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Understanding the interaction between groundwater salinity and irrigation decision making has important implications for groundwater management. Econometrics models were estimated using observed farmer behavior in response to different groundwater salinity levels in a region of Kansas. Estimation results demonstrate that farmers in the face of groundwater salinity change their irrigation decisions on irrigated acreage (i.e., extensive margin), crop choice (i.e., indirect intensive margin), and water application depth (i.e., direct intensive margin). The empirical results indicate an overall decrease in water use due to higher salinity, primarily through a decrease at the extensive margin.

Key words: extensive margin, groundwater salinity, intensive margin, irrigation

Introduction

Many of the most productive agricultural areas of the world, including in the United States, depend on groundwater. Dependence on groundwater for irrigation has grown rapidly over the last 20–40 years, even in areas with long dry seasons and/or regular droughts. The United Nations Food and Agriculture Organization (FAO) estimates that more than one-third of the world's irrigated lands (303 million hectares) are served by groundwater and that most irrigation in the United States (59% of its irrigated area) uses groundwater (FAO, 2019).

The value of groundwater depends on the sustainable availability of water that is of suitable quality and adequate quantity. Much attention has focused on conserving quantity through management strategies to reduce depletion of groundwater (e.g., Brozović, Sunding, and Zilberman, 2006; Merrill and Guilfoos, 2018; Quintana Ashwell, Peterson, and Hendricks, 2018), yet relatively little attention has been given to suitable quality. The likely reason for this can be attributed to the fact that the degradation of groundwater quality—-due to its hydrogeographic position—-takes a long time to be perceived by users. Even if it is noticeable, there exist difficulties in sampling and quantifying the change in quality (Suarez, 1989).

Groundwater salinity in irrigated lands is a prominent issue in groundwater quality degradation and closely aligned to an intrusion of saltwater into freshwater aquifers in the process of pumping for agricultural production (van Weert, van der Gun, and Reckman, 2009). The natural intrusion of saltwater is one reason for salinity, but excessive groundwater pumping triggers aquifer depletion and may also change the intrusion rate or flow patterns of the salinity through alterations in groundwater head (Rubin, Young, and Buddemeier, 2000). Because groundwater lateral flow is

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not instantaneous, an individual farmer's pumping decisions have the largest impact on saltwater intrusion at their well, but there is also spillover to neighboring wells. Therefore, farmers face a private incentive to avoid saltwater intrusion at their well, but the externality on neighboring wells means that farmers are unlikely to avoid saltwater intrusion in an economically efficient manner. While farmers have an incentive to reduce pumping to avoid salinity intrusion, there is also an incentive to increase the water application depth due to a washing effect to flush salts in the soils. Overall, many effects on farmer irrigation behavior are indeterminate.

Many previous studies have found evidence that elevated salinity adversely affects agricultural potential by reducing crop yields and increasing costs for salinity control (e.g., Haw, Cocklin, and Mercer, 2000; Shani and Dudley, 2001; George, Clarke, and English, 2008). The majority of the existing literature has highlighted crop responses to salinity rather than farmers' responses—-mainly in terms of reduction of crop yields. These studies presuppose that farmers make no behavioral changes to adjust to losses from groundwater salinity. This assumption, however, might overestimate the damages. The existing literature has also found that irrigation practice, current local hydrological properties, and the climate were all causes of groundwater salinity (e.g., Scanlon et al., 2007; Foster et al., 2018).

The limited economic literature examining groundwater salinity has focused on analyzing salinity control via improved irrigation efficiency and changing cropping pattern using mathematical programming approaches and calibration of crop-water production functions (e.g., Lee and Howitt, 1996; Heaney, Beare, and Bell, 2001; Schwabe, Kan, and Knapp, 2006). Some related papers have examined crop choice in the context of water/land environment and irrigation technology changes (e.g., Lichtenberg, 1989; Wu, Mapp, and Bernardo, 1994), policy or energy prices changes (e.g., Wu and Segerson, 1995; Pfeiffer and Lin, 2014b), and climate changes (e.g., Fleischer, Mendelsohn, and Dinar, 2011; Kurukulasuriya and Mendelsohn, 2008), yet few studies addressed groundwater salinity. There is a lack of econometric studies that estimate how farmers adapt to higher salinity through changes in irrigation decisions with observed behavior. Quantifying how farmers adapt to groundwater salinity has direct implications for agricultural stakeholders. These adaptations provide insights to water managers about what types of policy interventions are most likely to be effective.

Unlike the previous literature, we estimate econometric models using observed farmer behavior in response to different groundwater salinity levels in south-central Kansas. We analyze responses in terms of three main irrigation decisions: irrigated acreage, crop choice, and water application depth. In particular, we observe changes in such decisions in the context of total groundwater use and decompose them into extensive, indirect intensive, and direct intensive margin effects.

Background and Data Description

To understand how groundwater salinity impacts farmers' responses, it is necessary to provide background on the region's environmental setting. We focus on well-level decision making by constructing panel data of 1,749 unique wells during 1991–2014 from the High Plains Aquifer (HPA) in the eastern portion of Big Bend Groundwater Management District No. 5 (GMD5) underlying the Great Bend Prairie Aquifer of south-central Kansas (Figure 1).

Environmental Setting in GMD5

The eastern portion of GMD5 (outlined with the thick line in Figure 1) shows high salinity contamination in groundwater. The source of salinity is ascribed to natural saltwater intrusion from the Permian bedrock into the freshwater aquifer, called the Great Bend Prairie Aquifer. Since the Great Bend Prairie Aquifer is not effectively separated from the underlying Permian bedrock containing ancient brine (i.e., halite, known as rock salt, which is composed of sodium chloride in mineral form), saltwater in the bedrock intrudes freely into the base of the aquifer, then disperses upward in the aquifer with groundwater flow. As a result, the base of the Great Bend Prairie

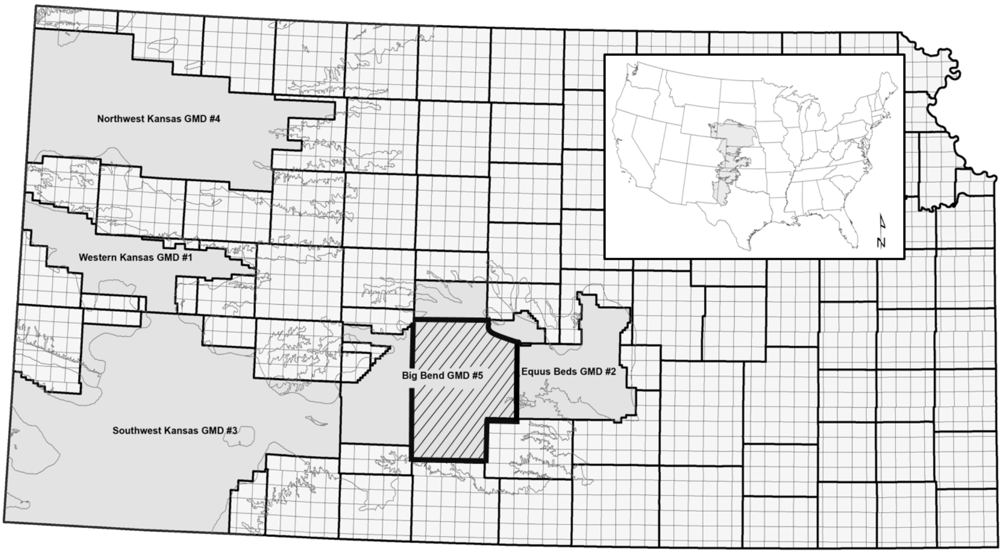

Figure 1. Map of the Kansas Portion of the High Plains Aquifer (HPA) and Study Region

Notes: The hatched lines illustrate the study region.

Aquifer shows a salinity pattern similar to Permian bedrock wells (Buddemeier, Sophocleous, and Whittemore, 1992).

The source of salinity is in the Permian bedrock, but intensive local pumping causes the water table to decline (i.e., the surface of the saturated part of the aquifer), leading to the increased upward movement of saltwater into the base of the aquifer. GMD5 in Kansas, which uses 99% of pumped groundwater for irrigated agriculture (Pfeiffer and Lin, 2014a) is expected to be particularly vulnerable to salinity during the growing season.

