Well Worth it: Well Capacity and the Cost of Aquifer Depletion for Irrigated Agriculture

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Well Worth it: Well Capacity and the Cost of Aquifer Depletion for Irrigated Agriculture

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Abstract

Groundwater is a critical source of water supply for irrigated agriculture. Multiple studies have highlighted the importance of declining well capacities as a critical factor affecting groundwater demand in agriculture. These studies show that well capacity, the maximum instantaneous flow rate of pumping from an aquifer, is a better determinant of groundwater use than saturated thickness, which measures the height of an aquifer above the bedrock. While the effects of declining well capacities on irrigation demand are well known, the costs of declining well capacities are not well understood. In this paper, we estimate the benefits of groundwater access and the value of irrigation well capacity using a hedonic valuation approach applied to agricultural property markets in the Colorado portion of the High Plains Aquifer. Specifically, we spatially link agricultural land sale transactions with the hydrologic characteristics of the aquifer and irrigation wells. This novel dataset allows us to estimate land values as a function of well capacity, saturated thickness, depth to water, hydraulic conductivity , and specific yield. In addition, we control for a range of non-hydrological attributes of farmland that may affect land values, such as proximity to urban areas, soil quality, and the dollar value of the improvements. We find that having access to groundwater is associated with about a 119% higher land values. On the other hand, a 10-foot higher saturated thickness is associated with 2% higher land values. We also find that both saturated thickness and well capacity are statistically significant determinants of land values. Specifically, we show that a 100 gpm increase in well capacity is associated with a 2% increase in land values ($127 in 2022 USD). Our results have important implications for valuing groundwater as natural capital. We find that the exclusion of well capacity can underestimate the shadow value of groundwater by more than 10%.

1 Introduction

Groundwater is a critical source of water supply for irrigated agriculture, particularly in arid and semi-arid regions where it often serves as the sole source of water for production. Yet, decades of over-extraction have led to a widespread depletion of aquifers around the globe, raising concerns about the long-term sustainability of agricultural production. As water tables continue to decline, important questions arise concerning the economic impact and cost of depletion. A growing body of research has examined how aquifer depletion affects irrigation behavior and agricultural output. In particular, recent studies highlight the importance of well capacity—the maximum instantaneous flow rate from a well—as a key determinant of groundwater demand in agriculture (Foster et al., 2014; Foster and Brozović, 2018; Rad et al., 2020; Mieno et al., 2021; Nozari et al., 2024; Hrozencik et al., 2017). These studies show that well capacity often proves more effective in determining agricultural groundwater demand than saturated thickness, which is the height of the aquifer above the bedrock and represents water stored but not necessarily extractable at rates sufficient for irrigation over the growing seasons.

While the effects of declining well capacities on irrigation demand are well known, the costs of declining well capacities are not well documented in the existing literature, largely due to lack of data availability on well capacity, especially in panel format. A strand of studies estimates the marginal value of groundwater and the cost of aquifer depletion through the hedonic valuation method (Sampson et al., 2019; Kovacs and Rider, 2023), or through its effect on agricultural production and returns (Perez-Quesada et al., 2024; Fenichel et al., 2016). These studies, however, focus on saturated thickness as the primary state variable of interest, leaving the explicit effects of well capacity unaccounted for. While saturated thickness communicates useful information about the aquifer's longevity, its relevance for welfare arises through its impact on well capacity—the flow of water that directly constrains production decisions and agricultural outcomes. Johnston et al. (2017) caution against relying on intermediate biophysical metrics in stated preference studies, as this can bias the valuation of environmental changes due to respondent speculation about how those metrics translate into the flow of final services. A similar concern arises in hedonic valuation when researchers rely on observed, but imperfect proxies—such as saturated thickness—to represent welfare-relevant outcomes like well capacity, which places an upper bound on the pumping rate. Since well capacity is what land buyers and producers ultimately care about, using saturated thickness as a stand-alone state variable can lead to biased estimates of the cost of depletion, particularly when the relationship between the two is noisy or variable across space.

In this paper, we first estimate the benefits of groundwater access and the implicit value of saturated thickness and irrigation well capacity by leveraging a rich dataset of agricultural land transactions in the High Plains Aquifer (HPA) region of Colorado. We use a hedonic pricing model to relate land values to well-level hydrological characteristics that control for both saturated thickness and well capacity as state variables. We then use the estimated coefficients to simulate the costs of aquifer depletion between 1990 and 2016.

We find that having access to groundwater is associated with about a 111% higher land values compared to dryland farms. On the other hand, a 100 foot higher saturated thickness is associated with 16% higher irrigated land values. We also show that both saturated thickness and well capacity are statistically significant determinants of land values. Specifically, we find that a 100 gpm increase in well capacity is associated with a 2% increase in land values.

