrometer, gravimetric, etc.) as part of the irrigation schedule, which works similarly to an irrigation schedule like AquaCrop’s, and which approximates how farmers actually manage irrigation.

2.3 Limited water availability

Foster et al. (2014) mentioned that most research had underestimated the impact of limited water availability by not adequately accounting for the impact of dynamic trajectory of groundwater depletion on agricultural production decisions. Meanwhile, there is an escalating problem of limited water availability mainly due to groundwater depletion (Buchanan et al. 2001). Failure to account for the effect of limited water availability will lead to inaccurate predictions for cropping strategies and underestimation of the effect of groundwater depletion on crop production.

Two factors limit water availability: (i) well capacity and (ii) water constraint policy. Well capacity is the amount of water that can be pumped in a given period of time, thus limiting the instantaneous rate of water applied in each irrigation cycle. Understandably, well capacity and instantaneous rate determine the time lag for an irrigation cycle. In the case of low well capacity and high instantaneous rate, that high rate creates a long time lag for the next irrigation cycle, which in turn may result in crop water stress and crop yield loss, as water depletion in the root zone may occur below the allowable depletion level before a farmer can trigger the next irrigation cycle. Next, water constraint policy addresses the limit of total water that can be extracted in a period of time either annually or assessed over a specified period of time. For example, most irrigators in Kansas are constrained to 24 inches per authorized acre for one growing season (Peterson and Ding 2005). There are also other water constraint policies such Sheridan 6 LEMA and Walnut Creek IGUCA that exact more binding constraints. However, both policies offer flexibility to farmers for managing the total water extracted on a 5-year basis.

Given that well capacity is affected by saturated thickness and hydraulic conductivity (Hecox, P. A. Macfarlane and Wilson 2002), the saturated thickness in the high plains aquifer is decreasing as groundwater sources are depleted over time due to agricultural irrigation (Buchanan et al. 2001). In turn, the decrease in saturated thickness reduces the water table elevation and potential extractable water, which results in lower well capacity (Hecox, P. A. Macfarlane, et al. 2002). The water that can be extracted from groundwater also depends on sediment type and distribution, which is called as hydraulic conductivity. An aquifer composed of clean sand and gravel, shown by lower hydraulic conductivity, will result in greater and more sustained well capacity (Hecox, P. A. Macfarlane, et al. 2002).

Well capacity may affect a farmer's decision on farm and irrigation strategy in various ways. O'Brien et al. (2001) indicated that a farmer might prefer to use a center pivot sprinkler system as it offers more profit than a furrow surface system if the irrigation system capacity falls below moderate level. Similarly, Peterson and Ding (2005) found that a farmer may prefer sprinkler irrigation to furrow if the farmer has below moderate level well capacity. However, a farmer may prefer a less efficient and less expensive irrigation system if there is high well capacity (Peterson and Ding 2005). Foster et al. (2014) found that a farmer with low well capacity who may be concerned about production risk will reduce water use by reducing irrigated acreage rather than irrigation intensity. Other studies emphasize the role of deficit irrigation (i.e., reducing irrigation intensity) to deal with limited water availability (Ali et al.

2007; English 1990; English and Raja 1996; Geerts and Raes 2009; Klocke et al. 2010). Previous studies use various optimization analysis methods in finding farmer decision on optimal irrigation strategy affected by limitation in well capacity.

Peterson and Ding (2005) use continuous optimization to determine best irrigation strategies with limited well capacity. Other studies (Foster et al. 2014; Foster et al. 2015a; Upendram et al. 2015) find the effect of well capacity proportional to optimal irrigation strategies by applying discrete optimization, which generates numerous possible options of irrigation strategies by assuming uniform soil moisture level in all growth stages (Foster et al. 2014; Foster et al. 2015a; Upendram et al. 2015). However, each of these studies uses a biophysical crop simulation model, which identifies different crop water response by growth stages. Thus, the assumption of uniform soil moisture level may lead to water over-use. The uniform soil moisture level for all growth stages assumes that the farmer assigned the same importance to each growth stages of crop development. However, the need for water for each growth stage is different. For instance, corn requires the most water during the reproductive (vegetative) growth stages. Therefore, a lot of water during the maturation stage will not significantly increase crop yield only the total water use. Alternatively, my study will use uniform and non-uniform soil moisture level for discrete optimization. A non-uniform soil moisture level, shown by a different MAD level for each growth stage, will allow the farmer to use different amounts of water for different growth stages. The non-uniform soil moisture level also emphasizes deficit irrigation by focusing more water on the most productive growth stage. Notably, deficit irrigation may generate greater profitability especially in the case of more limited water availability.

Water constraint policy will affect a farmer’s decision on irrigation management especially the farmer with high well capacity (Foster et al. 2014; Peterson and Ding 2005). Obviously, the water constraint policy is not a limiting factor for the farmer with low well capacity (Foster et al. 2014; Peterson and Ding 2005). Previous studies (Foster et al. 2014; T Foster, Brozović, et al. 2015a; Peterson and Ding 2005; Upendram et al. 2015) assume that the amount of water that can be extracted is governed by well capacity and annual water constraint. My study will apply a more flexible water constraint, one not only accounted for on an annual basis but also for specific period bases, such as a 5-year average time constraint. The period based water constraint policy will give a farmer more flexibility in managing irrigation strategies while adapting to weather uncertainty. Furthermore, the period based water constraint policy is motivated by the enforcement of Sheridan 6 LEMA and Walnut Creek IGUCA.

2.4 Adjustment in extensive and intensive margin

A farmer can use any of numerous irrigation strategies to adapt to limited water availability. The most common adjustment is reduced demand for water irrigation through intensive margin, extensive margin, and crop switching (D. Martin et al. 1989). The irrigation strategy that a farmer will choose depends on the severity of the water availability limitation problem.

The optimization of water irrigation through irrigated area adjustment is called adjustment at the extensive margin. For example, in the early stage of a growing season, a farmer may decide a portion of land will be irrigated or kept for rainfed cropping depending on water availability. This assumption is based on a farmer not having dependable information about future weather and therefore water demand. In this case, the portion of irrigated acreage and well capacity will determine the maximum instantaneous rate of application for a given period of time. A standard engineering formula can be used to calculate the upper bound of irrigation application rate for water use optimization research (Foster et al. 2014; Peterson and Ding 2005).

Adjustment in intensive margin is an irrigation strategy that optimizes water per acre of irrigated area. Reducing such irrigation water depends on water availability and precipitation. For example, one of the adjustment intensive margins is deficit irrigation, which will use less water but avoid crop stress at critical growth stages (Geerts and Raes 2009; Pereira, Oweis and Zairi 2002). Deficit irrigation can be managed by using uniform intensive irrigation or non-uniform intensive irrigation, and both techniques can be triggered using soil moisture level, or Management Allowed Deficit (MAD) (Vico and Porporato 2011b). Vico and Porporato (2011a) mentioned that deficit irrigation is expected to increase water productivity without causing a severe drop in crop yield. This is because such irrigation considers a minimum soil moisture level that needs to be maintained to avoid severe crop water stress.

Uniform soil moisture applies the same MAD level for all crop growth stages while non-uniform soil moisture applies a different MAD level for each crop growth stage. In fact, the non-uniform soil moisture method is governed by most crops needing different water productivity for each growth stage. Consequently, limiting water supply in the drought-sensitive growth stage may maximize the water application and crop productivity and stabilize crop yield rather than maximize the yield (Geerts and Raes 2009)

Ultimately, a trade-off between adjustment in extensive and intensive margin exists, according to English (1990). Thus, the marginal benefit of increasing irrigation acreage must equal the marginal benefit of increasing irrigation intensity (Wang and Nair 2013). Wang and Nair (2013) also stated that the maximum water resource rent is acquired when the return is equal for intensive and extensive margins. In the case of low water supply, shown by lower well capacity, the crop producer will change irrigated acreage to maintain a particular irrigation intensity that maximizes the marginal benefit of water. Likely, the crop producer will concentrate water into a fraction of farmland that can generate a maximum marginal benefit of water.

O'Brien et al. (2001) stated that in response to well capacity declining a crop producer typically reduces the irrigated acreage to the extent of being able to provide sufficient water for crop growth. A farmer may focus the strategy on adjustment in the extensive margin but still maintain adequate water for crop growth through adjustment in the intensive margin in response to the decrease in well capacity. Thus, limited water availability may yield optimal water allocation by reducing the irrigated acreage and focusing the available water on smaller irrigated acreages (D. Martin et al. 1989; Nair, Maas, et al. 2013). Baumhardt et al. (2009) stated that a farmer might concentrate available water on a portion of a field with a complementary non-irrigated area to maintain optimal water use efficiency. Moreover, evidence shows a farmer may optimize water for intensive irrigation by applying deficit irrigation when faced with limited water availability (Heeren et al. 2011; English 1990). Panda, Behera and Kashyap (2004) stated a minimum MAD level for irrigation schedules that a farmer should attain to avoid severe crop yield loss. Such a farmer may focus the available water for irrigation during the most productive (vegetative) growth stage (Heeren et al. 2011; Nair, Wang, et al. 2013). My study suggests that the non-uniform MAD is an intensive adjustment strategy to account for different crop water productivity at each growth stage. The non-uniform MAD may also work for a deficit irrigation strategy.

Previous studies used varied irrigation strategy choices in the optimization analysis (Baumhardt et al. 2009; Foster et al. 2014; Heeren et al. 2011; Nair, Wang, et al. 2013; Peterson and Ding 2005). For example, Foster et al. (2014) applied uniform soil moisture level for all crop growth stages and assumed non-irrigated acreage do not have any value. Foster et al. (2014) also assumed that intensive margin decisions can be characterized by constant soil moisture level for the whole growing season. However, previous studies found that the optimal level of soil moisture is different for each growth stage (Doorenbos and Kassam 1979; Payero et al. 2009). Meanwhile, Baumhardt et al. (2009) offered an even simpler strategy by using only fixed net irrigation application in their irrigation schedule. However, fixed net water application may cause irrigation water to have low marginal productivity. Meanwhile, Heeren et al. (2011) include both uniform and non-uniform soil moisture level as intensive irrigation choices. Earlier, Peterson and Ding (2005) found the optimal water allocation for different irrigation technologies by assuming the farmer does not change the irrigated acreage. Alternatively, my study will have adjustment in the extensive margin, the intensive margin with uniform soil moisture level, and the intensive margin with non-uniform soil moisture level in the decision model. The adjustment in intensive margin with non-uniform soil moisture level may enable the farmer to prioritize the allocation of groundwater irrigation based on crop growth stage. Consequently, my findings for the optimal irrigated acreage and profit may be larger than what previous studies found (Baumhardt et al. 2009; Foster et al. 2014). Notably, my study does not consider crop switching as an alternative choice to deal with limited water availability. D. Martin et al. (1989) stated that crop allocation is a viable option to deal with limited water supply when the farmer is facing a multi-year allocation system. However, I am not analyzing multi-year optimal allocation; instead, I am basing my model on only a one-period decision.

2.5 Adoption of more efficient and modern irrigation technology

Converting to more efficient modern irrigation technology may improve irrigation water use, crop yield, and farm returns. This is because such technology has higher water efficiency and delivers more water to the crop root zone. Moreover, an irrigator benefits from a more efficient system through crop yield increasing. However, the higher investment cost in modern irrigation technology may offset the benefit of higher revenue from crop yield increasing and lower irrigation cost (Frisvold and Deva 2012). Thus, the high investment cost may hinder a farmer's decision to adopt a modern irrigation technology. Caswell and Zilberman (1985) stated that the economic consideration of cost saving has a significant impact on new irrigation technology adoption. Therefore, the higher irrigation efficiency from modern irrigation technology does not always encourage the farmer to adopt it (Caswell and Zilberman 1985; Peterson and Ding 2005).

In fact, irrigation technology choice is heavily dependent on elasticity of marginal productivity of water (EMP) (Caswell and Zilberman 1986). Given that modern irrigation technology can increase irrigation efficiency directly, Caswell and Zilberman (1986) mentioned that a farmer would adopt the irrigation technology that offers the highest quasi-rent per acre. Thus, modern technology is more likely found on a farm with expensive water, low well capacity, and low soil quality (Caswell and Zilberman 1986; O'Brien et al. 2001).

The effect of more efficient and modern irrigation technology adoption to water use is ambiguous (Caswell and Zilberman 1986; Peterson and Ding 2005). For instance, Caswell and Zilberman (1986) stated that such technology would result in higher water use per acre if water use of the previous technology had low EMP and resulted in lower water use per acre in high EMP cases. Moreover, in the case of low EMP, adopting more efficient irrigation technology would increase land and water productivity greatly, resulting in farmers increasing water use per acre. In the case of high EMP cases, more efficient irrigation technology would have less impact on the increase in land and water productivity as the increase in irrigation efficiency may reduce the water use per acre (Caswell and Zilberman 1986). Ding and Peterson (2012) found that more efficient irrigation technology is more effective in reducing water use in areas with higher saturated thickness, for example in areas with high well capacity.

My study examines how the change in well depth might affect a farmer's decision to adopt more efficient technology. My study also examines how more efficient irrigation technology and groundwater depletion may affect water use. Previous studies included an annual water constraint that limits irrigation water use (Foster et al. 2014; Peterson and Ding 2005; Upendram et al. 2015). However, this study will examine the effect of both well capacity declining and flexibility in water constraint policy in relation to a farmer's decision to adopt more efficient technology. The flexibility in water constraint refers to 5-year average total water use. The main objective is to determine which would be the key factor in a farmer deciding to adopt a more efficient and modern irrigation technology that could modulate the problematic severity of the limit on water availability.

2.6 Decision under risk and uncertainty

Boggess et al. (1983) mentioned many possible objectives as a means of representing farmer decision regarding optimal irrigation strategies given risk and uncertainty. He simulated optimal irrigation strategy with different objectives such as maximizing net return, maximizing average yield per unit water, and maximizing yield. Consequently, he found a different optimal irrigation strategy for a different objective. Other studies used maximizing average net return (D.

Martin et al. 1989; D. L. Martin et al. 1989; Nair, Maas, et al. 2013; O'Brien et al. 2001) or certainty equivalent (Bernardo 1988; Foster et al. 2014; Nair, Wang, et al. 2013; Upendram et al. 2015) as the objective for irrigation planning.

This study uses an expected utility maximizing model to determine a farmer's optimal strategy for risk and uncertainty. The objective of the model is to maximize expected utility of a Von Neumann-Morgenstern utility of net return. This net return assumes the law of diminishing marginal utility $(u'(\pi) > 0 \; and \; u''(\pi) < 0)$. The expected utility analysis assumes that a farmer is not only concerned with expected net return but also the dispersion of net return around its expected value (Chavas 2004). In sum, the farmer's risk preference is represented by his or her utility function, which the farmer uses to decide how to maximize the expected utility.

Chavas (2004) stated that maximizing the expected utility is equivalent to maximizing the certainty equivalent. Thus, the certainty equivalent will be used to measure the robustness of the optimal risk efficient irrigation strategy. For a particular utility function, the certainty equivalent is the amount of payoff that a farmer would determine to be between that payoff and risky irrigation strategy. Comparing irrigation strategies for the certainty equivalent should yield the best optimal risk efficient irrigation strategy.

The choice of utility function may affect the finding of the simulated optimal irrigation strategy. For instance, my study assumes that a farmer has constant absolute risk aversion (CARA) and that the negative exponential utility is used to represent the CARA utility function. The CARA utility function has the benefit of flexibility for different decision makers' risk preference. Tsiang (1972) stated that the approximation using the CARA utility function is appropriate if the risky choice is relatively small compared to the decision maker's total wealth.

Accordingly, our study will analyze a hypothetical 160 acres of land owned by the farmer, which is small compared to the average land parcel owned by a Kansas farmer.

Study results vary concerning the effect of risk preference on farmer irrigation strategy and water use. Boggess et al. (1983) found that the risk-averse attitude induces a farmer to irrigate less frequently and use smaller amounts of water compared to the optimum irrigation strategy. Similarly, Peterson and Ding (2005) also found that a farmer with risk-averse behavior may choose to use less water when less is available. Furthermore, the farmer may reduce the water applied during preplant and vegetative growth stages as using more water may increase yield variability. However, another study found evidence that the risk-averse attitude may induce a farmer to apply more irrigation to reduce the incidence of low yield or high variability in net returns (Bernardo 1988).

The absolute risk aversion coefficient (ARAC) is often used to represent farmer risk preference in published studies (Nair, Wang, et al. 2013; Williams et al. 2014). This ARAC value shows the effect of risk aversion on farmer irrigation and farm strategy. Those studies assume the same range of ARAC for different well capacities. However, Babcock, Choi and Feinerman (1993) mentioned that the ARAC value does not convey enough information about whether the implied risk aversion is reasonable. Specifically, different well capacities may have different mean and variance of net return so that same value of ARAC may represent different risk preference for different well capacity. Also, any particular value of ARAC is possibly reasonable for a farmer with a particular well capacity but not for another farmer with a different well capacity. Clearly, the choice of the ARAC value is important to define the range of sensible risk preference behavior that a given farmer may possess. Thus, the choice of a sensible upper bound ARAC value for a farmer based on well capacity is necessary.

Babcock et al. (1993) introduced a method using risk premium and probability premium to estimate “sensible” risk preference for a decision maker with the CARA utility function. The Babcock et al. (1993) method will show that farmers with the same risk premium and probability premium but different well capacity may have different ARAC. This study will compare the upper bound of ARAC from the Babcock et al. (1993) method to the upper bound of ARAC generated from Mccarl and Bessler (1989). Mccarl and Bessler (1989) introduced three procedures for estimating the upper bound of ARAC in the case of unknown utility function. Comparing those methods will limit the maximum level of the absolute risk aversion coefficient (ARAC) that can be used in the analysis.

Chapter 3 - Research methodology

This chapter focuses on models and procedures I used to predict the optimal irrigation strategy given limited water availability. The research procedures and the steps in the analysis are detailed along with the model assumptions. My study considers a risk averse farmer who seeks to maximize expected utility by choosing the optimal soil moisture trigger for irrigation (i.e., management allowed deficit), the instantaneous rate of irrigation, the acres to irrigate, and the irrigation technology. I do not consider alternative cropping patterns and restrict the analysis for irrigated acreage to corn. This is because corn planted areas account for 19.8% of total all planted acreage and 59.44% of total all irrigated acreage (NASS 2016a). To simplify the modeling, the non-irrigated acreage is assumed to generate income through leasing.

The expected utility theory in this study is described in Section 3.1, which also describes the mean-variance analysis and stochastic efficiency with respect to function (SERF) to rank risky alternative strategy. Section 3.2 then explains the formulation of the producer decision-making model. Section 3.3 discusses adjustment to both intensive and extensive margins that will be generated as possible irrigation strategy choices for the producer. Next, Section 3.4 addresses meshing the producer decision-making model from Section 3.2 with discrete simulation optimization. Section 3.4 also describes the AquaCrop model, including weather and soil data,, used as the crop yield predictor in the discrete simulation model and therefore the production function in this study. I also discuss parameter assumptions to calculate net returns in Section 3.4. Section 3.5, then describes estimated welfare loss of limited water availability through either reduced well capacity or water constraint policy. Section 3.6 discusses how to estimate absolute risk coefficient using risk premium and probability premium. The final section 3.7 discusses the model validation on crop yield and expected net returns.

3.1. Expected Utility

This study uses a utility maximizing model to find the optimal irrigation strategy. This is because uncertainty in agriculture profitability is mainly because of random weather change and volatility in crop prices. My study examines the optimal irrigation strategy for a particular year given uncertain weather and simplifies the model by assuming price certainty. Granted, price uncertainty is likely to be a more important consideration for decisions made across growing seasons (e.g., irrigation technology and capital purchases) rather than for a single growing season (e.g., irrigation intensity and chemical purchases) ; however, farm output is a random variable when the agricultural inputs are chosen. Thus random agriculture output can be represented by a stochastic production function (Chavas 2004) shown as:

$$y = f(x, \mu) \tag{3.1}$$

where y is output, x is input, and μ is a random variable representing the uncertainty in production.

Next, the farmer's subjective probability distribution of the uncertainty (μ) would be generated from information gathered before growing season begins. My study assumes that farmer has uniform probability for all conditions and that he would use his subjective probability to decide inputs and predict output. Thus, the farmer will choose inputs to maximize the expected utility of wealth (Chavas 2004) shown as:

$$Max_x EU(\pi, r) = Max_x \{EU([pf(x, \mu) - \textstyle\sum_{i=1}^{N} c_i x_i], r)\} \tag{3.2}$$

where p is output price, r is absolute risk aversion coefficient, c_i is the price of input i, and π is wealth. Chavas (2004) states that maximizing the expected utility is equivalent to maximizing the certainty equivalent. Alternatively, the farmer's decision on input can be shown (Chavas 2004) as:

(3.3) $$Max_x\, CE \; = Max_x\{E[pf(x,\mu)] - \sum_{i=1}^{N} c_i x_i - R(x,.)\}$$

where $R(x,.)$ is the risk premium. The risk premium (R) is the minimum amount of money that would make the producer feels indifferent about a risky asset versus a risk-free asset. The risk premium (R) also can be interpreted as the producer's willingness to insure against risk and can be regarded as the implicit cost of private risk bearing. The necessary first order condition for maximizing the certainty equivalent (Chavas 2004) is:

(3.4) $$\frac{\partial E[py(x,\mu)]}{\partial x_i} = c_i + \frac{\partial R(x,.)}{\partial x_i}$$

The necessary first order condition of maximizing certainty equivalent in Equation 3.4 shows that the expected marginal value product of input ($\frac{\partial E[py(x,\mu)]}{\partial x_i}$) is equal to input cost (c_i) and marginal risk premium at optimal input chosen($\frac{\partial R(x,.)}{\partial x_i}$) (Chavas 2004). From maximizing expected utility of wealth and maximizing certainty equivalent, the marginal risk premium can be also defined (Chavas 2004) as:

(3.5) $$\frac{\partial R(x,.)}{\partial x_i} = -Cov\{U'[\frac{p\partial f(x,\mu)}{\partial x_i}\}/EU'$$

Equation 3.5 shows that the marginal risk premium ($\frac{\partial R(x,.)}{\partial x_i}$) represents the effect of input on the implicit cost of private risk bearing (Chavas 2004). The covariance term ($-Cov\{U'[\frac{p\partial f(x,\mu)}{\partial x_i}\}/EU'$) in the right hand side of Equation 3.5 measures the marginal effect of input i on the implicit cost of private risk bearing (Chavas 2004). The covariance term also shows how input may reduce or increase the implicit cost of risk, providing an incentive for the farmer to reduce or increase input use. The sign of marginal risk premium ($\frac{\partial R(x,.)}{\partial x_i}$) indicates whether input x_i is risk increasing ($\frac{\partial R(x,.)}{\partial x_i} > 0$) of risk reducing($\frac{\partial R(x,.)}{\partial x_i} < 0$). A farmer who is risk averse will use more input if the input reduces the implicit cost of private risk bearing ($\frac{\partial R(x,.)}{\partial x_i} < 0$) and less input if the input increases the implicit cost of private risk bearing($\frac{\partial R(x,.)}{\partial x_i} < 0$) (Chavas 2004). Based on this assumption, I expect that risk-averse behavior will induce the farmer to increase water use because water is an input that reduces the implicit cost of private risk bearing.

Also, I assume that the farmer has CARA risk behavior, which implies that the absolute risk aversion coefficient (r) is independent of initial wealth(π). CARA also implies that initial wealth (π) does not influence individual willingness to insure against risk (Chavas 2004). Thus the expected utility corresponding to negative exponential utility for a given risk absolute coefficient (r) is shown as:

(3.6)
$$EU(r) = \sum_{i=1}^{T} \left(\frac{1}{T}\right) [1 - e^{-r * \pi_t}]$$

where T is all possible conditions that may occur. The probability of ($\frac{1}{T}$) shows that we assume the farmer has uniform probability for all conditions. Chavas (2004) stated that under the CARA assumption and normality in wealth(π_t), maximizing expected utility [EU(.)] is globally valid with a maximizing certainty equivalent as shown below:

(3.7)
$$\begin{gathered} \max EU(\pi, r) = \max CE = \max E(\pi) - R \\ where\ R = -0.5 \frac{U''}{U'} Var(\pi) \\ r = -\frac{U''}{U'} \end{gathered}$$

Equation 3.7 represent the estimated expected utility or certainty equivalent using Mean-Variance analysis. The decision-maker who has risk averse (r>0) behavior always has the expected income higher than the certainty equivalent; meanwhile, the risk-loving decision maker (r<0) always has the certainty equivalent higher than the expected income. Naturally, an alternative decision strategy with its distribution will be preferred if it offers a higher certainty equivalent or higher expected utility compared to another strategy for the set range of the absolute risk aversion coefficient (r). Accordingly, the Mean-Variance analysis will rank the most preferred irrigation strategy in Chapters 4 and 6.

Another method of estimating the certainty equivalent and expected utility is the Stochastic Efficiency Respect to Function (SERF) model. The SERF method ranks risky alternative strategy for welfare loss analysis in Chapter 5. Notably, the mean-variance analysis has a very restricted condition such that the certainty equivalent and risk premium estimation is only globally valid under normality assumption (Chavas 2004) whereas the SERF method relaxes the assumption of distribution (Hardaker et al. 2004). Therefore, Chapter 5 focuses on welfare loss analysis estimating loss using a utility-weighted risk premium between risky alternatives proposed by Hardaker et al. (2004) and Mjelde and Cochran (1988).

The SERF method identifies efficient utility sets by ordering alternative sets according to the certainty equivalent (CE) over a range of risk aversion coefficients (r) (Hardaker et al. 2004). The certainty equivalent (CE) in my study corresponds to negative exponential utility ($U(x) = 1 - e^{-r*\pi}$), and a given risk averse coefficient (r) is calculated as an inverse function of expected utility as follows:

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

The CE is determined by expected utility and the degree of risk aversion.

This study identifies the irrigation strategy with the highest expected utility or highest certainty equivalent for several different values of the absolute risk aversion coefficient (r). Accordingly, the study used the method proposed by Mccarl and Bessler (1989) to determine the upper bound of absolute risk aversion coefficient (r) and then calculated the corresponding ARAC for particular risk averse behavior by using the method proposed by Babcock, Choi and Feinerman (1993). My study assumes that the lower bound for the absolute risk aversion coefficient (r) is 0 as a farmer is expected to have risk neutral or risk averse behavior but not risk loving behavior. The method of calculating the absolute risk aversion coefficient and upper bound of absolute risk aversion coefficient are discussed in Section 3.6.

3.2. Producer decision-making model

The producer decision-making model can be formulated as follows:

$$\text{Max}_{\{m_d, l,\, \delta, \alpha\}} \frac{1}{T}\sum_{t=1}^{T} U(r, \boldsymbol{\pi_t}) \tag{3.9}$$

$$s.t. \quad w_t = g(\boldsymbol{m_d}, l, \boldsymbol{\theta}_t) \leq q \quad for\ t = 1, \dots, 30 \tag{3.10}$$

$$l * \delta \leq \varphi * \gamma \tag{3.11}$$

where

$$\pi_t = \delta p f\big(\boldsymbol{m_d}, l, \alpha, \tau, \boldsymbol{\theta_t}\big) - \delta c(w_t, \alpha) - d(\alpha) - \delta n * f(.) - \delta * g + (A - \delta)k \tag{3.12}$$

Obviously, the producer faces risk in crop production due to weather uncertainty, which is shown by 30 years of possible weather conditions where years are denoted by t=1,…,30. Equation 3.9 shows that the producer's objective is to find the irrigation strategy that maximizes expected utility as a function of net return ($\boldsymbol{\pi_t}$) and risk-aversion coefficient (r). The producer's strategy concerning irrigation has four components consisting of MAD at each growth stage ($\boldsymbol{m_d}$), instantaneous rate(l), irrigated acreage (δ), and irrigation technology (α). The field irrigated acreage (δ) is referred to later as adjustment in extensive margin. In addition, MAD at each growth stage ($\boldsymbol{m_d}$) and instantaneous rate(l) refer to adjustment in intensive margin. The simulation of net returns will be based on 30 years historical data (1986-2015), t=1,…,30. The probability of $(\frac{1}{T})$ shows that I assume the farmer has uniform probability for all historical time periods.

Equation 3.10 shows the total irrigation water(w_t); irrigation intensity that can be applied during a growing season is limited by water constraint policy (q) imposed by the government. The total irrigation water $(\boldsymbol{w_t})$ depends on MAD from each growth stage (m_d), instantaneous rate (l), and weather conditions $(\boldsymbol{\theta}_t)$. My study assumes four crop growth stages for corn, denoted by d = 1,…,4.

Equation 3.11 expresses the irrigation constraint due to limitation in well capacity, which later is referred to as well capacity constraint. Equation 3.11 shows the total irrigation each day cannot exceed as the maximum water extraction per day. Total irrigation per day on the left-hand side is the instantaneous rate (l) times the irrigated acreage (δ). The instantaneous rate is the total maximum amount of water that can be applied per irrigated acre per day. On the right-hand side, the maximum water extraction per day is the well capacity (φ) times the maximum duration of extraction per day (γ). Equation 3.11 implies that a farmer with a particular well capacity may need to decrease irrigated acreage to increase the instantaneous rate. In addition, Equations 3.10 and 3.11 show that the total irrigation water $(\boldsymbol{w_t})$ also depends on irrigated acreage as the instantaneous rate determined by irrigated acreage.

The first few terms in the net return $(\boldsymbol{\pi_t})$ calculation in Equation 3.12 estimate the net returns from irrigation. The irrigated acreage is shown by δ, and the total area is shown by A. The crop production is denoted by $f(.)$, which, for irrigated acreage depends on MAD from each growth stage $(\boldsymbol{m_d})$, instantaneous rate (l), irrigation technology (α), soil characteristics (τ), and weather conditions$(\boldsymbol{\theta_t})$. The water productivity and irrigation efficiency in irrigated acreage are mainly determined by irrigation technology (α) and soil characteristics (τ). The cost of production in Equation 3.12 comprises irrigation water cost ($c(w_t, \alpha)$), fixed cost of irrigation technology ($\mathrm{d}(\alpha)$), non-irrigation variable cost $\left(\delta n * f(.)\right)$, and non-irrigation production cost based on acreage ($\delta * g$). The non-irrigation variable cost ($\delta n * f(.)$) for irrigated acreage (δ) depends on the crop production($f(.)$). The non-irrigation production cost based on acreage ($\delta * g$) is determined by irrigated acreage (δ) and fixed input cost per acreage of planting(g). The fixed input cost per acreage of planting (g) comprises seed, insecticide/fungicide, herbicide, machinery, crop consulting, non-machinery labor, irrigation labor, interest on non-land cost, and other miscellaneous cost. The irrigation cost ($c(w_t, \alpha)$) corresponds to energy price and total water applied to the field ($\boldsymbol{w_t}$) for each growing season. The irrigation cost is assumed to be independent of land quality. Non-irrigation variable cost ($\delta n * f(.)$) includes fertilizer and machinery harvest charge (extra charge and hauling). The revenue from non-irrigated acreage is shown in the last term and is generated from land leasing, where the rental rate of non-irrigated acreage is denoted by k.

3.3 Adjustment on extensive and intensive margin

Adjustment at the extensive margin is how a farmer allocates total area to irrigated and non-irrigated acreage. Also, any adjustment occurs prior to planting before growing season weather is known. The 160-acre hypothetical field is divided into a maximum irrigation area of a 125-acre crop circle (could be less than a 125-acre irrigate crop circle) and a minimum non-irrigated acreage of a35-acre plot (could be more than a 35-acre non-irrigated plot) for center pivot irrigation. Drip irrigation maximum area is the 160-acre hypothetical field.

The allocation of irrigated acreage is constrained by the instantaneous rate and well capacity. The relationship between maximum irrigated acreage and instantaneous rate for each well capacity is shown in Figure 3.1 for center pivot irrigation. The relation between well capacity, instantaneous rate, and maximum irrigated acreage is estimated using a standard engineering formula shown as follows:

$$\delta = \frac{\varphi * \gamma}{l} \quad (3.13)$$

where δ is irrigated acreage, φ is well capacity, γ is a maximum duration of extracting water per day, and l is the instantaneous rate of application per acre. My study assumes that maximum duration of extracting water per day (γ) is 24 hours. My model allows the farmer to choose any combination of instantaneous rate and irrigated acreage illustrated by the lines in Figure 3.1 as long as the combination is less than or equal to the assumed well capacity.

There are two components of adjustment at the intensive margin: the instantaneous rate and management allowed deficit (MAD). The instantaneous rate and MAD will generate irrigation scheduling. The instantaneous rate is the maximum rate of instantaneous application of water that can be applied in one day (mm/day), which in my research is between 1-16 mm at 1 mm increment[1].

The instantaneous rate corresponds to well capacity and irrigated acreage such that low well capacity may have a large irrigated acreage but a small instantaneous rate, or a small irrigated acreage may have a large instantaneous rate. The relationships among instantaneous rates, well capacity, and irrigated acreage are shown in Equation 3.13. This study considers a wide range of well capacities from 100-1500 GPM (gallons per minute) in 100 GPM increment. The well capacity limits the maximum instantaneous rate of water application and affects the ability to maintain the desired MAD level on irrigated acreage (Foster et al. 2014; Peterson and Ding 2005; Upendram et al. 2015).

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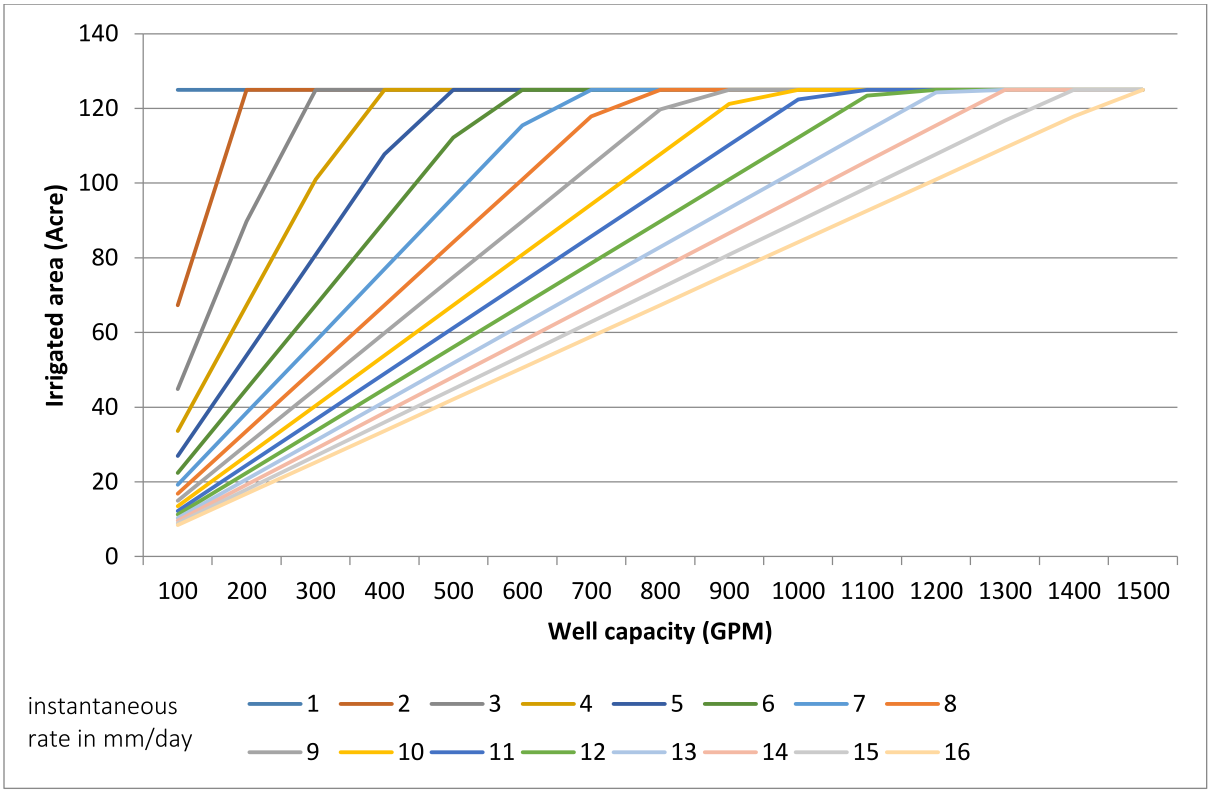
[1] 1 mm increment in the instantaneous rate is the smallest possible instantaneous rate changing in AquaCrop

Figure 3.1 Maximum irrigated acreage size and instantaneous rate of application (mm/day) for different combinations of well capacity (GPM) for center pivot irrigation[2]



The AquaCrop software simulates daily irrigation amounts based on the instantaneous rate to maintain the soil moisture level by setting MAD for each growth stage (i.e., irrigation scheduling). MAD is the maximum amount of total available water (TAW) that is allowed to be depleted from the soil before triggering irrigation. For example, a MAD of 75% means that farmers will allow a maximum of 75% of TAW to be removed from the soil before triggering the irrigation application. Therefore, larger MAD values imply less frequent irrigation.