The slope and permeability of the aquifer results in greater salinity accumulation in the eastern portion of GMD5. The water table in GMD5 slopes downward from west to east, resulting in a west-to-east flow of the water. Thus, the depth to the water table (i.e., the distance between the altitude of the land surface and the altitude of the water table) tends to increase toward the east, and the eastern part of GMD5 becomes a discharge area for either saltwater or freshwater (Buddemeier, Sophocleous, and Whittemore, 1992). If the aquifer has a confining layer, then saltwater intrusion can be blocked. Nearly all rocks and sediments contain pores of diverse size. The fraction of the pores through which water can flow relative to the total space is called porosity. Porosity depends on the size of the soil particle—which determines soil texture—and is associated with the permeability of soils (Nimmo, 2013). That is, clay—which has low porosity and small particles—can hold water longer than sand—which has high porosity, more easily drained soils with large particles. The GMD5—which has soils that are sandier and more easily drained than those in other regions—may be more prone to exposure to saltwater intrusion due to the lack of a confining layer acting as a saltwater shield.

GMD5's salinity by natural saltwater intrusion into the freshwater aquifer gives insights to other regions like Australia, which is a naturally salty continent with limited capacity to drain salt and water. Since Australia's salinity is formed from weathering rocks, Australian agriculture is likely to share similar aspects with GMD5. Given irrigated agriculture is a major human activity often leading to secondary salinity of water resources in conditions with less water availability, farmers' responses to salinity in GMD5 help build a better understanding of other areas facing salinity challenges (e.g., California's Central Valley, other western states, and arid and semi-arid regions worldwide).

Irrigated Acreage, Crop Proportion, Depth of Water

We construct three dependent variables for three irrigation decisions: (i) the number of total irrigated acres during the water-use year (i.e., *acres_irr* in Table S1 in the online supplement, see www.jareonline.org), (ii) probability of planting each of the crops, and (iii) depth of water applied conditional on crop choice (i.e., *depth_inches* in Table S1). These dependent variables are from a unique database known as the Water Information Management and Analysis System (WIMAS) administrated by the Kansas Department of Agriculture's Division of Water Resources (KDA-DWR) and the Kansas Geological Survey. WIMAS contains spatially referenced information on groundwater wells or surface water intakes, place of use, authorized quantity, reported water use, crop type, irrigation system type, along with an identification number and information on each farmer and the well. Farmers are required by law to report this information to the KDA-DWR annually. WIMAS does not report the number of acres planted to each crop nor the water applied to each crop. Because of this, we follow Hendricks and Peterson's (2012) methodology and simply assume that if k crops were grown, the proportion for each crop was calculated as $1/k$.

Based on this methodology, we identified seven major irrigated crops commonly grown in the study region. Corn (61.46%), soybeans (20.71%), and multiple crops (16.74%) account for the majority of the seven major crops, while alfalfa (6.79%), sorghum (3.87%), wheat (6.75%), and other crops (3.40%) comprise relatively small shares of the observations. "Multiple" is defined as more than one type of crop, but the specific crops grown were not indicated by farmers. "Other" is defined as the mixed composition of oats, barley, rye, dry beans, sunflowers, orchard grass, golf course, truck farm, and nursery. To constitute a more appropriate crop choice, this paper reduces the choice to four field crops by combining alfalfa, sorghum, and wheat into "other" crops. The four field crops include corn, soybeans, multiple crops, and other crops.

Groundwater Salinity

Total dissolved solids (TDS), the sum of all the substances dissolved in water, are generally used to measure of salinity. However, in regions where chloride or sulfate predominate, either chloride or sulfate concentration can be a better measure of groundwater salinity. GMD5 mainly displays chloride-type water and hence we use the level of chloride concentration with four salinity classifications: (i) freshwater (< 500 mg/L), (ii) low to moderate (500–1,000 mg/L), (iii) moderate to strong (1,000–5,000 mg/L), and (iv) very strong (> 5,000 mg/L). The first level, called freshwater, is used as the base category. This level appears where there is no salinity or very slight natural saltwater and does not cause yield losses.

The spatial variation of salinity is obtained from image files displaying maps of chloride contours for the Permian bedrock, the base, and the upper of the unconsolidated aquifer in the eastern part of GMD5. These maps of salinity concentrations were updated in 2017 from maps generated in a previous Kansas Geological Survey report (Whittemore, 1993). The 2017 updated maps were provided to us via personal communication (D. Whittemore, Kansas Geological Suvey). The base, which has a salinity pattern similar to the bedrock, is located at the lower part of the aquifer and has a higher concentration of salt than the upper portion of the aquifer because groundwater with a greater density due to its salt content naturally sinks toward the bottom.

Our key measure of salinity that impacts farmer behavior is the measure of salinity at the base of the aquifer. Groundwater wells typically pump from the lower portions, but not necessarily the base, of the aquifer (Whittemore, 1993). Nevertheless, the degree of salinity in the base should affect farmers' pumping decisions because farmers want to avoid intrusion of the salinity into the portion of the aquifer from which their well pumps (Whittemore, 1993). Pumping more water for irrigation increases how much salinity moves upward and thereby affects how much salinity is applied to the cultivated crops and, ultimately, crop yield. Another key advantage of using the salinity in the base of the aquifer as our measure of salinity is that it is not something the farmer can control (i.e., it is exogenously determined by natural causes). Salinity of the aquifer in the upper portion is endogenous because the amount of pumping causes changes of the salinity of the upper portion.

Based on the map of chloride concentrations for the base of the aquifer, we extract attribute values by georeferencing in ArcGIS and spatially merge the data to the well. Figure S1 illustrates an original image file and a new map by georeferencing for the spatial distribution of chloride concentrations at a point in time.[1] According to Whittemore Whittemore (1993), chloride concentrations at some sites remained almost constant, some slightly decreased or increased, some noticeably decreased or increased, while others fluctuated, but most wells overall exhibit constant salinity over time. Unfortunately, the only map of chloride concentrations available from the Kansas Geological Survey was for a single point in time, so data availability constrains us from incorporating changes over time.

Soils, Hydrology, and Weather

In addition to the primary variables of interest—the four salinity levels—we use soil characteristics, hydrological properties, and weather conditions as control variables that affect irrigation decisions. Table S2 reports the means and standard deviations for these explanatory variables. Crop prices and input costs are controlled by including year fixed effects in our regression models.

Soil characteristics are collected from the Soil Survey Geographic (SSURGO) and include soil organic carbon, bulk density, the proportion of cropland with a pH less than 6 and with a pH greater than 7.5, root zone available water storage, and the log of slope. These variables were selected based on the Soil Quality Indicator Sheets from the Natural Resources Conservation Service's *Soil Health Assessment* (US Department of Agriculture, 2019) and are the same variables selected by Hendricks (2018). Soil organic carbon improves soil structure or fertility by providing energy sources for soil microorganisms and nutrient availability through mineralization, which promotes plant growth. High bulk density indicates low soil porosity and soil compaction, which restricts root growth and impedes the movement of air and water through the soil. Soil pH, a measure of soil acidity or alkalinity, is an indicator of soil health. Soil pH levels that are too high or too low cause declines in crop yields, suitability, or plant nutrient availability, resulting in soil health deterioration. For example, if the pH is less than 6 or greater than 7.5, yields for most crops decrease due to limited availability of phosphate to plants. Root zone available water storage is plant-available water-holding capacity at the root zoon depth and supports crop yield potential and stability. The slope of the land affects crop productivity in relation to soil loss (e.g., soil loss tends to increase with steep slopes). The slope variable is skewed, with a few fields highly sloped, so we use the log of slope as our control variable. This specification implies that relative differences in slope matter rather than absolute differences.

For hydrology, we use predevelopment saturated thickness obtained from the Kansas Geological Survey. Saturated thickness is the distance from the Permian bedrock to the water table, representing the amount of water available. The current level of saturated thickness is endogenous with irrigation decisions because areas with more water use have less saturated thickness. Therefore, we use predevelopment saturated thickness rather than the current saturated thickness to avoid potential endogeneity issues because predevelopment values are estimated before the withdrawal of significant amounts of groundwater. In other words, variation in predevelopment saturated thickness is driven by natural causes rather than irrigation decisions. Saturated thickness can affect water use in two different ways. First, a larger saturated thickness means that farmers can extract the water at a faster rate (i.e., a larger well capacity), which is valuable to provide water to crops during seasons with high crop water demand. Second, a larger saturated thickness means that the distance to the water table, and therefore the cost of pumping water to the surface, is smaller.

