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Accounting for well capacity in the economic decision making of groundwater users

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Abstract

Water conflicts unfolding around the world present the need for accurate economic models of groundwater use which couple traditional producer theory with hydrological science. We present a static optimization problem of individual producer rents, given groundwater as a variable input to production. In a break with previous literature, the model allows for the possibility of binding constraints on well capacity which occur due to the finite lateral speed at which water can move underground. The theoretical model predicts that when well yield constraints bind, producers maximize profit by extracting as much water as possible. Therefore, if producers are constrained, regions with more available water should consume more of it. We test this hypothesis empirically by modelling the effect of well yields on crop cover and water usage data. Our empirical results reveal that areas with higher average well capacities tend to plant a more water intensive mix of crops, and use more groundwater. This straightforward result comes in contrast to previous economic models of groundwater use, which have assumed an interior solution to the irrigators' profit maximization problem. This research provides important inroads to understanding what really drives irrigators' behavior on the High Plains; a crucial step towards conserving this precious resource.

I. Introduction:

Groundwater depletion in portions of the High Plains aquifer raises concerns that existing institutions governing groundwater usage do not achieve the fullest economic potential of the resource. Groundwater access on the High Plains is governed by incomplete property rights, classifying groundwater there as a common pool resource. Multiple externalities persist in the usage of groundwater resources (Provencher 1993), meaning the private incentives of individual profit-maximizing firms do not align with social objectives. Economic theory suggests that the uncoordinated actions of individuals sharing a common pool resource, such as the groundwater in an aquifer, will lead to an inefficient outcome known as the 'tragedy of the commons' (Hardin 1968). Individuals who have access to a finite common-pool resource, but do not own it, have less incentive to conserve the resource for future use.

An extensive literature has considered this divergence between individually rational and socially optimal groundwater use (Koundouri 2004). Many of these studies compare a myopic strategy, in which an indivual maximizes annual profits and ignores stock-dependent costs, to a socially optimal outcome in which net benefits achieve a dynamic maximum. More recently, the groundwater management literature has considered which type of strategy better depicts groundwater users' behavior in the context of more realistic models of an aquifers' response to pumping. A lab experiment by Suter et al. (2012) showed that the answer depends on the spatial nature of groundwater use and the aquifers' characteristics. In settings where geological factors result in more complete ownership of groundwater, usage more closely resembles a privately optimal dynamic strategy. In settings where groundwater is more shared, and the costs of use are broadcast more evenly across users, individuals' actions will more closely resemble a myopic strategy.

The distinction between the two strategies is important because ultimately it will dictate the size of the welfare loss associated with open-access. At one extreme is the tragedy of the commons, and at the other is complete private ownership and dynamically optimal resource extraction. While considerable research has compared the welfare implications between each strategy, less research has attempted to describe which strategy actually depicts groundwater usage in real-world settings. A notable exception is a study of groundwater users in Kansas (Pfieffer et. al. 2012), which finds that groundwater-users in fact consider the negative impact of their pumping on future groundwater stocks. Instead of maximizing total annual profits, producers are said to dynamically balance the benefits and costs of groundwater extraction over time. To support this hypothesis, this literature points out that groundwater users in Kansas rarely consume as much groundwater as they are legally entitled to; despite institutions governing groundwater which practically encourage them to do so. As further evidence, these studies show that certain dynamic variables, which should not weigh into the decision making of a short-sighted producer, are in fact correlated with observed groundwater extraction patterns.

In this paper, we propose an alternative explanation for the importance of 'dynamic' variables. We extend the static optimization problem of the short-sighted producer to allow for instantaneous constraints on groundwater supplies. Well capacity constraints are physical limitations on the amount of water available to produce from a well, due to the very gradual nature of water movement underground. The model predicts that when well capacity constraints bind, producers maximize profit by extracting as much water as possible. This simple result reveals a connection between observed pumping quantities and aquifer characteristics, regardless of whether or not producers optimize dynamically.

With this in mind, we revisit the Kansas water use data, and the variables which have previously been associated with a dynamic extraction strategy. Over a study period of 2006 to 2013, areas with higher average well capacities saw more area planted with water intensive crops, and applied more irrigation per acre planted. These results are in line with previous econometric studies that find a positive correlation between the size of groundwater stocks and extraction quantities (Pfeiffer 2012, 2014). However, these studies attribute the relationship to a dynamic extraction pattern exercised by farmers, reasoning that farmers with smaller groundwater stocks consume less, knowing their future supplies are limited.

Here, we present evidence that the well capacity constraints play a role in the irrigation decisions of farmers. We argue that well capacity constraints present a second possible explanation for the positive correlation between groundwater stocks and water usage. As groundwater levels across the High Plains continue to fall, well capacity constraints will be an increasing reality for agricultural producers on the High Plains (Schneekloth 2015). This paper addresses the role that capacity constraints play in producer decisions, and provides empirical evidence that they are a reality.

II. Background Information and Literature

This research adds to a growing body of literature which couples economic producer theory with spatially complex aquifer characteristics. In the past, economists studied groundwater use in the context of a simplistic single cell, or 'bathtub' aquifer. Resource users were said to draw groundwater from an underground bathtub, in which the water level would decline uniformly as the result of any users' pumping. The seminal paper utilized dynamic programming methods to show that welfare gains from optimal control were negligible when compared to a baseline competitive pumping scenario (Gisser and Sanchez 1980). The so-called 'Gisser-Sanchez Paradox' has since been tested, and proven surprisingly resilient, to more robust sets of assumptions (Koundouri 2004). The Gisser-Sanchez model and its contemporaries follow the same basic procedure, in which discounted future net benefits of an optimal control extraction path are compared to competitive pumping scenarios. In the optimal control, pumping quantities are chosen to maximize the present value of social benefits. This depicts the pumping choice of a benevolent social planner, or that of an irrigator if they had complete ownership of the resource. In the competitive model, pumpers act myopically, and equate the private marginal benefits and costs of extraction.

Early research may have found little potential for welfare improving groundwater management, but it is unclear how well it depicts the pumping decision of actual irrigators who draw from aquifers with complex spatial characteristics. These papers utilize a 'bathtub' characterization of groundwater hydraulics, in which the drawdown caused by pumping is uniform across space. In reality, groundwater pumping forms a localized aquifer drawdown known as a cone of depression (Weight 2001). This phenomenon, coupled with the fact that groundwater movement can be extremely gradual, suggests that groundwater can be more of a private, rather than public resource. This topic was the focus of a study by Suter et al. (2012), conducted in the controlled setting of a laboratory economics experiment. The study found that levels of resource use were higher when the costs of use were more shared amongst users.