I allow for various MAD levels for the four different growth stages as illustrated in Figure 3.2: initial stage (emergence); canopy development (max canopy); mid-season stage (senescence); and late-season stage (maturity). The irrigation scheduling combination is

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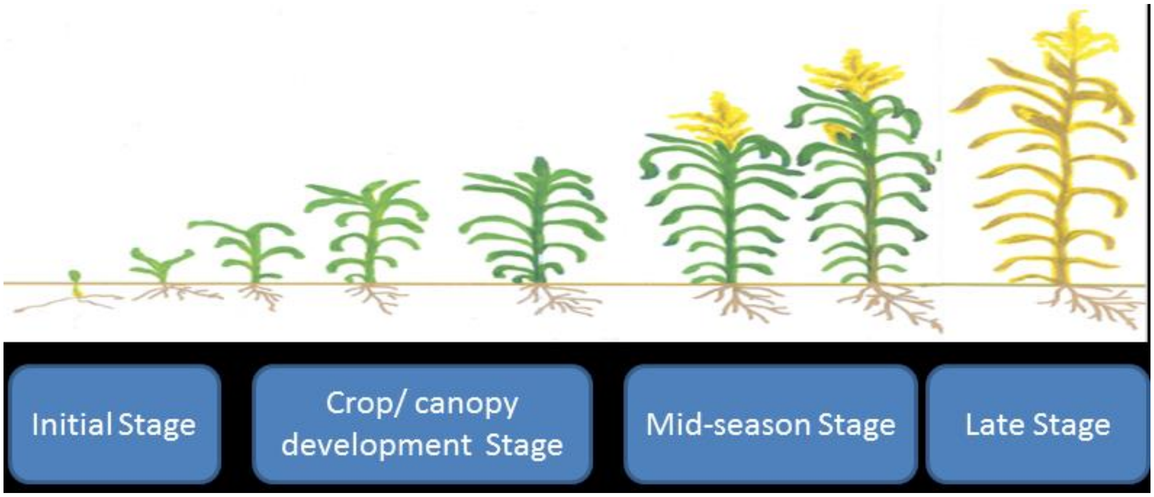
[2] The same graph pattern also found for drip irrigation with maximum irrigated acreage of 160 acres

generated with a range of MAD levels of 0%-100% in 10% increments. Moreover, the ranges of MAD levels apply to all four growth stages. Therefore, the total number of possible irrigation schedules for each instantaneous rate is 14641 (11*11*11*11). Furthermore, the total adjustment in intensive margin for each well capacity is the combination of MAD and instantaneous rates, which offers 234,256 (14641*16) strategies for a single irrigation technology. The instantaneous rate and MAD at growth stage determine the irrigation intensity, where irrigation intensity is defined as the total amount of irrigation water applied per growing season (acre-inches/year). Notably, irrigation intensity varies by the weather of a given year; thus, an irrigation schedule calls for greater intensity in dry years than in wet years. I assume that a farmer sets the irrigation schedule prior to planting when weather is unknown, but the water applied depends on the actual weather in the growing season. This is an important distinction from previous studies that assume the choice of irrigation intensity is fixed so that farmers are restricted to applying the same amount of water in dry and wet years (Llewelyn and Featherstone 1997; O'Brien et al. 2001; Peterson and Ding 2005).

Figure 3.2 Crop growth stage



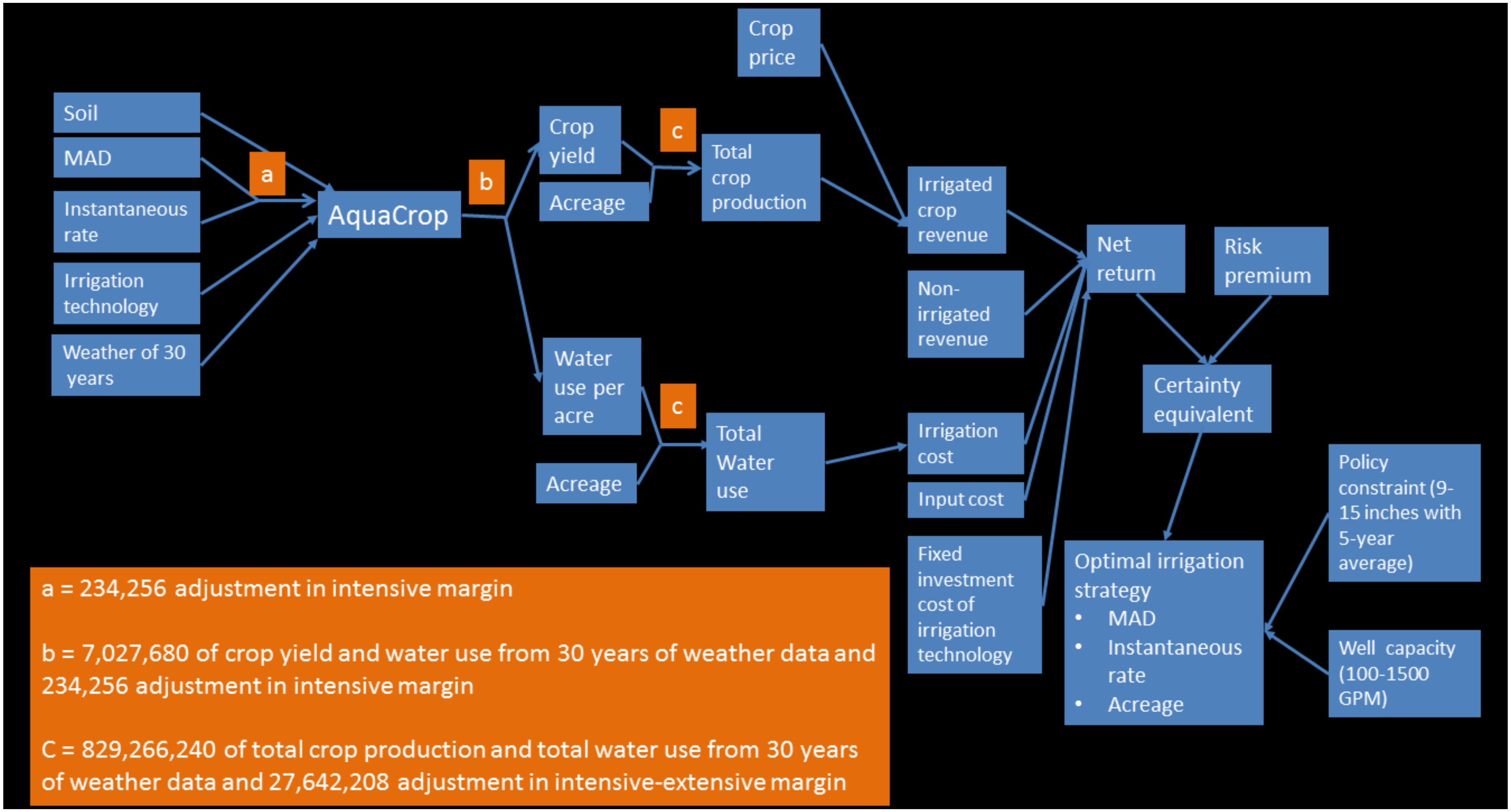
3.4 Discrete simulation model

My study uses discrete optimization with a historical simulation to find the optimal irrigation strategy under risk aversion. Previous studies have estimated optimal water use by using continuous optimization using an annual/seasonal crop water production model (Dinar and Knapp 1986; Llewelyn and Featherstone 1997; Peterson and Ding 2005). In contrast, my study uses discrete optimization because I use a daily biophysical crop simulation model so that continuous optimization is not feasible. The daily biophysical crop simulation model used in this study is AquaCrop.

The annual/seasonal crop water production model does not consider various water application timing and dynamic response of the crop to water (Hexem and Heady 1978). However, daily biophysical crop water production model can capture the dynamic response of the crop to water. All the same, discrete simulation may not result in the optimal solution. To find a solution near the optimum, this study applies a fine grid of potential irrigation strategies—234,256 strategies at the intensive margin alone denoted by ***a*** in Figure 3.3.

Figure 3.3 illustrates the discrete simulation approach. The simulation starts with input data for AquaCrop comprising adjustment at the intensive margin (MAD and instantaneous rate), soil characteristics, irrigation technology, and 30 years of weather data. The daily water uses from intensive irrigation along with soil, irrigation technology and weather data are used to calculate the crop yield and water use per acre using AquaCrop. The crop yield simulation is executed for each combination of MAD and instantaneous rate for 30 years of weather data to generate 7,027,680 observations of crop yield and water use per acre data denoted by ***b*** in Figure 3.3.

Figure 3.3 Discrete simulation model



a = 234,256 adjustment in intensive margin

b = 7,027,680 of crop yield and water use from 30 years of weather data and 234,256 adjustment in intensive margin

C = 829,266,240 of total crop production and total water use from 30 years of weather data and 27,642,208 adjustment in intensive-extensive margin

Adjustment at the intensive with extensive margin generates a combination of 27,642,208 total irrigation strategy combinations from which the producer can choose the optimal irrigation strategy. In addition, the simulation of all irrigation strategy along with 30 years of weather data generates 829,266,240 observations of crop production and total water use, which are denoted by $\boldsymbol{c}$ in Figure 3.3.

The net return is calculated for each strategy for each year of historical weather using total crop production, crop price, non-irrigated revenue, irrigation cost, fixed investment cost, and other input cost. The total irrigation cost is estimated based on total irrigation water use and the price of energy. The parameters of crop price and input cost for net return estimation are presented in detail later in Section 3.4.2. The optimal strategy is selected by choosing the highest certainty equivalent; as mentioned in Section 3.1, maximizing expected utility is equal to maximizing certainty equivalent. The certainty equivalent is calculated for each irrigation strategy as a function of the net returns across the 30 years of historical weather data for a given risk premium. The optimal irrigation strategy comprises MAD and instantaneous rate (intensive margin) and irrigated acreage (extensive margin). I conducted the simulation in Figure 3.3 separately for center pivot and drip irrigation technologies and can compare the certainty equivalent from the optimal strategies to determine the preferred irrigation technology.

I impose the well capacity and water constraint policies by considering only irrigation strategies that satisfy the relevant constraint. For example, for the well capacity, I only consider combinations of irrigated acreage and instantaneous rates that are feasible. The well capacity ranges from 100 to 1500 GPM in 100 GPM increments to reflect the range of well capacities in Kansas. For the policy constraint, I considered only irrigation strategies where the total water use over a given period of time (e.g., each growing season or a 5-year period) is less than or equal to the assumed policy constraint. For example, with a 5-year policy constraint, I exclude any irrigation strategy where total water use in any sequential 5-year period with the historical weather data exceeds the 5-year allocation. Finally, the water constraint policy ranges from 9 to 15 inches in 1-inch increments.

3.4.1 AquaCrop model

This study uses the AquaCrop model to simulate corn yield under different irrigation schedules (e.g., MAD in each growth stage and instantaneous rate). AquaCrop is computer software that simulates crop yield and crop growth based on water received by the crop. The AquaCrop model can be used as an empirical production function for estimating crop yield response to water (Raes et al. 2009). I describe weather and soils data and crop growth parameters used in AquaCrop in this section. I parameterize the model to correspond with characteristics of Garden City, KS in Finney County.

Five climate components are needed to simulate an AquaCrop model: daily rainfall, daily maximum and minimum air temperatures, reference evapotranspiration, and mean annual carbon dioxide concentration in the bulk atmosphere (Raes et al. 2009). Therefore, I obtained thirty years of weather data from Garden City from the weather data library Kansas Mesonet. The weather dataset comprises daily rainfall, daily maximum and minimum air temperatures, relative humidity, and solar radiation for 1986-2015. The carbon dioxide information came from the default AquaCrop data for carbon dioxide concentration. Finally, the reference evapotranspiration (ET_0) for the AquaCrop production estimation was calculated using the software ET_0 calculator (Raes 2012). Thus, the average rainfall during the growing season period for 30 years of data is 11.59 inches.

Soil characteristics and crop growth parameters are necessary for the AquaCrop production model. Therefore, this study uses two types of soil, namely Richfield Silt Loam and Valent-Vona Loamy Fine Sands, because of their large difference in soil water holding capacity and because they comprise a large portion of Finney County. Using the SPAW model and reference number for the soil texture, I calculated the average available water capacity for Richfield Silt Loam is 1.91 in/ft and Valent-Vona Loamy Fine Sands is 0.946 in/ft. According to USDA (1965) Richfield Silt Loam comprises 28.7% of the total area and is the most dominant soil type in Finney County. In addition, according to Web Soil Survey from NRCS (2016) Valent-Vona Loamy Fine Sands also comprises large proportion of soil in Finney County. Based on the soil survey data, we assumed the soil texture properties, using reference parameters, as shown in Table 3.1 below. The soil texture property was used to calculate the soil hydraulic conductivity for AquaCrop using the SPAW model (Saxton and Willey 2005).

Table 3-1 Soil characteristic for Richfield Silt Loam and Valent-Vona Loamy Fine Sands

Soil Type	Depth (inches)	% of Sand	% of Silt	% of Clay
Richfield Silt Loam	0-6	29	53	18
	6-17	9	52	39
	17-25	18	49	33
	25-79	22	52	26
Valent-Vona Loamy Fine Sands	0-8	78	16	6
	8-22	67	20	13
	22-60	64	27	9

3.4.2 Parameter of output and input price

Parameters for the cost of production came from KSU farm management guides developed by Kansas State Research and Extension (O’Brien and Ibendahl 2015) . The cost of production is based on a Southwest Kansas corn farm given 2015 conditions. Therefore, the corn price is assumed at $4.25 per bushel and the pumping cost is assumed at $5.26/inch (O'Brien and Ibendahl 2015) while the non-irrigated cash rental rate is $24.90 per acre (Taylor 2015). The parameters of the production cost are shown in Table 3.2. Importantly, I exclude the irrigated cash rent from the cost of production, so the estimated net returns represent the returns to land.

Table 3-2 The parameters of input cost of production

Input	Cost ($)
Irrigation water pumping cost	5.26/in
Seed, 1,000/acre*	3.96/1,000
Fertilizer	0.69/bushel
Herbicide	
Burndown	12.94/ac
Preemergence	33.73/ac
Postemergence	8.67/ac
Insecticide / Fungicide	
Fungicide	25.36/ac
Insecticide	11.47/ac
Machinery	91.97/ac
Harvest	
Base charge	29.78/ac
Extra charge for yields exceeding	0.25/bu
Hauling	0.2/bu
Non-machinery labor	18/ac
Irrigation labor	7.5/ac
Crop consulting	6.5/ac
Miscellaneous cost	10/ac
Interest on capital	0.065

Source: (O'Brien and Ibendahl 2015)

The cost of irrigation investment came from Lamm, O'Brien and Rogers (2015). I assume the investment cost of center-pivot irrigation based on irrigation system installation for 125 acres and investment cost of drip irrigation installation on 160 acres. The investment cost is assumed to be fixed based on maximum irrigated acreage and the same for all well capacity levels. I assume the investment cost for drip irrigation is proportional to the maximum irrigated acreage. This assumption is based on O'Brien et al. (1998) who estimate an almost linear relationship between irrigation technology investment and irrigation acreage for drip irrigation systems. Finally, Lamm et al. (2015) mentioned that drip irrigation investment cost is proportional to irrigated acreage, but this is not the case with center pivot irrigation.

3.5 Analysis of welfare loss affected by water constraint policy and lower well capacity

The estimation of welfare loss due to a water policy constraint, presented in chapter 5, is estimated as the amount of wealth compensation needed for the farmer to be indifferent to the constraint with compensation and no policy constraint. In particular, I seek to estimate the welfare lost (C) because of water policy constraint as follows:

(3.14) $$EU(\pi_1, W_1) = EU(\pi_2 + C, W_2)$$

where W_1 is irrigation water application without water constraint policy, W_2 is irrigation water application with water constraint policy, π_1 is net return gain without water constraint policy, and π_2 is net return gain with water constraint policy.

As suggested by Mjelde and Cochran (1988), the risk premium can determine the confidence of decision-makers choosing among risky alternatives. The utility-weighted risk premium at a given risk aversion level (r) can be calculated by subtracting the most preferred condition with the less preferred condition (Hardaker et al. 2004). In this study, I assume that the welfare loss (C) in applying water constraint policy is equal to the risk premium of two different risky conditions. Thus, the welfare loss is simply the difference between the certainty equivalent without a constraint and with a constraint:

(3.15) $$C = CE(r, \pi_1) - CE(r, \pi_2)$$

The estimation of welfare loss due to the decrease in well capacity will follow a similar procedure except where π_1 is the net return for higher well capacity and π_2 is the net return for lower well capacity.

3.6 Estimating upper bound and corresponding absolute risk aversion coefficient (r)

Using mean-variance analysis and stochastic efficiency with respect to a function (SERF) for expected utility maximization requires information about the risk aversion coefficient (r) to rank alternatives of risky strategies. In terms of the utility function of the decision maker, the risk aversion coefficient is represented as $-\frac{U''}{U'}$. While it is impossible to directly observe the utility function, several studies use empirical methods to elicit the risk aversion coefficient (r) for farmers in the USA (Brink and Mccarl 1978; Chavas and Holt 1996; Love and Buccola 1991; Saha, Shumway and Talpaz 1994; Atanu 1997). Those studies found different ranges of risk aversion coefficient (r). Indeed, varied estimates regarding risk aversion coefficients is not surprising as those studies most likely used different samples of farmers. Mccarl and Bessler (1989) mentioned that research procedure on ranking the alternative for risk strategies, which uses risk aversion coefficients (r) from other studies, is questionable since every study uses different utility assumptions and wealth levels.

Mccarl and Bessler (1989) introduced a procedure for estimating the upper bound of the risk aversion coefficient (r) given unknown utility function based on three ways of estimating the upper bound risk aversion coefficient (r). The first method is assuming non-negative certainty equivalent and risk premium to be no greater than expected wealth$(r = \frac{2*E(\pi)}{\sigma_\pi^2})$. The other two methods used the confidence interval and assumption on MOTAD analysis to calculate the upper bound of the risk aversion coefficient (r). My study uses the first method of Mccarl and Bessler (1989) to calculate the upper bound of risk aversion coefficient (r). The lower bound is expected to be zero as we assume the farmer has a risk neutral and risk-averse preference.

The risk aversion coefficient (r) is often used in risk and uncertainty models as a parameter to represent the degree of risk-averse behavior. However, the value of the risk aversion coefficient (r) is difficult to interpret without further information (Babcock et al. 1993). The method proposed by Babcock et al. (1993) shows how to interpret the risk aversion coefficient (r) using risk premium and probability premium.

This study will use the method proposed by Babcock et al. (1993) to calculate the risk aversion coefficient (r) and later compare it to the upper bound of risk aversion coefficient (r) from the Mccarl and Bessler (1989) method to get a reasonable range for the risk aversion coefficient (r). Babcock et al. (1993) calculate the risk aversion coefficient (r) value by using risk premium and probability premium for a particular gamble size. A gamble size is represented by the standard deviation of net return; in turn, the deviation shows the uncertainty for a particular strategy that a farmer will choose. The estimation of risk aversion coefficient (r) value using risk premium and probability premium (Babcock et al. 1993) is shown below:

(3.14) $$r\,(\rho,\sigma) = \frac{\ln[\frac{1+2\rho}{1-2\rho}]}{\sigma}$$

such that : (3.15)

$$\omega(\rho) = \frac{\ln[\frac{1+4\rho^2}{1-4\rho^2}]}{\ln[\frac{1+2\rho}{1-2\rho}]}$$

where ω is the risk premium as percentage of gamble size, ρ is the probability premium, and σ is a gamble size shown by standard deviation of net return.

The risk premium together with the probability premium is used to calculate a reasonable risk aversion coefficient (r) value for each well capacity. Different risk aversion coefficient (r) values generated for each well capacity are based on a different gamble size as represented by the standard deviation of net return. The estimation of risk aversion coefficient (r) values for Richfield soil and Valent-Vona soil for each well capacity are shown in Table 3.3.

The risk premium ranged from 10% to 80%. I found that the risk aversion coefficient (r) from a risk premium of 80% does not exceed the upper bound value in the Mccarl and Bessler (1989) method. Therefore, the risk premium of 80% represents the farmer with very strong risk averse behavior. Hudson, Coble and Lusk (2005) calculated the average risk premium for direct elicitation in yield context was about 10.5%. Bontems and Thomas (2000) found that the value of information together with risk premium account for about 20% of profit per acre. Babcock and Shogren (1995) estimated that the production premium accounts for 21-79% of the willingness to pay to eliminate all production risk.

Clearly, the risk aversion coefficient (r) value increases if the risk premium increases (see Table 3.3), meaning the farmer with more risk averse behavior is willing to spend a higher premium to eliminate the risk. For example, a risk premium of 10% indicates that a farmer is willing to spend a maximum of 10% of the total return to eliminate the risk. A higher risk premium indicates that a farmer is willing to spend a larger proportion of total net return to eliminate the risk; thus, a higher risk premium implies more risk averse behavior.

Table 3-3 Risk aversion coefficient (r) value for Richfield soil and Valent-Vona soil

Well capacity (in GPM)	Risk Premium							
	10%		15%		20%		80%	
	RSL	VVS	RSL	VVS	RSL	VVS	RSL	VVS
100	0.0001497	0.0002498	0.0002265	0.0003779	0.0003056	0.0005100	0.0025723	0.0042926
200	0.0000748	0.0001248	0.0001131	0.0001888	0.0001527	0.0002549	0.0012852	0.0021449
300	0.0000499	0.0000832	0.0000754	0.0001259	0.0001018	0.0001699	0.0008568	0.0014297
400	0.0000374	0.0000624	0.0000566	0.0000944	0.0000764	0.0001274	0.0006426	0.0010721
500	0.0000299	0.0000499	0.0000453	0.0000755	0.0000611	0.0001019	0.0005141	0.0008577
600	0.0000269	0.0000416	0.0000406	0.0000629	0.0000548	0.0000849	0.0004616	0.0007148
700	0.0000271	0.0000384	0.0000410	0.0000581	0.0000553	0.0000784	0.0004658	0.0006600
800	0.0000339	0.0000535	0.0000513	0.0000810	0.0000692	0.0001093	0.0005825	0.0009202
900	0.0000408	0.0000610	0.0000618	0.0000923	0.0000834	0.0001246	0.0007016	0.0010484
1000	0.0000455	0.0000595	0.0000688	0.0000900	0.0000929	0.0001214	0.0007815	0.0010218
1100	0.0000473	0.0000573	0.0000716	0.0000867	0.0000966	0.0001170	0.0008133	0.0009843
1200	0.0000486	0.0000577	0.0000735	0.0000872	0.0000992	0.0001177	0.0008347	0.0009908
1300	0.0000505	0.0000573	0.0000764	0.0000868	0.0001031	0.0001171	0.0008676	0.0009854
1400	0.0000513	0.0000617	0.0000777	0.0000933	0.0001048	0.0001260	0.0008822	0.0010603
1500	0.0000517	0.0000600	0.0000783	0.0000908	0.0001056	0.0001225	0.0008892	0.0010312

RSL=Richfield soil , VVS=Valent-Vona soil

A negative correlation exists between risk aversion coefficient (r) value and standard deviation of net return for a particular risk premium. The risk aversion coefficient (r) value for Richfield soil steadily increases with well capacity in the case of full-irrigated acreage (well capacity higher than 600 GPM). In particular, the ARAC values for a particular risk premium are found to be lower for Richfield soil than for Valent-Vona soil in all well capacity levels. This is because Richfield soil has a larger standard deviation of net returns than Valent-Vona soil.

3.7 Model validation

I use crop growth parameters for AquaCrop that have been calibrated based on actual crop production data under limited irrigation conditions in Garden City (A Araya et al. 2016).

The crop statistical validation results show significant goodness of fit for AquaCrop on calibration datasets (A Araya et al. 2016).

The estimation of crop yield using AquaCrop does depend on crop growth parameters. I am estimating regression analysis of corn yield using NASS (2016b) data from 1972-2010 for Finney Country, I estimate in-sample analysis for the corn yield in 2010 is at 199 bushels per acre. The AquaCrop simulation shows the average corn yield from optimal irrigation scheduling is 189-192 bushels per acre for Richfield soil and 194-198 bushels per acre for Valent-Vona soil where the well capacity is between 600-800 GPM. The comparison in average corn yield validates my corn yield model and crop growth parameter for AquaCrop.

Since, the estimated net returns from my model represent the net returns to the land; the results for a typical well capacity should correspond closely with those for irrigated cash rental rates. I estimate that the net return for a risk neutral farmer with Richfield soil is $111.16 /acre with the optimal irrigation strategy when the well capacity is 700 GPM. The estimated net return for a 600 GPM well is $103.48/acre. Taylor and Tsoodle (2015) estimated the cash rental rate for irrigated crop land for Finney County is $109 /acre. This comparison with cash rental rate data supports the validity of my model.

Chapter 4 - Optimal irrigation strategies with a limited well capacity or a water constraint policy

Reducing well capacity reduces the amount of irrigation that can be applied in a particular period of time, which could reduce corn production by reducing irrigation per acreage or actual acreage. Moreover, the impact of well capacity reduction by decreasing corn production is significantly greater during periods of drought. Thus, the decline in well capacity arguably reduces expected net returns and increases the risk associated with corn production. Also, reduced well capacities will become an increasingly common concern as an aquifer is depleted following aquifer saturated thickness decreasing, which results in well capacity diminishing. In this chapter, I use the discrete simulation model described in the previous chapter to examine the optimal adjustment to irrigation strategy in response to a decrease in the well capacity and the resulting impact on total water use. I consider both risk averse and risk neutral behavior on the part of the farmer. I also examine the effect of different water constraint policies on optimal irrigation strategies and on total water use.

The following analyses are organized into four separate sections. The first section analyzes the impact of the decrease in well capacity on the optimal adjustments along the intensive and extensive margins. I also explore potential expected net returns and water use. The second section examines how the optimal irrigation strategy differs for different degrees of risk aversion. The analyses in the first and second sections do not include water constraint policy, whereas in the third and fourth sections I do address water constraint policy. Specifically, the third section focuses on the impact of policy on net return and optimal irrigation strategy for the risk neutral farmer. The water constraint policy has two aspects: time constraint and quantity constraint. In the third section, I vary the quantity constraint by increments of 1” from 9 to 15 inches, for a 5-year time constraint. Then, the fourth section examines how the optimal irrigation strategy differs for different degrees of risk aversion when the government imposes a 5-year time constraint and an 11 inch quantity constraint. The analysis of the effect of limited well capacity and water constraint policy is available for two types of soil: Richfield silt loam and Valent-Vona loamy fine sand. In that analysis, I refer to the former as Richfield soil and the latter as Valent-Vona soil.

4.1. The impact of a decrease in well capacity on optimal irrigation strategy and water use

This section addresses risk neutral farmers and compares the two types of prevalent soil.

4.1.1 Risk neutral farmers with Richfield soil

The first section starts with the effect of a lower well capacity—perhaps caused by groundwater depletion—on the optimal irrigation strategy and water use for risk neutral farmers with Richfield soil. For each well capacity, I solve for the optimal irrigation strategy for a risk neutral farmer; then I examine how the optimal strategy, net returns, and standard deviation of net returns differ by well capacity.

Total irrigation increases with well capacity up to 600 GPM, but total irrigation remains more or less stable when the well capacity is at or above 600 GPM (see Figure 4.1). Also, clearly the farmer with a well capacity of 600 GPM or higher will show some variation in total irrigation even while utilizing irrigation for all of the acreage area (see Figure 4.1 and Figure 4.2). For well capacity below 600 GPM, any decrease in well capacity will lead to a faster decrease in total irrigation, which is predominantly driven by change in irrigated acreage.

Figure 4.1 Average total irrigation for Richfield soil

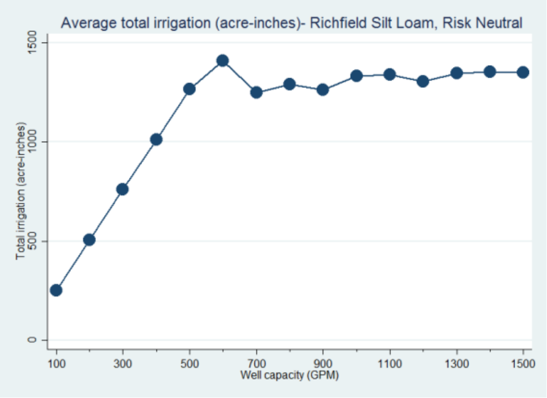
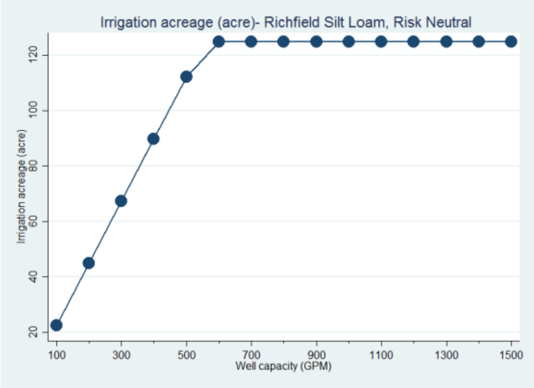


Figure 4.2 Average irrigation acreage for Richfield soil

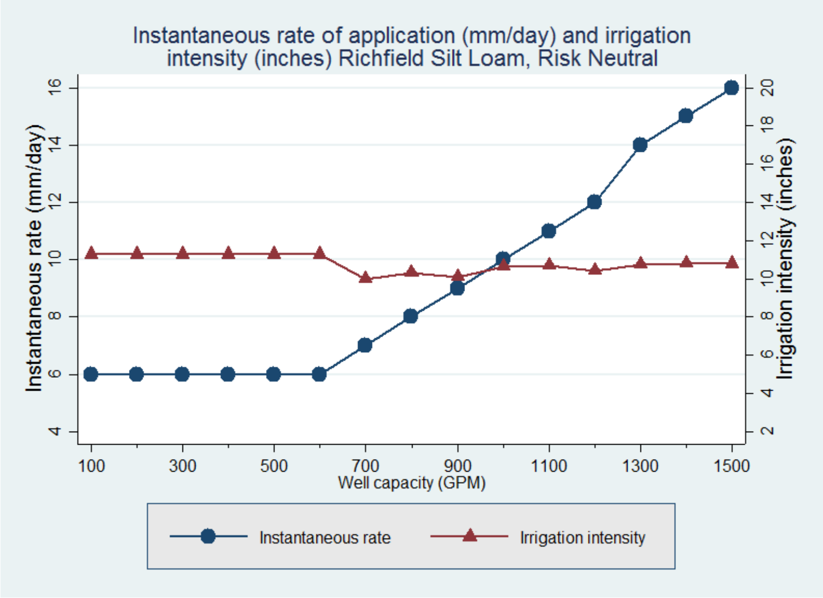


A counterintuitive result is that higher well capacity may not always result in higher total water use. Figure 4.1 shows the total irrigation for 700 GPM is lower than for 600 GPM by 11.3%. In addition, the highest total irrigation is when the well capacity is at 600 GPM. The lower total irrigation for700 GPM is due to a higher instantaneous rate (see Figure 4.3). Such a rate may generate lower levels of irrigation intensity and total irrigation with the same irrigated acreage, corn yield, and total corn production compared to the rate for 600 GPM (see Figure 4.1, 4.2 and 4.3). This finding differs from that of Foster, Brozović and Butler (2014) who determined that higher well capacity will result in higher total irrigation water use.

I also observe when well capacity is above 600 GPM a farmer will not reduce irrigated acreage in response to a decline in well capacity (see Figure 4.2). Instead, when faced by a decrease in well capacity, this farmer may change only irrigation intensity and instantaneous rate (see Figure 4.3). These results imply a well capacity threshold of 600 GPM when a farmer changes from the intensive margin adjustment to an extensive margin adjustment as an effect of groundwater depletion due to reduced well capacity.

Figure 4.3 shows that the instantaneous rate of application increases sharply when well capacity is above 600 GPM. The positive relationship between instantaneous rate of application and well capacity is for full-irrigated acreage (see Figure 4.2 and Figure 4.3). A farmer with high well capacity optimizes water use and net return through adjustment in the intensive margin by choosing the higher instantaneous rate of application. With such a rate, the farmer may generate less frequent irrigation application by managing a higher Management Allowed Deficit (MAD) for the irrigation schedule. In addition, the higher instantaneous rate will store a greater degree of water in the soil for each irrigation application making it less likely for corn to experience water stress.

Figure 4.3 Instantaneous rate of application and average irrigation intensity for Richfield soil



Furthermore, a minimum optimal instantaneous rate of application of 6 mm/day is required to deal with weather uncertainty and to obtain an optimum net return for the Richfield soil (see Figure 4.3). Instantaneous rate of application lower than 6 mm/day may not result in optimal net return but cause more frequent irrigation applications with lower Management Allowed Deficit (MAD) levels. In addition, less frequent irrigation but a higher instantaneous rate will result in lower irrigation intensity than will more frequent irrigation but lower instantaneous rate. For example, Figure 4.3 shows that well capacity lower than 600 GPM has higher irrigation intensity but a lower instantaneous rate than well capacity higher than 700 GPM. Thus, the lower instantaneous rate may result in higher irrigation cost.

However, a very low instantaneous rate may result in an insufficient irrigation water supply that may induce corn water stress and severe corn yield loss especially during unfavorable weather condition because a low rate may be less able to maintain the given MAD. For a particular well capacity, the instantaneous rate can only be adjusted by changing the irrigated acreage. Clearly, an economic trade-off exists between instantaneous rate and irrigated acreage due to constraint in well capacity. The farmer will try to optimize these two to obtain the highest net return depending on weather conditions. This finding corroborates that of O'Brien et al. (2001) that in response to well capacity declining, a farmer will change irrigated acreage to provide adequate supply of water for crop growth.

The minimum optimal irrigation intensity and instantaneous rate, 10 inches and 6 mm/day, addresses the optimal adjustment between intensive and extensive margins with no water policy constraint. English (1990) and Wang and Nair (2013) support this claim by stating that maximal water resource rent is attainable when marginal returns are equal at the extensive and intensive margins. In this scenario, a farmer with a particular well capacity may not decrease instantaneous rate below 6 mm/day to keep irrigated acreage constant. It is when instantaneous rate drops below 6 mm/day and irrigated acreage is constant that net return would reduce significantly. However, an instantaneous rate at or above 6 mm/day would create reduced irrigated acreage due to limited well capacity but with smaller degree in net return reduction. In such a case, the farmer would adjust the extensive margin to keep the instantaneous rate of 6 mm/day when the well capacity decreases below 600 GPM.