Additionally, we construct January–April and May–August growing season precipitation and May–August growing season reference evapotranspiration using daily precipitation and maximum

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[1] The original map, shown in Figure S1, contains eight categories of salinity, but not the particular salinity value for each point. We condense these eight categories into four categories for our econometric analysis.

and minimum temperatures from the PRISM climate group to represent well-level weather conditions. Reference evapotranspiration (ET_0) is defined as the loss of water from the soil (i.e., evaporation) and crops (i.e., transpiration) of a grass landcover. Therefore, high evapotranspiration causes both soil and plants to lose water faster, which impacts water use.

We do not include temperature as a separate control because temperature is embedded in the calculation of ET_0. With reference to Allen et al. (1998) and Hendricks (2018), in calculating reference ET_0, a reduced-set Penman–Monteith method that requires only maximum and minimum temperature is used as an alternative to the full Penman–Monteith method, which demands additional information on solar radiation, vapor pressure, and wind speed in addition to minimum and maximum temperature.

Conceptual Model

We consider a farmer's total water use from a well as a function of groundwater salinity, S_i. For each well i over time t, let $IA_{it}(S_i)$ denote irrigated acreage, let $C_{itj}(S_i)$ denote the proportion of irrigated acreage for each of the possible $j = 1, \ldots, J$ crop choices and let $W_{itj}(S_i)$ denote water applications depth per acre (inches per acre) for each of the possible $j = 1, \ldots, J$ crop choices. The summation of $C_{itj}(S_i) \times W_{itj}(S_i)$ constitutes average water applied per acre. Total water use is derived by multiplying the irrigated acreage by the average water applied per acre:

$$(1) \qquad \underbrace{TW_{it}}_{\substack{\textit{total}\\ \textit{water use}}} = \underbrace{IA_{it}(S_i)}_{\substack{\textit{irrigated}\\ \textit{acreage}}} \times \underbrace{\sum_{j=1}^{J} \underbrace{C_{itj}(S_i)}_{\substack{\textit{crop}\\ \textit{choice}}} \quad \underbrace{W_{itj}(S_i)}_{\substack{\textit{water}\\ \textit{application depth}}}}_{\substack{\textit{average water applied}\\ \textit{per acre}}} .$$

Differentiating each component in equation (1) with respect to S_i and multiplying by $1/TW_{it}$ in order to display the decomposition of the total water use as a percentage change in total water use due to the salinity gives

$$(2) \qquad \underbrace{\frac{\partial TW_{it}}{\partial S_i}}_{\substack{\textit{total}\\ \textit{margin}}} \frac{1}{TW_{it}} = \Bigg[\underbrace{IA'_{it} \sum_{j=1}^{J} C_{itj}(S_i) W_{itj}(S_i)}_{\substack{\textit{extensive}\\ \textit{margin}}} + \underbrace{IA_{it}(S_i) \sum_{j=1}^{J} C'_{itj} W_{itj}(S_i)}_{\substack{\textit{indirect intensive}\\ \textit{margin}}}$$

$$+ \underbrace{IA_{it}(S_i) \sum_{j=1}^{J} C_{itj}(S_i) W'_{itj}}_{\substack{\textit{direct intensive}\\ \textit{margin}}} \Bigg] \frac{1}{TW_{it}}$$

where primes denote first derivatives. Similar to Hendricks and Peterson's (2012) definitions, we refer to the first term in equation (2) as the "extensive margin" effect, the second as the "indirect intensive margin" effect, and the third as the "direct intensive margin" effect.

The extensive margin effect measures the effect of an incremental expansion in irrigated acreage holding the crop choice decision, C_{itj}, and water application depth on the crop, W_{itj}, constant. The indirect intensive margin effect is a change in water application depth per acre through a change of crop choice decision, holding total irrigated acres, IA_{it}, and water application depth on the crop, W_{itj}, constant. The direct intensive margin effect captures a change in water applied per acre through changes in the water applied on each crop choice, holding total irrigated acres, IA_{it}, and the crop choice decision, C_{itj}, constant.

Table S3 summarizes the expected sign for each of the marginal effects of an increase in salinity. Excessive pumping causes aquifer depletion, which leads to salinity intrusion in the upper parts of the aquifer. Accordingly, an increase in the level of salinity in the base of the aquifer will cause farmers to avoid future saltwater intrusion into the regions of the aquifer from which water is extracted. It is also possible that we are capturing the effect of existing salinity on crop productivity. For example, perhaps farmers irrigate fewer acres in regions with higher salinity because the salinity has already decreased crop yields.

Farmers may switch their crops due to salinity for one of two reasons. First, farmers may switch to more salt-tolerant crops to cope with higher salinity levels. Whether the switch in crops increases or decreases water use depends on whether these salt-tolerant crops are also water-intensive crops. If farmers switch to more salt-tolerant crops that happen to be less water-intensive, then pumping decreases. Alternatively, if farmers switch to more salt-tolerant crops that happen to be more water-intensive, then pumping increases. The second reason farmers may switch crops is to plant less water-intensive crops to reduce pumping and avoid future salinity intrusion. In summary, the sign of the effect of salinity on the indirect intensive margin is indeterminate.

The impact of groundwater salinity on water application depth per acre, conditional on crop choice, is expected to emerge from two different effects. On the one hand, if more water is applied, then the aquifer becomes more depleted, and salts move from the lower portions of the aquifer into the higher portions, so that pumping more means that there will be effectively more salinity in the water. Thus, farmers with greater salinity in the base of the aquifer would be induced to decrease the irrigation intensity to avoid saline groundwater application, which implies that greater salinity leads to less irrigation intensity (hereafter called "salinity intrusion effect"). On the other hand, lower irrigation intensity would lead salts to accumulate in the soil over time. In response to this, one might expect farmers to increase their irrigation intensity because the application of more water can flush out the salts in the soils (hereafter called "salinity washing effect"). Consequently, more salinity in the groundwater could lead to greater irrigation intensity. The overall impact of salinity on intensity is indeterminant because it comes down to whether the "salinity intrusion effect" or the "salinity washing effect" is larger.

Econometric Model

To estimate the decomposition for margin effects in equation (2), we exploit three econometric models, enabling us to accommodate each irrigation decision in response to groundwater salinity. In each of the models, we exploit cross-sectional variation in salinity in the base of the aquifer that arises due to natural causes after controlling for other soil, hydrology, and weather characteristics. Intuitively, our models compare wells that are overlying areas with high salinity in the base of the aquifer to similar wells overlying areas with low salinity. Our empirical strategy is analogous to that of Hornbeck and Keskin (2014), who compare outcomes in counties overlying the Ogallala Aquifer to similar counties nearby.

In panel data, observations within the panel typically share similar characteristics, thereby accounting for within-cluster correlation of the error term is needed. Not considering within-cluster dependence can lead to misleadingly narrow confidence intervals, large *t*-statistics, and low *p*-values and can be consequently misleading (Cameron and Miller, 2015). We cluster standard errors by the well. Standard errors from a spatial HAC (heteroskedastic and autocorrelation consistent) estimator are substantially smaller than clustering by the well so we choose the simpler and more conservative cluster standard errors (Cameron and Miller, 2015). Note that the consistency of our coefficient estimates does not depend on whether we include random effects (Wooldridge, 2010).

Irrigated Acreage Estimation

The regression model for irrigated acreage is

$$IA_{it} = \alpha_1 + \boldsymbol{\beta}_1 \boldsymbol{S}'_i + \boldsymbol{\gamma}_1 \boldsymbol{X}'_{it} + \theta_t + \varepsilon_{it}, \tag{3}$$

where IA_{it} are irrigated acres for each well i in year t and $\boldsymbol{S}'_i$ is a vector of indicator variables for each salinity category at each well i, as mentioned previously. The matrix $\boldsymbol{X}'_{it}$ is a vector of controls including soil organic carbon, proportion of cropland with a pH less than 6, proportion of cropland with a pH greater than 7.5, root zone available water storage, bulk density, the log of slope, saturated thickness, January–April precipitation, May–August precipitation, and May–August evapotranspiration. Soil characteristics and predevelopment saturated thickness are time invariant, but weather is time varying. The vectors $\boldsymbol{\beta}_1$ and $\boldsymbol{\gamma}_1$ are vectors of parameters to be estimated. The parameters θ_t are year fixed effects to estimate a separate parameter (i.e., intercept) for each year; they capture the effect of macro-level shocks, which affect all wells (e.g., changes in crop prices, energy prices, and other input prices). The variable ε_{it} is an idiosyncratic error term.