Furthermore, we show that if saturated thickness fully captured the economic value of groundwater access—either through its effect on pumping costs or its correlation with well capacity—then its coefficient would become statistically insignificant once well capacity and other aquifer variables are included. To quantify the implications for aquifer depletion, we use our estimated coefficients to simulate land value changes from 1990 to 2016 under two scenarios: one that includes both well capacity and saturated thickness, and another that includes only saturated thickness. We find that omitting flow-related variables like well capacity underestimates the economic cost of aquifer decline by approximately 11%.

Our results have important implications for valuing groundwater as natural capital. We find that the exclusion of well capacity can underestimate the shadow value of groundwater. This is particularly important for lower levels of saturated thickness where well capacities decline more rapidly in response to changes in saturated thickness . Our findings also highlight the need for collecting well capacity data to better estimate the value of this critical resource.

Our work contributes to the literature on groundwater valuation in two ways. First, several studies have used hedonic models to estimate the value of irrigation water access (Faux and Perry, 1999; Mendelsohn and Dinar, 2003; Petrie and Taylor, 2007; Schlenker et al., 2007; Buck et al., 2014), the stock of in-situ groundwater (Sampson et al., 2019), or capturing heterogeneity in water right attributes (Brent, 2017; Edwards et al., 2024; Mukherjee and Schwabe, 2015). In the context of HPA groundwater, Hornbeck and Keskin (2014) finds a price premium for agricultural lands that overlay the Ogallala aquifer. Sampson et al. (2019) leverages the variations in saturated thickness to estimate the marginal value of in-storage water in the Kansas portion of HPA. They find a price premium of between $3.4 to $15.8 per acre of land for each foot of saturated thickness. More recently, Sheng (2022) updates these estimates using repeated sales of irrigated parcels in Colorado and Nebraska and shows that land values are positively associated with saturated thickness, particularly in areas with lower groundwater stocks. Sheng's results suggest marginal values of approximately $5.7 to $26.9 per acre for each additional meter of saturated thickness (roughly $1.7 to $8.2 per foot), with higher values in Colorado. We build on this literature by moving beyond saturated thickness as a proxy for groundwater and incorporating well capacity—a physical measure of instantaneous pumping potential—into the valuation framework. While Suter et al. (2021) use stated preference methods to estimate willingness to pay for higher well capacity, their analysis does not control for underlying aquifer conditions such as saturated thickness. To our knowledge, ours is the first revealed preference study to isolate the marginal value of well capacity. We find that well capacity remains a statistically and economically significant predictor of land value after accounting for aquifer characteristics including saturated thickness. This suggests that well capacity captures distinct, operational dimensions of irrigation productivity not fully reflected in measures of groundwater stock alone. In our preferred specification for Colorado, we estimate that each additional foot of saturated thickness increases land value by $13 per acre, while a 100 gallon-per-minute increase in well capacity raises land value by approximately $127 per acre.

Second, we contribute to the literature on the economic cost of groundwater depletion. Fenichel et al. (2016) derive shadow prices of groundwater as a form of natural capital using a dynamic economic framework. They estimate that the marginal value of an additional acre-foot of water ranges from $7 to $17 per acre for the average farmland in Kansas. Perez-Quesada et al. (2024) find that reductions in saturated thickness lead to declines in irrigated acreage and land rental rates, with the magnitude of these effects varying depending on initial aquifer conditions—larger impacts occurring where saturated thickness is already low. Our work complements this by estimating the cost of depletion accounting for declines in both saturated thickness and well capacities. Through simulations based on observed and predicted changes in these variables, we show that hedonic models relying solely on stock-based indicators may understate the true economic losses from aquifer decline.

2 Study area

High Plains Aquifer is the largest groundwater resource in the United States and supports 20 percent of the nation's irrigated agricultural land (Steward and Allen, 2016). Water-level declines began in parts of the High Plains Aquifer soon after the beginning of substantial groundwater irrigation following WW1 and advancements in drilling and pumping technologies (Hornbeck and Keskin, 2014). Since 1950, aquifer has experienced significant declines in water levels, losing 286.4 million acre-feet of storage, with agriculture being the primary user of its water. Water-level declines have been especially severe in the Central and Southern portions of the aquifer. Between pre-development and 2019, average declines ranged from less than 1 foot in Nebraska to over 200 feet in some regions of Texas (McGuire and Strauch, 2024). These trends have been accompanied by reductions in saturated thickness, reduced well yields, and in some locations, the permanent loss of groundwater access for irrigation.