In the past decade, there has been a push among economists to extend the 'bath-tub' aquifer characterization, to more realistic, spatially explicit settings. In a series of papers by Brozović et al. (2006, 2010), the basic model of optimal control versus competitive pumping was extended to incorporate hydrologic equations of lateral groundwater flow. In contrast to the bathtub characterization, these papers calculated the effect of pumping on aquifer drawdown across space, using hydrologists' Theis equation (Theis 1935). Guilfoos and Pape (2013) parameterized a multi-cell aquifer model using data from Kern County, California, and found that gains from management were significantly higher in the spatially explicit setting, versus the bath-tub model.

A very recent branch of literature considers finite speeds of groundwater flows in a different light. Instead of considering how aquifer properties influence potential gains from groundwater management, this branch of literature considers how groundwater flows influence extraction decisions at the producer level. Foster et al. (2014) simulate the effect of hydrologic constraints on irrigators' decision making. In their model, irrigators react to climatic variation based on a previously chosen soil moisture target. A follow-up study (Foster et al. 2015), provides a comprehensive analysis of well capacities using observational data. The study utilizes well completion records from Nebraska's portion of the Republican River Basin, to compare well capacities to the size of irrigated acreage, and the saturated thickness of the underlying aquifer. The study finds that agricultural productivity exhibits a non-linear relationship to saturated thickness, and that well-capacity has a stronger influence on producers' decisions than depth to water (Foster et al. 2015).

Well capacity constraints have been shown to have substantial economic impacts outside the realm of groundwater resources. A working paper from the National Bureau of Economic Research highlights the divergence between observed extraction patterns of crude oil, and those predicted by economic theory (Anderson et al. 2014). Historically, oil extraction from existing wells has not responded to changing price incentives, in the way that the Hotelling model of nonrenewable resource extraction would suggest. Anderson et al. propose that well capacity constraints can explain the divergence between theory and observed oil extraction. Like groundwater wells, the maximum rate at which oil can be extracted from a well is determined by biophysical factors. As a consequence, oil producers have a limited ability to adjust production quantities in the short-run. Anderson's empirical results show that well capacity constraints limit producers' response to price incentives in the short-run; although in the long-run, oil producers can respond by drilling more wells.

IIb. Hydrology

The fundamental objective of this research is to point out that every groundwater well has a finite capacity, and to illustrate how a well's capacity can influence groundwater users' economic decisions. Up to this point, the term 'well capacity' has been used to loosely describe the maximum quantity of groundwater that can be produced from a well, in a given period of time. In the following analysis, reported rates of pumping are used as a proxy for overall well capacity, which makes it critical to establish the connection between these two related terms. A pumping rate is a volume of fluid passing a point per unit time. Pumping capacity is defined as the maximum pumping rate a well can sustain for an extended period of time. The connection between observed pumping rates, and a well's overall capacity to produce water, might not be immediately intuitive. For that reason, the following section provides a brief primer on the mechanics of irrigation systems, as well as the hydrologic factors which dictate well capacity.

An aquifer is a geologic formation comprised of porous medium, such as sand or fractured rock. An underlying dense layer of clay or bedrock prevents water from seeping deeper into the earth. The porous nature of an aquifer is critical to its overall quality. Hydrologists use the term transmissivity to describe rates of groundwater flow within an aquifer (Todd 2005). Transmissivity can be broken down into two components, hydraulic conductivity and saturated thickness. Hydraulic conductivity is the potential water velocity through a given aquifer layer. However, only saturated layers can contribute to groundwater flow. Therefore transmissivity is equal to the aquifers' saturated thickness multiplied by its conductivity. Transmissivity plays a critical role in determining well capacity, as it influences the potential for groundwater movement towards the well.

When groundwater is drawn from a well, a cone of depression is formed in the water table around the well site. The size of the cone of depression which results from pumping groundwater is influenced by the aquifers' conductivity. Higher conductivity corresponds to a shallower cone of depression, while low conductivity results in steep draw down (Weight 2001). Thus, for a given level of saturated thickness, areas with high conductivity can sustain greater pumping volumes, without the cone of depression intruding the well screen.

In practice, well capacity can be calculated with a well test. A well test involves running a well for an extended period, and measuring the resulting draw down inside the well. The well test allows engineers to parametrize analytic models pioneered by Theis (1935), which are used to quantify an aquifer's response to pumping. These formulas allow engineers to calculate the aquifer transmissivity surrounding the well (Weight 2001). Transmissivity measures the amount of water that can flow horizontally towards the well, and is typically measured as the aquifers' conductivity integrated across its saturated thickness.

The hydrologic factors which influence pumping capacity are well known, yet few existing studies have systematically analyzed well capacity across aquifer properties. Well tests are typically conducted by and for private individuals, meaning data collected across multiple test sites are not readily available. A notable exception utilized records from Nebraska's portion of the Republican River Basin, and found that well capacity had a strong influence on water use decisions (Foster et al. 2015). The only other known study was conducted by the Kansas Geological Survey, which relied on numerical methods to estimate the minimum saturated thickness required to sustain a given pumping rate for a range of aquifer parameters (Hecox 2002).

Given that so few sources of true well capacity data exist, the water use data from Kansas has some key advantages. Unlike well tests, which are usually conducted when a new well is installed, the Kansas data reveals how pumping capacities have evolved over time. The Kansas data also includes annual groundwater extraction quantities, which provides the means to analyze how pumping capacity influences groundwater users' decision making. The drawback to the Kansas data is that farmers' pumping rates are reported, not their true well capacity as measured by a well test.

Nevertheless, reported pumping rates are a useful proxy for a well's true capacity. A well's pumping rate can be thought of as a lower bound of its capacity, so long as the well was used to divert a substantial amount of groundwater. Farmers also face incentives to set pumping rates as high as they can. A well's pumping rate dictates how much water can be pumped in a 24 hour period. At the peak of summer, daily crop water requirements often outstrip supply, meaning it behooves farmers to set their pumping rate as high as possible, in order to minimize yield losses due to water stress.