Crop Choices Estimation

This section describes the multinomial logit (MNL) model for crop choice, deriving the indirect intensive margin effect by salinity. The probability of selecting crop j is

$$\text{Prob}\,(C_{it} = j) = \frac{\exp\left(\alpha_2^j + \boldsymbol{\beta}_2^j \boldsymbol{S}'_i + \boldsymbol{\gamma}_2^j \boldsymbol{X}'_{it} + \sum_m \lambda_m^j C_{it-1,m}\right)}{\sum_1 \exp\left(\alpha_2^l + \boldsymbol{\beta}_2^l \boldsymbol{S}'_i + \boldsymbol{\gamma}_2^1 \boldsymbol{X}'_{it} + \sum_m \lambda_m^l C_{it-1,m}\right)}, \tag{4}$$

where $\text{Prob}\,(C_{it} = j)$ is the probability that crop j is selected at the well i in year t. The index j represents four crop choice decisions—with $j = 1, 2, 3, 4$ for corn, soybeans, multiple crops, and other crops, respectively—at different levels of salinity. The descriptions of $\boldsymbol{\beta}_2^j \boldsymbol{S}'_i$ and $\boldsymbol{\gamma}_2^j \boldsymbol{X}'_{it}$ are the same as in equation (3) because the controls used for the estimation for the irrigated acreage decision are likely to have the same effect on the crop choice decision. The variable $C_{it-1,m}$ is the proportion of the well planted to each crop in the previous year. The parameters λ_m^j denote a regression coefficient on each crop, m. The lagged crop choice decision is likely to affect each crop choice decision this year due to the crop rotation patterns.

Water Application Depth Estimation

This section estimates the two-stage least squares (2SLS) model for water application depth. In estimating the model of water application depth, one potential econometric issue is that crop choices may be potentially endogenous due to omitted variables. Intuitively, potential unobserved factors that cause crop choices can also influence the water application depth decision. Comparing water use from a well cultivating corn to another well cultivating wheat may not give a reliable estimate of the difference in water use due to crop choice (Hendricks and Peterson, 2012). Possibly some unobservable characteristics of the farmer and the well where corn is grown may have corn selected more often, and therefore more water is applied to corn relative to other crops.

To address the omitted variable bias, we use an instrumental variable estimation approach, using 1-year lagged proportions of each crop choice as the instrumental variable. The instrumental variable should affect the outcome only via its connection with the endogenous variable. We assume that the lagged crop choice affects the current crop choice due to crop rotation incentives but that the lagged crop choice does not directly affect water use in the current year. One concern with this instrumental variable is that unobserved soil characteristics that are correlated with current crop choice are also likely correlated with lagged crop choice. This could induce bias in our coefficients on crop choice.

Importantly, our main coefficients of interest are the coefficients on salinity levels, and any bias on crop choice coefficients should only impact the indirect intensive margin results.

Also, considering a just-identified model with four endogenous variables instrumented by four variables, we incorporate conditional crop choices into the 2SLS estimation with the same controls used in other econometric regression models. Specifically,

$$\left[\begin{array}{c} W_{it} = \alpha_3 + \boldsymbol{\beta}_3 \boldsymbol{S}_i' + \boldsymbol{\gamma}_3 \boldsymbol{X}_{it}' + \sum_j \delta_j \widehat{C_{itj}} + \theta_t + u_{it} \cdots \textit{2nd stage} \\ \uparrow \\ C_{itj} = \alpha_4 + \boldsymbol{\beta}_4 \mathbf{S}_i' + \boldsymbol{\gamma}_4 \boldsymbol{X}_{it}' + \sum_m \emptyset_m C_{it-1,m} + \theta_t + n_{it} \cdots \textit{ 1st stage} \end{array}\right] \tag{5}$$

where the first stage estimates the impact of salinity and other controls on each crop choice decision.

In the first-stage crop choice model, C_{itj} represents the choice of which crop is planted for each well i in year t from among four choices (i.e., corn, soybeans, multiple crops, other crops). The products $\boldsymbol{\beta}_4 \boldsymbol{S}_i'$ and $\boldsymbol{\gamma}_4 \boldsymbol{X}_{it}'$ are the same controls applied in the other econometric regression models above. The term $\sum_m \emptyset_m C_{it-1,m}$ represents 1-year lagged proportions of each crop choice and is used as an instrumental variable to account for endogeneity at the second stage.

Results

The following estimation results support our hypothesis that groundwater salinity causes farmers' decisions to change. First, we present our results on the change in irrigated acres. Then we show the impact on crop choice and depth applied. Finally, we combine the results to show the decomposition of salinity impacts on water use.

Irrigated Acreage Results

Increases in the salinity level cause a reduction in irrigated acreage from each well (Table 1). Irrigated acreage decreases by 7.8 acres at the low to moderate salinity level compared to freshwater, 18.1 acres at the moderate to strong salinity level, and 10.3 acres at the very strong salinity level. These results are all statistically significant at either the 1% or 5% level.

In particular, farmers decrease irrigated acreage by 18.1 acres for moderate to strong salinity in the base of the aquifer (1,000–5,000 mg/L), the level at which the major crops in this region begin to be affected by salinity, compared to the base category. Specifically, crop yields experience a 10% yield loss when salinity concentration of the water applied reaches 605 mg/L for corn and 1,815 mg/L for soybeans (see Fipps, 2003). As the biggest reduction, this result implies that salinity in the base of the aquifer decreases the likelihood of acreage being irrigated since salinity-induced water quality degradation may cause yield loss, leading to lower farm profitability.

We find that wells with greater predevelopment saturated thickness (i.e., greater access to water quantity) have larger irrigated acres, as expected. The other controls for soil characteristics and weather conditions are mostly statistically significant. The significance of soil and weather variables indicates that we have controlled for heterogeneity unrelated to salinity.

Crop Choice Results

The results in Table 2 indicate how a unit change in the independent variable affects the probability of each crop choice. Note that the marginal effects for a given variable sum to 0 across crops. Our results at the salinity level with very strong salinity (> 5,000 mg/L) conform to expectations, showing that salinity causes a decrease in the acreage allocated to corn by 8.9%, increase in the acreage allocated to soybeans by 3.6% and multiple crops by 7.6%, and decrease in the acreage allocated to other crops by 2.4%. The marginal effects in Table 2 for very strong salinity are statistically significant.

Table 1. Regression Model Estimates of Irrigated Acreage (N = 27,565)

Variables	Coefficients
Low to moderate salinity: 500–1,000 mg/L[a]	−7.8487** (3.4783)
Moderate to strong salinity: 1,000–5,000 mg/L[a]	−18.0520*** (3.7371)
Very strong salinity: > 5,000 mg/L[a]	−10.3458** (4.2419)
Soil organic carbon in 0–150 cm depth (kg/m^2)	−0.0034*** (0.0008)
pH < 6	20.8806** (9.2507)
pH > 7.5	−18.7007*** (7.0542)
Root zone available water storage (mm)	0.4026*** (0.0614)
Bulk density (g/cm^3)	−74.3734 (46.5760)
Predevelopment saturated thickness (ft)	0.2516*** (0.0385)
Log of slope (%)	2.7761** (1.2978)
January–April growing season precipitation (mm)	0.0580** (0.0277)
May–August growing season precipitation (mm)	0.0182*** (0.0064)
May–August growing season evapotranspiration (mm)	0.8025*** (0.1515)
Constant	−425.4112*** (127.7887)
Year fixed effects	Yes
R^2	0.1073

Notes: The dependent variable is irrigated acreage (ac). Single, double, and triple asterisks (*, **, ***) indicate statistical significance at the 10%, 5%, and 1% levels, respectively. Robust standard errors clustered at the well level are reported in parentheses.

[a] The four salinity levels are measured in chloride concentration. The base category for chloride concentration (< 500 mg/L) indicates "freshwater" for groundwater.