The Colorado portion of the Ogallala, particularly within the Republican River Basin (RRB), is among the more affected regions. Nearly 88% of irrigated land in this area overlays the HPA, and the local economy is heavily dependent on irrigated crops such as corn and alfalfa. In parts of Phillips, Yuma, and Kit Carson counties, saturated thickness declined by more than 50 feet between the 1960s and 2019 . Declining saturated thickness has directly impacted well yields—ranging from under 100 gallons per minute to over 1,900 gallons per minute—thereby affecting irrigation feasibility and land productivity (Hrozencik et al., 2017).

The region is heavily regulated due to its obligations under the Republican River Compact, an interstate agreement signed in 1942 between Colorado, Nebraska, and Kansas to equitably allocate the waters of the basin. To support compact compliance, Colorado has implemented a range of aggressive water management and conservation measures. The state created the Republican River Water Conservation District (RRWCD) in 2004 to oversee compact-related activities. The district includes eight counties and eight groundwater management districts. A key strategy has been the retirement of irrigation wells through voluntary conservation programs such as CREP and EQIP, which compensate landowners for permanently reducing groundwater consumption. Surface water rights have also been purchased and retired. Additional compliance efforts include draining Bonny Reservoir—previously used for surface water storage—to reduce Colorado's evaporative losses on the South Fork, and constructing a $60 million Compact Compliance Pipeline that began delivering water in 2014. The pipeline, fed by 58 wells limited to historic consumptive use, delivers augmentation water to the North Fork of the Republican River to ensure Colorado meets its compact obligations.

3 Conceptual Framework

Consider a simple stylized model of a producer who intends to maximize her profits after purchasing the parcel. The Lagrangian of the producer's problem can be written as:

$$L = \sum_{t=1}^{\infty} \left(\delta^t \pi(x_t, c_t(s_t)) + \lambda_t(s_{t+1} - s_t + x_t) \right)$$

where δ is the producer's discount factor, $\pi(\cdot)$ is profit at time t, which is a function of irrigation water use x_t and well capacity c_t, itself a function of saturated thickness s_t. λ_t is the shadow value of the aquifer at time t. This formulation highlights two key state variables that determine the value of groundwater: saturated thickness and well capacity. The economic value of saturated thickness arises from scarcity—reflected in the shadow value λ_t—while the value of well capacity stems from its influence on irrigation productivity and profitability (Rouhi Rad et al., 2021). Although $c_t = c(s_t)$, the relationship is empirically noisy due to variation in well technology, aquifer transmissivity, and other site-specific factors.

The producer's optimization leads to a value function representing the net present value (NPV) of agricultural returns from the parcel:

$$V = \sum_{t=1}^{\infty} \delta^t \pi(x_t, c_t(s_t)) \quad \text{subject to} \quad s_{t+1} = s_t - x_t$$

This value V is capitalized into the price of land according to the Ricardian logic of hedonic models:

$$P = f(Z_i, V_i)$$

where P is the observed land price and Z_i is a vector of other observable parcel attributes (e.g. location, improvements). Because profits depend on well capacity, which is not perfectly predicted by saturated thickness, omitting c_i from the hedonic regression can bias the estimated coefficients. Suppose the true model of land price is:

$$\log P_{it} = \beta_0 + \beta_1 c_{it} + \beta_2 s_{it} + \gamma Z_i + \varepsilon_i$$

but the estimated model omits c_{it}:

$$\log P_{it} = \tilde{\beta}_0 + \tilde{\beta}_2 s_{it} + \tilde{\gamma} Z_i + u_i$$

Then the omitted variable bias formula implies:

$$\tilde{\beta}_2 = \beta_2 + \beta_1 \cdot \frac{\text{Cov}(c_{it}, s_{it})}{\text{Var}(s_{it})}$$

Since c_{it} and s_{it} are positively correlated, when c_{it} is omitted, the estimated coefficient on s_{it} will absorb some of the variation attributable to c_{it}. As a result, $\tilde{\beta}_2$ does not cleanly identify the marginal value of aquifer but rather reflects a combined effect of both saturated thickness and well capacity. To understand this bias from an economic perspective, differentiate the value function with respect to saturated thickness:

$$\frac{dV}{ds} = \sum_{t=1}^{\infty} \delta^t \left(\frac{\partial \pi}{\partial c} \cdot \frac{dc}{ds} \right)$$

This expression makes clear that the marginal value of saturated thickness depends on its effect on well capacity. If well capacity is excluded from the regression, the estimated effect of saturated thickness implicitly assumes a fixed $\frac{dc}{ds}$ across groundwater wells, which does not reflect reality. Therefore, controlling for c is crucial to cleanly identify the value of the groundwater and the cost of aquifer depletion.