III. Theoretical Model

The goal of this section is to explore how potential well capacity constraints affect agricultural producers' decision making. The theoretical model describes the problem of a representative farm, seeking to maximize annual profits. The farm must choose which crops to grow, and how much land and water to allocate to each crop grown. Both land and water choices are subject to physical constraints which may limit their use. The model's simplest possible case shows how aquifer properties can influence water use decisions. The model predicts a high degree of correlation between aquifer properties and water usage, in the context of a static optimization problem. Thus, the theoretical model provides a linkage between aquifer characteristics and groundwater use, which is not necessarily due to a dynamic extraction strategy.

In the model, two distinct decision stages describe the profit maximization problem of an individual farmer. In the first stage, the farmer must decide how to divide their land between crops, given uncertainty about the weather. In the second stage, the farmer chooses how much to irrigate each crop, once the weather is known. A two-stage stochastic dynamic program is used to solve both stages. In the simplest case, there are two possible crops, and two potential weather outcomes. For example, the farmer might choose between planting wheat or corn, and may experience a rainy or dry growing season.

Expected profits in the first stage are the sum of profits associated with each weather outcome, multiplied by the probability ε, or $(1-\varepsilon)$, of experiencing a rainy or dry growing season, respectively. The farmer chooses the number of acres to plant to wheat and corn, a_w, and a_c, subject to a constraint on the overall field size $\bar{A}$.

Stage 1:

$$\text{Max}_{\text{a}_\text{w},\text{a}_\text{c}}\text{: E}[\,\pi\,] = \ \varepsilon * \pi^{\text{r}}(\text{a}_\text{w}, \text{a}_\text{c} |\ \text{w}, \mathbf{P}, \boldsymbol{\psi}) + (1 - \ \varepsilon\,) * \ \pi^{\text{d}}(\text{a}_\text{w}, \text{a}_\text{c} |\ \text{w}, \mathbf{P}, \boldsymbol{\psi}) \quad \textit{(1)}$$

$$Subject\ to\text{:}\ a_w +\ a_c \leq \bar{A}$$

The profit earned under the rainy and dry outcomes are denoted π_r and π_d. Profits depend on the quantity of irrigation supplied, denoted w, a vector of input and output prices **P**, and a vector of farm specific attributes $\boldsymbol{\psi}$. Farm-specific attributes include soil quality, depth to groundwater, average climate conditions, and the overall size of the farm.

In the second stage, the farmer chooses the quantity of irrigation to apply, conditional on the number of acres planted, and the weather outcome. Revenues depend on the rainfall event, k ϵ {dry, rainy}, as well as prices and the site-specific variables. In stage 2, the total quantity of irrigation applied, *w*, is equal to the well pumping rate, Θ, multiplied by the amount of time that the well was operated, h. These components reflect the two ways irrigation quantities can be adjusted. Two constraints limit the choice of *w* in stage 2. The amount of time spent irrigating cannot exceed the season length, $\bar{H}$. Legal restrictions may also constrain the amount of irrigation applied, so that $w \leq \ \bar{W}$.

Stage 2:

$$Max_w\text{:}\, \pi =\ \pi^k(w \mid a_w, a_c, \boldsymbol{P}, \boldsymbol{\psi}) \qquad (2)$$

$$Subject\ to\text{:}\ \ w/\Theta\ \leq\ \bar{H}, \text{ and w} \leq \overline{\text{W}}.$$

Where: k ϵ {dry, rainy}, and w = $h * \Theta$

The two-stage dynamic program can be solved recursively, starting with stage 2. Stage two is solved for each distinct weather outcome, *k* ϵ *{dry, rainy}*. The Lagrangian for the stage 2 decision follows:

$$Max_w: L = \pi^k(w \mid a_w, a_c, \boldsymbol{P}, \boldsymbol{\psi}) + \lambda_1(\bar{H} * \Theta - w) + \lambda_2(\bar{W} - w)$$

First Order Conditions:

$$\frac{\partial \mathrm{L}}{\partial w} = \frac{\partial \pi^k(.)}{\partial \mathrm{w}} - \lambda_1 - \lambda_2 \leq 0 \qquad c.s. \qquad w \geq 0$$

$$\frac{\partial \mathrm{L}}{\partial \lambda_1} = \bar{H} * \Theta - w \geq 0 \qquad c.s. \qquad \lambda_1 \geq 0$$

$$\frac{\partial \mathrm{L}}{\partial \lambda_2} = \bar{W} - w \geq 0 \qquad c.s. \qquad \lambda_2 \geq 0$$

The first order conditions can be solved for each possible weather event. The solutions implied by the first order conditions are: $w^{r*}(a_w, a_c, \boldsymbol{P}, \boldsymbol{\psi}, \Theta, \bar{H}, \bar{W})$ and $w^{d*}(a_w, a_c, \boldsymbol{P}, \boldsymbol{\psi}, \Theta, \bar{H}, \bar{W})$. Profit maximizing irrigation quantities is a function of the acreage decision, prices, farm specific attributes, pumping capacity, growing season length, and possible legal constraints. These solutions are plugged into the stage 1 decision, to solve for the profit maximizing acreage allocation.

$$Max_{a_w, a_c}: L = \varepsilon * \pi^r(a_w, a_c | w^{r*}(.), \boldsymbol{P}, \boldsymbol{\psi}) + (1 - \varepsilon) * \pi^d(a_w, a_c | w^{d*}(.), \boldsymbol{P}, \boldsymbol{\psi})$$

$$+ \lambda(\bar{A} - a_w - a_c)$$

First Order Conditions:

$$\frac{\partial \mathrm{L}}{\partial a_w} = \varepsilon * \left[\frac{\partial \pi^r(.)}{\partial a_w} + \frac{\partial \pi^r(.)}{\partial w^{r*}(.)} \frac{\partial w^{r*}(.)}{\partial a_w}\right] + (1 - \varepsilon) * \left[\frac{\partial \pi^d(.)}{\partial a_w} + \frac{\partial \pi^d(.)}{\partial w^{d*}(.)} \frac{\partial w^{d*}(.)}{\partial a_w}\right] - \lambda \leq 0 \qquad c.s. \;\; a_w \geq 0$$

$$\frac{\partial \mathrm{L}}{\partial a_c} = \varepsilon * \left[\frac{\partial \pi^r(.)}{\partial a_c} + \frac{\partial \pi^r(.)}{\partial w^{r*}(.)}\frac{\partial w^{r*}(.)}{\partial a_c}\right] + (1-\varepsilon) * \left[\frac{\partial \pi^d(.)}{\partial a_c} + \frac{\partial \pi^d(.)}{\partial w^{d*}(.)}\frac{\partial w^{d*}(.)}{\partial a_c}\right] - \lambda \leq 0 \qquad \text{c.s. } a_c \geq 0$$

$$\frac{\partial \mathrm{L}}{\partial \lambda} = \bar{A} - a_w - a_c \geq 0 \qquad \text{c.s. } \lambda \geq 0$$

The solutions for the acreage allocation are $a_w^*(\varepsilon, \boldsymbol{P}, \boldsymbol{\psi}, \Theta, \bar{H}, \bar{W})$ and $a_c^*(\varepsilon, \boldsymbol{P}, \boldsymbol{\psi}, \Theta, \bar{H}, \bar{W})$. Critically, the area allocated to each crop, and the number of hours of irrigating, both depend on Θ, the well's pumping capacity. The capacity constraint reveals a connection between aquifer characteristics and pumping behavior, even when producers do not optimize dynamically.