Figure 4.4 shows corn yield increases as the well capacity increases. I measure corn yield as average simulated corn production per irrigated acre over the 30 years of historical weather. The yield ranges between a minimum of 189 bushels per acre to a maximum of 197 bushels per acre, and as long as the well capacity is below 700 GPM, corn yield is constant. However, corn yield rises when well capacity is higher than 700 GPM. This implies a minimum average corn yield of 189 bushels per acre for irrigated acreage, which the farmer wants to attain. The Richfield soil requires approximately 10 inches of irrigation per irrigated acre per year as optimal average irrigation intensity (see Fig 4.3). The above threshold (10 inches) of water is needed to optimize water-corn productivity and avoid severe corn water stress so that the farmer can obtain the minimum optimal productivity of 189 bushels per acre. In addition, an increase in instantaneous rate results in corn yields increasing. This implies the ability of higher well capacity to maintain the given MAD with a higher instantaneous rate resulting in higher corn yield.

I also find that average total corn production (i.e., corn yield per irrigated acre times irrigated acreage) increases as well capacity increases. Measuring average corn production from overall simulated corn production of the irrigated acreage using data for 30 years of historical weather. Figure 4.5 shows that the decrease in well capacity causes a sharp decrease in average total corn production when the well capacity is below 600 GPM. However, the corn yield is unchanged when well capacity is lower than 700 GPM (see Figure 4.4). Hence, this implies a sharp decrease in average total corn production due to the decline in well capacity is associated with reduced irrigated acreage. Specifically, the decrease in irrigated acreage for average total production can decline by 20% when the well capacity falls from 500 GPM to 400 GPM.

Figure 4.4 Corn yield for Richfield soil

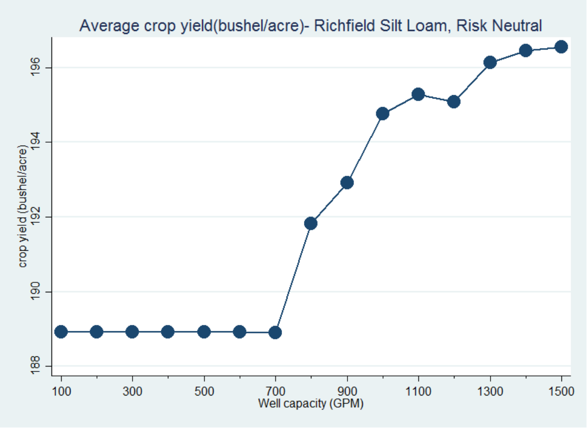


Figure 4.5 Average total production for Richfield soil

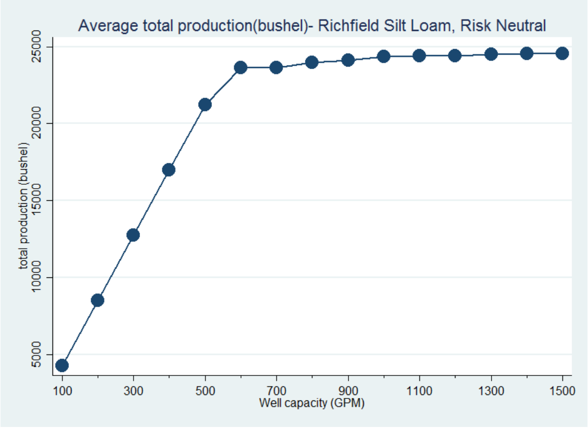
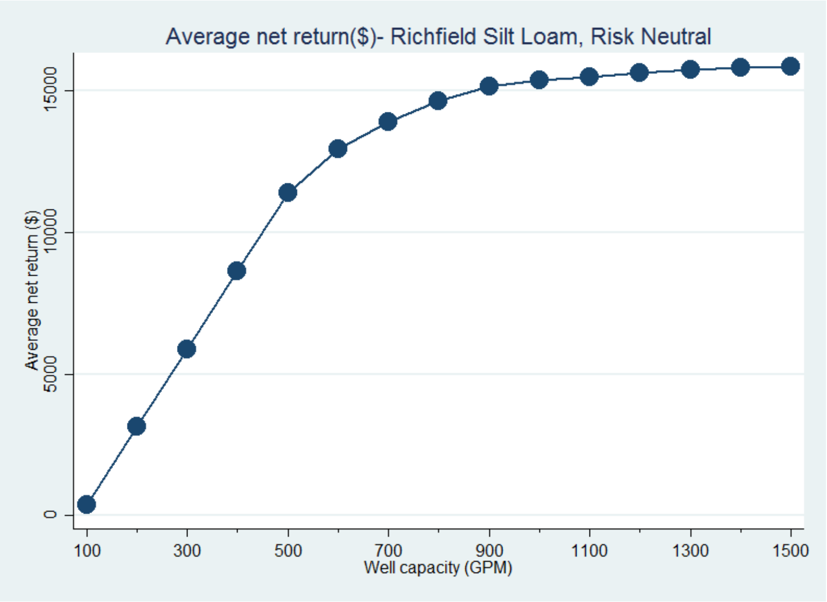


Figure 4.6 shows the expected net return from optimal irrigation strategy for each given well capacity level. Expected net return decreases when well capacity decreases (see Figure 4.6). Moreover, the rate of decline in expected net return increases with smaller well capacities. Clearly, the decline in well capacity affects irrigation, thus affecting corn yield and total production, which in turn reduces expected net return. Figure 4.6 indicates that when the well capacity falls below 600 GPM, expected net return falls faster. On the other hand, the rate falls relatively more slowly when the well capacity level is higher than 600 GPM. Likewise the expected net returns decrease by 24% when the well capacity decreases from 500 GPM to 400 GPM. Meanwhile, the expected net return decreases only by 5% when the well capacity decreases from 800 GPM to 700 GPM. The reason is that at high initial well capacities, subsequent reductions result in small changes in water use, but then those changes become much more substantial as the well capacity gets even smaller. In addition, the different rate of change in expected net return can be linked to any limitation in irrigation strategy choice that each well capacity level can generate. Thus, a low well capacity may have more limitation both for an

irrigated acreage and for instantaneous rate, which would result in significantly less water use and lower net return.

Figure 4.6 Expected net return Richfield soil



The sharp decrease in expected net return in the graph is caused by decrease in irrigated acreage; when well capacity is lower than 600 GPM; a farmer is compelled to reduce irrigated acreage to attain sufficient instantaneous rate and irrigation intensity (see Figures 4.2 and 4.3). Foster et al. (2014) find that a farmer with low well capacity focuses more on adjustment to the extensive margin. Based on my estimate, when well capacity falls below 600 GPM, the best irrigation strategy for maximizing net return is adjustment in the extensive margin instead of in the intensive margin.

The rate of change in expected net return is relatively small when well capacity decreases from 1500 GPM to 600 GPM. The expected net return decreases at a slower rate because the farmer only changes the irrigation intensity and not the irrigated acreage, which will result in only a slight decrease in corn productivity and total corn production (see figure 4.3, 4.4, and 4.5).

When well capacity is decreasing, a farmer with high well capacity can maximize expected net return by adjusting along the intensive margin instead of the extensive margin. This finding is similar to that of Foster et al. (2014).

The sharp decrease in expected net return as the well capacity decreases may induce a farmer to switch to dry land farming for all acreage. Amosson et al. (2005) mentioned that the conversion from irrigated land to dry land farming could be a viable economic decision in response to rapid depletion of the Ogallala Aquifer, especially in the Southern High Plains. With the assumption of non-irrigated cash rent of $24.90 per acre, a farmer with well capacity lower than 300 GPM may convert to full dry land farming since installing center pivot irrigation may not be economically profitable. However, this result may occur because my study assumes investment cost of center pivot irrigation is not proportional to any change in irrigated acreage.

Figure 4.2, 4.5, and Figure 4.6 show that irrigated acreage, total corn production, and expected net return decrease linearly with well capacity when capacity decreases below 600 GPM. This result shows the adjustment in the extensive margin that occurs when expected net return decreases proportionally with the decrease in irrigated acreage; a 1% decrease in net return would cause a 1% decrease in expected net return (i.e. constant return to scale). In the case of no acreage constraint and water policy constraint, a farmer will make adjustment to the extensive margin with the change in well capacity and adjust corn production at a constant return to scale.

Figures 4.3 and 4.4 show that the irrigation intensity is higher but the corn yield is lower for well capacity at or below 600 GPM compared to well capacity at or above 700 GPM. This result suggests that the marginal return of water is higher for larger well capacity. Also, the higher instantaneous rate for higher well capacity could result in more efficient irrigation application in response to weather uncertainty. This could be because a farmer with a higher well capacity is better able to maintain appropriate MAD for each growth stage, which results in higher corn yield.

Next, 600 GPM wells have higher total irrigation than do 700 GPM wells or higher. Both 600 and 700 GPM wells irrigate full acreage, but 600 GPM wells use 6 mm/day at an instantaneous rate, and 700 GPM wells use 7 mm/day at an instantaneous rate, which results in the 600 GPM well using higher irrigation intensity than the 700 GPM well. A lower instantaneous rate may be less able to maintain MAD for each growth stage, which may result in more frequent irrigation application and higher irrigation intensity. In the case of the same irrigated acreage, a lower instantaneous rate may induce higher irrigation intensity resulting in higher total water use. The higher total irrigation of 600 GPM wells compared to 700 GPM wells or higher also shows that the decline in well capacity due to groundwater depletion may increase water demand over time. Figure 4.1 shows that the water demand for irrigation is greatest when the well capacity is at 600 GPM and starts to decrease if the well capacity is at or below 500 GPM. This trend generates the “hump shape” in total irrigation water use as shown in Figure 4.1.

Declines in well capacity can reflect the effect of groundwater depletion over time and thus Figure 4.1 shows how water use is likely to change over time due to groundwater depletion. With the assumption of stationary demand for water, Brill and Burness (1994) found an ‘S’ shape regarding groundwater extraction when they simulated the groundwater extraction model from Gisser and Sanchez (1980) and Nieswiadomy (1985). The ‘hump shape’ of average total irrigation in Figure 4.1 is similar to Brill's and Burness' (1994) simulation of groundwater extraction on the assumption of non-stationary water demand and the possibility of water demand growing over time. However, the causes of increasing in water demand in my study versus Brill's and Burness' (1994) are different.

4.1.2 Comparison between results Richfield soil and Valent-Vona soil

I observe an almost identical positive relationship between well capacity and total irrigation for both Valent-Vona and Richfield soils for well capacity up to 600 GPM (see figure 4.7). I also observe that irrigation acreage shows a positive relationship to well capacity for both Valent-Vona and Richfield soils (for well capacity at or below 700 GPM for Valent-Vona, and 600 GPM for Richfield soil) (see Figure 4.8). Clearly, Valent-Vona soil irrigates less acreage than Richfield soil when the well capacity is at or below 600 GPM. In the case of full irrigated acreage, the total irrigation of Valent-Vona soil is higher than for Richfield soil (see Figures 4.7 and 4.8). The difference in total irrigation may be due to differences in soil water holding capacity with Richfield soil retaining more water than Valent-Vona soil.

Figure 4.7 Average total irrigation comparison between Richfield soil and Valent-Vona soil

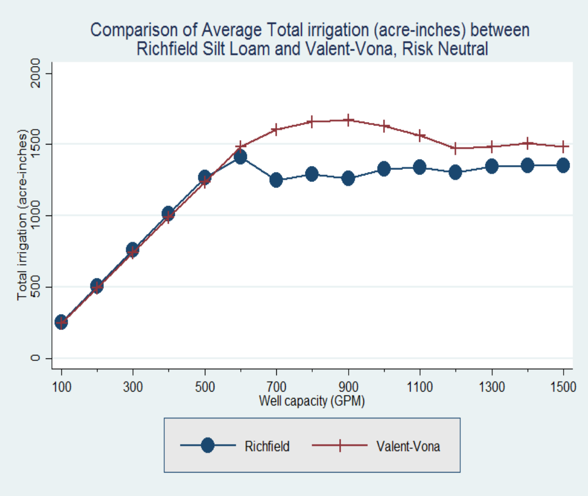
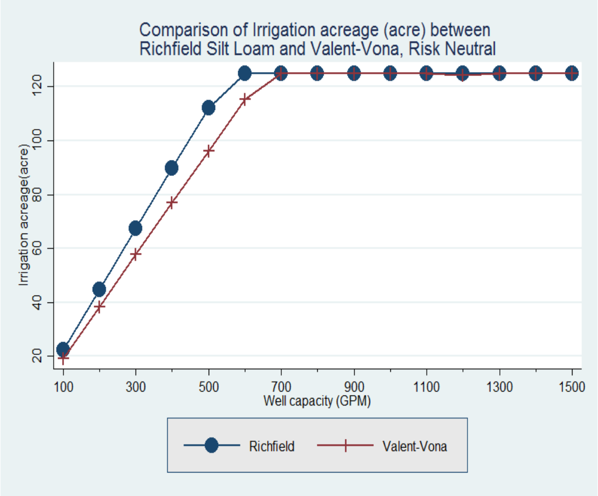


Figure 4.8 Average irrigation acreage comparison between Richfield soil and Valent-Vona soil



The ‘hump shape’ for total irrigation water also found for Valent-Vona soil. Figure 4.7 shows the water use is actually higher for 600-1100 GPM wells than for 1200-1500 GPM wells for Valent-Vona soil. My simulation result shows 1200-1500 GPM wells apply water at a higher instantaneous rate than do 600-1100 GPM wells (see Table 4.1). The high instantaneous rate allows 1200-1500 GPM wells to set higher MAD for an irrigation schedule especially at the second growth stage (crop/canopy development stage) and third growth stage (mid-season stage) when corn uses the most water (see Table 4.1). The high well capacity may more easily keep the soil moisture at a desired level using a high instantaneous rate. On the other hand, 600-1100 GPM wells are limited by smaller ranges of instantaneous rates that they can utilize. Consequently, 600-1100 GPM wells need to maintain lower MAD to cope with the risk associated with corn production especially during drought season (see Table 4.1). Thus, smaller well capacity triggers more frequent irrigation and results in higher total water use. Figure 4.9 shows 1200-1500 GPM wells use less irrigation intensity than 600-1100 GPM wells. This finding is different for Foster et al. (2014) as they found higher well capacity always results in higher total water use. The difference between the two findings may be due to different irrigation schedule choices in the discrete simulation optimization as Foster et al. (2014) limit the irrigation choices to only uniform MAD for all growth stages.

Table 4.1 shows the optimal MAD for each growth stage. The optimal irrigation scheduling is to supply more water during the second growth stage or at the most productive stage of corn growth. My results are consistent with those of Heeren et al. (2011) who recommended irrigating with more water at vegetative stages to generate maximum yield especially with limited water availability.

Conversely, Valent-Vona soil has lower soil water holding capacity causing greater losses of water. Thus, water holding capacity requires a higher optimal instantaneous rate of application and triggers more frequent water irrigation application. In the case of 1400 and 1500 GPM wells, Valent-Vona has higher irrigation intensity but higher MAD with the same instantaneous rate than Richfield soil (see Table 4.1 and Figure 4.9). Thus, as stated, even though Valent-Vona soil has higher MAD, it triggers more frequent irrigation application due to greater losses of water.

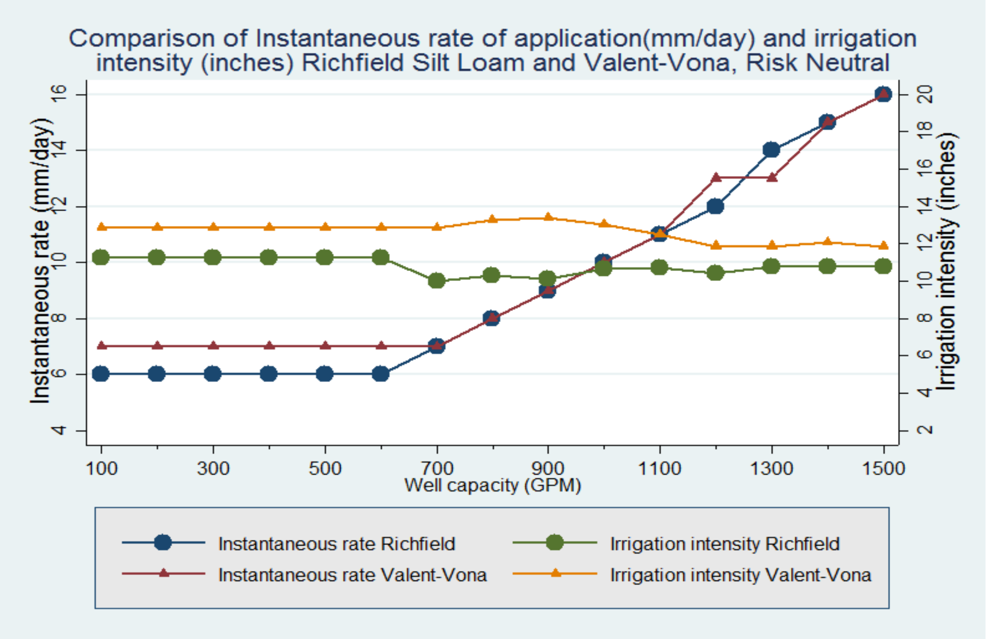
Table 4-1 Instantaneous rate and MAD for Richfield soil and Valent-Vona soil

Well capacity	RSL		VVS	
	Ir	D1-D2-D3-D4	Ir	D1-D2-D3-D4
100	6	60-0-40-90	7	100-10-40-100
200	6	60-0-40-90	7	100-10-40-100
300	6	60-0-40-90	7	100-10-40-100
400	6	60-0-40-90	7	100-10-40-100
500	6	60-0-40-90	7	100-10-40-100
600	6	60-0-40-90	7	100-10-40-100
700	7	60-10-50-90	7	100-10-40-100
800	8	60-10-50-100	8	90-10-40-100
900	9	60-10-50-100	9	90-10-40-100
1000	10	60-10-50-100	10	70-20-40-100
1100	11	60-10-50-90	11	100-20-40-90
1200	12	70-10-50-100	13	90-20-50-100
1300	14	60-10-50-100	13	90-20-50-100
1400	15	60-10-50-90	15	80-20-50-100
1500	16	60-10-50-100	16	90-20-50-100

* RSL = Richfield soil *VVS=Valent-Vona soil
*Ir = instantaneous rate *D1-D2-D3-D4 = MAD at growth stage 1, 2, 3 and 4

The optimal minimum instantaneous rate for Valent-Vona soil is 7 mm/day which is 1 mm more than for Richfield soil. On the other hand, we observe a similar pattern with the instantaneous rate for both soil types when well capacity is above 700 GPM. Also, Figure 4.9 shows Valent-Vona soil uses higher irrigation intensity than Richfield soil for all well capacity levels. Irrigation intensity with Valent-Vona soil is at least 1 inch greater than for Richfield soil, and it steadily decreases when the well capacity is above 900 GPM. Therefore, higher well capacity will offer the farmer the option to optimize expected net return by adjusting the intensive margin.

Figure 4.9 Instantaneous rate and average irrigation intensity comparison between Richfield soil and Valent-Vona soil



The corn yield with Valent-Vona soil is higher than for Richfield soil (see Fig 4.10), and it remains stable with well capacity up to 700 GPM but shows a sharp increase beyond 700 GPM. I also observe the corn yield difference between the two soils is less when well capacity is between 1300 GPM and 1500 GPM. For example, the yield difference between Richfield and Valent-Vona is 2.9% at 500 GPM, but only 0.4% at 1300 GPM.

I observe the average total corn production with Richfield soil is higher than for Valent-Vona soil when the well capacity is at or below 700 GPM (see Fig.4.11). In the case of well capacity at or below 700 GPM, the higher total corn production from Richfield soil compared to that from Valent-Vona soil arises because Richfield soil has larger irrigated acreage (see Figure

4.8). Well capacity at or below 700 GPM is a major limiting factor in corn production for Valent-Vona soil. Accordingly, Richfield soil requires lower optimal instantaneous rate and irrigation intensity to supply sufficient water for corn production compared to Valent-Vona soil. Even though a farmer with Richfield soil may observe lower corn yield compared to that from Valent-Vona soil, higher irrigated acreage results in higher total corn production when well capacity is at or below 700 GPM.

Figure 4.10 Corn yield comparison between Richfield soil and Valent-Vona soil

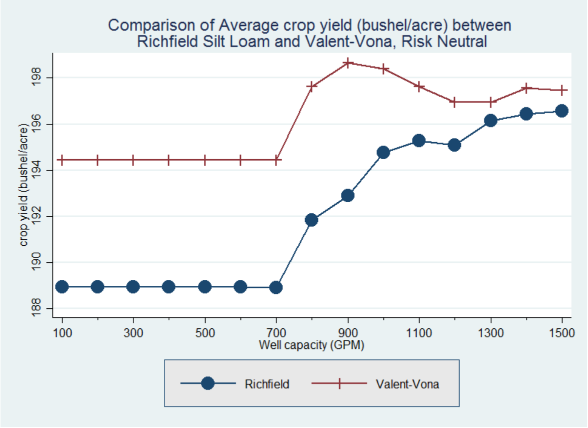
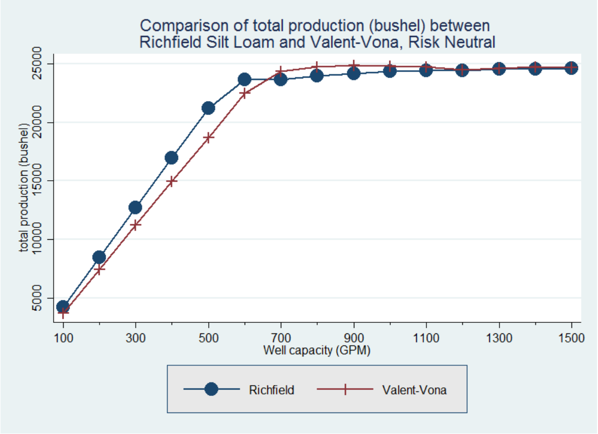


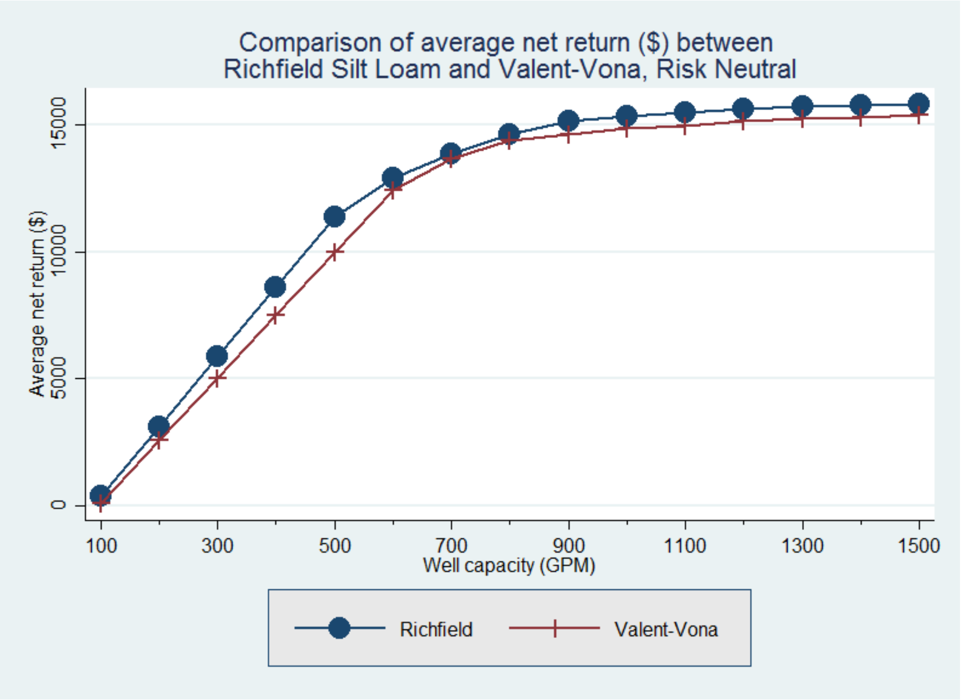
Figure 4.11 Average total production comparison between Richfield soil and Valent-Vona soil



Richfield soil results in a higher expected net return than Valent-Vona soil (see Figure 4.12). The expected net return of Richfield soil is higher by 1.5-4% than for Valent-Vona soil if the well capacity is at or above 600 GPM. The difference in expected net return becomes larger as the well capacity decreases, especially at or below 500 GPM.

The expected net return has a positive relationship with well capacity. A decline in well capacity will reduce expected net return at a faster rate, when well capacity is at or below 700 GPM for Valent-Vona soil. However, the expected net return decreases at a slower rate above the threshold of 700 GPM. For Richfield soil, that threshold was 600 GPM. Thus, conclusively, the expected net return with Valent-Vona soil is relatively more sensitive to the decrease in well capacity.

Figure 4.12 Expected net return comparison between Richfield soil and Valent-Vona soil



When well capacity is at or below 700 GPM, the lower expected net return for Valent-Vona soil in comparison to that for Richfield soil rises because of higher investment cost per acre and lower total corn production. These two variables for Valent-Vona soil are due to its smaller irrigated acreage when well capacity is at or below 700 GPM (see Figure 4.8). Furthermore, when well capacity rises above 700 GPM, Valent-Vona soil has higher total production but lower expected net return, likely due to higher irrigation cost compared to that of Richfield soil.

In the case of well capacity above 700 GPM, farmers with Valent-Vona soil will go for adjustment in the intensive margin thus reducing irrigation per acre to maximize net return. Figure 4.12 shows farmers with higher well capacity may attain higher expected net return, although the rate of change in net return becomes sluggish with rising well capacity above 700 GPM. The subsequent smaller increase in expected net return is due to adjustment in the intensive margin. On the other hand, the farmer with well capacity at or below 700 GPM will go for adjustment in the extensive margin to maximize net return, which causes significant change in expected net return (see Figures 4.8 and 4.12). A similar pattern between adjustment in intensive and extensive margins also found for Richfield soil with a threshold at 600 GPM. This result implies the change in soil water holding capacity will change the well capacity threshold as the farmer chooses the extensive margin over the intensive margin in response to well capacity reduction. The lower water holding capacity will increase the well capacity threshold with adjustment of the extensive margin over that of the intensive margin.

4.2. The impact of risk averse behavior on water use and welfare

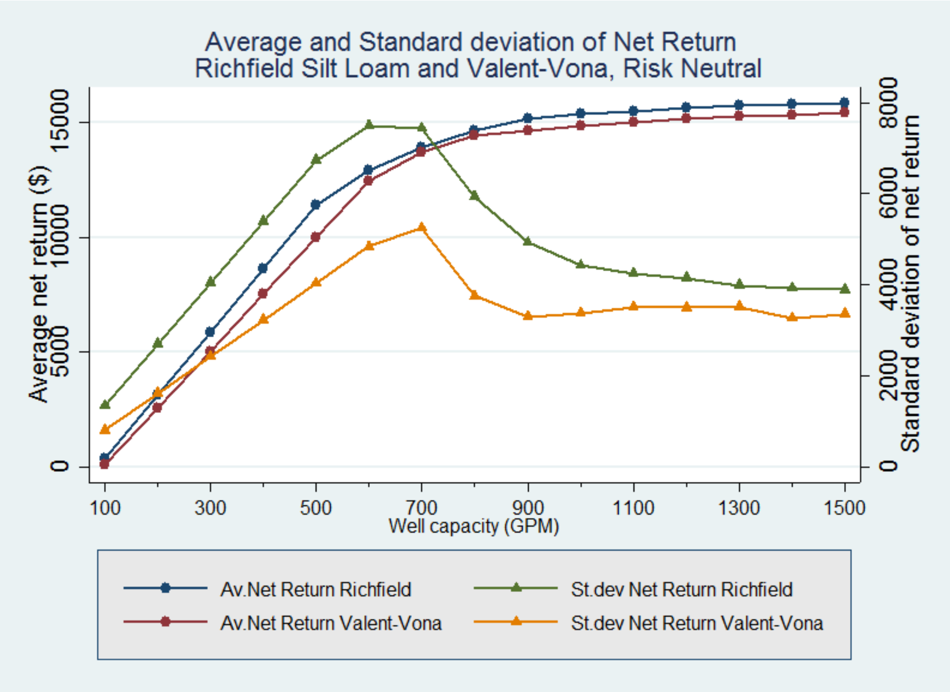
This section addresses net returns and irrigation strategy affected by risk averse behavior.

4.2.1 Average and standard deviation of net return for risk neutral farmer affected by well capacity

Before examining the impact of risk aversion on irrigation behavior, I first illustrate net returns and the variation in net returns for a risk neutral farmer. I notice that the standard deviation in net return for Richfield soil increases with an increase in well capacity, for well capacity up to 600 GPM. However, the standard deviation of net return declines with well capacity above the threshold (see Figure 4.13). The increase in average and standard deviation of net return for Richfield soil with a well capacity lower than 600 GPM is because a farmer increases irrigated acreage with well capacity increasing, and my model assumes for simplicity that non-irrigated acreage receives a fixed rental payment. On the other hand, a well capacity higher than 600 GPM may decrease the risk in net return by increasing instantaneous rate at the intensive margin. I observe the same pattern for Valent-Vona as well with the threshold defined at 700 GPM.

Figure 4.13 shows that both average return and standard deviation of net return for a risk neutral farmer are higher for Richfield soil than for Valent-Vona soil. The higher standard deviation of net return for Richfield soil is due to lower irrigation intensity (see Figure 4.8). If intensity were held constant across the two soil types, the variation in returns would likely be larger for Valent-Vona, but at the optimal point, Valent-Vona soil uses more water per acre than Richfield soil, and thus has less variability in returns.

Figure 4.13 Average and standard deviation of net return Richfield soil and Valent-Vona soil



I summarize the above discussion as follows. An increase in well capacity allows the farmer to go for a wider range of instantaneous rate (e.g. up to 16 mm per day). When farmers are able to irrigate their full acreage, they will be able to choose an adjustment in intensive margin that not only increases net return but also reduces risk. On the other hand, as the well capacity decreases, not only does a decrease in farm net return occur but also a decrease in the farm's ability to reduce risk.

4.2.2. The effect of risk averse behavior on irrigation strategies and water for Richfield soil without water constraint policy

I observe positive correlation between risk averse behavior and change in total water usage. Risk averse behavior induces the farmer to use more water (see Figure 4.14) whereas changes in the magnitude of water use not only depend on risk averse behavior but also on well capacity. Figure 4.14 shows that the magnitude of water usage increases faster with an increase in the parameter measuring risk averse behavior for a moderate well capacity of 600 GPM. The change from risk neutral to risk premium 20% increases the total irrigation as much as 30% for 600 GPM wells. On the other hand, the increase in risk averse behavior to risk premium 20% will increase total irrigation only by 15% for well capacity higher than 900 GPM.

The increasing impact of the risk averse behavior on the increase in total irrigation for low or medium well capacity is due to the limitation in instantaneous rate. A farmer with low or medium well capacity (e.g., 400-600 GPM) will apply irrigation more frequently at a low instantaneous rate (e.g., 6-7 mm/day), which in turn results in a higher rate of increase in total irrigation (see Figure 4.14 and Figure 4.15). This finding is different from that of Foster et al. (2014), who found greater impact on degree of risk aversion relative to the increase in water use for high well capacity. The difference between the findings may due to different adjustments on the intensive margin. However, my study includes the non-uniform MAD in irrigation choice that enables the risk averse farmer to focus on increasing irrigation application in the more productive growth stages instead of increasing irrigation application in all growth stages.

Figure 4.14 Average total irrigation for Richfield soil affected by risk averse behavior

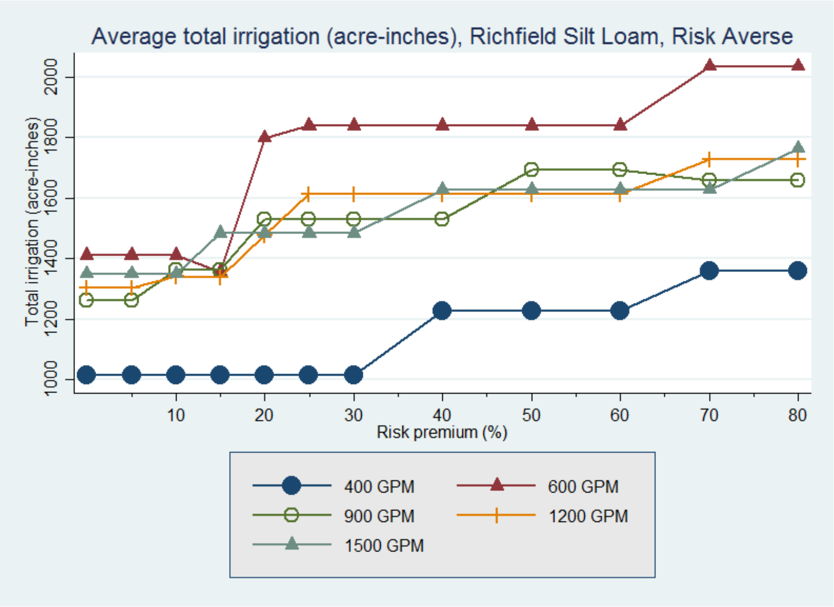
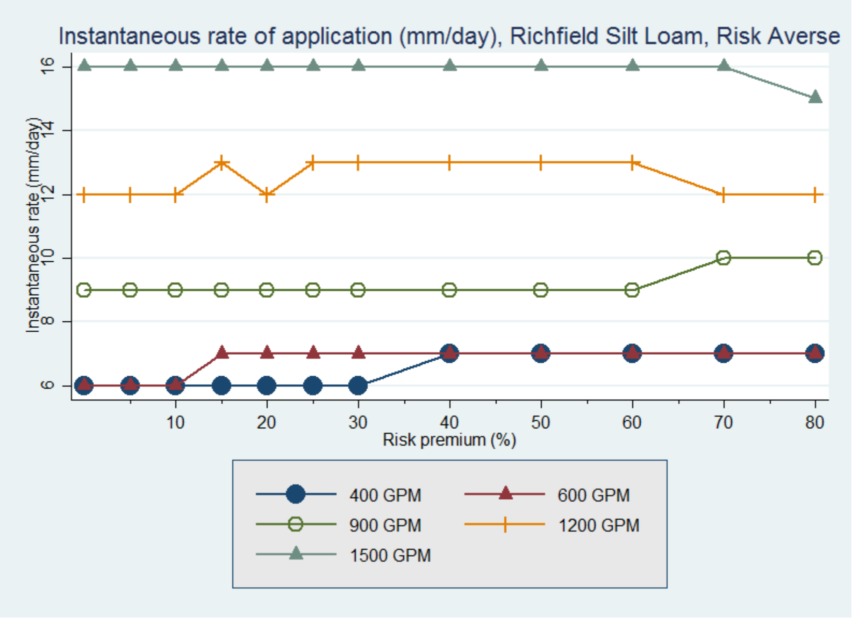


Figure 4.15 Instantaneous rate of application for Richfield soil affecting by risk averse behavior



Moreover, I observe a positive relationship between irrigation intensity and risk averse behavior (see Figure 4.16). Thus, more risk averse behavior induces the farmer to increase irrigation intensity. Figure 4.16 shows that the risk neutral farmer irrigates 10-11 inches per acre when well capacity is 600 GPM. On the other hand, a farmer with 600 GPM well capacity and a risk premium more than 20% will apply irrigation intensity at not less than 16 inches per acre. Meanwhile, smaller increases in irrigation intensity are found for higher well capacity. For instance, a 900 GPM well sees increased irrigation intensity only from 10 inches to 12 inches per acre if the risk premium increases from 0% to 20%.

As I mentioned earlier, the rate of increase in irrigation intensity not only depends on risk averse behavior, but also on well capacity. Two factors can influence irrigation intensity: adjusting the instantaneous rate, and MAD for irrigation scheduling. Figure 4.16 shows as the well capacity increases, the corresponding increase in irrigation intensity is relatively smaller. The higher rate of irrigation intensity for low or medium well capacity is due to a limitation in the instantaneous rate. A farmer with low or medium well capacity could increase the instantaneous rate by a smaller margin (see Figure 4.15). Thus, the increase in irrigation intensity is attained by setting a lower MAD level for irrigation scheduling (see Table 4.2). A lower MAD level added to a low instantaneous rate induces more frequent irrigation resulting in a higher rate of increase in water usage for low or medium well capacity. On the other hand, high well capacity induces increased irrigation intensity by changing the MAD to a slightly lower level with high instantaneous rate (see Table 4.2). Next, a high instantaneous rate with marginally lower MAD creates a marginal increment in frequent irrigation application and marginal increases in irrigation intensity.