These results suggest that farmers facing salinity tend to substitute away from salt-sensitive corn and other crops while switching to salt-tolerant soybeans and multiple crops (see Rhoades, Kandiah, and Mashali, 1992). Overall, the coefficients in low to moderate and moderate to strong salinity levels are statistically insignificant, indicating that farmers may not be attracted to switching crops because those levels do not significantly affect yield loss.

Another interesting result comes from the coefficient on multiple crops, indicated by significant coefficients at all salinity levels, which implies that these multiple crops are more likely to be planted in the presence of salinity, compared to the other crops as the base category. This, in large measure, may show that farmers prefer a change from corn or soybeans with the single crop composition

Table 2. Marginal Effects on the Probability of Crop Choices from the Multinomial Logit Regression Model Estimates (N = 17,570)

	Marginal Effects			
Variables	**Corn**	**Soybeans**	**Multiple Crops**	**Other Crops**
Low to moderate salinity: 500–1,000 mg/L[a]	0.0141	−0.0040	0.0218*	−0.0320**
	(0.0156)	(0.0117)	(0.0107)	(0.0107)
Moderate to strong salinity: 1,000–5,000 mg/L[a]	0.0127	−0.0128	0.0244*	−0.0243
	(0.0185)	(0.0125)	(0.0109)	(0.0134)
Very strong salinity: > 5,000 mg/L[a]	−0.0885***	0.0364*	0.0757***	−0.0236
	(0.0207)	(0.0154)	(0.0169)	(0.0157)
Soil organic carbon in 0–150 cm depth (kg/m^2)	0.0000	0.0000	0.0000	0.0000
	(0.0000)	(0.0000)	(0.0000)	(0.0000)
pH < 6	0.0520	−0.0272	0.0024	−0.0272
	(0.0384)	(0.0275)	(0.0197)	(0.0328)
pH < 7.5	0.0902**	−0.0138	0.0382*	−0.1146***
	(0.0322)	(0.0225)	(0.0172)	(0.0271)
Root zone available water storage (mm)	0.0009**	−0.0004*	−0.0002	−0.0003
	(0.0003)	(0.0002)	(0.0002)	(0.0002)
Bulk density (g/cm^3)	−0.3001	0.1287	0.1155	0.0559
	(0.2428)	(0.1597)	(0.1263)	(0.1708)
Predevelopment saturated thickness (ft)	0.0041***	−0.0005***	−0.0004***	−0.0006***
	(0.0002)	(0.0001)	(0.0001)	(0.0001)
Log of slope (%)	0.0053	0.0062	0.0006	−0.0122**
	(0.0066)	(0.0048)	(0.0042)	(0.0043)
January–April growing season precipitations (mm)	0.0004	−0.0005**	0.0001	0.0001
	(0.0003)	(0.0002)	(0.0002)	(0.0002)
May–August growing season precipitations (mm)	−0.0001	0.0002***	0.0000	−0.0001
	(0.0001)	(0.0001)	(0.0001)	(0.0001)
May–August growing season evapotranspiration (mm)	−0.0006	0.0001	0.0007	−0.0002
	(0.0008)	(0.0006)	(0.0005)	(0.0006)
One-year lagged crop choice for corn	0.3528***	−0.0586***	−0.3384***	0.0443**
	(0.0195)	(0.0109)	(0.0116)	(0.0141)
One-year lagged crop choice for soybeans	0.3784***	−0.0634***	−0.2613***	−0.0536**
	(0.0201)	(0.0133)	(0.0138)	(0.0188)
One-year lagged crop choice for multiple crops	0.1212***	0.2235***	−0.2410***	−0.1037***
	(0.0215)	(0.0120)	(0.0110)	(0.0191)
Year fixed effects	Yes	Yes	Yes	Yes

Notes: The dependent variable is the probability of planting each of the crops. Marginal effects are from the multinomial logit model for crop choices. The category of "Other crops" is used as the base category. "Multiple" means multiple crops were grown, but not which crops were grown. "Other" are mixed composition of oats, barley, rye, dry beans, sunflowers, golf course, truck farm, orchard, and nursery, wheat. The pseudo-R^2 value of this model is 0.20. Single, double, and triple asterisks (*, **, ***) indicate statistical significance at the 10%, 5%, and 1% levels, respectively. Robust standard errors clustered at the well level are reported in parentheses.

[a] The four salinity levels are measured in chloride concentration. The base category for chloride concentration (< 500 mg/L) indicates "freshwater" for groundwater.

Table 3. Two-Stage Least Squares Regression Model Estimates of Water Application Depth ($N = 19{,}881$)

Variables	Coefficients
Low to moderate salinity: 500–1,000 mg/L[a]	−0.0510 (0.2067)
Moderate to strong salinity: 1,000–5,000 mg/L[a]	−0.4380** (0.2067)
Very strong salinity: > 5,000 mg/L[a]	0.1535 (0.2716)
Soil organic carbon in 0–150 cm depth (kg/m^2)	−0.0002*** (0.0000)
pH < 6	0.0732 (0.5477)
pH < 7.5	0.9202*** (0.3442)
Root zone available water storage (mm)	0.0032 (0.0039)
Bulk density (g/cm^3)	−6.0793** (2.6360)
Predevelopment saturated thickness (ft)	−0.0021 (0.0025)
Log of slope (%)	0.2508*** (0.0929)
January–April growing season precipitations (mm)	−0.0013 (0.0022)
May–August growing season precipitations (mm)	−0.0078*** (0.0006)
May–August growing season evapotranspiration (mm)	0.0323*** (0.0085)
Corn	3.4170*** (0.7109)
Soybeans	4.4373*** (1.2477)
Multiple crops	2.3505*** (0.5546)
Constant	1.5682 (7.1123)
Year fixed effects	Yes
R^2	0.2552

Notes: The dependent variable is depth of water applied (in inches), conditional on crop choice. First-stage F-statistics are 484.59 for corn, 121.86 for soybean, and 206.50 for multiple crops. These are all larger than the rule-of-thumb value of 10 suggested by Staiger and Stock (1997). Single, double, and triple asterisks (*, **, ***) indicate statistical significance at the 10%, 5%, and 1% levels, respectively. Robust standard errors clustered at the well level are reported in parentheses.

[a] The four salinity levels are measured in chloride concentration. The base category for chloride concentration (< 500 mg/L) indicates "freshwater" for groundwater.

to multiple crops with mixed crop composition. Farmers may also lower the risk of salinity by diversifying the crop composition.

Several of the marginal effects of characteristics for soil, hydrology, and weather are significant. As expected, results indicate that wells with greater predevelopment saturated thickness and available water storage in the soil are more likely to be planted with corn.

The marginal effects of the coefficients on the lagged crop choices are all statistically significant at either the 1% or 5% level despite their different statistical signs. We find that planting corn in the previous year increases the probability of planting corn in the current year by 35.3% and other crops by 4.4%, compared to the case when other crops were planted in the previous year. Planting corn in the previous year also decreases the probability of planting soybeans by 5.9% and multiple crops by 33.8%, compared to previously planting other crops. Planting soybeans in the previous year increases the probability of planting corn in the current year by 37.8% but decreases the acreage allocated to all other alternatives (i.e., 6.3% decrease for soybeans, 26.1% for multiple crops, and 5.4% for other crops).

Water Application Depth Conditional on Crop Choice Results

Table 3 presents parameter estimates from the 2SLS model for water application depth. We have hypothesized that there are two potentially opposing effects on water application depth per acre: intrusion effect and washing effect. The intrusion effect would lower irrigation intensity to avoid increasing water salinity, while the washing effect would increase irrigation intensity to wash salinity out of the root zone.

Reduction in water application depth is most pronounced at the moderate to strong salinity level (1,000–5,000 mg/L). At this level, salinity reduces irrigated groundwater application by 0.4 inches relative to the base category of freshwater. This reflects that the salinity intrusion effect dominates the washing effect. The effect is not statistically significant at the low to moderate salinity level (500–1,000 mg/L), possibly because salinity at this level does not lead to crop yield loss; accordingly, there may be minimal need to adjust water application depth to reduce intrusion or to increase the washing effect. At the highest levels of salinity (> 5,000 mg/L), the effect is statistically insignificant, potentially because the intrusion and washing effects are roughly the same magnitude at a higher level of salinity.