In an aggregate view, there likely exists a mix of constrained and unconstrained water users. This can raise problems when analyzing groundwater data, which generally does not reveal if a producer is capacity constrained. Nevertheless, statistics drawn across the entire population have consistently found that groundwater users exhibit very low price-elasticity of water demand (Scheierling et al. 2006). Extremely low elasticity of demand estimates could be due to capacity constrained producers' inability to respond to changing marginal incentives.

Figure 1 illustrates the effect of well capacity constraints on individual farmers' groundwater demand. The figure depicts two possibilities, in which a farmer is either constrained or unconstrained by well capacity. For the unconstrained producer, water use is determined by the intersection of the marginal cost and benefit curves. Two marginal cost curves are shown, signifying that an upward shift in marginal costs will result in less water use by the unconstrained producer. Water consumption by the unconstrained producer shifts from w_{UC}^1 to w_{UC}^2. For the capacity constrained farmer, the shift in marginal costs does not affect the amount of water used. Total water consumption is equal to $w_C^{1,2}$ in both cases. The illustration shows that a water constrained producer will appear very unresponsive to shifts in the marginal incentives of water use.

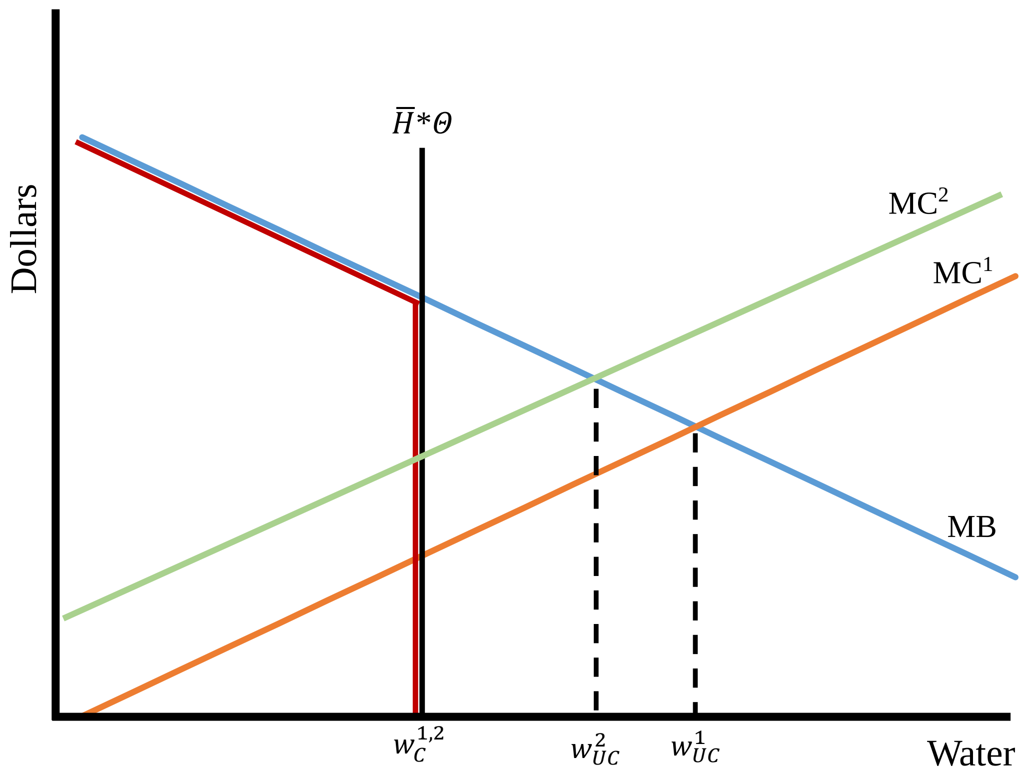

Figure 1. Profit maximizing water use when supply is constrained and unconstrained.

Having considered the theoretical model's predictions for optimal water use, we now turn to the irrigator's optimal land use decision. The specific question addressed is how capacity constraints inform a farms' acreage allocation. The water constraint could be caused by multiple factors, including well capacity or legal restrictions. Water constrained farmers have two choices: they may either reduce the amount of water used per-acre, or plant less acres of water intensive crops. On the High Plains, farmers with low capacity wells have tended to overplant corn and experience large yield losses, in the hopes that favorable weather will induce an economic windfall (Schneekloth 2012, 2015). When the weather does not cooperate, crop insurance serves as an economic backstop.

The two stage maximization problem presented earlier can be used to explain this behavior. In the two crop example, the net marginal gain of planting either wheat or corn is equal. Once the well capacity constraint is reached, there will be diminishing returns to planting the water intensive crop. This occurs because the crop receives less irrigation than the full requirement, which will impact its yield. Despite losses in crop yields per acre, ultimately the marginal benefit of the alternate land use determines the optimal field size. On the High Plains, growing irrigating corn has been lucrative, making it optimal to accept yield losses in comparison to growing less water intensive crops. The problem with this strategy is that it results in inefficient water usage. Low capacity farms adopt strategies like pre-watering fields before they are planted, and running irrigation during rain events, simply to try to keep up with the season's anticipated irrigation deficit. Often, these farms cannot supply enough water in the heat of summer, when corn growth is at its most sensitive stages.

Corn ET data from Kansas State's Northwest Research Station was used to generate Figure 2. On average, daily corn irrigation requirements peak around the end of July. The figure shows the daily water requirements for a typically sized, 120 acre center pivot. If no precipitation or soil moisture is available for crop use, an irrigation system with 90% efficiency would need to pump over one million gallons of water per day at the peak of summer. Left continuously running, the well would have to pump at 754 gallons per minute in order to meet the full requirement.