4 Empirical strategy

Hedonic models are widely used to study the demand for differentiated goods with heterogeneous characteristics (Rosen, 1974), and are particularly well-suited for valuing non-market environmental amenities and disamenities that are bundled with property and not traded separately (Chay and Greenstone, 2005; Christensen et al., 2023; Albouy et al., 2020; Li, 2023). Our model estimates the benefits of groundwater access and the value of irrigation well capacity using the following hedonic valuation approach applied to agricultural property markets in the Colorado portion of the HPA:

$$Y_{it} = \alpha \mathrm{GW}_i + \gamma ST_{it} + \theta A_i + \rho X_i + \beta \mathrm{GW} \times (\mathrm{WC}_{it}, \mathrm{ST}_{it}, \mathrm{A}_i) + \Gamma_{dt} + \epsilon_{it} \tag{1}$$

where Y_{it} is the natural log of price per acre for parcel i sold in year t. GW_{it} is a dummy variable if property i has access to groundwater (i.e., has a groundwater well) and 0 if it is not irrigated. Access at the time of transaction is important due to a well drilling moratorium that is in place. WC_{it} is the well capacity of the farm measured in gallons per minute, ST_{it} is the saturated thickness of the aquifer at the location of the well, and A_i is a vector of time-invariant aquifer characteristics that includes depth to groundwater table for each well, aquifers' hydraulic conductivity, and specific yield. The latter two variables account for the lateral speed of aquifer flow and are correlated with well capacity. X_i includes proximity to urban areas, soil quality, and the dollar value of the improvements on the parcel. Γ_{dt} is a groundwater management district (GWMD) by year fixed effect, which captures all unobserved GWMD and year-specific variations in factors that affect land values, such as unobserved shocks and policies in a given year at the GWMD level.

5 Data

We construct a dataset that links georeferenced agricultural land transactions to groundwater access characteristics for each property. Table (1) reports summary statistics for the model variables, disaggregated by irrigation status. The final sample includes 6,140 transactions across 5,125 unique properties, with 935 transactions identified as irrigated, representing 743 distinct properties with tested groundwater wells.

Table 1: Summary statistics for Irrigated and Non-Irrigated Transactions

Variable	**Description**	**Irrigated**		**Non-Irrigated**	
		Mean	SD	Mean	SD
Price	Real price per acre ($/acre)	6,383	7,337	3,088	4,996
Well capacity	Well capacity/yield (gallon per minute)	774.2	357.3	–	–
Aquifer attributes					
Saturated thickness	Saturated thickness (hundreds of feet)	147.4	75.5	80.4	69.9
Depth to water	Average depth to water	149.5	49.6	134.5	57.3
Specific yield	Aquifer specific yield	0.16	0.02	0.17	0.02
Hydraulic conductivity	Aquifer hydraulic condictivity	77.7	26.5	79.8	25.1
Other variables					
Improvements	Value of land improvements ($1000)	11.1	41	13.3	54.2
Pastureland	Dummy for pasture use	0.01	0.11	0.04	0.21
Distance to urban areas	Distance to nearest city with >10k	65.39	24.92	62.42	28.39
Clay content	Soil clay content (%)	19.2	8.4	21	8.26
Sand content	Soil sand content (%)	48.5	27.1	42.4	25.8
Silt content	Soil silt content (%)	32.1	19.5	36.3	18.7
Slope	Average slope (%)	2.6	2.1	3.5	3.6
Erodibility	K-factor	0.27	0.10	0.30	0.11
Observations		935		5,222	

Transaction data and property basics

We obtain property characteristics and historical transaction records for agricultural properties in the HPA portion of Colorado from CoreLogic's property dataset. We begin by identifying agricultural transactions using CoreLogic land use codes reported at the time of the transaction. Only parcels classified as agricultural prior to the transaction are retained. To ensure we capture genuine market activity, we exclude inter-family transactions, which are likely non-market exchanges and may not reflect fair market values, and limit our transactions to arm's-length transactions (Nolte et al., 2024) using data providers' verification indicators. Several data cleaning steps are then applied. First, we remove parcels smaller than 2 acres (likely residential plots or hobby farms) or larger than 5,000 acres (potentially federal or public lands). Next, to limit the influence of urban land markets on agricultural land values (Buck et al., 2014), we drop transactions where the real per-acre price exceeds $40,000. We also remove transactions with the price per acre being less than $200 per acre since they are the obvious outliers. Transactions are also dropped if the post-sale land use transitions out of agriculture, as these sales may reflect the value of converting agricultural water to urban uses through land developments. We further remove transactions with missing data on key characteristics, including soil variables and well capacity values. Additionally, we exclude properties with over $500,000 in improvement value (e.g., structures, buildings), as these may reflect residential or commercial influences inconsistent with agricultural valuation. Finally, we restrict the sample to transactions occurring in 1990 or later, as earlier sales data are sparse. Although our data include some sales from 2023, we exclude them because coverage only extends through the first few months of the year. Figure (1) presents the average real per-acre price of farms across different years for irrigated and non-irrigated transactions, along with the number of transactions in each year. All nominal prices are adjusted to constant 2022 dollars using the Consumer Price Index.