The coefficients for water demand conditional on the choice of crop indicate that soybeans use the most water in this region, followed by corn and multiple crops. Also, crop choice results in the previous section indicated that farmers tend to switch from corn to soybeans, which are more salt tolerant, as salinity increases. Considering these two results together implies that farmers switch to more salt-tolerant crops that happen to be more water intensive, leading to increased pumping.

Weather controls all have the expected signs. An increase in precipitation during the May–August growing season results in a decrease in depth applied and an increase in evapotranspiration demand increases depth applied. Less water is applied to wells with a high bulk density since the soil is less permeable to absorb water when bulk density is larger. More water is also applied to wells with greater slope.

Marginal Effect Decomposition Results

Table 4 reports total marginal effect of an increase in the groundwater salinity decomposed into the extensive and intensive margins measured in acre-inches, acre-feet, and the relative impact. We compute each decomposed component using coefficients and predicted values from each econometric model in Tables 1–3, according to equation (2).

The extensive margin effect shows that farmers reduce irrigated acres in the face of groundwater salinity and the result is statistically significant. The indirect intensive margin effect shows that farmers increase water use due to groundwater salinity through switching to more salt-tolerant

Table 4. Total Margin Effect and Decomposition into Extensive, Indirect Intensive, and Direct Intensive Margin Effects

Margin Effects	Extensive	Indirect Intensive	Direct Intensive	Total
Low to moderate salinity: 500–1,000 mg/L				
Measured in inches	−100.4628**	8.6447	−5.3887	−97.2068**
	(42.7553)	(5.3603)	(22.0922)	(49.0433)
Measured in acre-feet	−8.3719**	0.7204	−0.4491	−8.1006**
	(3.5629)	(0.4467)	(1.8410)	(4.0869)
Measured in relative impact	−0.0740**	0.0064	−0.0040	−0.0716**
	(0.0315)	(0.0039)	(0.0163)	(0.0361)
Moderate to strong salinity: 1,000–5,000 mg/L				
Measured in inches	−231.0650***	4.6262	−46.2598**	−272.6985***
	(49.5855)	(6.1222)	(21.2415)	(56.2060)
Measured in acre-feet	−19.2554***	0.3855	−3.8550**	−22.7249***
	(4.1321)	(0.5102)	(1.7701)	(4.6838)
Measured in relative impact	−0.1703***	0.0034	−0.0341**	−0.2009***
	(0.0365)	(0.0045)	(0.0157)	(0.0414)
Very strong salinity: > 5,000 mg/L				
Measured in inches	−132.4258**	3.9298	16.2156	−112.2804*
	(57.9772)	(11.8844)	(27.7702)	(67.4128)
Measured in acre-feet	−11.0355**	0.3275	1.3513	−9.3567*
	(4.8314)	(0.9904)	(2.3142)	(5.6177)
Measured in relative impact	−0.0976**	0.0029	0.0119	−0.0827*
	(0.0427)	(0.0088)	(0.0205)	(0.0497)

Notes: Single, double, and triple asterisks (*, **, ***) indicate statistical significance at the 10%, 5%, and 1% levels, respectively. Robust standard errors clustered at the well level are reported in parentheses. Robust standard errors are estimated using a cluster bootstrap with 400 replications.

crops that happen to be more water-intensive. Yet the indirect intensive margin is not statistically significant. The direct intensive margin effect at the moderate to strong salinity level (1,000–5,000 mg/L) shows a statistically significant decrease in water use, indicating that farmers in the face of groundwater salinity respond by reducing water application depth to avoid inducing saltwater intrusion.

The estimated total margin effect of salinity at the low to moderate salinity level (500-1,000 mg/L) illustrates that salinity of this level reduces total water use by 97.2 acre-inches (8.1 acre-feet) relative to a well with access to freshwater. Average water use in the sample period was 1,357.1 acre-inches (113.1 acre-feet), so the relative impact is a 7.2% decrease in water use compared to freshwater. The total margin effect of salinity at the moderate to strong salinity level (1,000–5,000 mg/L) indicates that salinity at this level reduces total water use by 272.7 acre-inches (22.7 acre-feet) relative to a well with access to freshwater. The relative impact is a 20.1% decrease in water use compared to freshwater. The estimated total margin effect of salinity at very strong salinity (> 5,000 mg/L) demonstrates that salinity of this level reduces total water use by 112.3 acre-inches (9.4 acre-feet) relative to a well with access to freshwater. The relative impact is an 8.3% decrease in water use compared to freshwater.

Farmers facing salinity challenges primarily change their water use through changes at the extensive rather than at the intensive margin. At the low to moderate salinity level (500–1,000 mg/L), farmers reduce water use by 7.4% at the extensive margin, with a total decrease in water use of 7.2%

compared to freshwater. At the moderate to strong salinity level (1,000–5,000 mg/L), farmers reduce water use by 17.0% at the extensive margin, with a total decrease in water use of 20.1%. Similarly, the extensive margin dominates the reduction in water use when the groundwater is very strong salinity.

In general, where farmers face water availability constraints, high water usage, or water quality degradation, farmers reduce water use by lowering irrigation water applications or irrigated acreage and shifting to less water-intensive crops (Schwabe, Kan, and Knapp, 2006; Drysdale and Hendricks, 2018; Gollehon, Quinby, and Aillery, 2003). Among these mechanisms, reducing irrigated acreage can fundamentally reduce water consumption. That said, the reduction in irrigated acreage reduces the need for irrigation water itself. Foster, Brozović, and Butler (2014) support this by finding that farmers reduce irrigated acreage rather than water use intensity once well capacities become sufficiently constraining (i.e., a constraint in water quantity). Our estimates show that farmers adjust mostly at the extensive margin to reduce the amount of water extracted to avoid inducing intrusion of salt into the upper aquifer, which would harm water quality.

We provide two different robustness checks in the online supplement. First, we exclude crop controls from the depth applied equation (Tables S4 and S5). This allows us to avoid using lagged crop choice as an instrument but only allows us to estimate an overall intensive margin effect rather than direct and indirect intensive margin effects. Overall, the results are similar when excluding crop choice so none of our main results are affected by potential endogeneity of lagged crop choice. Second, we show results when we model the effect of salinity on total water in a reduced form model (Table S6). Impacts on total water use are similar to the results reported in Table 4.

Conclusions

Farmers face difficult decisions, such as whether and how much to irrigate, what to plant, and how much water to apply. Multiple factors can influence this decision making, including the natural environment, water supply, global markets, and government programs. Our study tests the hypothesis that groundwater salinity may be an important driver of farmers' irrigation decision making. To test this hypothesis, we estimate econometric models using observed farmer behavior in response to different groundwater salinity levels based on well-level panel data in south-central Kansas.

There are a couple of limitations of our study that are important to acknowledge. First, we measure salinity at the base of the aquifer rather than in the upper portions of the aquifer to avoid endogeneity problems where irrigation decisions impact salinity concentrations. Therefore, the concentration levels do not reflect the concentration levels of water actually being pumped for irrigation. These same salinity concentration levels would likely have much larger impacts on irrigation decisions if they were naturally occurring in the upper portions of the aquifer. Second, our estimates likely suffer from attenuation bias due to measurement error in salinity. The salinity measures are interpolated so they are not a perfect measure at each well. Therefore, we are likely to underestimate (i.e., bias toward zero) the impact of salinity concentrations on irrigation decisions.

Our results support the hypothesis that farmers in the face of groundwater salinity change their decisions on irrigated acreage, crop choice, and water application depth. We find that farmers reduce water use along the extensive margin by reducing irrigated acres in response to groundwater salinity. Farmers increase water use along the indirect intensive margin by switching to more salt-tolerant crops that happen to be more water intensive, though the effect is small and statistically insignificant. Farmers decrease water use along the direct intensive margin by reducing water application depth conditional on the same crops to avoid inducing saltwater intrusion. This result shows that the salinity intrusion effect dominates the salinity washing effect. The overall impact of an increase in salinity is a decrease in water use, predominantly through changes at the extensive margin.