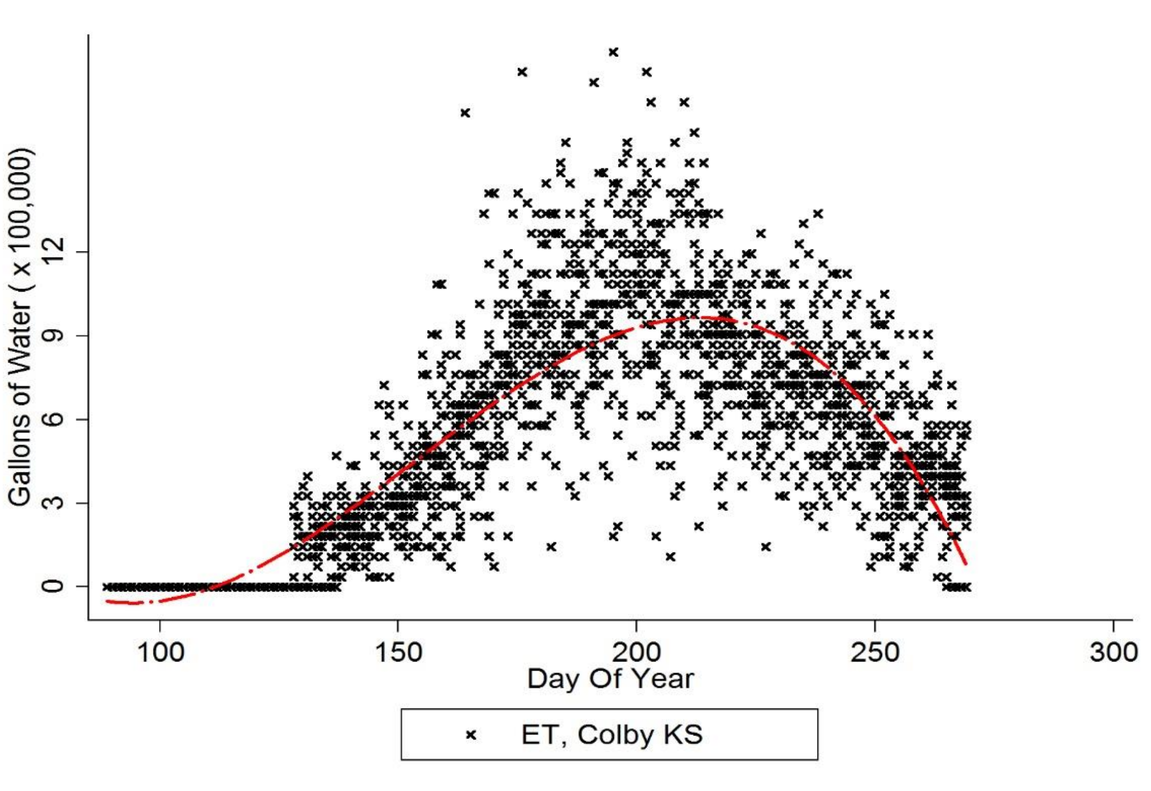

Figure 2: Daily Corn ET Requirement for a 120 Acre Pivot, Colby Kansas, 2004-2014

IV. Empirical Application

In this section, the implications of well capacity constraints are examined using agricultural groundwater use data from Kansas. Since 1990, Kansas has mandated that groundwater wells install meters and report total annual withdrawals. These records are part of the Water Rights Information System (WRIS) dataset and are publically available online. Numerous economic studies have made use of Kansas' high quality groundwater data, including

Hendricks 2012, and Pfeiffer 2012 and 2013. The data is comprised of the spatial locations of each well-site, as well as corresponding annual water use records from 1990-2013. Each observation includes an identification number of the person who filled out the report. For some observations, the data includes the well's pumping rate, as well as the total accumulated amount of water use.

An additional set of records contains the spatial locations of land tracts authorized for use with irrigation, and a list of each water right that is legally authorized to apply water on that acreage. The tracts of land in the data are 'quarter-quarter' 40 acre sections, categorized by the Public Land Survey System (PLSS). A typical center pivot irrigation system comprises four of these sections, covering a rectangular area of 160 acres. Linking these PLSS sections back to the annually reported water use data allows us to collect data on farmers' cropping decisions at an unprecedented level of spatial clarity. Previous studies using Kansas's groundwater use data have relied on acreage numbers self-reported by farmers in the WIMAS dataset. Using this data, if multiple crops were grown on the same parcel, it is impossible to discern how many acres of each crop were planted. We overcome this obstacle by gathering additional land cover data at the PLSS section level.

Satellite land cover data was sourced from the United States Department of Agriculture's National Statistics Service. Several papers have used this data in the context of groundwater pollution, including Fitzgerald 2013, and Hendricks 2014. The Cropland data layers are raster images of the United States, in which each pixel of the image corresponds to a specific crop. The raster files have a 30 by 30 meter resolution; a land area of less than a quarter of an acre. The crop cover data for Kansas are available for the years 2006-2013, in which an eight year panel of water and land use data are available. A crucial step in linking these two sources of data was using individual farmer-year combinations as the unit of analysis. The water use data is recorded for each well site, but often multiple wells are authorized to irrigate the same tract of land. Grouping observations at the farmer level greatly improved the ratio of unique mappings between well sites and PLSS sections, and potentially reduces noise that may occur due to multi-year cropping rotations. These data steps were completed using Arcmap Geographical Information System software.

In total, the data includes 61,082 unique farmer-year combinations in the years 2006-2013. The data was screened to include only irrigation water-use, which accounted for 92% of total groundwater withdrawals during the study period. Other water uses, such as domestic, industrial, and municipal, were omitted. Farmers who reported a mix of surface and groundwater sources were screened from the data. The data contained some outliers that seemed to have been caused by human record keeping errors. Extreme outliers were removed from both the water use and pump rate variables. In total, the data had 48,065 distinct, usable, farmer-year observations.

The pumping rate variable used in the analysis is an average of the pumping rates recorded at each of a farmers' wells, weighted by the quantity of water pumped at each well. Pumping rates frequently were not reported, only 32,416 farmer-year observations had data for this field. Wells with no reported pumping rate, or a rate of 0 GPM were not included in the weighted average.