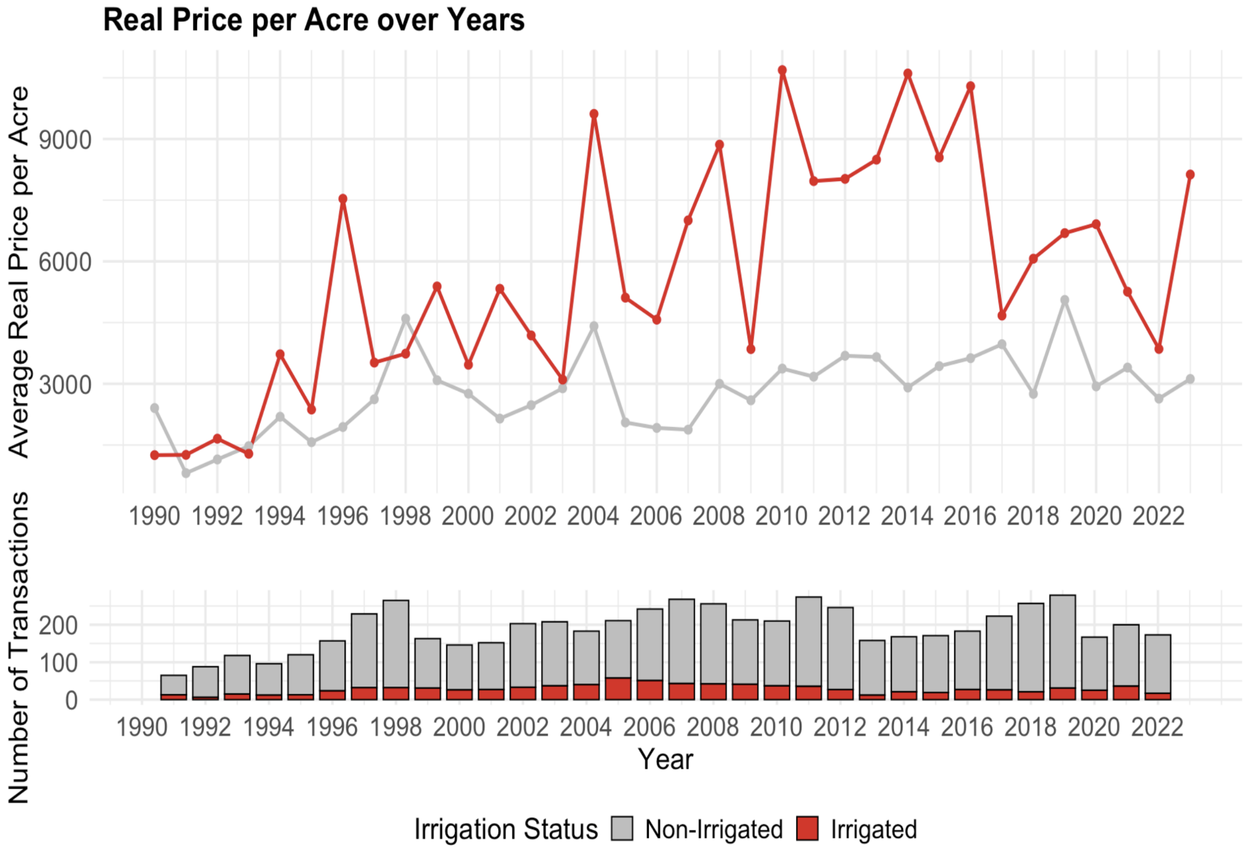

Figure 1: Average real price (in 2022 USD) per acre over time

Irrigated land

Irrigated land data and their water access attributes come from the Colorado Decision Support System (CDSS). We use the 2020 irrigated parcels dataset, which is the most recent dataset for the region. Each irrigated parcel includes information on water sources (surface water, groundwater, or both) and the water structure (e.g., ditch, well, reservoir) delivering water. There are only a handful of surface water rights still available in the basin, therefore, our analysis only studies parcels using groundwater for irrigation. Using this dataset, we identify irrigated land transactions by spatially merging CDSS irrigated parcels with CoreLogic agricultural transaction shapefiles. This allows us to link agricultural sales to their irrigation status and determine whether the transferred land had ongoing irrigation activity. Figure (2) presents a map of the property transactions included in our analysis.