Table 4-2 Instantaneous rate and MAD for Richfield soil affected by risk averse behavior

Well capacity (GPM)	risk neutral		risk premium 10%		risk premium 20%		risk premium 50%		risk premium 80%	
	Ir	D1-D2-D3-D4	Ir	D1-D2-D3-D4	Ir	D1-D2-D3-D4	Ir	D1-D2-D3-D4	Ir	D1-D2-D3-D4
100	6	60-0-40-90	6	60-0-40-90	6	60-0-40-90	7	20-0-40-90	7	10-0-40-90
200	6	60-0-40-90	6	60-0-40-90	6	60-0-40-90	7	20-0-40-90	7	10-0-40-90
300	6	60-0-40-90	6	60-0-40-90	6	60-0-40-90	7	20-0-40-90	7	10-0-40-90
400	6	60-0-40-90	6	60-0-40-90	6	60-0-40-90	7	20-0-40-90	7	10-0-40-90
500	6	60-0-40-90	6	60-0-40-90	6	60-0-40-90	7	20-0-40-90	7	10-0-40-90
600	6	60-0-40-90	6	60-0-40-90	7	20-10-40-90	7	20-0-40-90	7	10-0-40-90
700	7	60-10-50-90	8	40-0-50-100	8	40-0-50-100	8	30-0-50-100	8	20-0-50-100
800	8	60-10-50-100	8	40-0-50-100	8	40-0-50-100	9	40-0-50-100	9	30-0-50-100
900	9	60-10-50-100	9	50-10-50-100	9	40-0-50-100	9	40-0-50-100	10	30-0-50-100
1000	10	60-10-50-100	10	60-10-50-100	10	50-10-50-100	10	40-0-50-100	10	30-0-50-100
1100	11	60-10-50-90	11	60-10-50-90	11	40-10-50-100	12	30-10-50-100	12	30-0-50-100
1200	12	70-10-50-100	12	60-10-50-100	12	40-10-50-100	13	30-10-50-100	12	30-0-50-100
1300	14	60-10-50-100	14	60-10-50-100	14	40-10-50-90	14	30-10-50-100	14	30-0-50-100
1400	15	60-10-50-90	15	40-10-50-100	15	40-10-50-100	15	30-10-50-100	15	30-0-50-100
1500	16	60-10-50-100	16	60-10-50-90	16	40-10-50-100	16	30-10-50-100	15	30-0-50-100

*Ir = instantaneous rate *D1-D2-D3-D4 = MAD at growth stage 1, 2, 3 and 4

Figure 4.17 shows that risk averse behavior will induce the farmer to reduce irrigated acreage when well capacity is lower (e.g. at or below 600 GPM). However, a farmer with well capacity at or above 1200 GPM shows no change in irrigation acreage with changing risk premium. Meanwhile, Figure 4.16 and Figure 4.17 show that a farmer with a well capacity of 1200 GPM or 1500 GPM will increase the irrigation intensity but maintain the same irrigated acreage as risk premium increases. This farmer increases intensity by using a lower MAD for irrigation scheduling to trigger more frequent irrigation application and thereby reduce the varation in corn yield.

Figure 4.16 Average irrigation intensity for Richfield soil affected by risk averse behavior

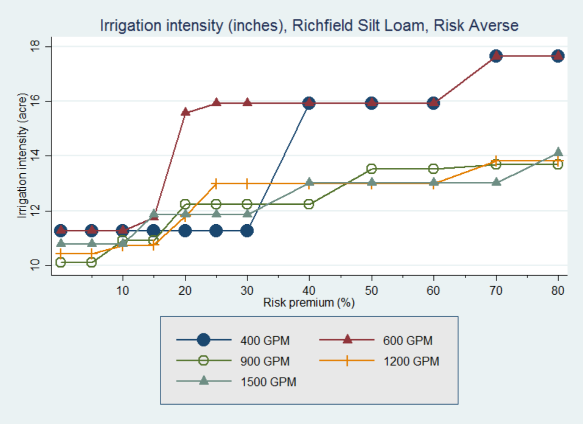


Figure 4.17 Irrigated acreage for Richfield soil affected by risk averse behavior

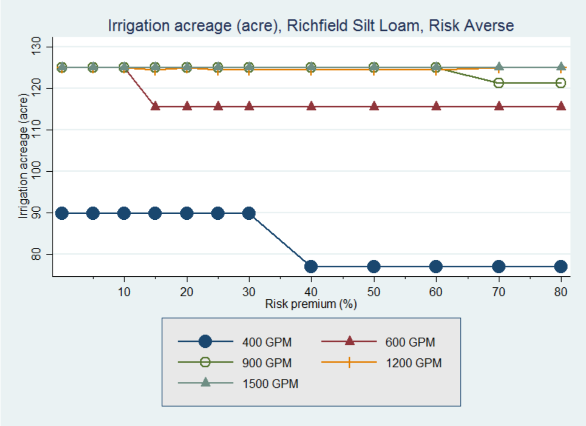


Figure 4.17 demonstrates that a farmer with 900 GPM well capacity reduces irrigated acreage as the risk premium increases above 60%. On the other hand, a farmer with 400 GPM well capacity reduces irrigated acreage as the risk premium increases above 30%. With lower well capacity, a farmer needs to increase irrigation intensity with a higher instantaneous rate and set a lower MAD level for irrigation scheduling. This in turn increases irrigation intensity, but it is more efficient with a smaller acreage Additionally, the adjustment in the extensive margin due to risk averse behavior is greater for low and medium well capacities (e.g. at or below 600 GPM). My finding is different from that of Foster et al. (2014), which found the adjustment in irrigated acreage due to risk averse behavior is higher when the well capacity is high.

4.2.3. The effect of risk averse behavior on irrigation strategies and water use for Valent-Vona soil without water constraint policy

The impact of changes in risk premium on water usage is less sensitive for a farmer with Valent-Vona soil than for a farmer with Richfield soil (see Figure 4.14 and Figure 4.18). In fact, there is almost no change in total water use for Valent-Vona soil when the risk premium is lower than 20%. The lower change in total irrigation in response to a higher risk premium is because a risk neutral farmer would use large quantities of irrigation water, so net returns would be less variable. In Figure 4.7 and Figure 4.10, a risk neutral farmer produces a large corn yield for which Valent-Vona soil has higher average total irrigation water than does Richfield soil. In addition, Valent-Vona soil has less variation in net return than does Richfield soil (see Figure 4.13). The increase in total irrigation would somewhat reduce the risk in crop production but would moderately increase the irrigation cost.

Figure 4.18 Average total irrigation for Valent-Vona soil affected by risk averse behavior

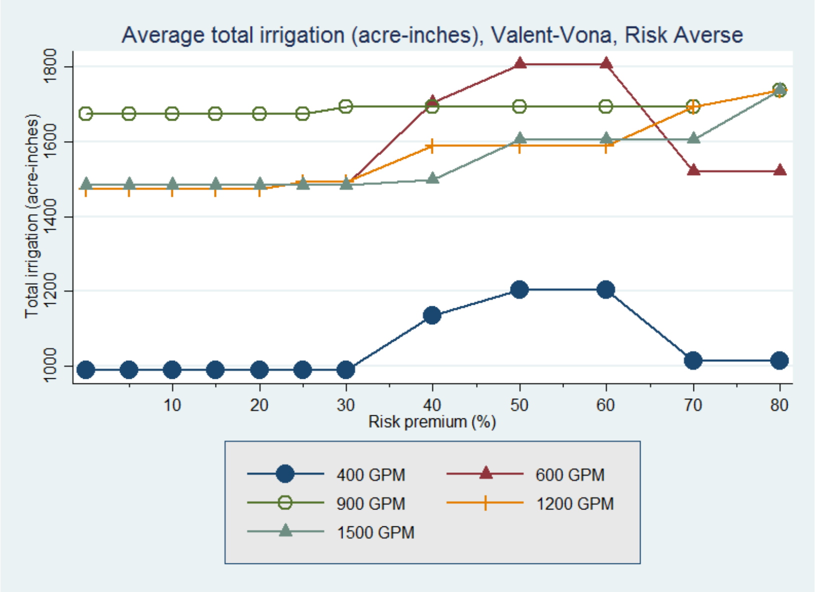


Figure 4.19 shows irrigation intensity changes when a farmer's risk premium goes above 25%. Specifically, the irrigation intensity increases by 15% for 600 GPM wells, 7.7% for 900 GPM wells, and 1% for 1500 GPM wells. Thus, the increase in irrigation intensity is higher for low and medium well capacities. Next, Figure 4.20 shows that the irrigated acreage varies when risk premium goes above 60%. Thus, change in irrigation intensity is more sensitive to change in risk premium than to changes in irrigated acreage.

Figure 4.19 Average irrigation intensity for Valent-Vona soil affected by risk averse behavior

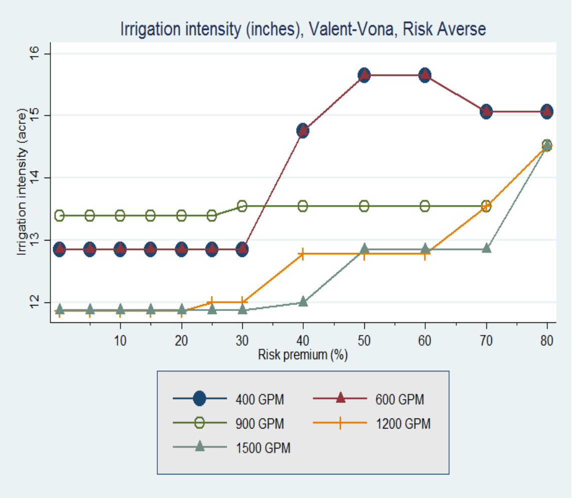
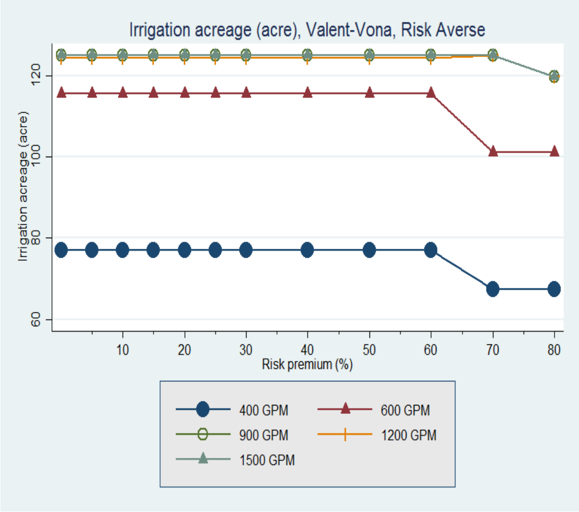
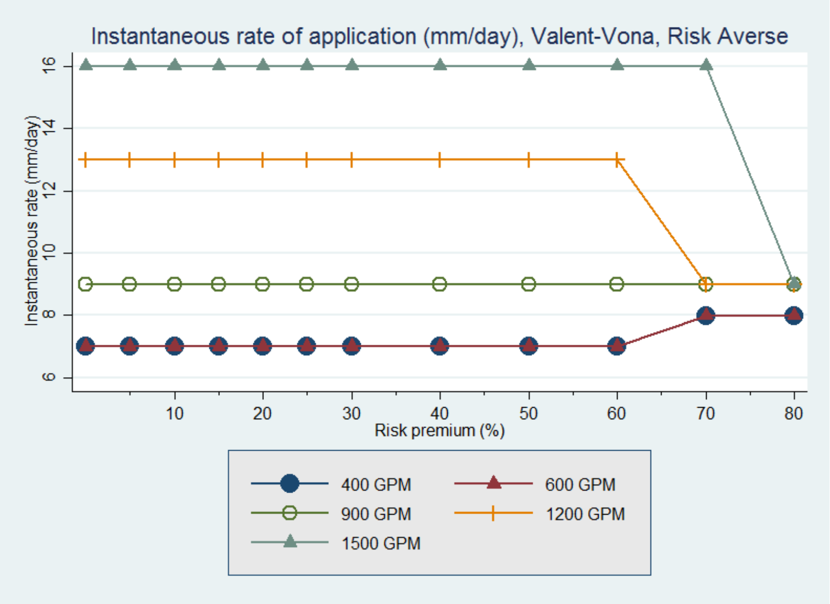


Figure 4.20 Irrigated acreage for Valent-Vona soil affected by risk averse behavior



A farmer with risk premium higher than 60% and well capacity 400-600 GPM would need to decrease irrigated acreage to increase the instantaneous rate for higher irrigation intensity. Figure 4.20 and Figure 4.21 show that a farmer with risk premium higher than 80% and well capacity higher than 900 GPM would reduce the irrigation acreage but not increase the instantaneous rate. Thus, a farmer with risk premium higher than 80% and well capacity higher than 900 GPM would reduce variability in net return by increasing the proportion of income coming from non-irrigated acreage leasing. However, this finding may be due to a limitation in the research framework as I assume the non-irrigated area revenue is from constant cash rent. Therefore, this finding may only occur if the farmer has extremely risk averse behavior.

Figure 4.21 Instantaneous rate of application for Valent-Vona soil affecting by risk averse behavior



For the farmer with risk premium lower than 60%, I find no change in irrigated acreage, but I see irrigation intensity changes. Likely, this is because the farmer would change irrigation intensity by changing the MAD level for irrigation scheduling without changing the instantaneous rate (see Figure 4.21 and Table 4.3). Specifically, a farmer increases irrigation intensity through more frequent irrigation by way of a lower MAD level for irrigation scheduling. On the other hand, the changes in irrigation intensity for a farmer with risk premium higher than 60% differ by well capacity level. A farmer with a well capacity of 400 GPM to 600 GPM will increase irrigation intensity by increasing the instantaneous rate, thus decreasing the irrigated acreage (see Figure 4.19 and Table 4.3). Meanwhile, the farmer with high well capacity (e.g. higher than 900 GPM) with very risk averse behavior (e.g., risk premium higher than 80%), would increase irrigation intensity with a lower MAD level and lower instantaneous rate for irrigation scheduling (see Table 4.3). However, the resulting increase in irrigation intensity would reduce both average and standard deviation of net return.

Table 4-3 Instantaneous rate and MAD for Valent-Vona soil affected by risk averse behavior

Well capacity (GPM)	risk neutral		risk premium 10%		risk premium 20%		risk premium 50%		risk premium 80%	
	Ir	D1-D2-D3-D4	Ir	D1-D2-D3-D4	Ir	D1-D2-D3-D4	Ir	D1-D2-D3-D4	Ir	D1-D2-D3-D4
100	7	100-10-40-100	7	100-10-40-100	7	100-10-40-100	7	40-0-40-100	8	40-10-40-100
200	7	100-10-40-100	7	100-10-40-100	7	100-10-40-100	7	40-0-40-100	8	40-10-40-100
300	7	100-10-40-100	7	100-10-40-100	7	100-10-40-100	7	40-0-40-100	8	40-10-40-100
400	7	100-10-40-100	7	100-10-40-100	7	100-10-40-100	7	40-0-40-100	8	40-10-40-100
500	7	100-10-40-100	7	100-10-40-100	7	100-10-40-100	7	40-0-40-100	8	40-10-40-100
600	7	100-10-40-100	7	100-10-40-100	7	100-10-40-100	7	40-0-40-100	8	40-10-40-100
700	7	100-10-40-100	7	100-10-40-100	8	90-10-40-100	8	40-10-40-100	8	40-10-40-100
800	8	90-10-40-100	8	90-10-40-100	8	90-10-40-100	8	40-10-40-100	9	50-10-40-100
900	9	90-10-40-100	9	90-10-40-100	9	90-10-40-100	9	80-10-40-100	9	50-10-40-100
1000	10	70-20-40-100	10	70-20-40-100	10	70-20-40-100	10	80-10-40-100	9	50-10-40-100
1100	11	100-20-40-90	11	80-20-40-100	11	80-20-40-90	11	80-20-40-90	9	50-10-40-100
1200	13	90-20-50-100	13	90-20-50-100	13	90-20-50-100	13	80-20-40-100	9	50-10-40-100
1300	13	90-20-50-100	14	100-20-50-100	14	100-20-50-100	14	100-20-40-100	9	50-10-40-100
1400	15	80-20-50-100	15	80-20-50-100	15	80-20-50-100	15	80-20-50-100	9	50-10-40-100
1500	16	90-20-50-100	16	90-20-50-100	16	90-20-50-100	16	80-20-40-100	9	50-10-40-100

*Ir = instantaneous rate   *D1-D2-D3-D4 = MAD at growth stage 1, 2, 3 and 4

4.2.4. The comparison of the effect of risk averse behavior to average net return and distribution of net return between Richfield soil and Valent-Vona soil

The higher risk premium shows the increase in risk averse behavior, which would affect irrigation strategy and net return. Average and standard deviation of net return shows how a farmer makes a trade-off between risk and expected net return affected by the risk averse behavior.

The change in irrigation strategy in response to change in risk averse behavior causes a decrease in expected net return and a decrease in variation of net return. Figure 4.22 shows that as the risk averse behavior increases, the farmer will choose the irrigation strategy that reduces the variation in net return. However, such a strategy requires higher irrigation water use that results in lower net return. Nevertheless, the increase in irrigation water use will produce more stable corn yield.

A farmer with Richfield soil is more sensitive to risk averse behavior in changing water use than is a farmer with Valent-Vona soil. In the case of the 600 GPM well capacity, a farmer with Valent-Vona soil will change irrigation strategy if the risk premium goes higher than 35% (see figure 4.22). On the other hand, a farmer with Richfield soil will start to change irrigation strategy when the risk premium moves higher than 15%. Similarly, in the case of the 1200 GPM well capacity, a farmer with Valent-Vona soil will change irrigation strategy if the risk premium goes higher than 30% but with Richfield soil start to change if risk premium is higher than 20%.

Figure 4.22 Comparison of average and standard deviation net return for risk averse farmer with Richfield soil or Valent-Vona soil

Average and Standard deviation Net Return Richfield Silt Loam and Valent-Vona ,400 GPM, Risk Averse

Average and Standard deviation Net Return Richfield Silt Loam and Valent-Vona ,600 GPM, Risk Averse

Average and Standard deviation Net Return Richfield Silt Loam and Valent-Vona ,900 GPM, Risk Averse

Average and Standard deviation Net Return Richfield Silt Loam and Valent-Vona ,1200 GPM, Risk Averse

4.3. The effect of water constraint policy on irrigation strategy and water use

This section is divided into two parts. The first part discusses the effect of water constraint policy on the risk neutral farmer. The second section analyzes the impact of both risk averse behavior and water constraint policy for optimal irrigation strategy. Analysis in the second section mostly focuses on the impact of risk averse behavior on optimal irrigation strategy and water use if the government imposes a particular water constraint policy such as the 5-year time constraint and 11 inches quantity constraint. In addition, the impact of different quantity constraints on optimal irrigation strategy for the risk averse farmer is discussed briefly.

4.3.1 The effect of water constraint policy on irrigation strategy and water use for risk neutral farmer with Richfield soil

Water constraint policy comprises quantity and time constraints where quantity is the maximum irrigation intensity that a farmer can apply for a particular period, and time is a range within which a farmer can apply a particular maximum average quantity constraint, e.g. 11 inches quantity constraint with a five years average time constraint. This means that a farmer can apply irrigation intensity with a maximum average of 11 inches for five years. That farmer can apply more than 11 inches for a particular year within the five years' time range, but the average of irrigation intensity for five years must not exceed 11 inches. This study will analyze the effect of quantity constraint on water use and welfare by setting the baseline time constraint to a 5-year average.

The water constraint policy will decrease both expected net return and total water use (see Figures 4.23 and 4.24). Figure 4.23 shows see that a lower quantity constraint, with a baseline of the 5-year average time constraint, will result in a significant negative impact on a farmer’s net returns if the quantity constraint is lower than 13 inches. However, the impact of quantity constraint to a decrease in expected net return depends on well capacity.

Figure 4.23 Expected net return for Risk neutral farmer with Richfield soil affected by quantity constraint with 5 year average time constraint

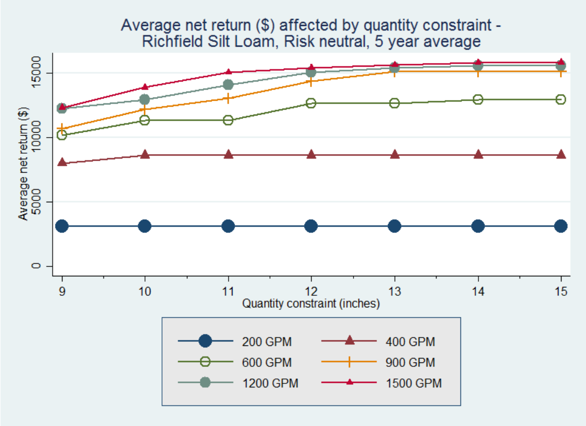
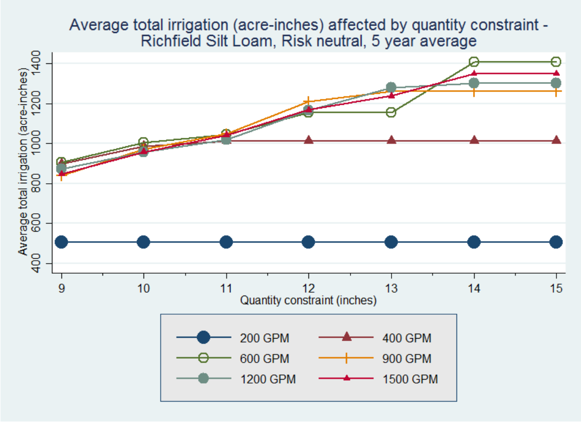


Figure 4.24 Average total water use for Risk neutral farmer with Richfield soil affected by quantity constraint with 5 year average time constraint



There is a smaller effect of quantity constraint on change in expected net return for small and high well capacities, and a higher impact of lower quantity constraint on the decrease in expected net return for medium and medium-high well capacity, 600-1100 GPM (see figure 4.23). Additionally, the 11 inches quantity constraint decreases an expected net return by 12-14% for 600-1100 GPM wells but only decreases the net return 5-10% for 1200-1500 GPM wells. Clearly, high well capacity provides more strategy alternatives to deal with the water constraint and weather uncertainty. Thus, the negative impact of the lower quantity constraint to net return is smaller for high well capacity. In addition, water constraint policy has a negligible impact on irrigation strategy and net return for low well capacity because the low well capacity, rather than the water constraint policy, has become the major limiting factor in irrigation and corn production. Ultimately, the net return of medium and medium high well capacity is more sensitive to adjustment in the intensive and extensive margins because of limitation in the instantaneous rate.

The impact of lower quantity constraint on decreasing water use depends on well capacity; for example, a quantity constraint does have a negligible effect on changing total water use for smaller well capacity. However, it has a significant impact on the decrease in total water use for well capacity higher than 600 GPM (see figure 4.24). In addition, the impact of lower quantity constraint to decrease total water use is the greatest for medium well capacity (900GPM wells). Next, the 11 inches quantity constraint decreases water use by 26% for 600 GPM wells but only decreases water use by 17% for 900 GPM wells and 22% for 1200 GPM wells.

Accordingly, quantity constraint will affect adjustment in the extensive and intensive margins, causing change in total water use. Figures 4.25 and 4.26 show that lower quantity constraint will result in lower irrigation intensity and smaller irrigated acreage, so clearly, the change in irrigated acreage and irrigation intensity depends on well capacity. Next, lower quantity constraint has no impact on the change in irrigated acreage for well capacity below 400 GPM, but a higher rate of change in irrigated acreage and smaller change in irrigation intensity exists for 600 GPM wells (see Figures 4.25 and 4.26). The lower quantity constraint requires a farmer to reduce irrigation intensity even though higher instantaneous rate may reduce the irrigation intensity and lead to higher efficiency. Due to limitations in the range of instantaneous rate that 600 GPM wells can attain, irrigation acreage needs to be reduced at a higher rate to attain higher instantaneous rate (see Figure 4.27).

Figure 4.25 Irrigation acreage for Risk neutral farmer with Richfield soil affected by quantity constraint with 5 year average time constraint

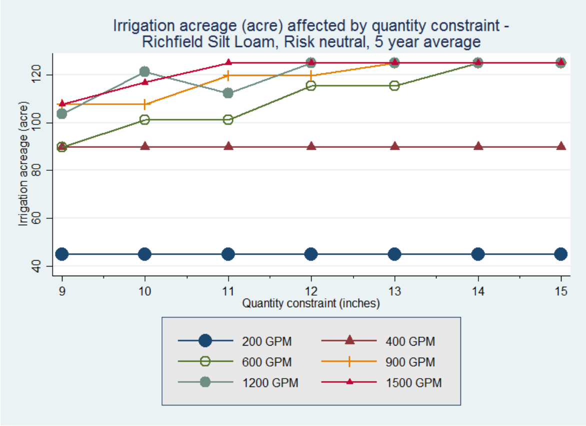


Figure 4.26 Average irrigation intensity for Risk neutral farmer with Richfield soil affected by quantity constraint with 5 year average time constraint

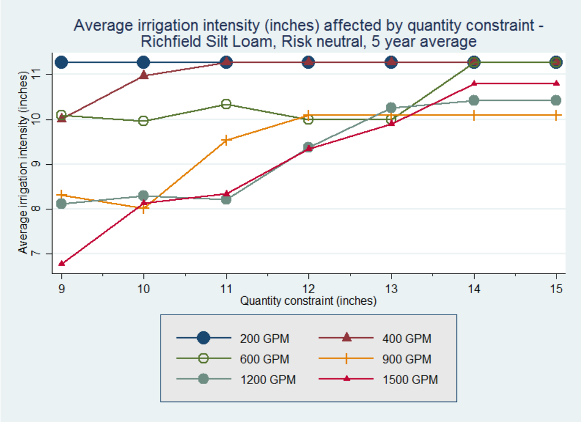
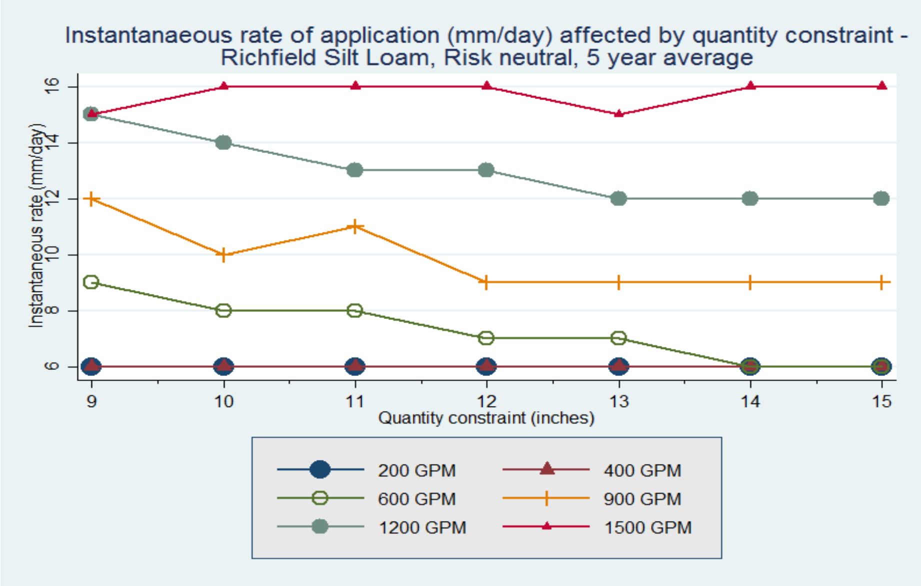


Figure 4.26 shows that the impact of lower quantity constraint on the decrease in irrigation intensity is higher as the well capacity increases. The graph shows a smaller reduction in irrigation acreage for higher well capacity, which results in higher reduction for irrigation intensity. The larger range of applicable instantaneous rate for higher well capacity enables a farmer to make more adjustment in the intensive margin rather than in the extensive margin in response to smaller quantity constraint. For example, a farmer with well capacity 1500 GPM could reduce the irrigation intensity by setting higher MAD for irrigation scheduling. On the other hand, a farmer with a well capacity between 600 and 1200 GPM could reduce irrigation intensity by increasing the instantaneous rate and setting higher MAD for irrigation scheduling. Next, Figure 4.27 shows a negative relationship between quantity constraint and instantaneous rate. Here, the lower quantity constraint would induce the farmer to use a higher instantaneous rate with higher MAD so that it can trigger less irrigation application and decrease the irrigation intensity.

Figure 4.27 Instantaneous rate of application for Risk neutral farmer with Valent-Vona soil affected by quantity constraint with 5 year average time constraint



Different patterns exist for how farmers with high well capacity, 900-1500 GPM, adjust their irrigation strategy when they face limited water availability from a water constraint policy instead of from decrease in well capacity. High well capacities mean adjustment only on the intensive margin when the well capacity is decreasing. On the other hand, farmers with high well capacities make adjustments both on intensive and extensive margins when they face a more restricted water constraint policy. In response to lower quantity constraint, farmers with high well capacities reduce the irrigation intensity to a level where it still provides an adequate supply of water to the crop. However, to comply with low quantity constraint and to attain minimum optimal irrigation intensity, those with high well capacities need to reduce irrigation acreage. In addition, medium (600-900 GPM) and medium high (900-1200 GPM) well capacities may attain a higher instantaneous rate because of irrigated acreage reduction, resulting in a more efficient irrigation schedule for irrigation intensity reduction.

The expected net return is negatively affected considerably when the quantity constraint causes adjustment in the extensive margin by decreasing the irrigated acreage. For instance, the 11 inches quantity constraint, which does not cause decrease in irrigated acreage for a 1500 GPM well, will only decrease the expected net return by 4.9%. On the other hand, a 10 inches quantity constraint causes significantly larger reduction in expected net return, as much as 12.3%, due to the decrease in irrigated acreage. In the case of 600 GPM wells, both 10 and 11 inches quantity constraints reduce irrigated acreage and decreases net return by 12.1%. Ultimately, the degree of negative impact of quantity constraint on welfare is significantly dependent on well capacity.

4.3.2 The effect of water constraint policy on irrigation strategy and water use for risk neutral farmer with Valent-Vona soil

I find the effect of water constraint policy on expected net return and water use is more extensive for Valent-Vona soil than for Richfield soil (see Figure 4.23 and Figure 4.28). In the case of well capacity at or above 400 GPM, the 11 inches quantity constraint will decrease the expected net return by 5-12% for Richfield soil and 11-32% for Valent-Vona soil. Furthermore, an 11 inches quantity constraint will decrease the water use by 13-26% for Richfield soil and 11-39% for Valent-Vona soil. The greater reduction in net return may arise because Valent-Vona soil has less soil water holding capacity so that the restrictions on water use have a higher negative impact on corn yield. In addition, greater change in water use may be due to initial water use without restriction being higher for Valent-Vona soil.

Next, I see a positive correlation between quantity constraint and water use. Figure 4.29 shows that the lower quantity constraint will promote less water use. Thus, the lower quantity constraint could have a higher impact on water savings for medium and medium high well capacity. Specifically, the 11 inches quantity constraint would decrease water use by 30-39% for

600-1100 GPM wells but by 27-28% for 1200-1500 GPM wells. Moreover, the lower total water use is predominantly affected by more adjustment in the extensive margin.

Lower quantity constraint will result in decreased irrigation acreage, but the impact of irrigation intensity is indefinite (see Figure 4.30 and Figure 4.31). In fact, the pattern for adjustment in the intensive margin in response to lower quantity constraint is different for Valent-Vona soil than for Richfield soil. In addition, greater decrease in irrigation acreage occurs as an impact of lower quantity constraint for Valent-Vona soil than for Richfield soil (see Figure 4.25 and Figure 4.30). The difference between those two soils is that Valent-Vona soil requires higher optimal irrigation intensity than does Richfield soil.

Figure 4.28 Expected net return for Risk neutral farmer with Valent-Vona soil affected by quantity constraint

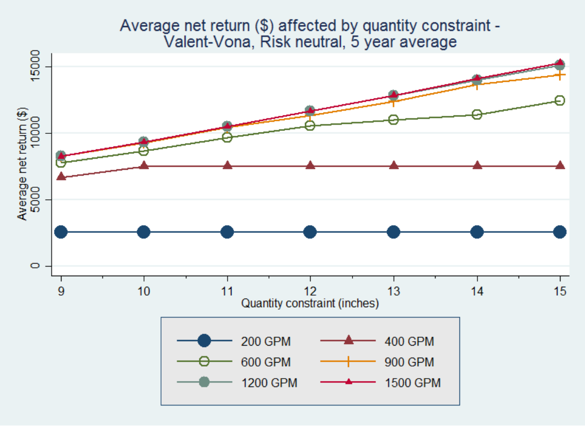


Figure 4.29 Average total water use for Risk neutral farmer with Valent-Vona soil affected by quantity constraint

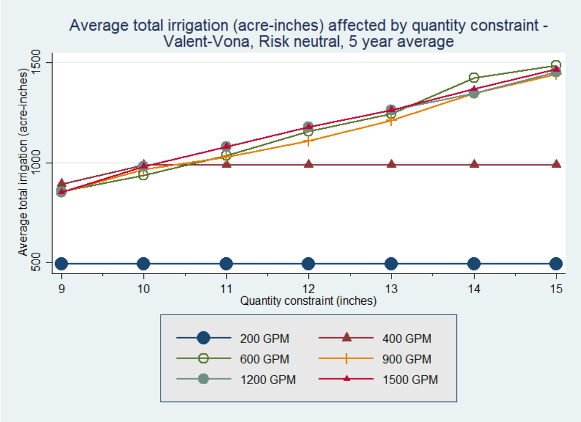


Figure 4.30 and Figure 4.31 show that the farmer with 900-1500 GPM well capacity can reduce the irrigation acreage extensively but slightly decrease the irrigation intensity. On the other hand, a farmer with medium well capacity, 600 GPM, sees greater change not only in the extensive margin but also in the intensive margin in response to the lower quantity constraint. The difference in the intensive margin adjustment is due to the difference in the instantaneous

rate. Figure 4.32 shows 600 GPM wells have a lower instantaneous rate than 900-1500 GPM wells. This suggests greater adjustment to the intensive margin when well capacity is smaller and water constraint policy binds irrigation strategy choices. , However, quantity constraint offers little to no effect on irrigation acreage, irrigation intensity, and instantaneous rate for a well capacity at or below 400 GPM (see Figure 4.30 4.31 and 4.32). This is because water constraint policy is not binding, but low well capacity does limit water use.