The water use data indicates which type of irrigation system is used with each well. Since farmers typically operate more than one well, it was common for individual farmers to also operate more than one type of irrigation technology. To keep matters simple, the analysis makes use of a binary variable called 'center pivot', in order to control heterogeneous irrigation efficiency. The center pivot variable was set equal to one for farms that exclusively operated Low Energy Precision Application (LEPA) center pivots. In our sample, just over half of the observations fell into this category. The remaining observations operated a mixture of LEPA and traditional center pivots, flood irrigation and sprinkler systems other than center pivots.

Data on aquifer characteristics was sourced from the United States Geological Survey's repository of spatial data. Saturated thickness was taken from a map of 1997 estimates, which predates our study period by nine years. The older data was used to limit the possibility of an endogenous relationship between saturated thickness, pumping capacity, and overall water usage. Both 1997 saturated thickness and conductivity class are categorical variables. In the spatial dataset, separate polygon features represent distinct 'bins' of each variable. Very few observations fell into the lowest conductivity class, and the highest saturated thickness, categories. These observations were lumped into the next-closest bin, leaving a total of three bins each for conductivity and saturated thickness classes.

Gridded precipitation data was retrieved from the Parameter-Elevation Regressions on Independent Slopes Model (PRISM) group at Oregon State University (2015). The spatial PRISM data was extracted to each well-site in the water use data, providing unique weather observations that vary across both time and space. In the analysis, monthly precipitation totals were aggregated into spring, and summer components. Spring precipitation includes the months of January to April, and summer includes the months of May through August. The groupings are meant to capture the effect of precipitation before and after the spring planting decision, while limiting multicollinearity which occurs with separate variables for each month.

Soil data was retrieved from the Natural Resources Conservation Services' Soil Survey Geographic Database (SSURGO). Of the many useful attributes in the soil data, 'Irrigation Capability Class' was chosen for use in the analysis. Capability classes range from 1 to 8, but in Kansas, the overwhelming majority of our observations fell into classes 1 and 2. Capability class 1 refers to soils with few limitations which restrict their use, and class 2 refers to moderate limitations. A binary variable was set equal to one for soils in Capability Class 1, and zero otherwise. Average slope, referring to land's percentage grade, was also retrieved from the soils data. A slope of zero refers to completely flat ground, and increasing numbers correspond to steeper inclines.

Summary Statistics

Variable	Obs.	Mean	Std. Dev.	Min	Max
Water Use (Acre-Feet)	48065	480.5	633.9	0.0	4993.8
Pump Rate (GPM)	31480	598.8	248.9	60.0	1400.0
Corn (acres)	48065	218.8	314.6	0.0	4579.1
Winter Wheat (acres)	48065	128.7	213.0	0.0	4665.6
Grassland/Pasture (acres)	48065	82.6	133.2	0.0	2902.9
Fallow (acres)	48065	51.9	116.4	0.0	2982.7
Irrigated Area (acres)	47987	416.7	509.0	1.0	8080.0
Total Area (acres)	48065	624.7	698.7	0.8	9458.7
Slope (pct)	48065	2.0	2.8	0.0	45.0
Center Pivot (binary)	48065	0.6	0.5	0	1
Irrigation Capability (binary)	48065	0.4	0.5	0	1

Spring Precipitation (mm)	48065	106.5	54.4	13.7	290.5
Summer Precipitation (mm)	48065	288.6	115.7	73.6	709.4

Table 1: Summary Statistics

Table 1 summarizes the data used in the empirical analysis. The summary statistics include two variables which relate to overall farm size. ‘Irrigated Area’ was reported by the actual farmers in the water use data. ‘Total area’ is the physical area of every PLSS section operated by a given farmer. Total area is fixed, while irrigated area is possibly chosen by the farmer, and will always be less than total area due to legal restrictions. Total area is exogenous to planting decisions, as opposed to irrigated area, which can be chosen by the farmer each year.

An additional table of summary statistics (table 2), splits observations into three equal size groups. The groupings divide split observations between low, medium and high reported pumping capacities. The summary statistics reveal acute distinctions between the pumping capacity classes. Producers in the highest pumping capacity class, 714- 1400 gallons per minute, have the highest average water use, and highest irrigated area. Simply dividing these averages reveals that high capacity producers tend to apply more groundwater per acre, and tend to irrigate a higher portion of their farms’ total area. Producers in the lowest third of pumping capacities, which ranged from 60 – 490 gallons per minute, operate their wells for more hours, and dedicated more acreage to less water intensive uses, including wheat, fallow and sorghum. The summary statistics reveal a strong positive correlation between pumping capacities, and the number of acres devoted to corn. Simple pairwise comparisons were used to test for statistical differences between the group means. Every variable in the table below showed significant differences at a 99.9% confidence level, between the means of each pumping capacity group.

	Reported Pumping Rate		
	60 - 490 GPM	*490 - 715 GPM*	*714 - 1400 GPM*
Water Pumped, *acre-feet*	301.2	479.9	569.2
Irrigated Area, *acres*	315.6	415.9	466.2
Total Area, *acres*	566.0	620.6	629.3
Hours Pumped	1626.3	1306.3	1060.7
Corn, *acres*	154.9	221.2	251.1
Winter Wheat, *acres*	147.8	125.7	101.0
Grassland, *acres*	84.9	82.8	75.1
Fallow Cropland, *acres*	67.3	50.6	32.4
Sorghum, *acres*	53.9	42.6	38.1
Soybeans, *acres*	10.9	30.5	57.6
Alfalfa, *acres*	16.2	29.0	24.5

Table 2. Summary statistics, grouped by pumping capacity tercile.

The first step of the empirical analysis is to model the pumping capacities from Kansas's water use records. Pumping capacities are critical to the analysis, as they explain the link between physical aquifer characteristics and groundwater extraction quantities. Pumping capacity constraints motivate this linkage, whether or not farmers optimize groundwater extraction dynamically across multiple growing seasons. The goal in this stage is to create an instrument for the pumping capacity, and to check whether the recorded pumping capacities are consistent with hydrologic science. Over time, pumping capacities have been gradually declining. Although farmers reported pumping capacities that varied substantially from year to year, only time-invariant explanatory variables are used in the regression. As a result, the model simply predicts an average pumping capacity for a given area. Parameters were estimated by the following model:

$$Pump\ Rate_{it} = \beta_0 + \beta_{1\text{-}2}*Conductivity\ Class_i + \beta_{3\text{-}5}*Saturated\ Thickness\ Class_i$$

$$+ \beta_6*Latitude_i + \beta_7*Longitude + e_{it}$$

The model is estimated by ordinary least squares, and the results show that pumping capacities are positively correlated with conductivity and saturated thickness. The coefficient estimates for each ‘bin’ of these two categorical variables have increasingly large magnitudes. The explanatory variables were explicitly chosen to identify the model. Over time, there could be an endogenous relationship between saturated thickness, and well pumping capacities. Here, saturated thickness estimates predate the study period by 10 years, eliminating any potential feedback between these two variables.