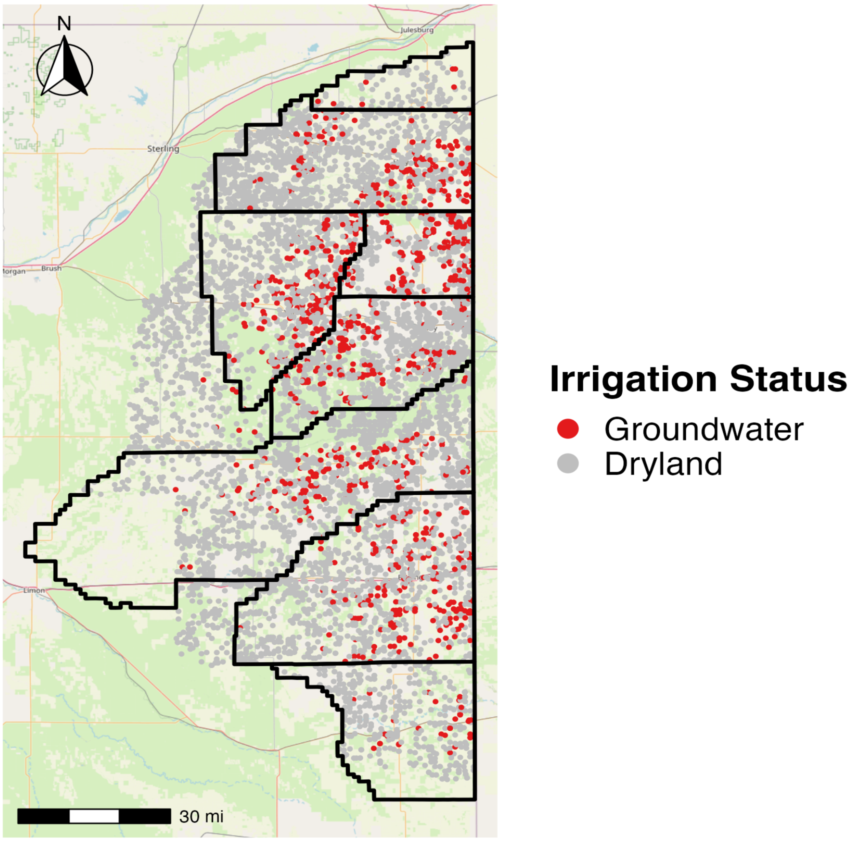

Figure 2: Irrigated and non-irrigated transactions in Republican River Basin

Well Capacity

Data on groundwater wells are publicly available through Colorado's Decision Support System (CDSS). These records include well-level information on tested pumping capacity, test dates, and annual groundwater use. Since 2009, all active high-capacity irrigation wells in our study area are required to be equipped with a totalizing flow meter or an approved alternative measurement method—most commonly the power conversion coefficient method—for conducting pump tests.

However, well capacity test data are only available from 2011 to 2016. To estimate well capacities outside this window, we exploit the panel structure of our data and predict annual well capacities using a generalized additive model (GAM) that incorporates time-varying saturated thickness and well fixed effects:

$$W\hat{C}_{it} = f(ST_{it}) + \lambda_j \tag{2}$$

where $W\hat{C}_{it}$ denotes the predicted well capacity for well i at time t, ST_{it} is the saturated thickness, $f(\cdot)$ is a smooth function estimated by the GAM, and λ_i captures well-specific fixed effects. The fitted values from the model exhibit a close match to the observed well capacity data, with narrow standard errors around the estimated fit (Figure 3). This approach allows us to impute missing well capacity values across the full sample period for use in the hedonic analysis.