Figure 4.30 Irrigation acreage for Risk neutral farmer with Valent-Vona soil affected by quantity constraint

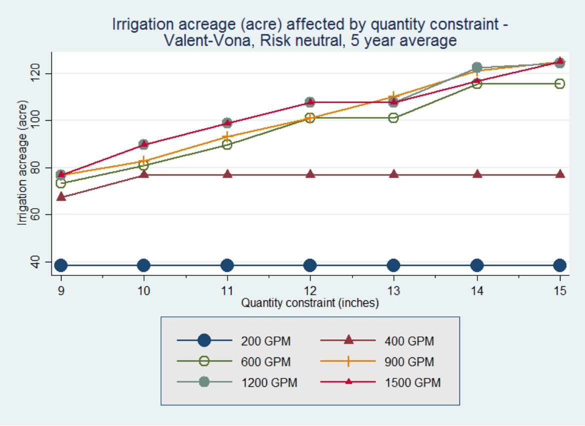
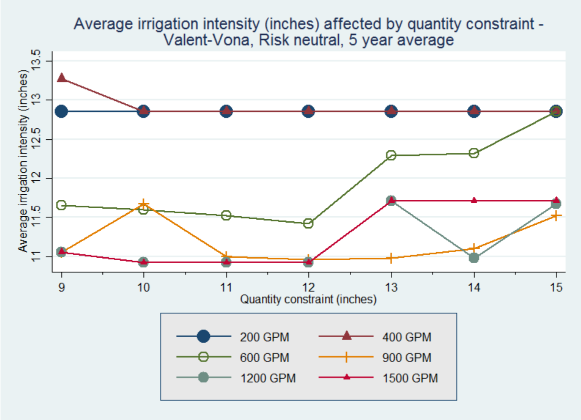
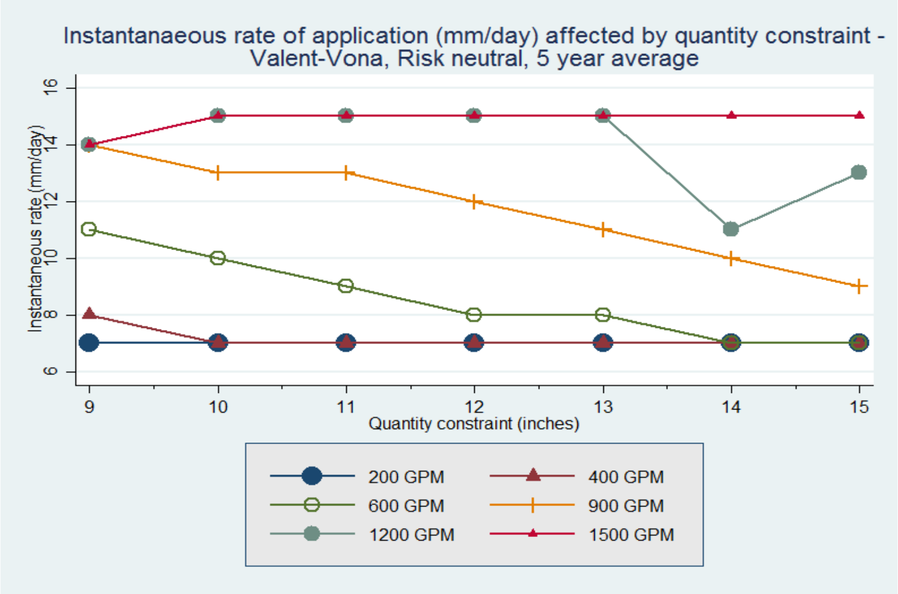


Figure 4.31 Irrigation intensity use for Risk neutral farmer with Valent-Vona soil affected by quantity constraint



Finally, a negative relationship exists between the lower quantity constraint and the instantaneous rate of application. Here, the lower quantity constraint will induce the farmer to reduce irrigated acreage, and as a consequence use a higher instantaneous rate of application with a well capacity higher than 400 GPM or lower than 1500 GPM (see figure 4.32). Moreover, the higher instantaneous rate will generate a more efficient irrigation scheduling for irrigation intensity reduction.

Figure 4.32 Instantaneous rate of application for risk neutral farmer with Valent-Vona soil affected by quantity constraint with 5 year average time constraint



4.3.3. The effect of risk averse behavior on irrigation strategy and water use for Richfield soil with government enforced water constraint policy

This section analyzes how a farmer decides on water use change based on the water constraint policy in tandem with risk averse behavior. The analysis focuses on a farm with Richfield soil with well capacity defined at 400, 600, 900, and 1200 GPM. The numbers represent low, medium, medium-high, and high well capacities to determine farm ability to adjust irrigation strategy.

The increase in risk premium will induce the farmer to choose an irrigation strategy that provides less expected net return but also less variation in net return (see Figures 4.33 and 4.34). From figure 4.33, we can observe that for a 5-year time constraint and an 11 inches quantity constraint, a negative relationship between risk premium and expected net return exists. Thus, the more risk averse farmer will choose an irrigation strategy that generates lower variation in net return but consequently also a lower expected net return. This finding is also typical when farmers are not exposed to any water constraint policy.

Figure 4.33 Expected net return for risk averse farmer with Richfield soil affected by water constraint

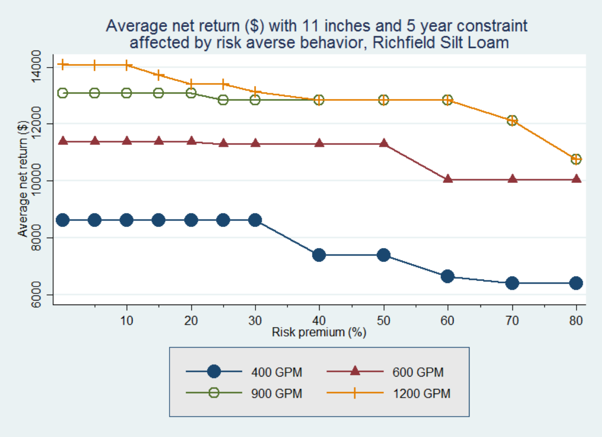


Figure 4.34 Standard deviation of net return for risk averse farmer with Richfield soil affected by water constraint

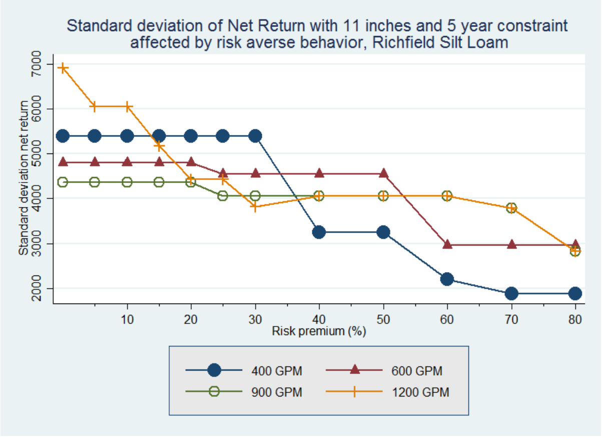


Figure 4.35 with a binding water constraint policy in place, namely an 11 inches quantity constraint and a 5-year average, shows a farmer faces a higher risk premium to use more water if the well capacity is higher than 900 GPM. The data do not show any conclusive evidence of a relationship between risk premium and total water usage for medium or low well capacity, 400-600 GPM. This finding differs from earlier findings with no water constraint policy. Ultimately, without a water constraint policy, as risk premium increases, water usage also rises for all well capacity levels (see Figure 4.14).

The impact of risk premium on the change in total water use is lower with a binding water constraint policy as the policy limits the maximum total water that farmer can use**.** For example, figure 4.14 shows that total water use for a 900 GPM well begins to change if the risk premium reaches 5% without a water constraint policy. However, the total water use starts to change if the risk premium reaches 20% when there is a binding water constraint policy (see

Figure 4.35). Thus, a water constraint policy may encourage a farmer with a relatively high-risk premium not to over-irrigate.

Figure 4.35 Average total irrigation for risk averse farmer with Richfield soil affected by water constraint

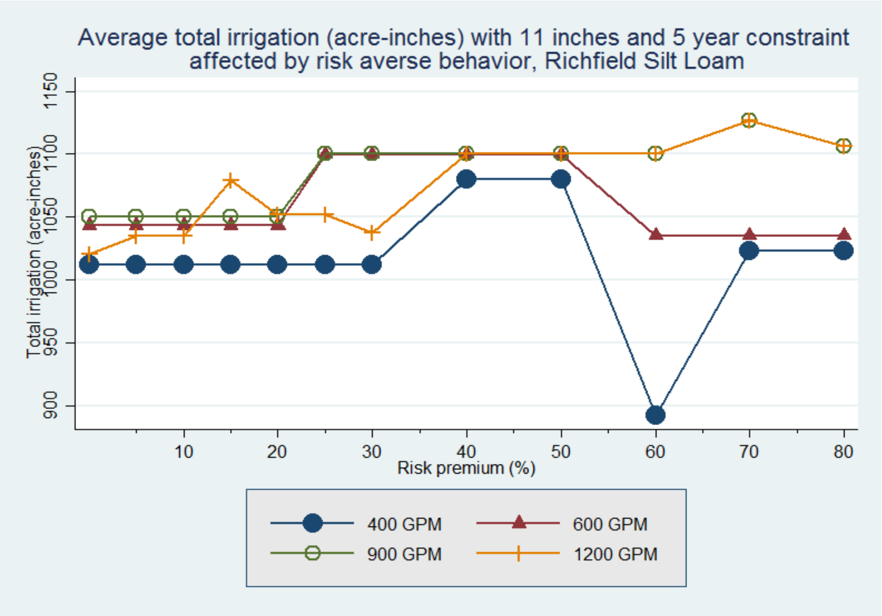


Figure 4.36 and Figure 4.17 show that the impact of increase in risk premium on decline in irrigated acreage is higher with a binding water constraint policy. On the other hand, the impact of change in risk premium relative to the rate of change in irrigation intensity is lower with a water constraint policy than without one (see Figure 4.16 and Figure 4.37). However, the water constraint policy still causes the farmer to lower irrigation intensity. This is because a risk averse farmer wants to attain a minimum optimal irrigation intensity to manage the risk in corn production versus the binding water constraint policy. Thus, a farmer governed by a water constraint policy will reduce the irrigated acreage at a higher rate than the farmer who does not face any water constraint. This result also implies a possible greater impact of a constraint policy on welfare loss for the farmer with more risk averse behavior.

Figure 4.36 Irrigation acreage for Risk averse farmer with Richfield soil affected by water constraint

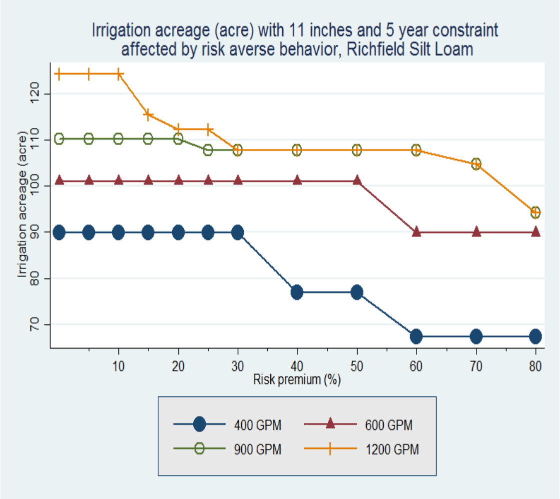


Figure 4.37 Irrigation intensity of net return for Risk averse farmer with Richfield soil affected by water

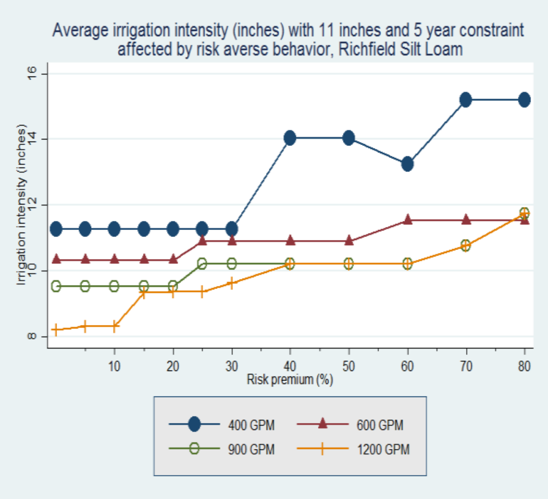
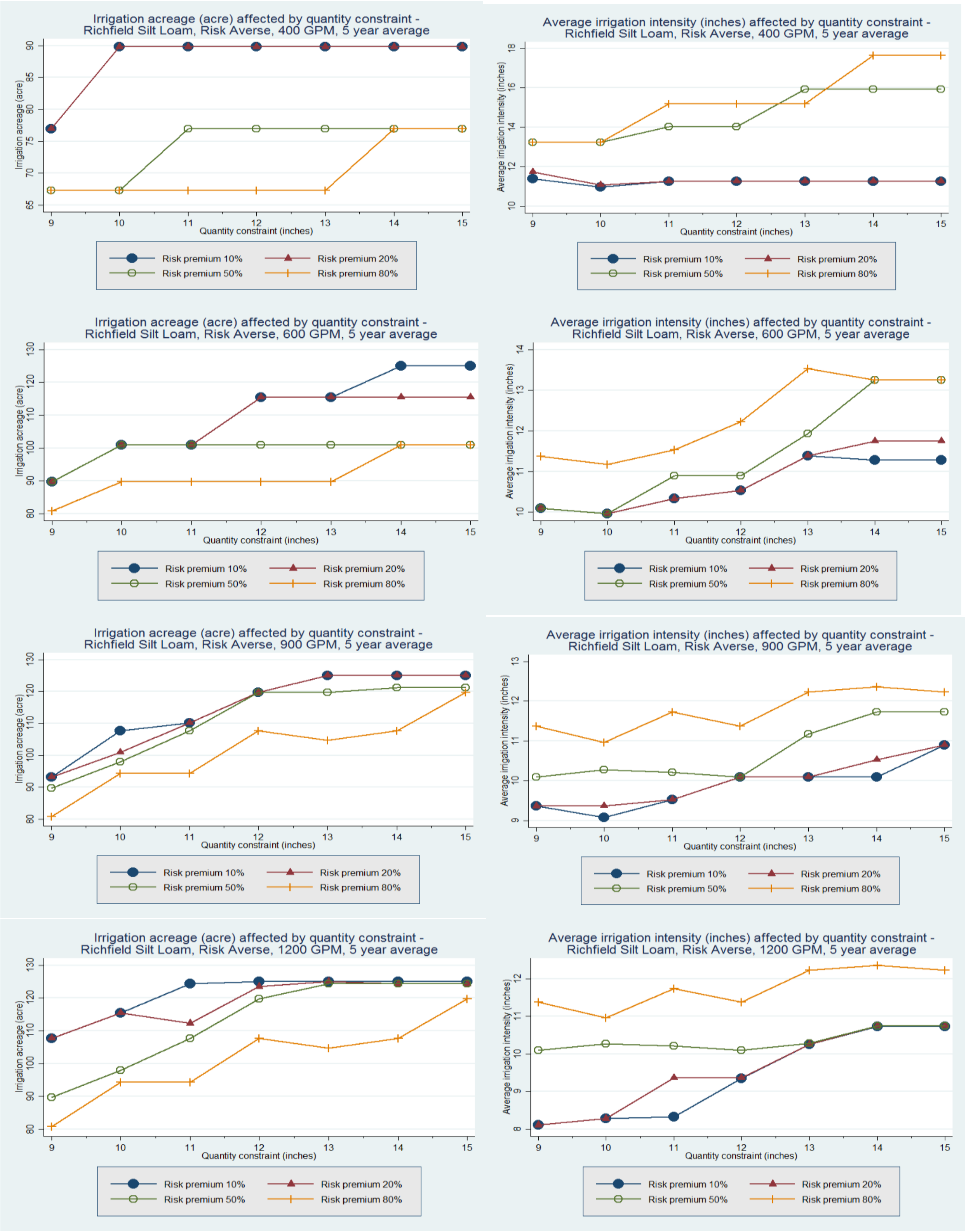


Figure 4.38 shows a greater impact of lower quantity constraint on the rate of decrease in irrigation intensity for the risk averse farmer with a smaller well capacity. Moreover, the change from risk neutral to risk premium 25% will increase the irrigation intensity of 600 GPM wells by 29% and 900 GPM wells by 17%. In addition, a farmer with a higher risk premium will reduce the acreage more in response to a lower quantity constraint and offsets the effect of reduced acreage by increasing the irrigation intensity to reduce the risk to corn yield. Furthermore, when well capacity is at or above 600 GPM, the effect of lower quantity constraint on the decrease in irrigated acreage is smaller as well capacity increases (see Figure 4.38).

Figure 4.38 Irrigation acreage and average irrigation intensity for risk averse farmer with Richfield soil affected by quantity constraint


Irrigation acreage (acre) affected by quantity constraint - Richfield Silt Loam, Risk Averse, 400 GPM, 5 year average

Average irrigation intensity (inches) affected by quantity constraint - Richfield Silt Loam, Risk Averse, 400 GPM, 5 year average

Irrigation acreage (acre) affected by quantity constraint - Richfield Silt Loam, Risk Averse, 600 GPM, 5 year average

Average irrigation intensity (inches) affected by quantity constraint - Richfield Silt Loam, Risk Averse, 600 GPM, 5 year average

Irrigation acreage (acre) affected by quantity constraint - Richfield Silt Loam, Risk Averse, 900 GPM, 5 year average

Average irrigation intensity (inches) affected by quantity constraint - Richfield Silt Loam, Risk Averse, 900 GPM, 5 year average

Irrigation acreage (acre) affected by quantity constraint - Richfield Silt Loam, Risk Averse, 1200 GPM, 5 year average

Average irrigation intensity (inches) affected by quantity constraint - Richfield Silt Loam, Risk Averse, 1200 GPM, 5 year average

4.3.4. The effect of risk averse behavior on irrigation strategy and water use for Valent-Vona soil with a binding water constraint policy

The impact of a higher risk premium on net return and water use is smaller for Valent-Vona soil than for Richfield soil. Figure 4.39 and Figure 4.40 show that the change in average and standard deviation of net return to a farmer with a 600 GPM well capacity starts when risk premium is 70%. On the other hand, the change for 600 GPM wells and Richfield soil starts when risk premium is 55%. Thus, a farmer with Valent-Vona soil is less sensitive to the change in risk premium than the farmer with Richfield soil as regards the binding water constraint policy.

Figure 4.39 Expected net return for risk averse farmer with Valent-Vona soil affected by water constraint

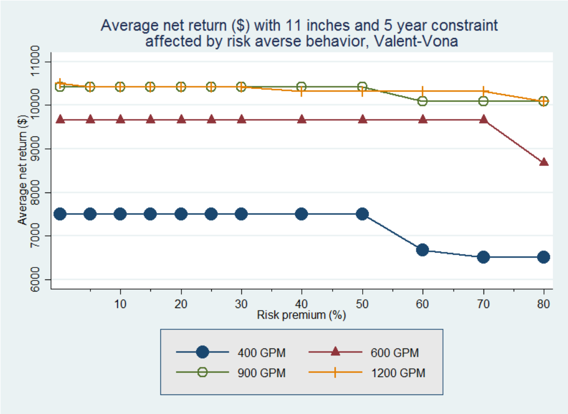
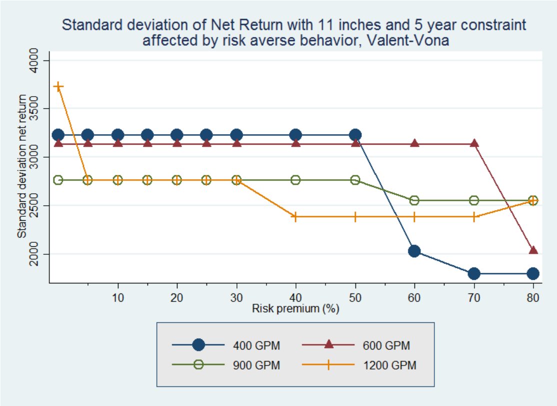


Figure 4.40 Irrigated acreage for risk averse farmer with Valent-Vona soil affected by water constraint



Clearly, a higher risk premium will encourage the farmer to choose an irrigation strategy that results in lower expected net return and slightly higher total water use (see Figure 4.39 and 4.41). The change in total water use would be due to the change in irrigated acreage and irrigation intensity. Accordingly, Figure 4.41 shows that a farmer's decision to change total water use is less sensitive to change in risk premium.

Figure 4.41 Average total irrigation for risk averse farmer with Valent-Vona soil affected by water constraint

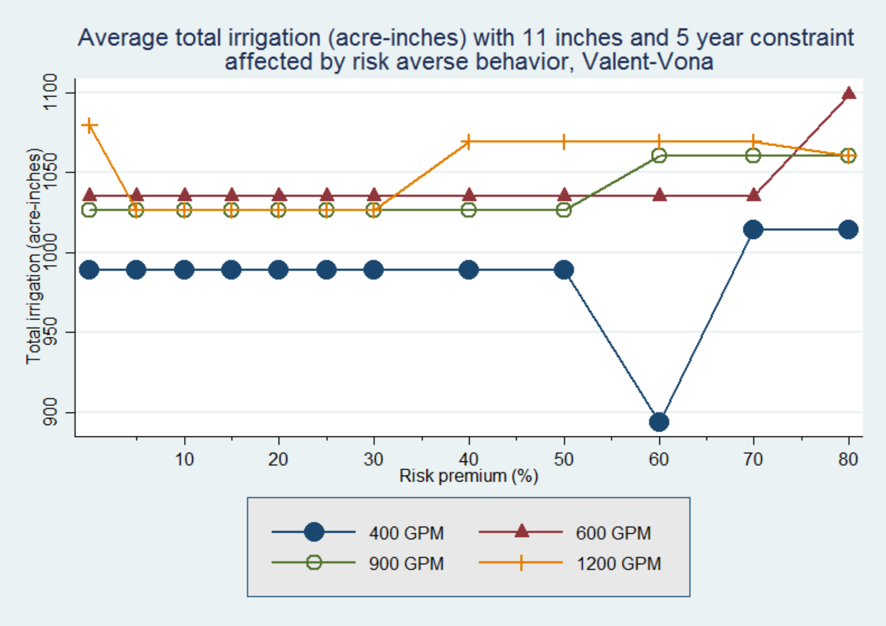


Figure 4.42 and Figure 4.43 show that a higher risk premium encourages reduced irrigated acreage but increases irrigation intensity. However, the effect of risk averse behavior relative to the decrease in irrigated acreage and increase in irrigation intensity is relatively smaller for Valent-Vona soil than for Richfield soil. In the case of 1200 GPM wells, the change from risk neutral to risk premium 40% will increase irrigation intensity by only 9% for Valent-Vona soil but will increase the irrigation intensity of Richfield soil by 24%. The lower change in irrigation intensity and irrigated acreage for Valent-Vona soil is due to its higher initial irrigation intensity for the risk neutral farmer. However, higher irrigation intensity results in slightly lower variation in net return and crop yield. Thus, the impact of risk averse behavior is relatively less sensitive to adjustment in extensive and intensive margins for Valent-Vona soil than for Richfield soil.

Figure 4.42 Irrigation acreage for Risk averse farmer with Valent-Vona soil affected by water constraint

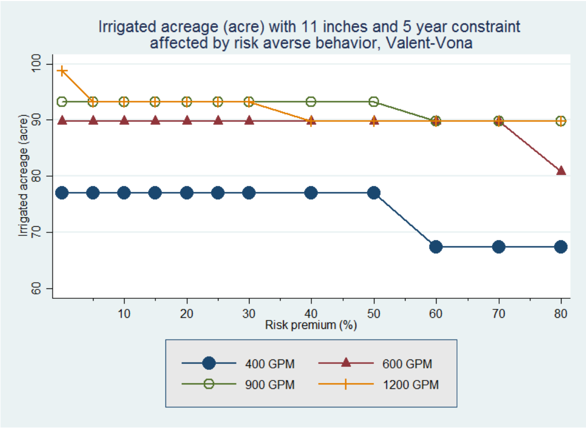
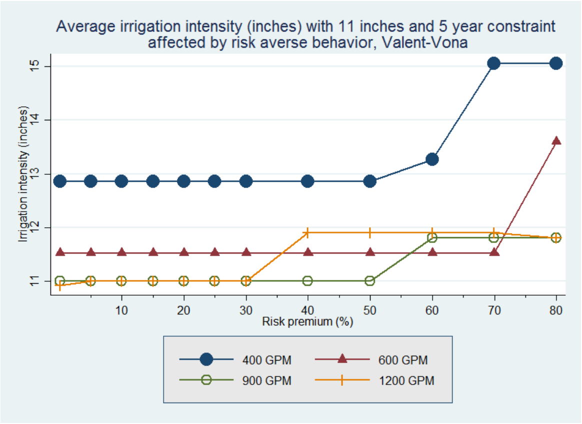


Figure 4.43 Irrigation intensity of net return for Risk averse farmer with Valent-Vona soil affected by water

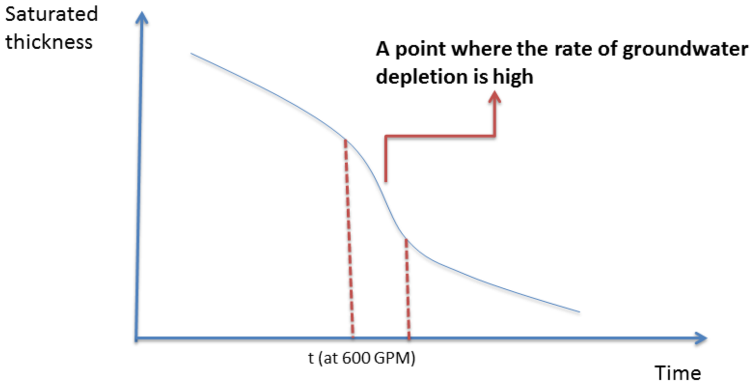


4.4. Economic implication

The 'hump shape' of total irrigation in Figure 4.1 and Figure 4.7 in the first section gives the economic implication that groundwater depletion may accelerate when depletion reaches a particular saturated thickness. For example, Figure 4.44 shows faster depletion in saturated thickness that could be associated with the well capacity reaching 600 GPM. The resulting pattern of groundwater depletion is consistent with the pattern described by Brill and Burness (1994) when water demand grows over time and the cost of pumping increases nonlinearly over time. However, the reason for the backward 'S' shaped depletion in my model is different. The backward 'S' shaped depletion is also consistent with data on actual depletion rates from the High Plains Aquifer (Steward and Allen 2016).

Specifically, an increase in risk averse behavior will greatly increase total irrigation, and more so for wells with medium capacity. This result suggests that the economic model that does not include well capacity and risk aversion will substantially underestimate total water use. Examining the dynamic of well capacity and risk averse behavior will be critical on groundwater depletion studies. In addition, higher rates of groundwater depletion may occur the more risk averse behavior a farmer has. Another implication is that a water constraint policy could be an effective means to reduce total water use especially in the case of high risk averse behavior.

Figure 4.44 Implication of groundwater depletion over time



Chapter 5 - The welfare loss as a result of reductions in well capacity and water constraint policy

A water constraint policy will limit irrigation water use to maintain sustainable irrigation resources for a longer period. However, a restricted water constraint policy increases the risk in crop production and, moreover, decreases the net return. Thus, farmers face welfare loss due to enforcement of a water constraint policy. My study analyzes the impact and extent of water constraint policy on welfare loss and water saving.

The analyses are organized into four sections. The first section focuses on the effect of reductions in well capacity through groundwater depletion and how that effect speaks to welfare loss. The second section analyzes the impact of water constraint policy on welfare loss. In the third section, I examine how the findings in the first section change with respect to risk premium, where risk premium represents any change in risk averse behavior. In the final section, I discuss variation in the quantity constraint, namely 9 to 15 inches by increments of 1 inch.

The water constraint policy for the analysis in the second section has two aspects: a5-year time constraint and an 11 inch quantity constraint. Also the analysis is based on a range of well capacities, 100-1500 GPM, which will offer insight into the effect of groundwater depletion simultaneously with water constraint policy on welfare loss. Additionally, the analysis includes the effect of a water constraint policy on saving water.

Accordingly, three terms will be used extensively in the last three sections: welfare loss, water saving, and cost of saving water. We measure welfare loss as the difference between two conditions, with and without a water constraint policy, as it concerns the welfare of the producer. Next, water saving refers to the difference in total water use between a water constraint policy and no such policy. Finally, the cost of saving water is defined as the price of saving per inch water ($\frac{welfare\ loss}{water\ saving}$).

I use SERF analysis to rank various water use strategies and to estimate the certainty equivalent in this chapter. This method of ranking is different from the Mean-Variance analysis used in the fourth chapter. However, my estimation shows similar results for both SERF analysis and Mean-Variance analysis. Lastly, the estimation of certainty equivalent is on a per acre basis so that estimating welfare loss and cost of saving water will be on a per acre basis.

5.1. The effect of well capacity reduction on welfare loss for Richfield soil and Valent-Vona soil

The certainty equivalent for the farmer decreases as the well capacity decreases (see Figure 5.1 and Figure 5.2). In turn, the decline in well capacity affects irrigation, thus affecting crop productivity and total production, which in turn reduces the certainty equivalent through smaller average net return and greater variation in net return. Thus, the rate of decline in certainty equivalent increases with the decline in well capacity. Meanwhile, diminishing marginal productivity and marginal net return occur as the well capacity increases. Figure 5.1 and Figure 5.2 show a significant decrease in the certainty equivalent when a farmer with low well capacity encounters a small decrease. On the other hand, a farmer with high well capacity will encounter small decrease in net return with a small decrease in well capacity.

Figure 5.1 and Figure 5.2 show a steep slope of certainty equivalent when well capacity is low. On the other hand, a flat slope of certainty equivalent occurs when the well capacity is high. The steep slope shows the high marginal productivity and marginal net return of land and water when the well capacity is low. Thus, an increase in well capacity will encourage an increase in irrigated acreage, an adjustment in the extensive margin. The increase in irrigated acreage would greatly increase corn production and net return. Table 5.1 shows that the increase in well capacity from 400 GPM to 500 GPM will increase the certainty equivalent for a risk neutral farmer with Richfield soil by 32% and for Valent-Vona soil by 33%, but both 400 and 500 GPM wells do not irrigate full acreage for either soil. The flat slope of certainty equivalent occurs when a farmer with high well capacity irrigates full acreage. In this case, a small marginal productivity and marginal net return of water occurs if the well capacity is high, and the increase in total irrigation will slightly increase the net return. Thus, the increment in well capacity will induce a farmer to increase net return by slightly changing the total irrigation through an adjustment in the intensive margin. Table 5.1 also shows that an increase in well capacity from 700 GPM to 800 GPM would increase the certainty equivalent of a risk neutral farmer with Richfield soil by only 5.4% and for Valent-Vona soil by only 5.5%.

Figure 5.1 Certainty equivalent per acre without water constraint policy for Richfield soil

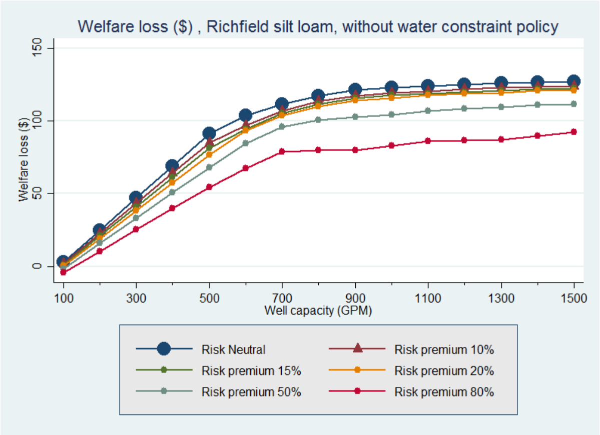
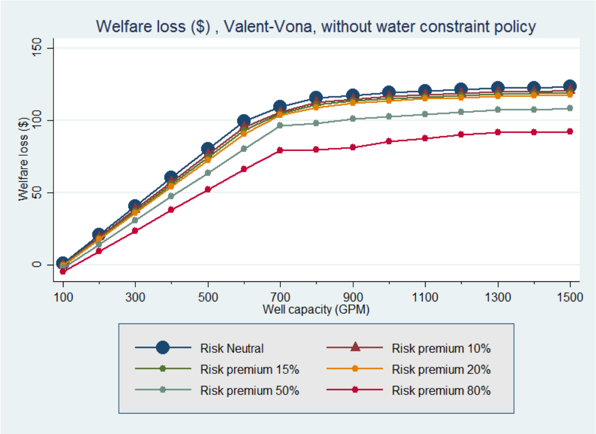


Figure 5.2 Certainty equivalent per acre without water constraint policy for Valent-Vona soil



To illustrate the implications for aquifer depletion, I examine a couple of hypothetical scenarios of aquifer depletion. Hecox, Macfarlane and Wilson (2002) estimated that the decrease in saturated thickness from 60 feet to 40 feet would reduce the well capacity from 800 GPM to 400 GPM assuming 90 days of pumping a single well and hydraulic conductivity of 150 feet/day (Hecox, P. a Macfarlane, et al. 2002). The decrease in saturated thickness from 60 feet to 40 feet would cause a corresponding welfare loss of 48.11 $/acre[3] to a risk neutral farmer with Richfield soil. On the other hand, the decrease in saturated thickness from 60 feet to 40 feet would cause a welfare loss of 55.3 $/acre[4] to a risk neutral farmer with Valent-Vona soil. Thus, a decrease in well capacity has a higher negative impact on Valent-Vona soil.

Macfarlane, Wilson and Bohling (2006) estimated the mean of practical saturated thickness for Four Corners (which includes Finney, Grant, Haskell, and Kearny Counties) before the predevelopment era likely was 188 feet. The mean of practical saturated thickness in 2003-2005 is estimated at 105 feet. Based on Hecox et al. (2002) assumptions' 90 days of pumping a single well and the 25 feet/day of hydraulic conductivity parameter value, the change in saturated thickness would cause a decline in well capacity from approximately 1500 GPM to 500 GPM. Subsequently, this decrease in thickness would cause a welfare loss of 35.88 $/acre[5] for risk neutral farmer with Richfield soil.

From the two scenarios on saturated thickness depletion above, we can see the magnitude of welfare loss is not only determined by how large the depletion is but also by the nonlinear relationship between well capacity and welfare. In the first scenario, smaller depletion, from 800

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[3] In the case of Richfield soil and risk neutral farmer, the CE of 800 GPM is 117.09 $/acre and 400 GPM is 68.98 $/acre.

[4] In the case of Valent-Vona soil and risk neutral farmer, the CE of 800 GPM is 115.36 $/acre and 400 GPM is 60.06 $/acre.

[5] In the case of Richfield soil and risk neutral farmer, the CE of 1500 GPM is 126.85 $/acre and 500 GPM is 90.97 $/acre.

GPM to 400 GPM, occurs, but it has a bigger effect on welfare loss. On the other hand, the second scenario shows larger depletion, from 1500 GPM to 500 GPM, but it registers smaller welfare loss.

In Figure 5.1 and Figure 5.2, the farmer has a lower certainty equivalent if the risk premium is higher, which suggests different risk behavior may induce a farmer to have a different irrigation strategy. For example, a farmer with a higher risk premium would be more sensitive to uncertainty in net return. Thus, a more risk averse farmer would choose an irrigation strategy that offers lower variability in net return but consequently also results in lower net return. The lower certainty equivalent for a more risk averse farmer is not only because of lower net return but also because of the variation in net return.

The certainty equivalent difference between risk neutral and risk premium lower than 20% is smaller when the well capacity increases and greater for medium well capacity, 400-700 GPM (see table 5.1). Also, the certainty equivalent for a risk neutral farmer with Richfield soil and a 600 GPM well is 7% higher than for a farmer with a risk premium of 10%. On the other hand, the certainty equivalent of a risk neutral farmer with Richfield soil and 700 GPM well is only 4.2% higher than for a farmer with a risk premium of 10%. Regarding risk aversion and land rental bargaining, Turvey, Baker and Weersink (1992) stated that the exogenous market for land rental is independent of risk preference so that less the risk averse farmer can take advantage of land rental bargaining due to a low opportunity cost for the more risk averse farmer. The implication is that a less risk averse farmer may take greater advantage of land rental bargaining as well capacity decreases, whereas a more risk averse farmer, more sensitive to variation in net return due to the decrease in well capacity, is less likely to. Additionally, groundwater depletion that results in medium well capacity may offer the greatest advantage for a less risk averse farmer in rental bargaining.

Regarding soils, the certainty equivalent for Richfield soil is higher than that for Valent-Vona soil (see Table 5.1); however, with no water constraint policy, there is a small difference in the certainty equivalent between those two soils when well capacity is at or above 600 GPM, but the difference is greater when the well capacity decreases below 500 GPM. Table 5.1, which considers no water constraint policy' shows that the certainty equivalent of a risk neutral farmer with Richfield soil is $111.16 /acre when the well capacity is at 700 GPM. On the other hand, the certainty equivalent of a risk neutral farmer with Valent-Vona soil is lower, at 109.39 $/acre, when the well capacity is at 700 GPM. In the case of the risk neutral farmer with Richfield soil with a 200 GPM well, a 17.8% higher certainty equivalent would pertain than with Valent-Vona soil. This result implies that the cash rent difference based on different soil characteristics would be smaller as the well capacity increases.