Dependent Variable: Pump Rate (GPM)			
VARIABLES	Coefficient	Std. Error	Significance
Conductivity:			
50 to 100 ft./day	31.54	(3.555)	***
100+ ft./day	38.93	(3.833)	***
Saturated Thickness 1997:			
100 – 200 ft.	98.51	(2.927)	***
200 – 400 ft.	170.5	(4.210)	***
400 – 600 ft.	255.4	(16.07)	***
Latitude	-56.86	(2.018)	***

Longitude	50.39	(1.080)	***
Constant	7,735	(107.2)	***
Observations	29,057		
R-squared	0.248		
*** p<0.01, ** p<0.05, * p<0.1			

Table 3: Statistical results for the pumping capacity model.

The variables latitude and longitude were included to allow for directional trends in pumping capacities. Their coefficient estimates translate to the highest average pumping capacities in South-East Kansas. The Southern component makes sense, given that the deepest parts of the Ogallala sit under Kansas' Southern border with Oklahoma. The Eastern directional trend suggests climate might play a factor in well capacity, as Eastern Kansas receives considerably more precipitation. Going from West to East, average summer precipitation roughly doubled in the parts of Kansas which overly the Ogallala.

The categorical variables are admittedly imprecise, yet their coefficient estimates exhibit directional trends that are consistent with hydrologic science. Additionally, the model's predictions can be used to instrument for pumping capacities in further regressions. The instrumental variables approach overcomes the possibility of biased estimates that might result from endogenous explanatory variables. Using instrumental variables clears up this issue of causality.

The next set of regressions regard the farmer's crop mix decision. In two separate regressions, the number of acres planted with corn and wheat are used as dependent variables. These two crops are by far the most prevalent in Kansas, and are an important signal of how much water a farmer intends to use. Corn is more water intensive than wheat, and almost always requires irrigation in Kansas. Wheat is less water intensive, but it is still common to irrigate wheat in Kansas. Acreage devoted to each crop was estimated using the following functional form:

$$Acreage_{jit} = \beta_0 + \beta_1 * \widehat{Pump\ Rate}_i + \beta_2 * Spring\ Precip_{it} + \beta_3 * Spring\ Precip_{it} * \widehat{Pump\ Rate}_i + \beta_4 * Total\ Area_{it} + \beta_5 * Latitude_i + \beta_6 * Longitude_i + \beta_7 * Center\ Pivot_i + \beta_8 * Irr.\ Capability\ Class_i + \beta_9 * Slope_i + \beta_{10\text{-}16} * Year\ Fixed\ Effects_t + e_{it}$$

Subscripts *jit* indicate the number of acres of crop *j*, planted by farmer *i*, in year *t.* The first independent variable is the predicted pumping capacity estimated in the previous regression. An interaction term allows the effect of spring precipitation on pumping quantities to vary depending on the farm's pumping capacity. Total area is included to allow for a scale effect, based on the overall size of the farm. Latitude and longitude allow for directional trends in planting decisions which occur due to climatic trends. Finally, the year fixed effects are meant to capture the influence of spatially invariant factors. For instance, the theoretic model predicts that relative prices influence the planting decision, yet in our analysis we are unable to observe prices that vary over space as well as time.

Dependent Variables: Planted Area		
VARIABLES	Corn (acres)	Winter Wheat (acres)
Predicted Pumping Capacity (GPM)	0.805***	-0.522***
	(0.0223)	(0.0158)
Spring Precipitation (mm)	1.384***	-0.897***
	(0.118)	(0.0839)
Spring Precip, Predicted Pumping	-0.00183***	0.00140***
Capacity Interaction	(0.000159)	(0.000113)
Total Area (acres)	0.361***	0.226***

	(0.00133)	(0.000945)
Latitude	90.91***	-60.22***
	(1.995)	(1.416)
Longitude	-24.76***	-1.119
	(1.293)	(0.917)
Center Pivot (LEPA)	27.28***	-5.956***
	(1.885)	(1.338)
Irrigation Capability Class	-10.95***	15.46***
	(2.100)	(1.490)
Slope (percent)	-5.203***	-3.632***
	(0.360)	(0.256)
2007 Fixed Effect	18.79***	10.10**
	(5.545)	(3.934)
2008 Fixed Effect	40.33***	14.37***
	(3.607)	(2.559)
2009 Fixed Effect	29.30***	16.50***
	(4.438)	(3.149)
2010 Fixed Effect	55.38***	-2.318
	(4.243)	(3.011)
2011 Fixed Effect	61.94***	12.32***
	(3.597)	(2.552)
2012 Fixed Effect	39.24***	17.20***
	(4.474)	(3.174)
2013 Fixed Effect	35.17***	25.54***
	(3.707)	(2.630)
Constant	-6,512***	2,491***
	(168.9)	(119.8)
Observations	44,499	44,499
R-squared	0.652	0.623

Standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Table 4: Statistical results from the acreage allocation models.

The empirical results are consistent with the model of water constrained producers. Predicted pumping capacities have a statistically significant impact on the number of acres allocated to corn and wheat. Higher pumping capacities correspond to more acres planted with corn, and less acres planted with wheat. These results are intuitive given that corn yields are more responsive to irrigation, and requires more irrigation. The results suggest that producers with greater irrigation capacity tend to plant more water intensive crops.

Acres of corn is positively correlated with spring precipitation, while acres of wheat is negatively correlated with spring precipitation. Again, these results are intuitive, given that high initial soil moisture means that less irrigation will be required. The interaction term reveals that the impact of spring precipitation diminishes at higher predicted pumping capacities. In a dry spring, farmers with low pumping capacities tended to plant more acres of corn. Conversely, farmers with low pumping capacities showed less acres of wheat planted in a wet spring. This result might seem puzzling, given that Winter Wheat recorded in the data had to be planted the previous fall. The negative relationship between acres of wheat and spring precipitation is probably due to the way the NASS data was recorded. In a wet spring, farmers were more likely to follow wheat with a crop of soybeans. In the data, double-cropped acres are treated as their own distinct crop, and thus results in less overall area regarded as wheat.