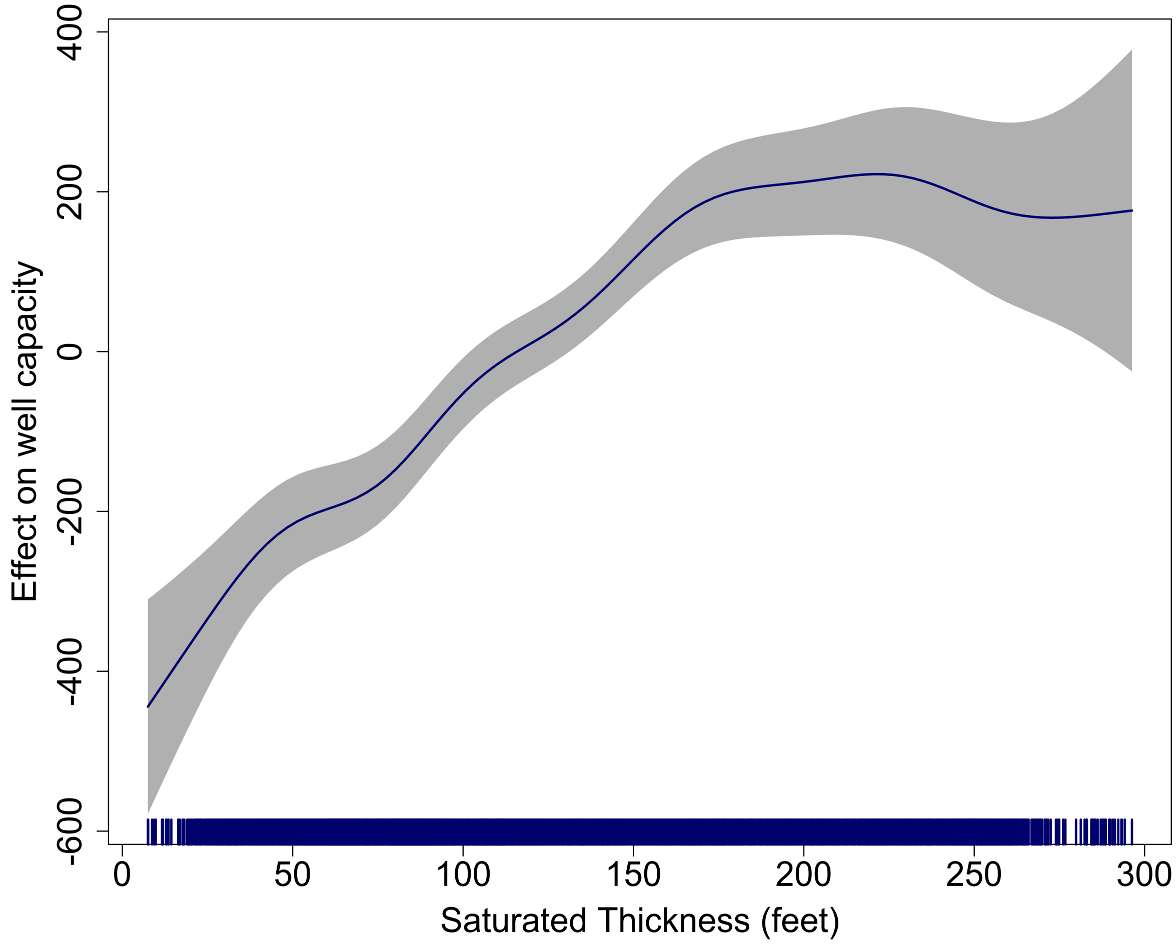

Figure 3: Non-parametric relationship between well capacity and saturated thickness

Aquifer characteristics

We incorporate several key aquifer attributes into our analysis to account for variation in groundwater availability and productivity across space and time. Saturated thickness data are obtained from Haacker et al. (2016), which provide annual estimates of the vertical thickness of the saturated portion of the aquifer from 1970 to 2016. These values are spatially and temporally matched to parcels using geographic coordinates and the year of transaction. Additional aquifer properties—specific yield, hydraulic conductivity, and depth to water table—are sourced from the U.S. Geological Survey (USGS). Specific yield reflects the fraction of water that can be drained from the saturated zone and varies across soil and geologic formations. Hydraulic conductivity measures the ease with which water can move through the aquifer material and influences both recharge and well performance. Depth to water table provides information on the vertical distance from the land surface to the groundwater, which affects the energy cost of pumping. These variables are spatially joined to parcels using GIS and serve as important controls in our regression framework to isolate the effect of groundwater access and infrastructure on land values.

Other control variables

We account for several factors that influence agricultural property prices, including whether the property is pastureland, the value of improvements, the presence and size of permanent buildings, soil quality, and proximity to major urban areas. The CoreLogic property basics dataset includes the total dollar value of land improvements and the total square footage of buildings within the property. Soil quality is controlled for using multiple variables sourced from the SSURGO database collected by the National Resources Conservation Service (NRCS). Specifically, we capture soil productivity through measures such as slope, clay, sand, and silt contents, and the soil erodibility index (k-factor).

To account for urban influence on land values, we include measures of distance to the nearest city. Specifically, we control for the distance to the nearest big city with over 5,000 residents. We obtain the geolocation and population of cities in Colorado from the U.S. Census Bureau. Distances from each property to the nearest city in each category are calculated using the R "sf" package. These variables capture the potential effects of urban expansion, market accessibility, and development pressures on agricultural land prices. Properties closer to major urban centers may have higher per-acre prices due to potential future conversion to non-agricultural uses, while those farther away may remain more insulated from urban market influences.

6 Results and Discussion

We present our main results in Table 2. Column (1) reports the estimated land value premium associated with groundwater access. The coefficient on the groundwater access dummy is positive and highly significant, suggesting a substantial capitalized value of access to irrigation. After converting the log-point estimate to percentage terms, the results imply that irrigated parcels sell for approximately 119% more than comparable dryland parcels. This corresponds to a dollar premium of about $3,600 per acre.