There are at least a few important implications of our result that farmers adjust their irrigation behavior to reduce saltwater intrusion. First, our results suggest that there are likely economic gains from coordinated management to reduce salinity intrusion. The fact that farmers adjust their behavior to avoid intrusion is evidence that there are economic costs of salinity intrusion. Slow lateral flows of the aquifer create private incentives to reduce intrusion and our results indicate that these private incentives are large enough to affect irrigation behavior. However, we also know from hydrology that salinity intrusion will eventually affect nearby farmers as well. If farmers are only acting independently to mitigate intrusion, then they are likely to exert too little effort due to the classic free-rider problem arising from sharing a common aquifer. Therefore, our results support policy initiatives that would reduce water use to reduce salinity intrusion. Estimating the magnitude of the economic benefits of coordinated management is an important topic for future research.

Second, our results indicate that these policy initiatives should focus on either reducing total water use or reducing water use at the extensive margin. One approach is to support local governance approaches that limit total water use (see Drysdale and Hendricks, 2018). However, local governance has had only limited success in Kansas (Perez-Quesada and Hendricks, 2021). Government intervention has tended instead to focus on incentivizing technologies to reduce irrigation intensity (Pfeiffer and Lin, 2014a; Li and Zhao, 2018) or water right retirement (Tsvetanov and Earnhart, 2020; Manning et al., 2020). Our results indicate that water right retirement to reduce irrigated acres would be a more cost-effective approach since this is how farmers mostly respond to the private incentives.

Third, our results indicate that policy makers and researchers should increase their emphasis on water quality and not just water quantity in the High Plains Aquifer. There is a need for greater data collection on salinity conditions (Stanton et al., 2017). There is also a need for more research to quantify the economic impacts of salinity and optimal management approaches to achieving sustainability in terms of both quantity and quality.

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Online Supplement: Irrigation Decisions in Response to Groundwater Salinity in Kansas

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Table S1. Mean and Standard Deviation for Dependent Variables

	Dependent Variables	Mean	SD
Irrigated acreage	Irrigated acres (ac) i.e., *acres_irr*	105.4714	52.0769
	Proportion for corn	0.5036	0.4817
	Proportion for soybeans	0.1713	0.3521
Crop choice	Proportion for multiple crops	0.1379	0.3448
	Proportion for other crops	0.1873	0.3623
Water application depth	Volume of water applied measured in acre-feet (ac-ft) i.e., *af_used*	113.0883	72.3639
	Depth of water applied measured in feet (ft) i.e., *depth_feet = (af_used/acres_irr)*	1.0694	0.4278
	Depth of water applied measured in inches (in) i.e., *depth_inches = (af_used/acres_irr)*12*	12.8333	5.1335

The material contained herein is supplementary to the article named in the title and published in the *Journal of Agricultural and Resource Economics* (*JARE*).

Table S2. Mean and Standard Deviation for Explanatory Variables

	Explanatory Variables	**Mean**	**SD**
Four salinity levels[a]	Freshwater: <500 (mg/L)	0.6324	0.4821
	Low to moderate salinity: 500-1,000 (mg/L)	0.1354	0.3421
	Moderate to strong salinity: 1,000-5,000 (mg/L)	0.1421	0.3492
	Very strong salinity: >5,000 (mg/L)	0.0901	0.2863
Soil characteristics	Soil Organic Carbon in 0-150 cm depth (kg/m2)	6541.4460	2653.9180
	pH less than 6	0.0351	0.1466
	pH greater than 7.5	0.1265	0.2431
	Root zone available water storage (mm)	206.5541	32.4031
	Bulk density (g/cm3)	1.5294	0.0348
	Log of slop (%)	0.5385	1.0110
Hydrological properties	Predevelopment saturated thickness (ft)	128.8869	34.2058
Weather conditions	January-April growing season precipitations (mm)	154.5996	60.5895
	May-August growing season precipitations (mm)	389.0493	123.9330
	May-August growing season evapotranspiration (mm)	655.1060	38.2282

Notes: [a] The four salinity levels are measured in chloride concentration. The base category for chloride concentration (< 500 mg/L) indicates “freshwater” for groundwater.

Table S3. Expected Effects on Farmer Behavior in response to Groundwater Salinity

Margin of Adjustment		Expected Effects
Irrigated acreage	Extensive (negative sign)	More pumping causes more depletion of the aquifer, thereby increasing saltwater intrusion from the lower portions of the aquifer into the higher portions of the aquifer, leading to greater salinity of water that is extracted from the aquifer. Consequently, farmers seek to reduce irrigated acres to reduce pumping that leads to intrusion.
Crop choice	Indirect Intensive (negative sign)	Farmers switch to more salt-tolerant crops that happen to be less water-intensive, leading to reduced pumping, or farmers switch to less water-intensive crops to reduce salinity intrusion.
	or	
	Indirect Intensive (positive sign)	Farmers switch to more salt-tolerant crops that happen to be more water-intensive, leading to increased pumping.
Water application depth	Direct Intensive (negative sign) “Salinity intrusion effect”	More pumping causes more depletion of the aquifer, thereby increasing saltwater intrusion from the lower portions of the aquifer into the higher portions of the aquifer. This gives an incentive to reduce water application to avoid increasing water salinity.
	or	
	Direct Intensive (positive sign) “Salinity washing effect”	Increasing irrigation intensity can flush the salts out of the soil and prevent the accumulation of salts in the soil over time.

Original image	Newly georeferenced map

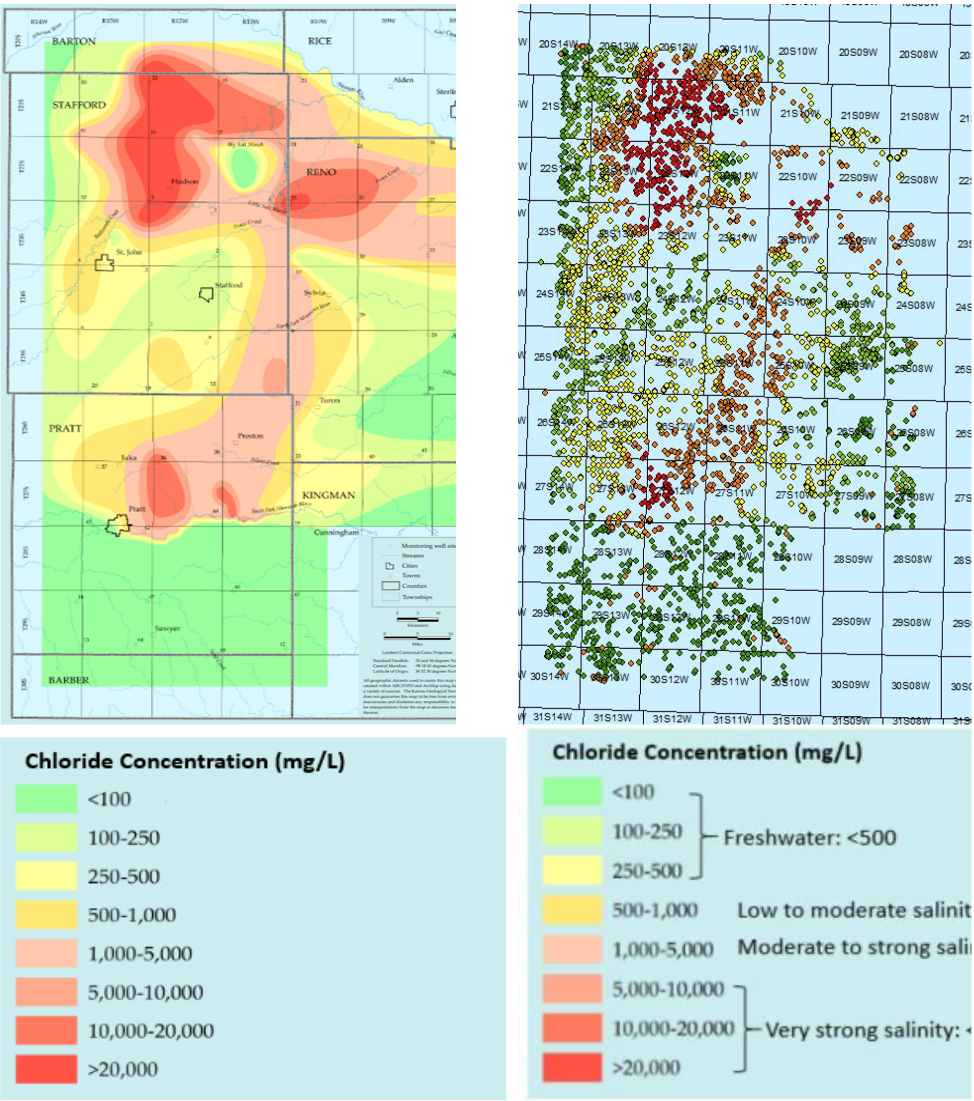

Figure S1. Maps displaying chloride contours for the base of the unconsolidated aquifer in the eastern part of GMD5

Notes: Points on the map denote groundwater points of diversion.