Table 5-1 Certainty equivalent affected by well capacity and risk premium

		Richfield Soil			**Valent-Vona soil**		
	Well capacity	**Risk neutral**	**Risk premium 10%**	**Risk premium 20%**	**Risk neutral**	**Risk premium 10%**	**Risk premium 20%**
Without water constraint	100	3.02	1.81	0.13	0.78	0.08	-0.75
	200	25.00	22.59	19.23	20.54	19.14	17.47
	300	46.99	43.37	38.33	40.30	38.19	35.69
	400	68.98	64.16	57.43	60.06	57.25	53.91
	500	90.97	84.93	76.54	79.81	76.30	72.13
	600	103.48	96.75	93.13	99.57	95.36	90.36
	700	111.16	106.65	103.78	109.39	105.74	103.57
	800	117.09	113.39	109.70	115.36	112.28	108.68
	900	121.25	117.35	113.88	117.27	114.62	111.64
	1000	123.06	119.36	115.60	118.93	116.26	113.41
	1100	123.95	120.39	117.41	119.98	117.42	114.69
	1200	125.04	121.61	118.46	121.24	118.46	115.44
	1300	125.87	122.58	119.31	122.01	119.38	116.64
	1400	126.47	123.38	120.62	122.47	119.87	117.02
	1500	126.85	123.64	120.98	123.23	120.59	117.79

		Richfield Soil			Valent-Vona soil		
	Well capacity	**Risk neutral**	**Risk premium 10%**	**Risk premium 20%**	**Risk neutral**	**Risk premium 10%**	**Risk premium 20%**
With 5-year and 11 inches constraint	100	3.02	1.81	0.13	0.78	0.08	-0.75
	200	25.00	22.59	19.23	20.54	19.14	17.47
	300	46.99	43.37	38.33	40.30	38.19	35.69
	400	68.98	64.16	57.43	60.06	57.25	53.56
	500	84.89	77.36	73.45	71.11	69.62	67.87
	600	90.97	88.35	85.05	77.24	75.58	73.69
	700	98.54	96.67	94.56	80.71	79.19	77.55
	800	104.49	100.56	97.99	80.82	79.42	77.92
	900	104.72	101.52	97.99	83.37	81.54	79.60
	1000	107.15	103.48	99.14	83.37	81.54	79.80
	1100	109.20	103.77	99.14	83.94	81.54	79.80
	1200	112.86	104.90	99.14	83.94	81.54	79.80
	1300	115.31	106.25	99.14	83.94	81.54	79.80
	1400	118.29	108.53	99.14	83.94	81.54	79.80
	1500	120.66	112.79	101.42	83.94	81.54	79.80

I find that the certainty equivalent with a water constraint policy is smaller than the certainty equivalent without a water constraint policy if the well capacity is at or above 500 GPM for Richfield soil. I also found a similar pattern for Valent-Vona soil if the well capacity is at or above 400 GPM. This result implies a non-binding water constraint policy for small well capacity. Furthermore, the well capacity threshold of when water constraint policy is binding depends on soil type. In the case of a risk neutral farmer with a 500 GPM well, the water constraint policy would decrease the certainty equivalent by 6.7% for Richfield soil and by 10.9% for Valent-Vona soil (see Table 5.1). Moreover, the difference in certainty equivalent for a particular well capacity is higher between Richfield soil and Valent-Vona soil when the government imposes a water constraint policy. The implication is the enforced water constraint policy may reduce the cash rental rate for irrigated crop land. In addition, the water constraint policy would have a greater effect on decreasing cash rental rate for soil with lower soil water holding capacity.

5.2 Welfare loss of water constraint policy affected by the decrease in well capacity

This section addresses the effect of water constraint policy to welfare loss, water saving and cost of saving water for risk neutral farmer.

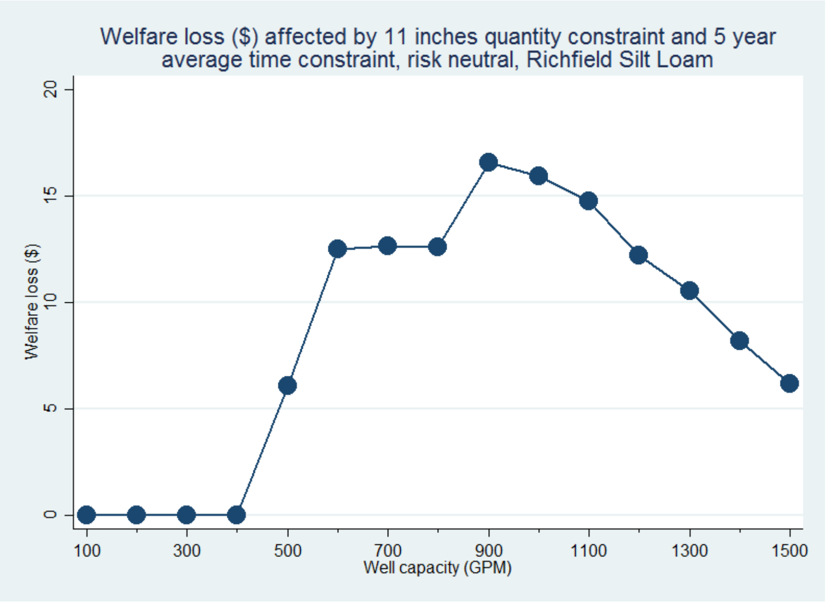
5.2.1 Welfare loss of water constraint policy affected by the decrease in well capacity for risk neutral farmer with Richfield soil

The groundwater extraction for irrigation activity causes groundwater depletion and reduces saturated thickness, which reduces the amount of water that can be extracted from the well. Thus, the range of irrigation strategies that farmer can utilize becomes more limited. In addition, government policy on water use further restricts irrigation strategy. Consequently, farm net return will fall and risk in crop production will increase.

The welfare loss varies substantially by well capacity. For example, a farmer does not experience welfare loss abiding by the water constraint policy when the well capacity is at or below 400 GPM (see figure 5.3). This result implies that, when the well capacity is at or below 400 GPM, the water constraint policy is not a limiting factor in water use but instead low well capacity is.

A main research finding is that the welfare loss does not always increase with well capacity increase. For example, Figure 5.3 shows that the welfare loss increases with higher well capacity when the well capacity is between 500 GPM and 900 GPM. However, a decreasing trend in welfare loss appears when the well capacity goes above 1000 GPM. The varied trends of welfare loss of 500-900 GPM wells and above 1000 GPM wells can be attributed to limitation on the instantaneous rate at which well capacity can be utilized in response to the water constraint policy.

Figure 5.3 Welfare loss water constraint policy affected by well capacity declining to Richfield soil



The water constraint policy also may induce a farmer to reduce irrigation intensity and irrigation acreage; however, the extent of the decrease will depend on well capacity. The reduction in the irrigated acreage may enable a farmer to attain a higher instantaneous rate, which could generate smaller irrigation intensity with a more efficient irrigation schedule. Ultimately, the welfare loss for well capacity 500 GPM to 900 GPM is because of two factors: the decrease in corn yield and the decrease in irrigated acreage. The decrease in corn yield is due to lower irrigation intensity. Secondly, with respect to decrease in irrigated acreage, even though the reduction would be smaller for a higher well capacity, due to higher initial net return, the welfare loss would be higher with the increase in well capacity for wells 500 GPM to 900 GPM.

The change in trend in welfare loss can also be attributed to different changes in irrigation strategy for well capacity above 1000 GPM in comparison to 500 – 900 GPM. A farmer with well capacity above 1000 GPM will focus more on adjustment in the intensive margin in response to a water constraint policy, thus reducing the irrigation intensity to minimize the welfare loss. Conversely, a higher well capacity would provide a larger range of instantaneous rates the farmer could use for irrigation. Thus, the reduction in acreage would be very small or not needed in the case of well capacity beyond 1000 GPM. Instead, the farmer would change the irrigation schedule to attain lower irrigation intensity by setting higher MAD. The higher MAD would trigger less frequent irrigation that would result in lower irrigation intensity. The process of reducing irrigation intensity becomes more efficient when the farmer can utilize a higher instantaneous rate. Thus, a higher well capacity would offer better efficiency in reducing the irrigation intensity resulting in smaller decrease in total corn production and lower impact on welfare loss.

The relatively small change or no change in irrigated acreage for well capacity above 1000 GPM is due to Richfield’s high soil water holding capacity that has enabled farmers with high well capacity to reduce irrigation intensity with small or no change in irrigated acreage. In conclusion, higher well capacity will offer the farmer the ability to minimize the welfare loss by adopting adjustment in intensive margin. Given these disparate variables, namely different strategies, different well capacities, and therefore different responses to water constraint policy, the end result is varied welfare loss. Thus, an economic model that did not include well capacity may misestimate the effect of water constraint policy on welfare loss.

Finally, a negative correlation exists between water saving and well capacity declining. In particular, Figure 5.4 shows a smaller impact of the water constraint policy on water saving than the decline in well capacity. In fact, the water constraint policy will not reduce water use if the well capacity decreases below 400 GPM because low well capacity as a limiting factor up to 400 GPM. I observe that the highest water saving is for well capacity at 600 GPM when the water constraint policy results in three inches of water saving per acre. This saving is largely attributed to the biggest likely reduction in irrigated acreage. In addition, 600 GPM wells use the highest total irrigation amounts initially. In the case of well capacity at and above 700 GPM, the positive correlation between water saving and well capacity is largely attributed to the reduction in irrigation intensity. I find that farmers apply larger reductions in irrigation intensity when the increase in well capacity rises above 700 GPM. The larger reduction in irrigation intensity arises because a farm with higher well capacity has a larger range of instantaneous rates, and thus it generates a more efficient irrigation schedule with lower irrigation intensity. I also found that the corn yield is higher with the increase in well capacity, when it is at or above 700 GPM.

Figure 5.4 Water saving affected by well capacity declining to Richfield soil

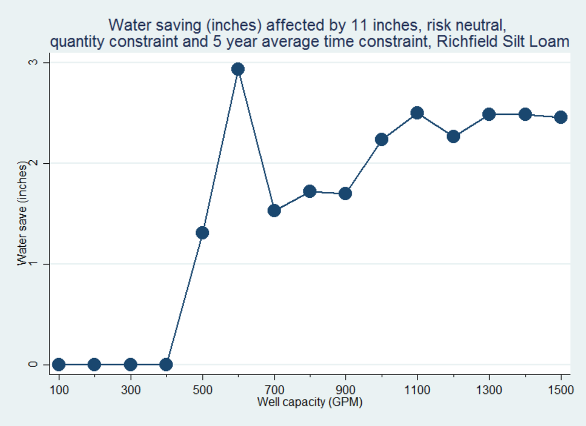
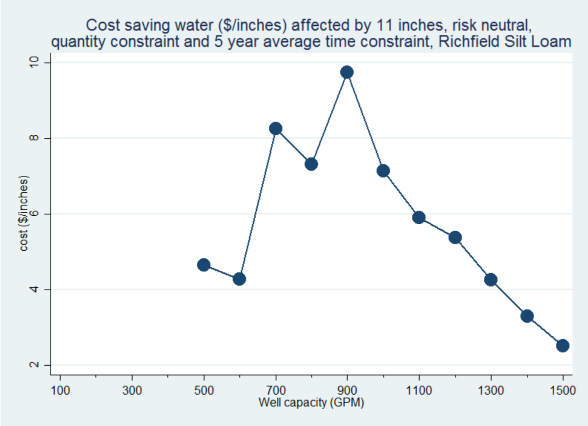


Figure 5.5 Cost of water saving affected by well capacity declining to Richfield soil



When the well capacity is at or below 900 GPM, the cost of saving water increases as the well capacity increases. On the other hand, when the well capacity is at or above 1000 GPM, the cost of saving water decreases as the well capacity increases(see Figure 5.5). Figure 5.3 and Figure 5.4 show that the welfare loss is decreasing and water saving is increasing with the increase in well capacity, when well capacity is at or above 1000 GPM. This trend results in a lower cost of saving water for higher well capacity. The possible greater adjustment in the intensive margin with less adjustment in the extensive margin could cause a lower cost of saving water for higher well capacity. Thus, I can conclude that groundwater depletion will decrease the effectiveness of a water constraint policy on water saving.

5.2.2 Welfare loss of water constraint policy affected by the decrease in well capacity for risk neutral farmer with Valent-Vona soil

As the soil type changes, I observe the welfare loss is relatively higher for Valent-Vona soil than for Richfield soil (see Figure 5.3 and Figure 5.6). The difference in welfare loss may be due to differences in soil water holding capacity. Valent-Vona soil retains less water as it has lower soil water holding capacity than Richfield soil. Thus, Valent-Vona soil requires higher optimal irrigation intensity than Richfield soil, which means its lower soil water holding capacity causes a larger impact from the water constraint policy in reducing irrigated acreage for Valent-Vona soil. The larger decrease in irrigated acreage causes a greater reduction in total crop production and net return. Thus, the welfare loss is higher for Valent-Vona soil than for Richfield soil when the water constraint policy becomes the limiting factor of water use.

I observe similar patterns for Valent-Vona and Richfield soils when well capacity is below 400 GPM. The farmer does not suffer a welfare loss abiding by the water constraint policy when the well capacity is at or below 400 GPM. This result implies that, for the well capacity at or below 400 GPM, that well capacity is the limiting factor for water use. A different welfare loss scenario occurs for Valent-Vona and Richfield soils when the well capacity is at or above 500 GPM. The welfare loss of Valent-Vona soil is higher by 43-535% than for Richfield soil. Next, for 900 GPM wells, the welfare loss of Valent-Vona soil is higher by 106% than for Richfield soil. The implication is the effect of a water constraint policy to profitability depends on soil characteristic. Therefore, a water constraint policy that does not include spatial variability in soil may underestimate or overestimate the effect of the policy on farm profitability.

Given the different effects of well capacity and water constraint policy on welfare loss depending on soil type, the water constraint policy induces a farmer to reduce the irrigation intensity. However, the farmer may do so only slightly due to lower soil water holding capacity of Valent-Vona soil, which means too large a decrease in irrigation intensity will greatly reduce the corn yield. Thus, as Valent-Vona soil only allows small decreases in irrigation intensity, this means larger decreases in irrigated acreage compared to those for Richfield soil. The different rate of changing in irrigation intensity and irrigated acreage due to soil characteristic result in different pattern of welfare loss related with well capacity between Valent-Vona soil and Richfield soil as shown in Figure 5.4 and 5.6.

Figure 5.6 Welfare loss from water constraint policy affected by well capacity declining for Valent-Vona soil

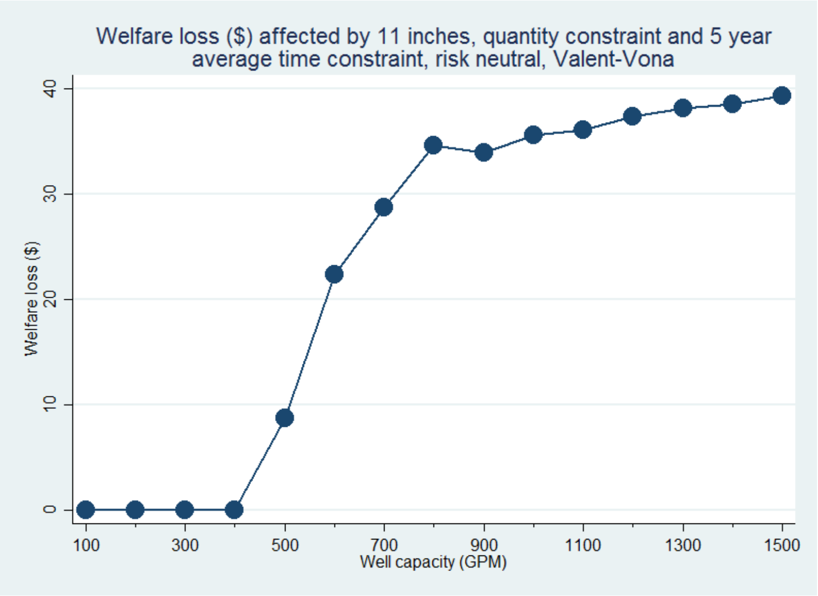


Figure 5.6 shows that the welfare loss is positively correlated with well capacity when the well capacity is above 500 GPM. The positive correlation can be attributed to the larger decrease in total crop production for higher well capacity in response to a water policy constraint. Due to smaller allowable decreases in irrigation intensity, a farmer would not only need to make adjustment in the intensive margin but also in the extensive margin to comply with the water constraint policy. Notably, the extensive margin permits smaller adjustment as well capacity increases. However, the decrease in total production is greater for higher well capacity because of its higher initial total production without a water constraint policy.

The highest water saving occurs when well capacity is at 900 GPM. The highest water saving is attributed to the biggest reduction in irrigated acreage and irrigation intensity for the farmer to comply with a water constraint policy. In the case of well capacity between 500 GPM and 900 GPM, the positive correlation between water saving and well capacity is attributable to the reduction in irrigation acreage and irrigation intensity. Moreover, I find a higher reduction in irrigation acreage and irrigation intensity with an increase in well capacity when the well capacity is between 500 GPM and 900 GPM.

The effect of a water constraint policy on the decrease in irrigation intensity with the increase in well capacity is smaller when well capacity is above 1000 GPM. In addition, the decrease in irrigated acreage is relatively similar to that of a lower well capacity when the capacity is above 1000 GPM. Thus, higher well capacity will result in lower water saving (see Figure 5.7).

Figure 5.7 Water saving affected by well capacity declining for land with Valent-Vona soil

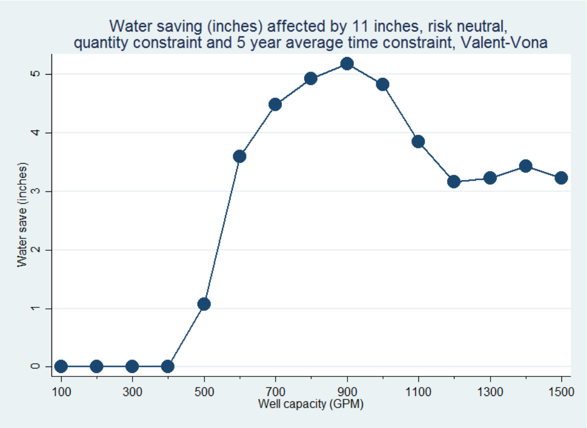
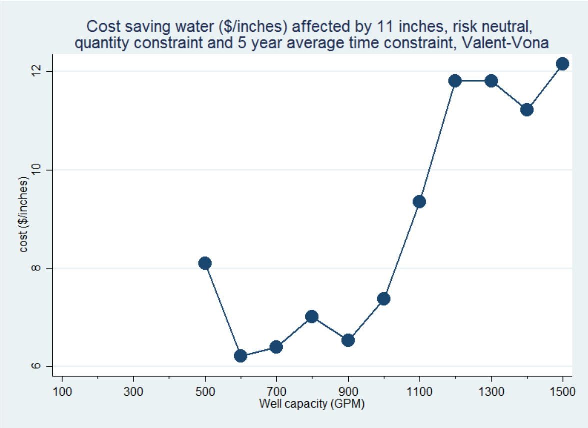


Figure 5.8 Cost of water saving affected by well capacity declining for land with Valent-Vona soil



There is a negative correlation between well capacity declining and cost of saving water when well capacity is at or above 600 GPM (see Figure 5.8). Thus, the cost of saving water is lower when the well capacity declines and this is due to a smaller welfare loss for a lower well capacity. Meanwhile, the cost of saving water is higher for 500 GPM wells than for 600 GPM wells. This is because the water constraint policy is less binding for 500 GPM wells, which results in lower water saving, less welfare loss, and higher cost of saving water compared to those findings for wells with 600 GPM. I find that for Valent-Vona soil, the water constraint policy has higher effectiveness when the well capacity is between 600 GPM and 900 GPM, as it generates higher water saving at lower cost.

5.3 Welfare loss from water constraint policy affected by risk premium

This section addresses the effect of water constraint policy to welfare loss, water saving and cost of water saving for risk averse farmer.

5.3.1 Welfare loss from water constraint policy affected by risk premium regarding Richfield soil

Figure 5.9 shows that a higher risk premium will induce higher welfare loss when the well capacity is at or above 1100 GPM. In addition, the welfare loss for a more risk averse farmer increases as well capacity increases. A farmer with a risk premium 20% and 1100 GPM well will experience 24% higher welfare loss than will a risk neutral farmer. Similarly, a farmer with a risk premium 20% and 1500 GPM well will experience 216% more welfare loss than will a risk neutral farmer. In fact, the positive relationship between risk premium and welfare loss for higher well capacity, at or above 1100 GPM, is due to adjustment in the extensive margin. Thus, a farmer with a high well capacity and a higher risk premium makes greater reduction in irrigation acreage in response to a water policy constraint, which results in higher welfare loss. Also, a farmer with a higher risk premium maintains relatively higher irrigation intensity, which in consequence means they will reduce the irrigation acreage at a higher rate in response to a water policy constraint. This is so because relatively high irrigation intensity will offset the effect of irrigation acreage reduction with less risk in corn production. However, this pattern is not found for lower well capacity. Figure 5.9 shows a higher risk premium does not necessarily result in higher welfare loss for lower capacity, e.g. well capacity at or below 900 GPM.

Water saving increases as risk premium increases for all well capacity levels (see Figure 5.10), and any increase in water saving is predominantly due to higher reduction in irrigation acreage as a result of risk premium increases. The higher risk premium will induce a farmer to increase irrigation intensity and reduce irrigation acreage with or without a water policy constraint. However, the rate of increase in irrigation intensity is lower a with water constraint policy than without such a policy. On the other hand, a higher rate of irrigation acreage reduction occurs as risk premium increases with a water constraint policy compared to without water constraint policy. Figure 5.10 shows the highest water saving is when a well capacity is 600 GPM since 600 GPM wells have the greatest reduction in irrigation acreage and irrigation intensity. Furthermore, 600 GPM wells have the highest initial water use without a water constraint policy. In addition, the effect of a water constraint policy on water saving for the risk averse farmer differs substantially by well capacity if capacity is above 200 GPM.

Figure 5.9 Welfare loss of water constraint policy affected by risk premium for land with Richfield soil

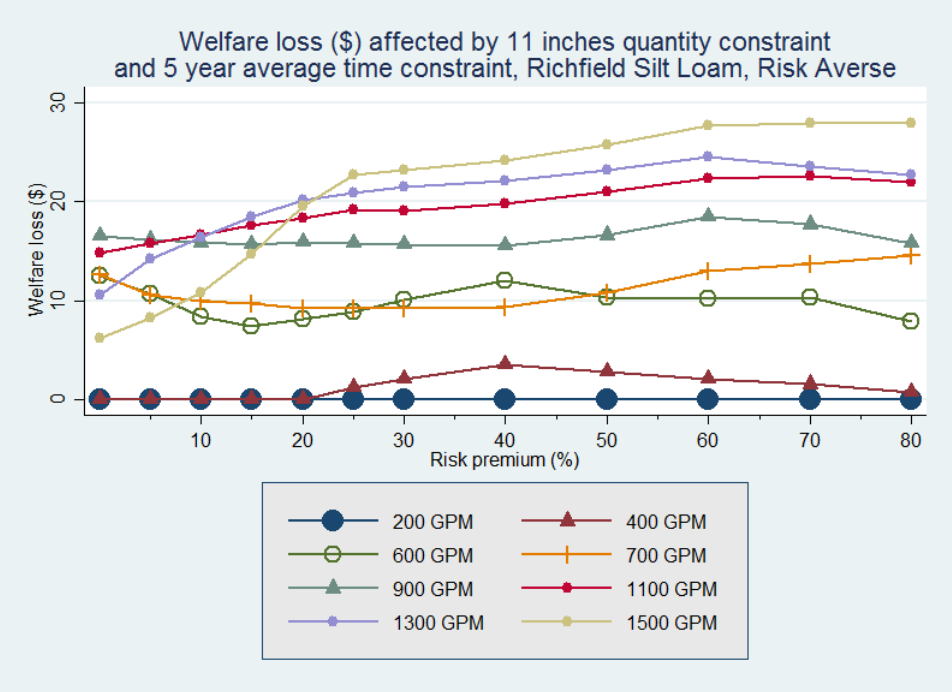


Figure 5.11, shows the cost of saving water is negatively correlated with risk premium, a condition largely attributable to the effect of water saving. Here is a higher rate of increase in water saving compared to the increase in welfare loss as the risk premium increases. Thus, higher risk premium will result in a decrease in cost of saving water. In addition, the cost of saving water differs substantially by well capacity.

Figure 5.10 Water saving affected by risk premium for land with Richfield soil

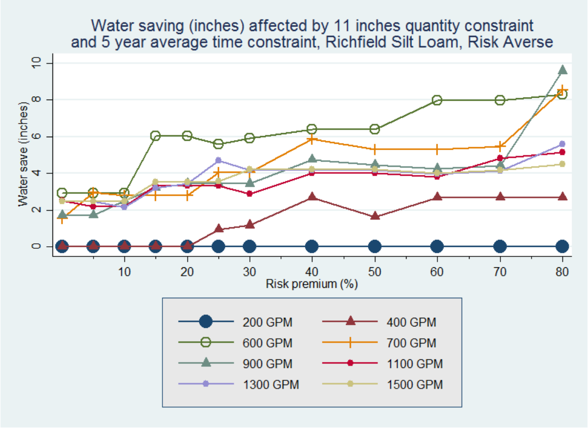
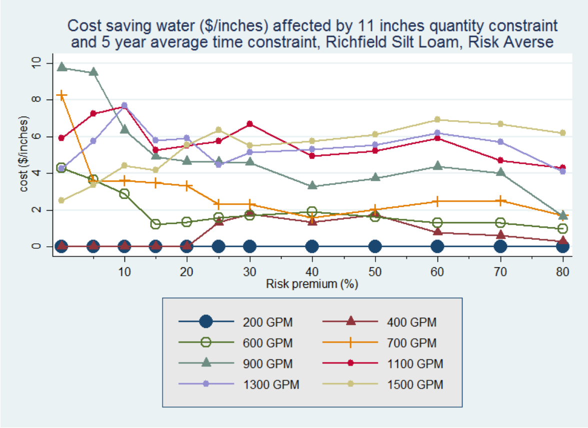


Figure 5.11 Cost of water saving affected by risk premium for land with Richfield soil

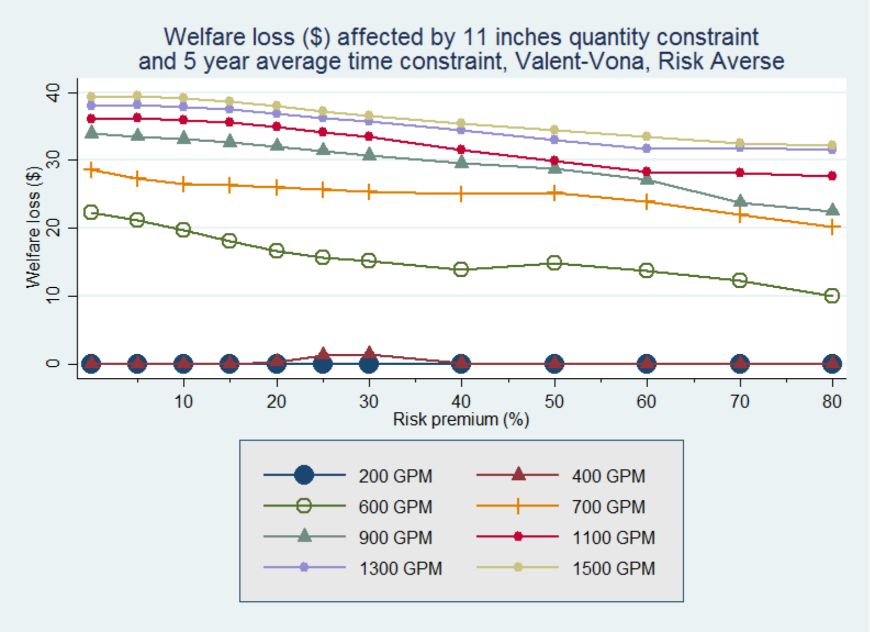


5.3.2 Welfare loss from water constraint policy affected by risk premium of Valent-Vona soil

As the soil type changes, different correlations emerge between welfare loss and risk premium. For example, higher risk premium will induce lower welfare loss when well capacity is at or above 600 GPM for Valent-Vona soil (see Figure 5.12). This is due to the change in optimal strategy having less effect on the change in risk premium for Valent-Vona soil. However, the increase in risk premium will slightly decrease the irrigation acreage and slightly increase the irrigation intensity. The small change in optimal irrigation strategy is due to Valent-Vona soil initially having required high irrigation intensity, which results in a small variation in corn yield. In addition, the change in optimal irrigation strategy with the increase in risk premium is smaller with a water policy constraint. Thus, a higher risk premium will result in smaller reduction in welfare loss due to less sensitivity to change in optimal irrigation strategy. In addition, a relatively small impact of risk averse behavior on welfare loss exists when well capacity is at or below 400 GPM because a water constraint policy is not a limiting factor in water use when a farmer has low well capacity.

Figure 5.9 and Figure 5.12 show that the welfare loss is higher for Valent-Vona soil than for Richfield soil. In the case of risk premium 20%, the welfare loss for Valent-Vona soil is higher by 38-182% than for Richfield soil. Also, the impact of a water constraint policy on the decrease in welfare loss is greater for Valent-Vona soil due to its lower soil water holding capacity. However, a farmer with Richfield soil is more sensitive to risk premium changing an optimal irrigation strategy. While the higher soil water holding capacity would allow Richfield soil to accommodate greater changes in irrigation strategy, this is not the case with Valent-Vona soil as a risk neutral farmer would have used high amounts of water initially.

Figure 5.12 Welfare loss of water constraint policy affected by risk averse behavior for land with Valent-Vona soil



The relationship between water saving and risk premium is indefinite when well capacity is at or below 600 GPM (see Figure 5.13). Thus, more risky behavior does not always stimulate more water saving. On the other hand, there is a positive relationship between risk premium and water saving when well capacity is at or above 700 GPM. The higher risk premium will induce relatively higher reduction in irrigated acreage for high well capacity. Meanwhile, the water saving in Valent-Vona soil is relatively less sensitive to the change in risk premium than is Richfield soil (see Figure 5.10 and Figure 5.13). This is due to Valent-Vona soil having less sensitivity to change in optimal irrigation strategy as the risk premium changes. In the case of 600 GPM wells, the change in risk premium from risk neutral to 20% will increase the water saving by 106% for Richfield soil but for only 49% for Valent-Vona soil. Similarly for 1100 GPM, the change in risk premium from risk neutral to 20% will increase the water saving by 33% for Richfield soil but only by 11% for Valent-Vona soil.

The correlation between cost of water saving and risk premium also is indefinite when well capacity is at or below 600 GPM (see figure 5.14). On the other hand, there is a negative correlation between risk premium and cost of saving water when well capacity is at or above 700 GPM (see figure 5. 14). Typically, a higher risk premium will induce lower cost of saving water. The negative relationship between risk premium and cost of saving water is because the higher risk premium induces more water saving but lower welfare loss when well capacity is at or above 700 GPM.

Figure 5.13 Water saving affected by risk averse behavior for land with Valent-Vona soil

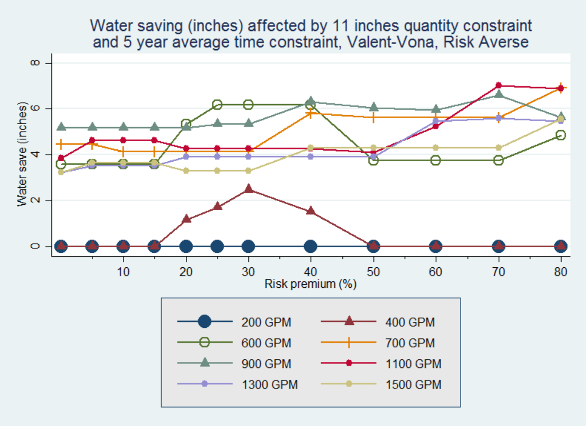
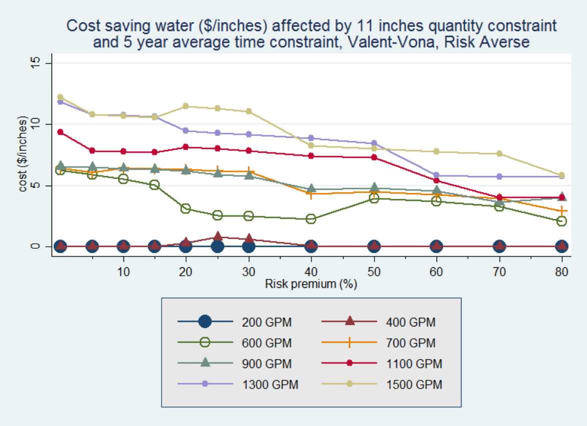


Figure 5.14 Cost of water saving affected by risk averse behavior for land with Valent-Vona soil



5.4 The effect of different quantity constraints on welfare loss

This section addresses different quantity constraint on welfare loss for risk neutral and risk averse farmer.

5.4.1 The effect of quantity constraint on welfare loss for Richfield soil

I analyzed the effect of quantity constraint by varying it with the 5-year average as a baseline for time constraint. I vary the quantity constraint from 9 to 15 inches, in increments of 1 inch. The range in quantity constraint will give a sense of when the constraint policy starts to have a negative impact on welfare.

From Figure 5.15 and Figure 5.16, I find negative correlation between welfare loss and quantity constraint for both a risk neutral and a risk averse farmer, the latter having a risk premium of 20%. Lower quantity constraint not only reduces the irrigation acreage but also decreases the irrigation intensity. As a consequence, as an impact of lower quantity constraint, both corn yield and total corn production would decrease. In addition, lower quantity constraint not only decreases the net return but also increases the risk to crop production.

Figure 5.15 Welfare loss affected by quantity constraint for risk neutral farmer with Richfield soil

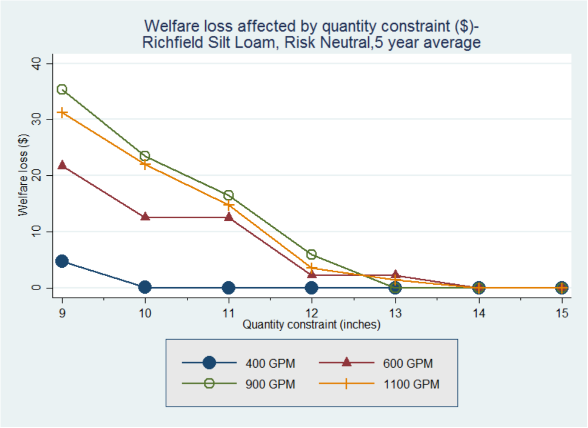
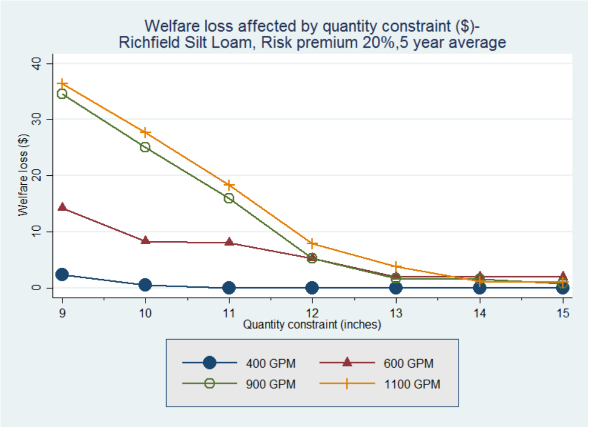


Figure 5.16 Welfare loss affected by quantity constraint for risk averse farmer with Richfield soil



I find negative correlation between quantity constraint and water saving for both a risk neutral and a risk averse farmer (see Figure 5.17 and Figure 5.18). The lower quantity constraint induces lower water use as the farmer decreases the irrigated acreage and irrigation intensity. Accordingly, the rate of decrease in irrigated acreage and irrigation intensity increases as the quantity constraint decreases.