Column (2) adds interactions between groundwater access and underlying aquifer characteristics. The coefficient on the interaction with saturated thickness is positive and statistically significant, indicating that thicker saturated zones provide a higher irrigation premium. Specifically, the interaction term implies that a 100-foot increase in saturated thickness (conditional on groundwater access) is associated with a 25% increase in land value.

Column (3) introduces the interaction between groundwater access and well capacity, allowing us to isolate the marginal contribution of physical pumping potential. The coefficient on this interaction is also positive and economically significant, indicating that well capacity is an economically meaningful attribute of irrigated land even after controlling for saturated thickness and other aquifer characteristics. We estimate that each additional 100 gpm of well capacity raises irrigated land values by about 0.2%, corresponding to a value of approximately $127 per acre. The coefficient for the interaction term between access and

Table 2: Regression results

	Log real price per Acre		
	(1)	(2)	(3)
Groundwater access	0.796***	0.669**	0.534*
	(0.037)	(0.288)	(0.295)
Saturated thickness	0.068**	0.046*	0.046*
	(0.026)	(0.027)	(0.027)
Specific yield	0.572	0.946	0.900
	(0.547)	(0.597)	(0.597)
Hydraulic conductivity	0.001*	0.001	0.001
	(0.001)	(0.001)	(0.001)
Depth to water	−0.001**	−0.001**	−0.001**
	(0.0003)	(0.0003)	(0.0003)
GW× Saturated thickness		0.228***	0.189***
		(0.061)	(0.063)
GW× Well capacity			0.0002**
			(0.0001)
GW× Specific yield		−2.315*	−2.014
		(1.367)	(1.374)
GW× Hydraulic conductivity		0.001	0.001
		(0.001)	(0.001)
GW× Depth to water		0.001	0.001
		(0.001)	(0.001)
Improvements	0.002***	0.002***	0.002***
	(0.0002)	(0.0002)	(0.0002)
Pastureland	−0.386***	−0.400***	−0.404***
	(0.065)	(0.065)	(0.065)
Distance to cities	0.007***	0.007***	0.007***
	(0.002)	(0.002)	(0.002)
Sand content	0.017***	0.017***	0.017***
	(0.004)	(0.004)	(0.004)
Slope	0.001	0.001	0.001
	(0.004)	(0.004)	(0.004)
Erodibality	−0.988***	−1.070***	−1.071***
	(0.382)	(0.383)	(0.383)
Silt content	0.029***	0.029***	0.029***
	(0.005)	(0.005)	(0.005)
Controls	No	Yes	Yes
GWMD-Time FE	Yes	Yes	Yes
N	6,140	6,140	6,140
R^2	0.308	0.310	0.310
Adjusted R^2	0.275	0.277	0.277

Notes: ***Significant at the 1 percent level.
**Significant at the 5 percent level.
*Significant at the 10 percent level.

saturated thickness remains positive and statistically significant, but Together, these results highlight that both saturated thickness and well capacity play important and distinct roles in shaping land values.

Implication for the cost of aquifer depletion

To quantify how omitting well capacity affects estimates of the cost of aquifer depletion, we simulate the change in land values between 1990 and 2016 for 800 irrigated parcels in our sample with multiple well tests. Parcel-level saturated thickness data for both years are obtained from Haacker et al. (2016), and well capacities are predicted using Equation (2) based on a non-parametric model with well-level fixed effects.

We then estimate the change in land values due to aquifer depletion using two alternative methods. The first method considers only changes in saturated thickness, using the coefficient estimates from Column (2) of Table 2:

$$\Delta Y_1 = \gamma_1(ST_{2016} - ST_{1990})$$

The second method incorporates both changes in saturated thickness and changes in well capacity, using coefficients from Column (3) Table 2:

$$\Delta Y_2 = \gamma_2(ST_{2016} - ST_{1990}) + \beta(W\hat{C}_{2016} - W\hat{C}_{1990})$$

We find that failing to account for changes in well capacity leads to an underestimation of the economic cost of aquifer depletion. The implied downward bias in estimated value loss is approximately 11%:

$$\text{Bias } \% = \frac{\Delta Y_1 - \Delta Y_2}{\Delta Y_1} \times 100 = -11\%$$

This result indicates that studies relying solely on saturated thickness to assess the cost of groundwater depletion may significantly understate the true economic losses borne by landowners. Well capacity—capturing the productivity dimension of groundwater access—represents an essential component of the capitalized value of irrigated land. Future valuation studies and groundwater policy evaluations should incorporate both the saturated thickness and well capacity dimensions of groundwater infrastructure to more accurately estimate the cost of depletion.

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