S1. Robustness check - excluding crop choice

In our main specification, the lagged crop choice variables are included in the crop choice model and they are also included as instruments for crop choice in the model with depth applied as the dependent variable. A concern is that endogeneity of the lagged crop choice could bias our estimates. Unfortunately, finding a good instrument can be very difficult. As we mentioned in the manuscript, lagged crop choice is a strong. Conley et al. (2012) note that bias can be smaller when using an instrument with a strong first-stage that has some violation of the exclusion restriction. Hence, we think lagged crop choice is the best available option to measure the salinity impact for water application depth conditional on crop choice.

To check the robustness of our results, another approach that we explore is to not explicitly model crop choice as a function of salinity. In other words, we estimate how salinity impacts irrigated acres and depth applied but do not include crop choice as a control so we do not need to use lagged crop choice as an instrument. This alternative approach allows us to estimate the extensive margin, the overall intensive margin, and the total effect of salinity. However, it does not allow us to estimate how much of the intensive margin was due to changes in crop choice.

Total water use when excluding crop choice is defined as:

(S1)
$$\underbrace{TW_{it}}_{\substack{total\\water\ use}} = \underbrace{IA_{it}(S_i)}_{\substack{irrigated\\acreage}} \times \underbrace{W_{it}(S_i)}_{\substack{water\\application\\depth}}$$

Differentiating each component in equation (S1) with respect to S_i and multiplying by $1/TW_{it}$ in order to display the decomposition of the total water use as a percent change in total water use due to the salinity gives:

(S2)
$$\underbrace{\frac{\partial TW_{it}}{\partial S_i}}_{\substack{total\\margin}} \frac{1}{TW_{it}} = \left[\underbrace{IA'_{it} W_{it}(S_i)}_{\substack{extensive\\margin}} + \underbrace{IA_{it}(S_i) W'_{it}}_{\substack{intensive\\margin}} \right] \frac{1}{TW_{it}}$$

Table S4 shows the regression coefficients for the depth applied equation that does not include crop choice as control variable. Table S5 shows the decomposition of the marginal effects. In general, the results in Table S5 are similar to the results from the main manuscript. Therefore, even though there could be some concerns about endogeneity of lagged crop choices, it does not have any substantial effect on our main conclusions from the study.

Table S4. Regression Model Estimates of Water Application Depth when Excluding Crop Choice Controls

Variables	Coefficients
Low to moderate salinity: 500-1,000 (mg/L)[a]	-0.3935*
	(0.2247)
Moderate to strong salinity: 1,000-5,000 (mg/L)[a]	-0.6111***
	(0.2080)
Very strong salinity: >5,000 (mg/L)[a]	-0.2188
	(0.2751)
Soil Organic Carbon in 0-150 cm depth (kg/m^2)	-0.0002***
	(0.0000)
pH less than 6	-0.0905
	(0.5964)
pH greater than 7.5	0.6726*
	(0.3506)
Root zone available water storage (mm)	0.0051
	(0.0038)
Bulk density (g/cm^3)	-6.8706**
	(2.8643)
Predevelopment saturated thickness (ft)	0.0016
	(0.0023)
Log of slope (%)	0.2208**
	(0.1003)
January-April growing season precipitations (mm)	-0.0000
	(0.0022)
May-August growing season precipitations (mm)	-0.0082***
	(0.0006)
May-August growing season evapotranspiration (mm)	0.0298***
	(0.0092)
Constant	8.7875
	(7.7773)
Year fixed effects	Yes
R^2	0.2200
Observations	23,577

Notes: Single, double, and triple asterisks (*, **, ***) indicate statistical significance at the 10%, 5%, and 1% levels, respectively. Robust standard errors clustered at the well level are reported in parentheses. The dependent variable is depth of water applied (in inches).

[a] The four salinity levels are measured in chloride concentration. The base category for chloride concentration (< 500 mg/L) indicates “freshwater” for groundwater.

Table S5. Total Margin Effect and Decomposition into Extensive and Overall Indirect Intensive Margin Effects when Excluding Crop Choice

Salinity Levels	Margin Effects	Extensive	Intensive	Total
Low to Moderate 500-1,000 (mg/L)	Measured in Inches	-100.2350***	-41.5590*	-141.794***
		(31.1800)	(21.3680)	(45.2480)
	Measured in Acre-Feet	-8.3529***	-3.4633*	-11.8162***
		(2.5983)	(1.7807)	(3.7707)
	Measured in Relative Impact	-0.0739***	-0.0306*	-0.1045***
		(0.0230)	(0.0157)	(0.0333)
Moderate to Strong 1,000-5,000 (mg/L)	Measured in Inches	-230.541***	-64.543**	-295.0840***
		(73.1160)	(26.1000)	(78.4480)
	Measured in Acre-Feet	-19.2118***	-5.3786**	-24.5903***
		(6.0930)	(2.1750)	(6.5373)
	Measured in Relative Impact	-0.1699***	-0.0476**	-0.2174***
		(0.0539)	(0.0192)	(0.0578)
Very Strong >5,000 (mg/L)	Measured in Inches	-132.126***	-23.1110	-155.2370***
		(36.612)	(20.9690)	(50.2480)
	Measured in Acre-Feet	-11.0105***	-1.9259	-12.9364***
		(3.0510)	(1.7474)	(4.1873)
	Measured in Relative Impact	-0.0974***	-0.0170	-0.1144***
		(0.0270)	(0.0155)	(0.0370)

Notes: Single, double, and triple asterisks (*, **, ***) indicate statistical significance at the 10%, 5%, and 1% levels, respectively. Robust standard errors clustered at the well level are reported in parentheses. Robust standard errors are estimated using a cluster booststrap with 400 replications.

S2. Robustness Check – Modeling Total Water Use

Table S6 shows the result of a regression model where the dependent variable is the total water application depth measured in acre-feet. The effect on total water use in acre-feet compared to freshwater is as follows: -12.001 for low to moderate salinity, -23.612 for moderate to strong salinity, and -12.171 for very strong salinity (>5,000 mg/L), respectively. These results are similar to the total marginal effect in acre-feet in table 4 in the main paper. Therefore, we confirm that the impact of salinity is similar when using a reduced-form model for total water use.

Table S6. Regression Model Estimates of Total Water Use

Variables	Coefficients
Low to moderate salinity: 500-1,000 (mg/L)[a]	-12.0006***
	(4.2246)
Moderate to strong salinity: 1,000-5,000 (mg/L)[a]	-23.6123***
	(4.4304)
Very strong salinity: >5,000 (mg/L)[a]	-12.1706**
	(5.0977)
Soil Organic Carbon in 0-150 cm depth (kg/m^2)	-0.0052***
	(0.0009)
pH less than 6	19.7199*
	(11.0421)
pH greater than 7.5	-13.1640*
	(7.9697)
Root zone available water storage (mm)	0.4569***
	(0.0695)
Bulk density (g/cm^3)	-131.4137**
	(55.5146)
Predevelopment saturated thickness (ft)	0.2502***
	(0.0463)
Log of slope (%)	5.2477***
	(1.6043)
January-April growing season precipitations (mm)	0.0494
	(0.0352)
May-August growing season precipitations (mm)	-0.0520***
	(0.0083)
May-August growing season evapotranspiration (mm)	1.1513***
	(0.1770)
Constant	-516.0866***
	(147.8875)
Year fixed effects	Yes
R^2	0.1700
Observations	27,565

Notes: Single, double, and triple asterisks (*, **, ***) indicate statistical significance at the 10%, 5%, and 1% levels, respectively. Robust standard errors clustered at the well level are reported in parentheses. The dependent variable is total water use measured in acre-feet.

[b] The four salinity levels are measured in chloride concentration. The base category for chloride concentration (< 500 mg/L) indicates "freshwater" for groundwater.

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