Next, I observe a relatively different threshold of quantity constraint that will impact water saving between a risk neutral and a risk averse farmer. Figure 5.17 shows that a water constraint policy starts to affect water use for the risk neutral farmer with 1100 GPM, as shown by the water saving being not zero when the quantity constraint is at 13 inches. On the other hand, when the quantity constraint is at 15 inches, it starts to have an effect on water use for a risk averse farmer with 1100 GPM (see figure 5.18). A similar pattern also emerged for the farmer with 900 GPM where the quantity constraint at 12 inches registered an effect for the risk neutral farmer. However, a quantity constraint at 15 inches becomes the limiting factor for water use when a farmer becomes more risk averse. The different quantity constraint threshold that will affect water use between the risk neutral and the risk averse farmer is due to the risk averse farmer initially use higher amounts of irrigation water to reduce the risk in corn production. This result also suggests risk averse farmer is more sensitive to water constraint policy.

The effect of a water constraint policy on water saving is different for a risk neutral versus a risk averse farmer such that a water constraint policy has a greater effect on water saving for the risk averse farmer than for the risk neutral farmer. In the case of a 600 GPM well, the 5-year and 9 inches policy will save 100% more water for the risk averse farmer than for the risk neutral farmer. Similarly, for a 900 GPM well, the 5-year and 9 inches policy will save approximately 43% more water for the risk averse farmer than for the risk neutral farmer.

Figure 5.17 Water saving affected by quantity constraint for risk neutral farmer with Richfield soil

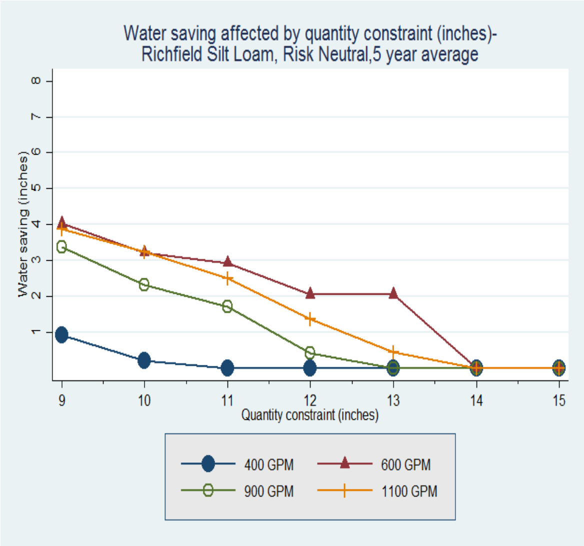
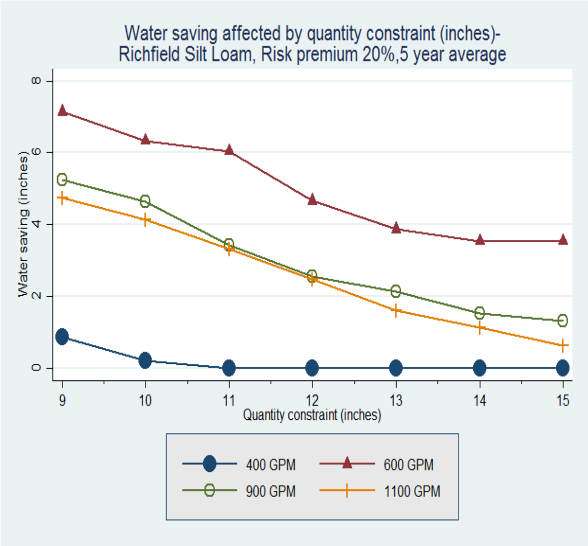


Figure 5.18 Water saving affected by quantity constraint for risk averse farmer with Richfield soil



I find a negative correlation between quantity constraint and cost of water saving for both a risk neutral and a risk averse farmer (see Figure 5.19 and Figure 5.20). The negative correlation is largely attributable to the higher rate of increase in welfare loss compared to the increase in water saving given the decrease in quantity constraint. Figure 5.19 and Figure 5.20 also show that the cost of saving water is higher for a risk neutral farmer than for a risk averse farmer. In the case of a 900 GPM well with a 5-year and 9 inches policy, the cost of saving water for the risk averse farmer is 36% lower than for the risk neutral farmer. My result suggests that the economic models that ignore risk averse behavior will overstate the cost of reducing water use. While the overall welfare loss is relatively similar, reduction in water use is larger for the risk averse farmer.

Figure 5.19 Cost of water saving affected by quantity constraint for risk neutral farmer with Richfield soil

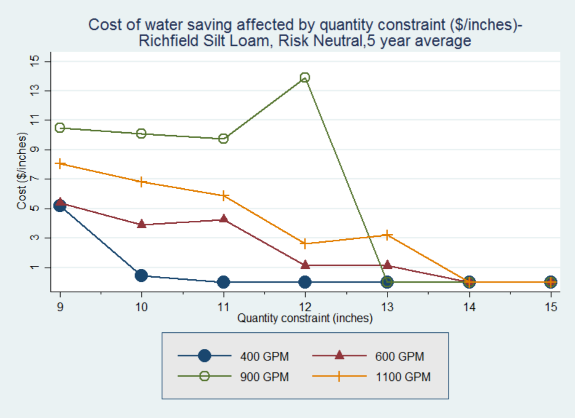
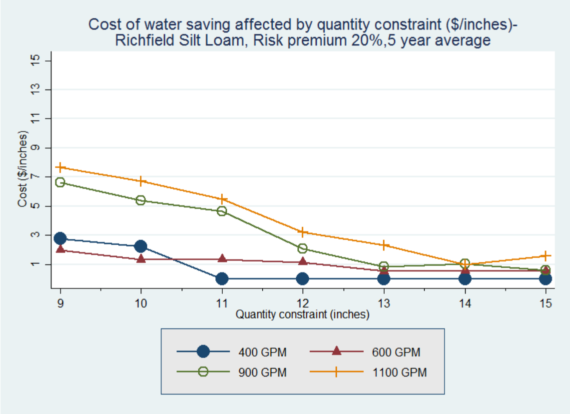


Figure 5.20 Cost of water saving affected by quantity constraint for risk averse farmer with Richfield soil



5.4.2 The effect of quantity constraint to welfare loss for Valent-Vona soil

The welfare loss for both the risk neutral and the risk averse farmer for Valent-Vona soil is relatively the same (see figure 5.21 and figure 5.22). in general, the welfare loss for Valent-Vona soil is higher than that for Richfield soil (see Figure 5.15-16 and Figure 5.21-22). This is due to Valent-Vona soil having lower water holding capacity so that more restricted quota constraint has a greater negative impact on welfare loss. In addition, Valent-Vona used more water without a water constraint so that a given constraint causes larger reduction in water use.

I find negative correlation between quantity constraint and water saving for both the risk neutral and the risk averse farmer (see Figure 5.23 and Figure 5.24). The lower quantity constraint induces lower water use as a farmer decreases the irrigated acreage and irrigation intensity. Additionally, the rate of decrease in irrigated acreage and irrigation intensity increases as the quantity constraint decreases. Moreover, the risk neutral farmer with Valent-Vona soil shows a greater decrease in irrigation acreage than the risk neutral farmer with Richfield soil. In addition, I also find relatively little difference in water saving between the risk neutral and the risk averse farmer with Valent-Vona soil. Thus, I may conclude that the farmer with Valent-Vona soil less sensitivity to change in risk premium.

Figure 5.21 Welfare loss affected by quantity constraint for risk neutral farmer with Valent-Vona soil

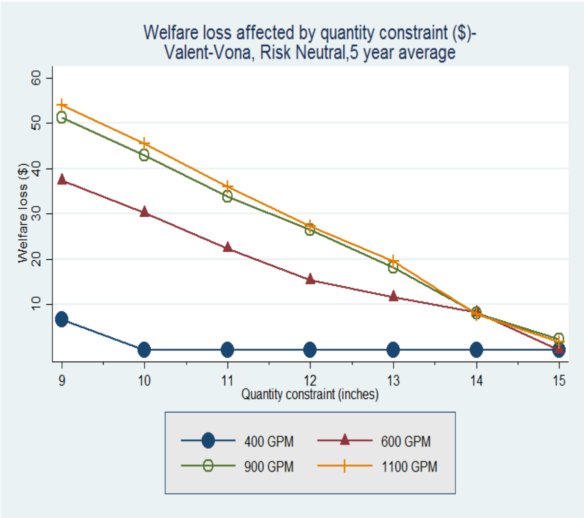
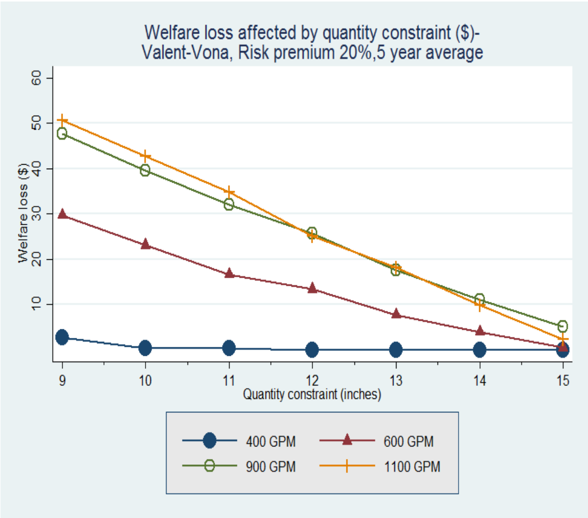


Figure 5.22 Welfare loss affected by quantity constraint for risk averse farmer with Valent-Vona soil



Another effect of lower soil water holding capacity is when the quantity constraint becomes a limiting factor in water use. For instance, Figure 5.17 and Figure 5.23 show 14 inches as a limiting factor for the risk neutral farmer with Valent-Vona soil, but 13 inches as a limiting factor for the risk neutral farmer with Richfield soil. Clearly the uniform quantity constraint has a different impact for different soils,, specifically a more negative impact on welfare loss for soil with lower soil water holding capacity.

All the same, I find negative correlation between quantity constraint and cost of water saving for both the risk neutral and the risk averse farmer (see Figure 5.25 and Figure 5.26). In fact, a lower quantity constraint will induce higher cost of saving for water for both the risk neutral and the risk averse farmer. The negative correlation is largely attributable to the higher rate of increase in welfare loss compared to the rate of increase in water saving with the decrease in quantity constraint.

Figure 5.23 Water saving affected by quantity constraint for risk neutral farmer with Valent-Vona soil

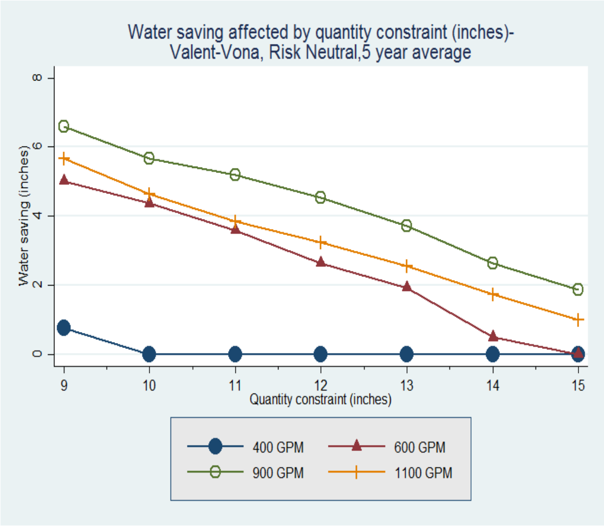
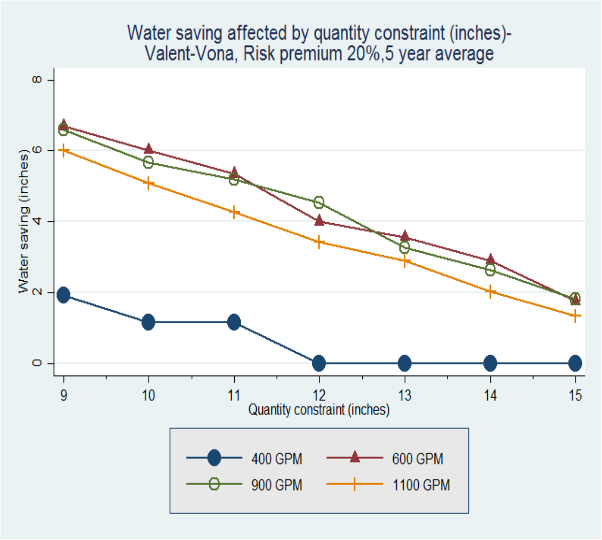


Figure 5.24 Water saving affected by quantity constraint for risk averse farmer with Valent-Vona soil



The impact of a water constraint policy to water saving and cost of saving water differs by soil characteristics and risk averse behavior. Less impact of risk averse behavior on water saving and cost of saving water arises for soil with lower soil water holding capacity. It is due to risk-neutral farmer with lower soil water holding capacity uses higher water initially. The implication is the model that does not includes spatial variability in soil may misestimate the impact of risk-averse behavior and water constraint policy on water saving and cost of saving water.

Figure 5.25 Cost of water saving affected by quantity constraint for risk neutral farmer with Valent-Vona soil

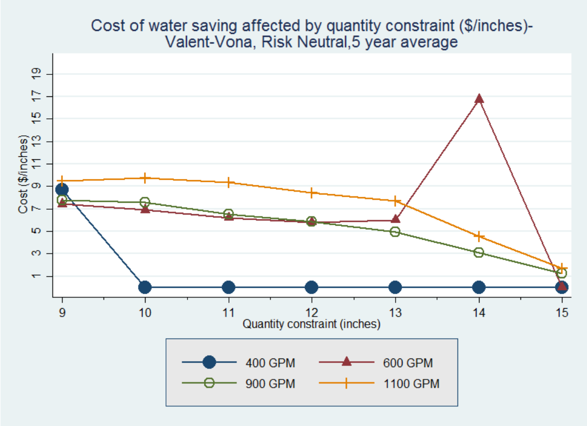
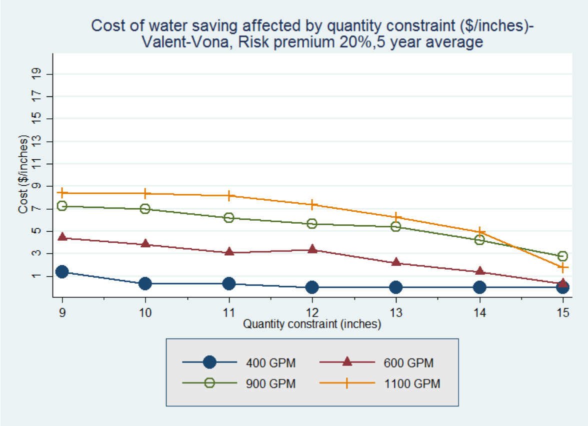


Figure 5.26 Cost of water saving affected by quantity constraint for risk averse farmer with Valent-Vona soil



5.5 Economic implication

Clearly, the impact of groundwater depletion on the decrease in welfare loss differs by soil type. Also, a threshold in well capacity reduction dictates where the groundwater depletion causes a rapid decline in welfare. That threshold is when a farmer moves from adjustment in the intensive margin to adjustment in the extensive margin in response to a decrease in well capacity. The threshold is different for each soil type, and the threshold is higher for soil with lower soil water holding capacity. However, identifying this threshold is critical for policymakers monitoring the impact of groundwater depletion on welfare loss.

Imposing a uniform policy constraint will have substantially different welfare impacts depending on well capacity and soil type. In addition, a less restricted water constraint policy may not work for small well capacity. Also, higher well capacity may not always experience greater welfare loss due to a water constraint policy. Ultimately, the impact of a water constraint policy based on a particular well capacity differs by soil type. As stated, the greatest negative impact of a water constraint policy on welfare loss for Richfield soil is for medium and medium high well capacity, but it is different with Valent-Vona soil, which shows greater negative impact for higher well capacity. Thus, an economic model that does not include well capacity and spatial variability in soil type may misestimate the effect of a water constraint policy on welfare loss.

The impact of a water constraint policy on welfare loss, water saving, and cost of saving water for a particular well capacity are substantially different for risk averse behavior. The impact of such a policy on water saving is significantly greater for the more risk averse farmer. Therefore, a model that does not include spatially different water availability and risk behavior may misestimate the effect of a water constraint policy. Clearly, identifying risk averse behavior is essential to estimate the impact of water constraint policy on water saving.

Chapter 6 - The incentive for adoption of more efficient irrigation technology and the effect of adoption on water use

A more efficient irrigation technology can be one strategy to deal with weather uncertainty and groundwater depletion since such technology increases irrigation water productivity. In this chapter, I study drip irrigation and its impact on water use. First, higher irrigation efficiency can increase crop production while also reducing the production risk from weather uncertainty. However, despite the benefits of drip irrigation for crop production, the high investment cost is one of the major causes of low adoption rates among farmers in the High Plains (Bekchanov, Lamers and Martius 2010; Frisvold and Deva 2012). Furthermore, the impact of the adoption on total water use is ambiguous (Caswell and Zilberman 1986; Huffaker and Whittlesey 2003; Peterson and Ding 2005; Pfeiffer and Lin 2014).

In general, limited water availability as a function of decrease in well capacity can encourage a farmer to adopt more efficient irrigation technology. First, groundwater depletion causes a decrease in well capacity that may limit a farm's ability to manage extensive and intensive margin adjustments. A farmer may adjust the extensive margin by changing irrigated acreage and the intensive margin by changing irrigation intensity--the amount of water that can be applied per acreage. The adjustment in the extensive margin may affect total crop production, whereas the adjustment in irrigation intensity may alter corn yield. Thus, low well capacity may not be profitable for more efficient irrigation technology because it can irrigate only a small acreage, which would result in low total crop production. Thus, low well capacity may not offset the high investment cost of more efficient irrigation technology. Frisvold and Deva (2012) mention that one of the important barriers to adopting more efficient irrigation technology is that the installation cost is greater than the expected operational cost saving from energy use.

Moreover, efficient irrigation technology comes with higher water efficiency, but it does not always promote water saving. Instead, an ambiguous impact of more efficient irrigation technology on water use often occurs (Huffaker and Whittlesey 2003; Peterson and Ding 2005). Additionally, higher investment cost of efficient irrigation technology requires a larger irrigated area to make that technology more profitable. Pfeiffer and Lin (2014) state that more efficient irrigation technology accordingly might induce a farmer to increase total water use by increasing irrigated acreage or increasing irrigation amount per acre. In addition, a farmer may have less non-irrigated acreage after adopting more efficient irrigation technology (Pfeiffer and Lin 2014). Another issue in many cases is that the key variable of interest is water consumption rather than the amount of water pumped. Because a water conservation subsidy is unlikely to give a crop producer incentive to reduce water depletion, this situation can, in fact, increase water depletion (Ward and Pulido-Velazquez 2008). The issue is that even the inefficient system that pumps more water than necessary returns that water to the water system as a recharge. On the other hand, drip irrigation may generate higher water consumption that leads to less water recharge and a higher rate of depletion. In this chapter, I examine the effect of drip irrigation on groundwater extraction rather than consumption as I do not attempt to model aquifer recharge. I find an increase in water extraction due to drip irrigation and the effect on water consumption is likely to be even larger than center pivot irrigation, so my estimates of the effect of adoption on water use are likely conservative.

A water constraint policy may promote more efficient irrigation technology, but it will limit the total water that farmer can apply. However, more efficient irrigation technology will provide greater water productivity so that the crop yield reduction because of the water constraint policy can be minimized. Less efficient irrigation technology, conversely, will use higher irrigation intensity so that its profitability is more sensitive to a water constraint policy.

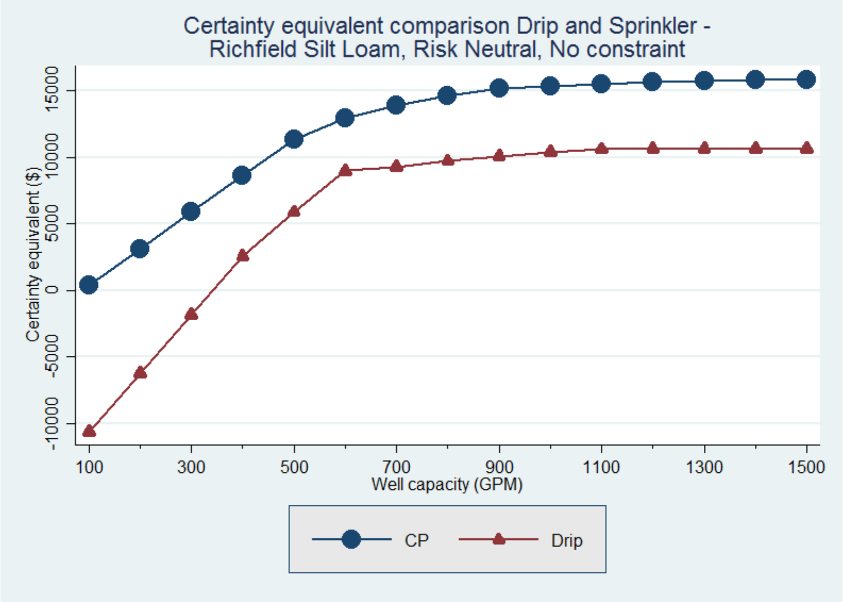
The irrigation technology I discuss comprises center pivot irrigation and drip irrigation, the latter being the more efficient technology, potentially. This study assumes for hypothetical simulation that the maximum irrigated acreage is 160 acres. Specifically, the maximum irrigated acreage for center pivot irrigation is 125 acres while the minimum irrigated acreage is 35 acres. On the other hand, the maximum irrigated acreage for drip irrigation is 160 acres. The different maximum irrigated acreages for center pivot and drip irrigation are due to the shapes of the irrigation system. Drip irrigation is assumed to have a square shape that can irrigate all areas, while center pivot irrigation has a circle shape with non-irrigated areas in the corners of the perceived square.

My analyses are organized into three separate sections. The first section analyzes the impact of groundwater depletion on adopting a more efficient irrigation technology. I also explore the impact of adopting more efficient irrigation technology on total water use. Next, I evaluate the change in total water by focusing on potential changes in irrigated acreage and irrigation intensity. The second section analyzes the impact of a water constraint policy and risk averse behavior on adopting more efficient irrigation technology. The risk premium accounts for risk averse behavior of the farmer. The final section analyzes the impact of government subsidy on adopting more efficient irrigation technology. The analysis of government subsidy will give a sense of how the fixed investment cost may affect a farmer's decision to adopt more efficient irrigation technology. Another restriction, the acreage constraint, is applied to drip irrigation such that upon being granted the subsidy by the government, a farmer with drip irrigation cannot irrigate more than 125 acres. I also explore how drip irrigation, with the acreage constraint being imposed, compares to the existing center pivot irrigation in terms of total water use.

6.1 The effect of the decrease in well capacity on adopting more efficient irrigation technology

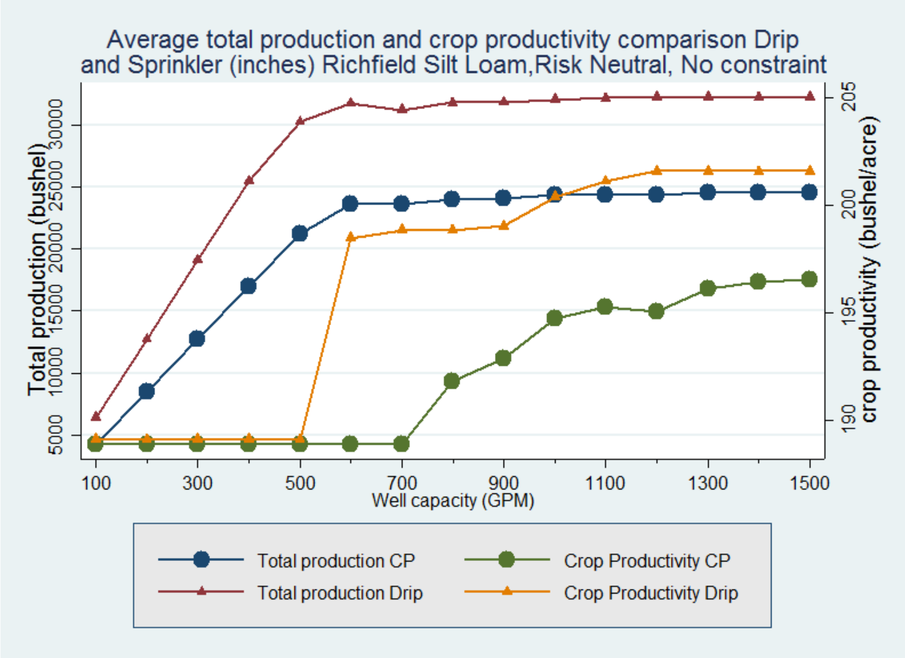
Clearly, drip irrigation is less profitable than center pivot irrigation, and Figure 6.1 shows that center pivot irrigation is the more favorable choice for a risk neutral farmer with any well capacity level. Additionally, groundwater depletion, shown by lower well capacity, will not affect a farmer's decision to adopt drip irrigation. As a matter of fact, the certainty equivalent difference between drip irrigation and center pivot irrigation gets higher if well capacity decreases to below 600 GPM.

Figure 6.1 Certainty equivalent comparison between Drip and Center pivot irrigation without water constraint policy for risk neutral farmer with Richfield



Drip irrigation is less profitable than center pivot irrigation not because of lower revenue from corn production but due to higher investment cost. In fact, drip irrigation generates higher revenue from higher total corn production than does center pivot irrigation. However, the higher revenue cannot off-set the high investment cost. Thus, drip irrigation is less likely to be adopted by a risk neutral farmer, unless a government subsidy program encourages the farmer to adopt it. Figure 6.2 shows that drip irrigation generates not only higher total crop production but also higher average corn yield for all well capacity levels. The higher total corn production is not only because of higher average corn yield and also because of larger irrigated acreage.

Figure 6.2 Crop Production and corn yield comparison between Drip and Center pivot irrigation without water constraint policy for risk neutral farmer with Richfield soil



I find a small difference in corn yield between drip and center pivot irrigation when well capacity is below 600 GPM (see figure 6.2). On the other hand, the highest difference in corn yield between drip irrigation and center pivot irrigation occurs when the well capacity is 600-700 GPM. Figure 6.2 and Figure 6.3 show that the higher total crop production of drip irrigation for land with well capacity below 600 GPM is predominantly due to larger irrigated acreage. In addition, in the case of well capacity at or above 600 GPM, the higher total crop production of drip irrigation is due to larger irrigation acreage and higher corn yield.

Next, drip irrigation has higher total water use than center pivot irrigation (see Figure 6.4), but even so, the irrigation cost per acreage is lower than for center pivot irrigation. Additionally, Figure 6.5 shows that drip irrigation uses lower irrigation intensity than center pivot irrigation; therefore, drip irrigation has higher irrigation efficiency and higher water productivity because it uses less water per acreage and still generates higher corn yield. Also, the higher total water use for drip irrigation is due to larger irrigation acreage. Nevertheless, the conversion from center pivot irrigation to drip irrigation will not save water; instead, it will cause faster rate of groundwater depletion.

Figure 6.3 Irrigated acreage comparison between Drip and Center pivot irrigation without water constraint policy for risk neutral farmer with Richfield soil

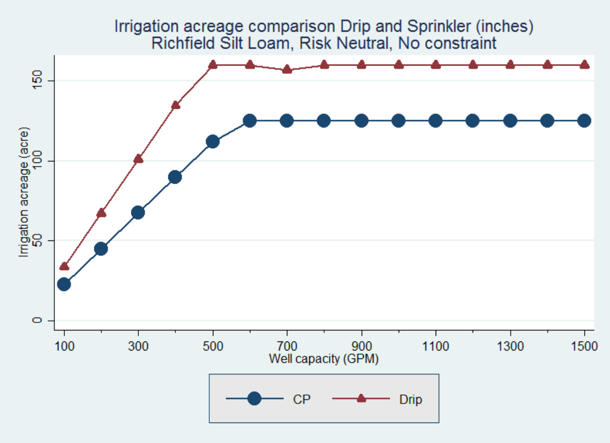
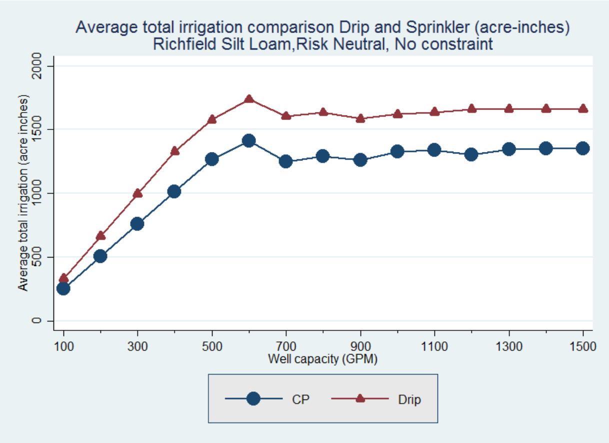
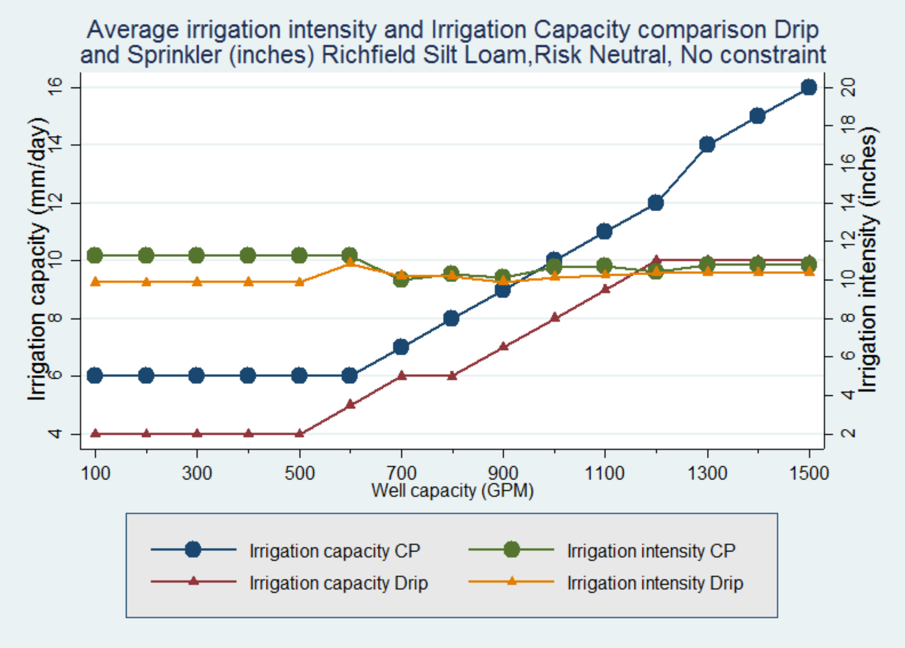


Figure 6.4 Total irrigation comparison between Drip and Center pivot irrigation without water constraint policy for risk neutral farmer with Richfield soil



My research results show significant decrease in corn yield for drip irrigation when well capacity decreases from 600 GPM to at or below 500 GPM (see Figure 6.2). Similarly, total corn production using drip irrigation starts to show significant decrease when well capacity decreases from 600 GPM to 500 GPM. The significant increase in corn yield when well capacity increases from 500 GPM to 600 GPM is because of the increase in instantaneous rate application. Changing the instantaneous rate of application from 5 mm/day to 6 mm/day significantly increases the corn yield (see Figure 6.2 and Figure 6.5). Thus, higher well capacity will not only give an advantage to drip irrigation by allowing larger irrigated acreage but also significantly increase the corn yield.

Figure 6.5 Irrigation intensity and instantaneous rate comparison between Drip and Center pivot irrigation without water constraint policy for risk neutral farmer with Richfield soil



Drip irrigation uses lower instantaneous rate than center pivot irrigation (see Figure 6.5). Thus, converting to drip irrigation enables a farmer to increase the irrigated acreage. Unfortunately, this result can be counter-productive for the objective of more efficient irrigation technology to reduce water use and decrease the rate of groundwater depletion, as the increase in irrigated acreage will significantly increase total water use.

6.2 The effect of water constraint policy and risk averse behavior on adopting more efficient irrigation technology for land with Richfield soil

The water constraint policy may induce adjustment in intensive and extensive margins, which may result in lower corn yield and higher risk in corn production. Furthermore, a water constraint policy may have greater negative impact on irrigation technology with lower efficiency, which may in turn induce the farmer to adopt a more efficient irrigation system. However, the trade-off between high investment cost and higher irrigation efficiency for a more efficient irrigation system needs further analysis. In addition, higher variation in crop yield for a less efficient irrigation system may affect the risk averse farmer considering a more efficient irrigation system.

This section will use the baseline time constraint of 5 years average varying the quantity constraint from 9 to 15 inches, in increments of 1 inch. The analysis will focus on land with well capacity of 600 GPM. Finally, I analyze different well capacities (400, 900, 1100, 1500 GPM) briefly in this section.

Quantity constraint and risk averse behavior do not increase the adoption of drip irrigation for land with a 600 GPM well capacity. Figure 6.6 shows no incentive for a risk-neutral farmer with such a capacity to adopt drip irrigation for any quantity constraint level. Similarly, a farmer with risk premium 20% would not adopt drip irrigation for any quantity constraint level (see Figure 6.7).

Figure 6.6 and Figure 6.7 show that the difference in certainty equivalent between drip irrigation and center pivot irrigation increases for both the risk neutral and the risk averse farmer if the quantity constraint becomes smaller. The implication is a smaller quantity constraint may decrease the adoption of a drip system for medium well capacity. Furthermore, the effect of quantity constraint on adoption of drip irrigation is similar for different well capacity levels. Supporting this claim, Figure 6.8 shows no connection between quantity constraint and adoption drip irrigation for the risk averse farmer with either 400, 900, 1100 or 1500 GPM well capacity.