The potential for double cropping might also explain directional planting trends captured in the latitude and longitude variables. The directional trends indicate that corn is preferred in the North-West (since longitude is always negative in the sample), and that wheat is preferred towards the South, conditional on the model's other explanatory variables. Southern regions of Kansas have a longer growing season, and therefore farmers have a greater potential to establish winter wheat after corn has been harvested.

Of the remaining variables included in these regressions, total area, center pivot, and slope had coefficient estimates of the expected signs. Irrigation capability class also had unexpected signs, with the higher-quality soil being preferred for growing wheat.

A final regression considers the effect of pumping capacities on the actual quantity of water used by farmers. A statistical model was fit according to the following functional form:

$$Water\ Use_{it} = \beta_0 + \beta_1 * \widehat{Pump\ Rate}_{it} + \beta_2 * Summer\ Precip_{it} + \beta_3 * \widehat{Pump\ Rate}_{it} * Summer\ Precip_{it} + \beta_4 * Center\ Pivot_i + \beta_5 * Capability\ Class_i + \beta_6 * Acres\ Corn_{it} + \beta_7 * Acres\ Wheat_{it} + \beta_8 * Latitude_i + \beta_9 * Longitude_i + \beta_{10\text{-}16} * Year\ Fixed\ Effects_t + e_{it}$$

Dependent Variable: Water Use (acre-feet)

VARIABLES	Coefficient	Std. Error	Significance
Predicted Pumping Capacity (GPM)	1.155	(0.0447)	***
Summer Precipitation (mm)	0.581	(0.0924)	***
Pumping Capacity, Summer Precip			
Interaction	-0.00149	(0.000137)	***
Center Pivot (binary)	-19.83	(3.360)	***
Capability Class (binary)	-48.14	(3.389)	***
Corn (acres)	1.366	(0.00562)	***
Winter Wheat (acres)	0.654	(0.00853)	***
Latitude	-56.39	(3.661)	***
Longitude	-43.69	(2.242)	***
2007 Fixed Effect	-126.7	(6.334)	***
2008 Fixed Effect	-95.53	(6.330)	***

2009 Fixed Effect	-144.6	(6.410)	***
2010 Fixed Effect	-102.8	(6.453)	***
2011 Fixed Effect	-50.33	(6.929)	***
2012 Fixed Effect	-57.95	(7.362)	***
2013 Fixed Effect	-61.53	(6.480)	***
Constant	-2,612	(295.3)	***
Observations	44,499		
R-squared	0.727		

*** p<0.01, ** p<0.05, * p<0.1

Table 5. Statistical Results for the water use regression.

Results from the water use regression confirm the importance of well capacity constraints. Predicted pumping capacities had a positive and significant impact on the amount of water used. At first glance, it may appear that summer precipitation has the incorrect sign. Precipitation should have a negative sign, since precipitation should decrease the amount of irrigation that is needed. The interaction term clears up this confusion. When the negative interaction coefficient is multiplied by a farms' pumping capacity, the marginal impact of a millimeter of rain is almost always negative. Farms with extremely low pumping capacities tended to apply use more water, on average, as a result of precipitation. In years with high precipitation, farms with high pumping capacities cut back on the amount of water used.

Every single coefficient estimate in this regression had the expected sign. Water use was negatively correlated with the center pivot, and soil quality variables. These signs are intuitive, given that less water is required with the efficient irrigation technology, and with higher-quality soils. The coefficient estimates on the corn and wheat variables translate to the number of acre feet of water applied to each acre planted. On average, corn received twice as much water as wheat per acre planted. The directional tends indicate that more water is used in the South West of Kansas. This is not surprising, given that Eastern Kansas receives considerably more precipitation, and Southern Kansas has higher potential crop evaporative losses due to higher temperatures and a longer growing season.

Although these regression results are satisfying, they must be taken with a grain of salt. The analysis makes use of observational data, and suffers the classic consequences. Because the pumping capacities were not randomly assigned, it is impossible to say for certain whether the correlation between pumping capacities, planting decisions, and water use, were in-fact caused by the pumping capacities. We do our best to control for this, by using a strictly exogenous instrument for pumping capacities. Still, the crop-acreage variables are not fully identified. These variables might require instruments of their own, but the theoretical model shows that crop acreage, and water usage decisions are simultaneously determined, making it hard to think of an instrument that influences one decision and not the other.

V. Conclusion:

In the Western United States, and in many other parts of the world, groundwater is being used faster than it is being replenished. Farmers know that declining groundwater reserves will also mean lower well capacities. Despite these facts, very few economic models of groundwater use feature constraints that can limit the amount of water consumed. This thesis made the case that supply constraint are indeed relevant, and are important to, groundwater use decisions. This argument was made using theoretical and empirical methods. The theoretical model showed how aquifer characteristics can influence water use decisions. By omitting this relevant feature, previous theoretical work reached misguided conclusions, which often were not supported by empirical results. In contrast, this paper's empirical results broadly support the theoretical models' predictions. Pumping capacities exhibited the expected relationships with planting decisions and overall water use.

These results have broad implications. Economic models which accurately depict the decisions of irrigators do a better job of explaining water use outcomes. For example, many economic studies have estimated very low responsiveness of water use to factors which should influence the profits associated with irrigation. Depth to water strongly impacts the costs of pumping, yet few studies are able to show a negative correlation between pumping depth and extraction quantities. Low elasticity of groundwater demand has also stymied attempts to curb groundwater extractions in Colorado's San Luis basin. For many farmers there, irrigation remains attractive, even when it comes with an extremely high bill.

This paper also shows how planting strategies change depending on a farms endowment of groundwater. On farms with low capacity wells, the strategy can be to plant an ambitious amount of corn, and try to keep up with the season's irrigation requirement. As a result, policies seeking to reduce water use by limiting the amount of acres planted, might not work as intended on their own. If farmers adjust the amount of water applied per acre, then the water saved by planting less irrigated area might simply be diverted to smaller fields.

Hopefully, this thesis has highlighted the importance of well capacity constraints. This research opens up a world of future extensions. Most importantly, will be to understand the extent that capacity constraints affect water use efficiency on an aquifer-wide scale. Laws governing groundwater use on the High Plains are mostly outdated, meaning that water use decisions are ultimately at the discretion of individual farmers. This thesis showed why these farmers often do not optimize water efficiency in the way experts would hope.

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