Figure 6.6 Certainty equivalent comparison between Drip and Center pivot irrigation affected by quantity constraint for risk neutral farmer with Richfield soil and 600 GPM

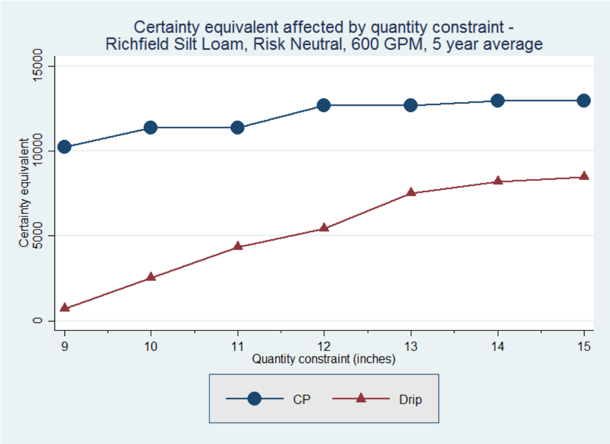


Figure 6.7 Certainty equivalent comparison between Drip and Center pivot irrigation affected by quantity constraint for risk averse farmer with Richfield soil and 600 GPM

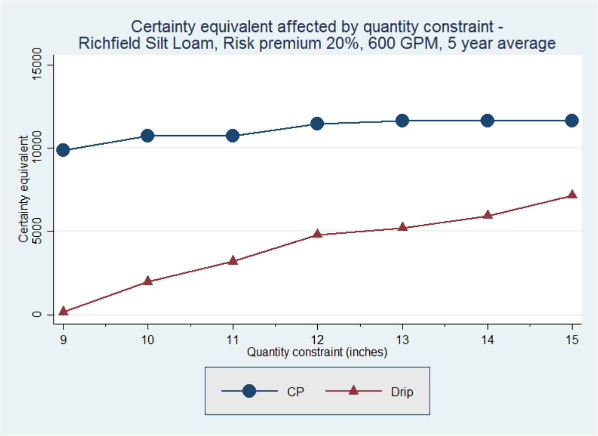
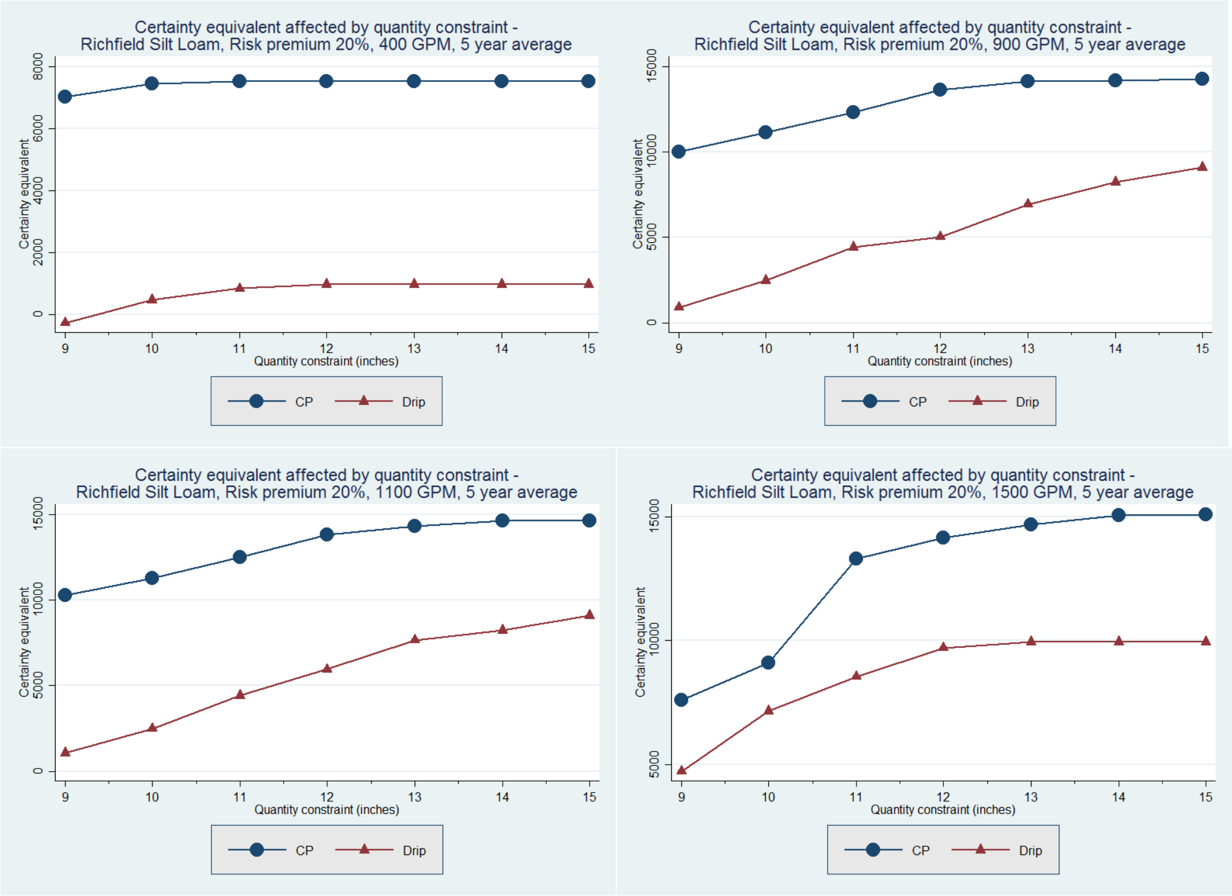


Figure 6.9 shows a positive correlation between quantity constraint and irrigated acreage. Similarly, irrigation intensity is positively correlated with quantity constraint. Thus, lower quantity constraint will result in lower total water use for both drip irrigation and center pivot irrigation (see Figure 6.9). I also find that total irrigation amount with drip irrigation is higher than with center pivot system when the quantity constraint is at or above 11 inches. Thus, lower quantity constraint will promote less water use for both irrigation systems; however, changing from center pivot irrigation to drip irrigation will not promote water saving.

Figure 6.8 Certainty equivalent comparison between Drip and Center pivot irrigation affected by quantity constraint for risk-averse farmer with Richfield soil and 400, 900, 1100 GPM well capacity



Certainty equivalent affected by quantity constraint - Richfield Silt Loam, Risk premium 20%, 400 GPM, 5 year average

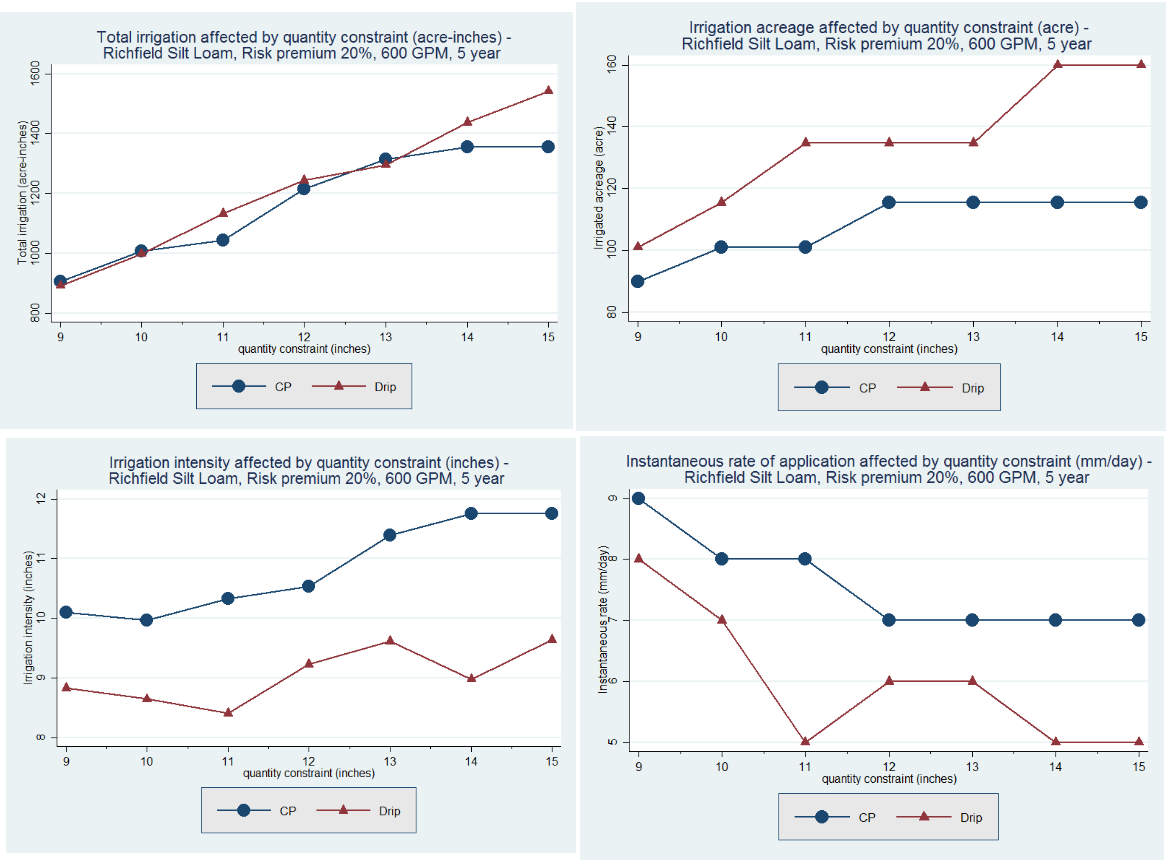
Certainty equivalent affected by quantity constraint - Richfield Silt Loam, Risk premium 20%, 900 GPM, 5 year average

Certainty equivalent affected by quantity constraint - Richfield Silt Loam, Risk premium 20%, 1100 GPM, 5 year average

Certainty equivalent affected by quantity constraint - Richfield Silt Loam, Risk premium 20%, 1500 GPM, 5 year average

Figure 6.9 shows that the risk averse farmer with drip irrigation uses lower irrigation intensity and instantaneous rate than does the farmer with center pivot irrigation. In part, this is because drip irrigation offers higher irrigation efficiency, which results in a farmer using lower optimal irrigation intensity. However, it also induces a farmer to irrigate a larger area. Thus, the higher total irrigation in drip irrigation is due to its larger irrigated acreage.

Figure 6.9 Total irrigation, irrigation acreage, irrigation intensity and instantaneous rate comparison between Drip and Center pivot irrigation affected by quantity constraint for risk averse farmer with Richfield soil and 600 GPM



6.3. The effect of investment subsidy to adoption of drip irrigation

The low adoption of drip irrigation is predominantly due to higher investment cost. Addressing cost in this section, I cover government subsidy for drip irrigation investment. The Environmental Quality Incentive Program (EQIP) is a voluntary program that assists the farmer and promotes agricultural production and managing sustainable environmental quality (NRCS 2016a). One of the EQIP requirements is to subsidize drip irrigation to conserve groundwater and surface water resources. In addition, EQIP promotion of drip irrigation is intended to enhance crop production by better maintaining MAD at a given level with high uniform irrigation water application (NRCS 2016a) . LEMA and Walnut Creek IGUCA are two of the main priority areas for EQIP implementation due to declining groundwater level and current water constraint policy enactment.

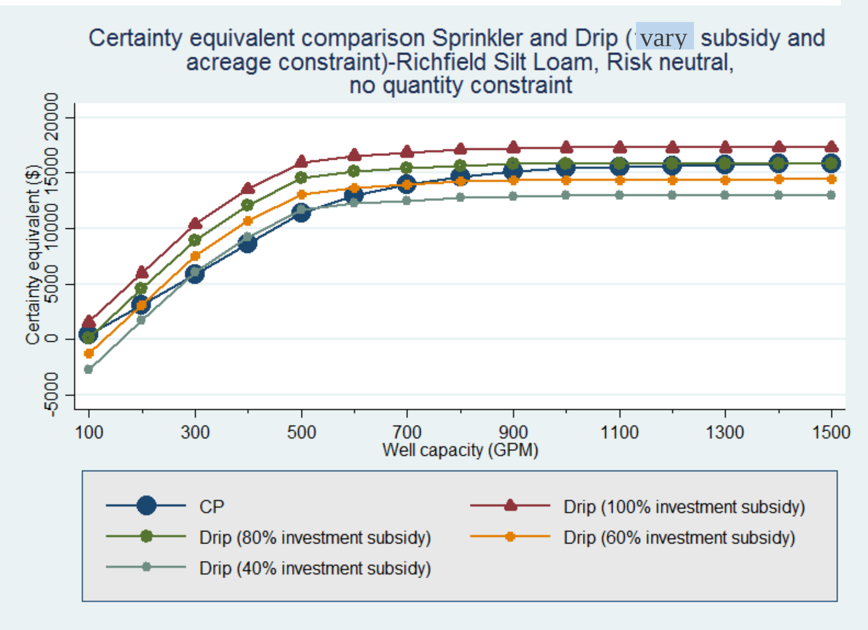
Adopting drip irrigation will not necessarily reduce total water use. Therefore, the Environment Quality Incentive Program (EQIP) has set an additional requirement of 10% total water use reduction for the drip irrigation subsidy program (NRCS 2016a). Consequently, the benchmark of total water use will be from 5-year average irrigated acres divided by water right authorized acres.

I vary the drip irrigation subsidy from 40% to 100%in increments of 20% keeping in mind the maximum EQIP subsidy program is $1,698.33 per acre (NRCS 2016a), which is higher than 100% of the subsidy for my study. Overall, EQIP tries to provide about 60% cost share subsidy according to “Regulatory Impact Analysis (RIA)” (NRCS 2014). I also impose two constraints: acreage constraint and water constraint. The acreage constraint is the maximum 125 acres of irrigated acreage for both drip irrigation and center pivot irrigation, and the water constraint is the 5-year time average with 11 inches’ constraint. I include two scenarios in the subsidy analysis; the first includes only the acreage constraint, but the second scenario includes both acreage constraint and water constraint. The comparison between the two scenarios will show how the effect of a less restrictive constraint policy affects the adoption of drip irrigation and total water use.

In the case of the first scenario Figure 6.10 shows that the risk neutral farmer, for all well capacity levels, will adopt drip irrigation if the subsidy for drip investment is not less than 80%. Thus, the government subsidy would significantly increase the certainty equivalent of drip irrigation. For a 60% subsidy, only land with well capacity 300-500 GPM would adopt drip irrigation due to the difference in irrigated acreage between drip irrigation and center pivot irrigation. For well capacity 300-500 GPM, the farmer with drip irrigation can irrigate a larger area; thus, the result is higher total crop production compared to that with center pivot irrigation. In addition, the farmer with drip irrigation also uses smaller irrigation intensity generating lower irrigation cost per acre. This result implies that the decrease in well capacity to a certain level may encourage the adoption of drip irrigation. This result also shows non-monotonic adoption of drip irrigation according to well capacity.

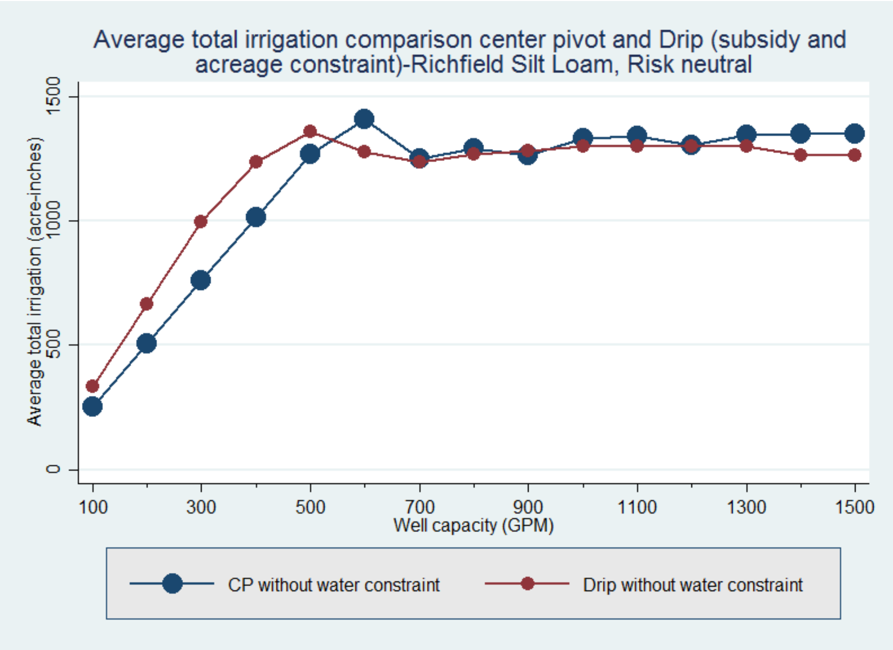
For the 60% subsidy in the first scenario, a farmer with land with well capacity at or above 600 GPM would not adopt drip irrigation. However, the research shows no irrigated acreage different between center pivot and drip irrigation when the well capacity is at or above 600 PM. Thus, relatively similar total production is likely, but higher investment and maintenance cost for drip irrigation would result in lower certainty equivalent for drip irrigation.

Figure 6.10 Certainty equivalent comparison between Center pivot irrigation and Drip irrigation with investment subsidy and acreage constraint for risk neutral farmer with Richfield soil



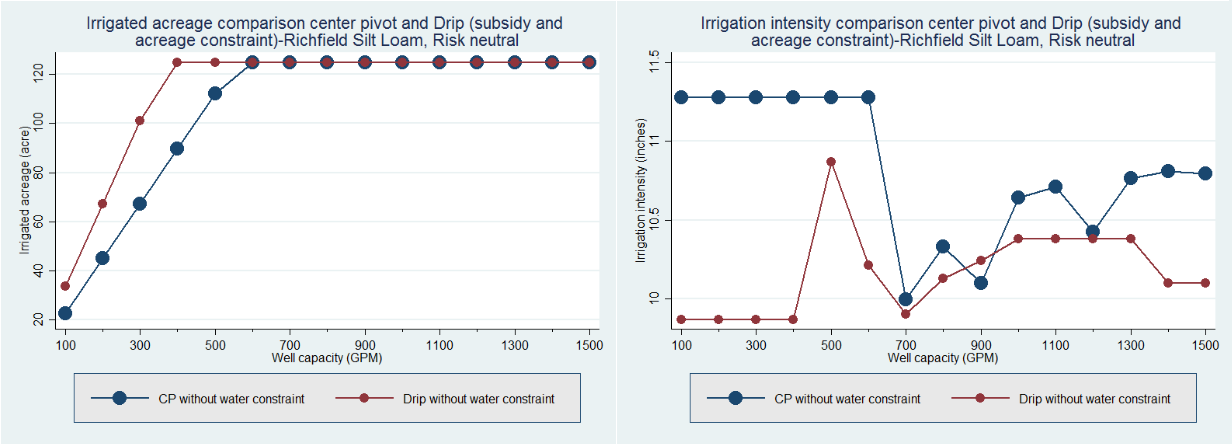
Unfortunately, the subsidy for drip investment may have a backfiring effect on water saving. In the case of no water policy constraint, Figure 6.11 shows that drip irrigation would use higher total irrigation than would center pivot irrigation when the well capacity is at or below 500 GPM. The higher total irrigation of drip irrigation would be due to larger irrigated acreage (see Figure 6.12). On the other hand, the irrigation intensity of drip irrigation is lower than for center pivot irrigation (see Figure 6.12). Thus, drip irrigation may have an effect on water saving when the well capacity is at or above 600 GPM because it uses lower irrigation intensity for the same irrigated acreage compared to center pivot irrigation. This finding is corroborated by Caswell and Zilberman (1986), who state that more efficient irrigation technology would result in more water use for low marginal productivity of water, but would result in less water use for high marginal productivity of water. Ding and Peterson (2012) also found that the cost-share program for converting to more efficient irrigation technology is less effective in reducing water use in areas with lower saturated thickness, meaning low well capacity. Conversely, converting to a more efficient irrigation technology would have more effect on water saving in areas with higher saturated thickness. Ultimately, then, higher total water use for well capacity at or below 500 GPM is due to lower marginal productivity of water. On the other hand, drip irrigation adoption with well capacity at or above 600 GPM would result in water saving due to high marginal productivity of water.

Figure 6.11 Total irrigation water use comparison between Center pivot irrigation and Drip irrigation with investment subsidy and acreage constraint but without water constraint for risk neutral farmer with Richfield soil



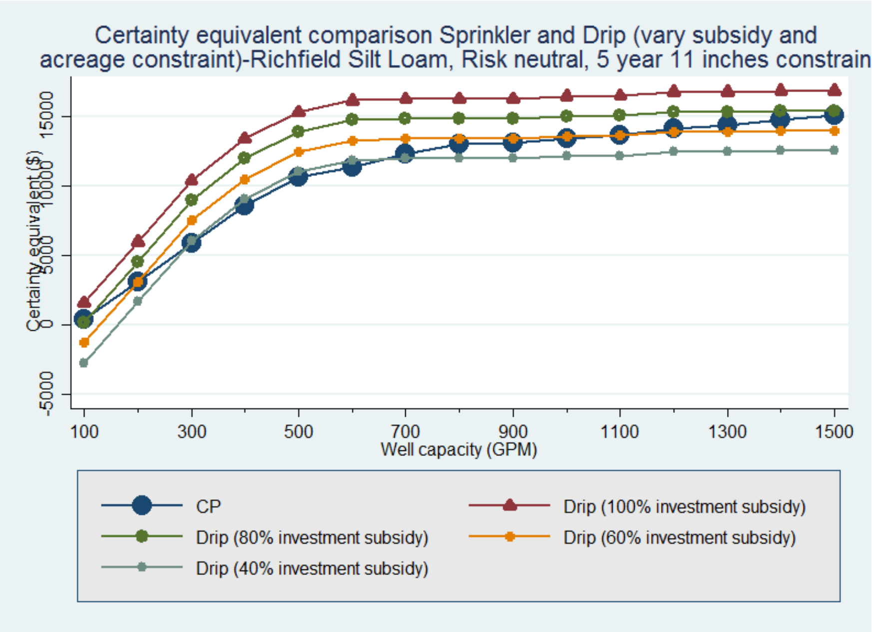
In the case of no water constraint policy, a drip system would generate some water saving for medium and high well capacity, but not a significant amount. However, adopting a drip system for either a medium or a high well capacity requires a large subsidy. On the other hand, a drip system requires less subsidy at lower well capacities but has a counter effect on water saving. The greatest incentive for adopting drip irrigation is for a well at 300-500 GPM, which would also result in greater water use. However, if the intent is to achieve water saving, the drip system must be backed up with decreases in the quantity of water that farmer can extract because the drip system by itself is less effective at generating water saving. In addition, a low well capacity, 100-200 GPM, may bear too high a subsidy cost and be less effective in generating water saving. While the EQIP policy has required farmers to reduce their historical total water, the relevant comparison runs counter to what the farmer would have pumped under the same water restriction with center pivot irrigation system. The farmer who adopts a drip irrigation system could decrease irrigation water from historical use but increase water use relative to what they would have with a water restriction and a center pivot irrigation system.

Figure 6.12 Irrigated acreage and irrigation intensity comparison between Center pivot irrigation and Drip irrigation with investment subsidy and acreage constraint but without water constraint for risk neutral farmer with Richfield soil



Next,, enforcing a water constraint policy would increase the adoption rate of drip irrigation. In the case of a 60% subsidy in the second scenario, Figure 6.13 shows that the drip irrigation would be adopted by a farmer who has a well capacity 300-1000 GPM. Thus, the enforcement of a water constraint policy would have increased the range of the well capacity to accommodate the drip irrigation. The wider range in well capacity would be due to drip irrigation having more advantage on larger irrigation acreage than would a center pivot irrigation under a government enforced water constraint policy because that farmer would have reduced irrigated acreage. On the other hand, a farmer with drip irrigation does not reduce irrigated acreage. The higher irrigation efficiency of drip irrigation enables that farmer to irrigate more acreage by applying smaller irrigation intensity than would center pivot irrigation.

Figure 6.13 Certainty equivalent comparison between Center pivot irrigation and Drip irrigation with investment subsidy, acreage constraint and water constraint for risk neutral farmer with Richfield soil



This research shows no impact of drip irrigation adoption on water saving if the government enforces a water constraint policy. Figure 6.14 shows that drip irrigation uses relatively more total water than does center pivot irrigation for all well capacity levels. The higher total irrigation is due to larger irrigated acreage when the well capacity is at or below 1000 GPM (see Figure 6.15). Furthermore, the higher total irrigation for drip irrigation when well capacity is at or above 1100 GPM is due to drip irrigation having higher irrigation intensity but the same irrigated acreage as center pivot irrigation.

Overall, the water constraint policy causes lower marginal productivity of water and land relative to the crop. Also, the increase in water use would greatly increase the total corn production especially for smaller well capacities. My simulation results show that drip irrigation can increase the total corn production by up to 50% compared to center pivot irrigation. In addition, drip irrigation might increase the water use by up to 31%. Thus, adopting a more efficient irrigation technology would result in higher total irrigation water use.

Figure 6.14 total irrigation water use comparison between Center pivot irrigation and Drip irrigation with investment subsidy, acreage constraint, quantity constraint, and no quantity constraint for risk neutral farmer with Richfield soil

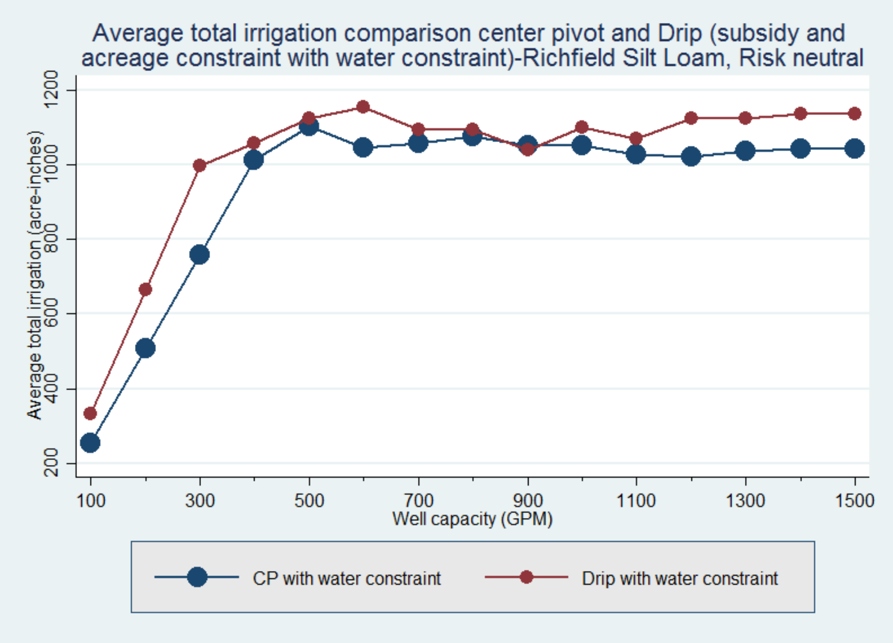
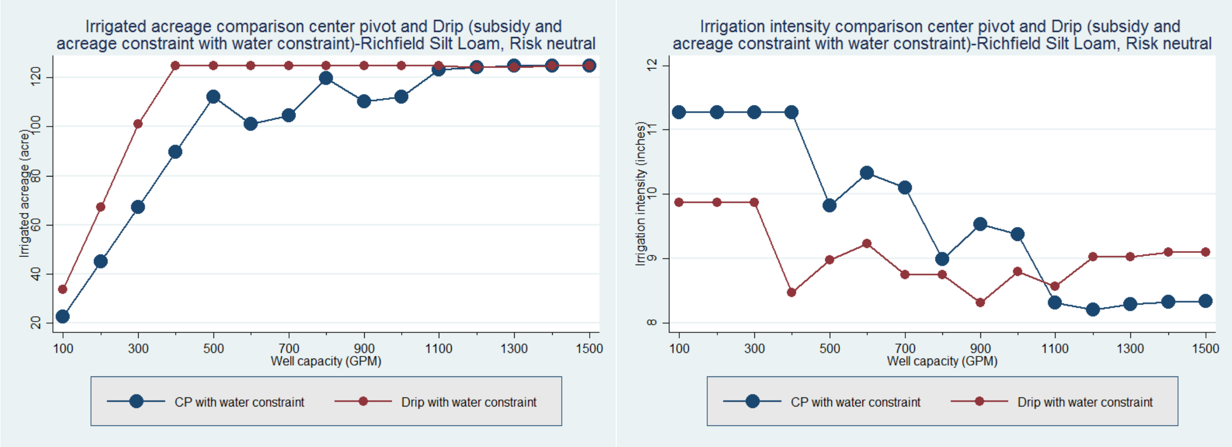


Figure 6.15 Irrigated acreage and irrigation intensity comparison between Center pivot irrigation and Drip irrigation with investment subsidy, acreage constraint and quantity constraint for risk neutral farmer with Richfield soil



Chapter 7 - Summary and conclusion

The risk in crop production due to weather uncertainty and limited water availability are two major challenges of managing irrigation water. Understanding how a farmer decides an irrigation strategy requires understanding how risk averse behavior impacts the decision. For instance, the effort to reduce risk caused by weather uncertainty will be limited by water availability; e.g. limited well capacity and water constraint policy.

Consequently, I investigated the impact that decrease in well capacity has on optimal irrigation strategy. I found a particular minimum optimal instantaneous rate per irrigated acreage depending on soil water holding capacity since lower soil water holding capacity requires a higher optimal instantaneous rate and higher irrigation intensity to provide sufficient water for the corn. Moreover, a minimum optimal instantaneous rate will provide sufficient water for a crop in response to weather uncertainty. I found that farmers with initially large well capacities adjust along the intensive margin in response to reductions in the well capacity because such adjustments offer decreasing returns to intensity, which in turn results in small reductions in returns. Conversely, I found that farmers with initially low well capacity adjust along the extensive margin in response to reductions in well capacity. This adjustment is optimal because the extensive margin exhibits constant returns to scale whereas further adjustments along the intensive margin offer increasing returns to intensity resulting in large decreases in returns—corn yield becomes highly sensitive to further reductions in water intensity.

Importantly, I was able to identify the well capacity threshold when a farmer moves from adjustment in the intensive margin to adjustment in the extensive margin in response to reduced well capacity. This threshold indicates when the well capacity decline begins to cause rapid reduction in welfare. Furthermore, I find that the threshold is different by soil type. The net return for land with lower soil water holding capacity soil is more sensitive to decline in well capacity than land with higher capacity. Thus, land with lower soil water holding capacity will have a higher well capacity threshold at which the farmer will move from adjustment in the intensive margin to the extensive margin. Identifying this threshold accounting for spatial variability is critical for policymakers monitoring the welfare impact of groundwater depletion.

I also analyzed how risk averse behavior will affect the change in optimal irrigation strategy. Apparently, the increase in risk averse behavior induces the farmer to increase total irrigation water use significantly. This result implies models that do not account for risk averse behavior will underestimate total water use. Thus, a higher rate of groundwater depletion may occur if a farmer has more risk averse behavior. Also, such behavior will induce higher irrigation intensity but lower irrigated acreage for farmers with low and medium well capacity. Accordingly, a farmer likely will increase irrigation intensity by using higher instantaneous rate but as a consequence will have to reduce the irrigated acreage. The lower net return due to lower irrigated acreage would be offset by less risk in corn yield due to higher irrigation intensity and higher instantaneous rate. Meanwhile, the farmer with high well capacity likely will increase the irrigation intensity but keep the irrigated acreage constant since they are already constrained by a maximum acreage. Overall, the increase in irrigation intensity is higher for low and medium well capacity than for high well capacity. The former is due to a lower range of instantaneous rate, which may result in a less efficient irrigation schedule to increase irrigation intensity.

Next, the impact of changes in risk premium to changes in water use is smaller for Valent-Vona soil than for Richfield soil. This is because Valent-Vona has initial higher irrigation intensity for a risk neutral farmer and offers less variation in corn yield than does Richfield soil.

Meanwhile, higher variation in corn yield causes Richfield soil to be more sensitive to risk averse behavior changing.

Then, I analyzed the impact of a more restricted water constraint policy on optimal irrigation strategy and found ower quantity constraint will result in lower average net return and lower total water use. Moreover, the effect of the quantity constraint on average net return and water use depends on well capacity. A quantity constraint as small as 9 inches has no impact on a well capacity below 400 GPM, which means the water constraint policy is not a limiting factor in water use for low well capacity. On the other hand, lower quantity constraint has a direct impact on a decrease in total water use for medium and high well capacities. Lower quantity constraint will induce the farmer to reduce irrigation intensity and irrigation acreage. The decrease in irrigated acreage may enable the farmer to increase the instantaneous rate, which may generate more efficient irrigation scheduling to acquire lower irrigation intensity. Also, the higher instantaneous rate may enable the farmer to have relatively larger reduction in irrigation intensity but without significantly decreasing the corn yield. Moreover, I found a larger effect of lower quantity constraint on net return and water use for Valent-Vona soil than for Richfield soil. The difference in the degree of impact of quantity constraint of water use for each soil type is due to the difference in soil water holding capacity.

The impact of risk averse behavior on total water use is different for a farmer who is exposed to water constraint policy versus the farmer who faces no restriction. In the former case, the higher risk premium will always result in higher total water use, and specifically, a higher risk premium will induce the farmer with the high well capacity to increase total water use. However, the effect of higher risk premium on total water use for a farmer with lower well capacity is uncertain when the government enforces a water constraint policy. Furthermore, a water constraint policy reduces the impact of a higher risk premium on increased total water use, and the higher risk premium will induce the farmer to irrigate less acreage and increase irrigation intensity with or without a water policy constraint. Next, the rate of decrease in irrigated acreage is higher for a farmer facing a water constraint policy than for a farmer without a binding water constraint. In addition, the impact of a higher risk premium on change in total water use is relatively smaller for Valent-Vona soil than for Richfield soil. It is due to Valent-Vona soil requiring relatively higher irrigation intensity than Richfield soil, thus having lower variation in corn yield.

Next, I examined the impact of the decrease in well capacity on welfare loss. The magnitude of welfare loss due to well capacity declining is not only determined by how large the depletion is but also by what extent that well capacity decreases. Thus, a smaller depletion but with a lower level of saturated thickness may have a bigger effect on welfare loss. On the other hand, a larger depletion but with moderate level of saturated thickness may cause a smaller welfare loss. Likewise, the decrease in well capacity from 1500 GPM to 600 GPM may generate a smaller welfare loss than a decrease from 800 GPM to 400 GPM.

More closely, I investigated the impact of water constraint policy on welfare loss. The prominent result is that welfare loss due to water constraint policy does not always increase with increases in well capacity, depending on soil type. This result can be attributed to a limitation on the instantaneous rate for each well capacity that can be utilized in response to water constraint policy and soil water holding capacity characteristic. A farmer with very high well capacity will focus more on adjustment in the intensive margin in response to water constraint policy, thus reducing irrigation intensity to minimize the welfare loss. Higher well capacity provides a larger range of instantaneous rates that a farmer can utilize for irrigation. Thus, any reduction in acreage is very small or not needed in the case of very high well capacity. Indeed, the adjustment on the intensive margin only without changing irrigated acreage may only occur if the soil has high soil water holding capacity. This is because such capacity allows a farmer to have a large reduction in irrigation intensity without severely reducing the corn yield. However, this is not the case for soil with lower soil water holding capacity. The water constraint policy has a greater welfare loss effect for such soil combined with higher well capacity. Thus, model that does not include spatial variability in well capacity and soil type may overestimate or underestimate the impact of policy constraint on welfare loss.

Then, I examined the difference in welfare loss for both the risk neutral and risk averse farmer. The welfare loss per unit of reduced water use is higher for the risk neutral farmer than for the risk-averse farmer. The overall welfare losses are relatively similar, but reduction in water use is greater for the risk averse farmer. The reduction in water use being higher for the risk averse farmer is due to that farmer using higher irrigation intensity initially without water constraint policy. Thus, limiting water use may greatly reduce water use of the risk averse farmer, and a water constraint policy may be an effective means to reduce total water use especially for the farmer with very risk averse behavior. My result suggests that the economic models that ignore risk averse behavior will overstate the cost of reducing water use.

Finally, I examined the incentive to adopt drip irrigation technology. Groundwater depletion, shown by the decrease in well capacity, will not induce the adoption of drip irrigation; similarly, lower quantity constraint does not generate a sufficient incentive for the risk neutral or risk averse farmer to change the irrigation system from center pivot irrigation to drip irrigation. The benefit from increasing irrigation efficiency, namely a strategy to deal with the decrease in well capacity, is not sufficient to offset the effect of high investment cost. Therefore, the lower profitability of drip irrigation is predominantly driven by its significantly higher investment cost compared to that of center pivot irrigation.

Drip irrigation requires lower optimal instantaneous rate of application and lower irrigation intensity than does center pivot irrigation. Thus, adopting drip irrigation will enable a farmer to increase the irrigated acreage but also result in an overall increase in water use. Additionally, adopting drip irrigation is most likely to occur with landowners with small and medium well capacity, both of which have a low marginal productivity of water. In such cases, drip irrigation may greatly increase the total crop production and income. However, it may cause a backfire effect on water saving as drip irrigation may generate higher total irrigation water use than center pivot irrigation when the land has a low marginal productivity of water. My study also simulates water use with drip and center pivot irrigation assuming government applied water policy constraint and acreage constraint. The counterfactual finding is that a farmer who adopts drip irrigation system may use less water than historical use would show, but use more water than with center pivot irrigation. Clearly, a water constraint policy causes drip irrigation to use more water than center pivot irrigation since drip irrigation irrigates more acreage. Those results imply that a government subsidy for drip irrigation might actually increase groundwater extraction in areas with a policy constraint.

Future research could evaluate the sensitivity of water price and corn price in the analysis as both would greatly affect the total water use and optimal irrigation strategy. Another research direction is the impact of non-irrigated cash rental rates to optimal irrigation strategy. The higher non-irrigated cash rental rate may induce a farmer to reduce irrigated acreage to lessen the risk of weather uncertainty with regard to crop production. Thus, such rental rate may significantly affect total water use.

Analysis of a larger range of soil parameters is also a possible avenue for future research. Added to research of risk averse behavior, such variables may give more implications for spatial policy. The effect of different distributions of weather uncertainty could also be explored, particularly in relation to risk averse behavior. Different distributions may generate patterns of how limitation in well capacity may affect total water use.

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