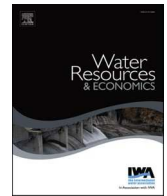




Contents lists available at ScienceDirect

Water Resources and Economics

journal homepage: www.elsevier.com/locate/wre

Groundwater quality vs. groundwater quantity. Combining information on irrigator concerns with past water use and cropping behavior.

Grant Gardner^a, Gabriel S. Sampson^{b,*}^a Department of Agricultural Economics, University of Kentucky, USA^b Department of Agricultural Economics Kansas State University, USA

ARTICLE INFO

Keywords:

Irrigation
Water scarcity
Water quality
Perceptions
Survey
High plains aquifer

ABSTRACT

The effectiveness of groundwater in fulfilling crop water deficits depends on its quality and quantity. This paper examines the relationship between irrigators' stated concerns over groundwater quality and groundwater quantity and their past water use and cropping decisions. Information on irrigator concerns over groundwater quality and quantity is obtained from 626 survey responses of agricultural producers in the Kansas portion of the High Plains Aquifer. We combine 20 years of field-level water use and cropping data with each of the 626 survey responses. We find that irrigators indicating elevated concern over either groundwater quality or groundwater quantity correlates with less total water use, fewer total irrigated acres, and fewer acres of irrigated corn. Additionally, concerns over groundwater quantity generally correlate with a greater reduction in water use along multiple water use margins compared to equal concerns over groundwater quality.

1. Introduction

Irrigated crop production expanded rapidly in major crop-producing regions of the US during the 20th century [1,2]. However, a combination of weak governance, increasing water demand, and limited aquifer stocks has given rise to widespread questioning of the future viability of irrigated crop production for many of the groundwater basins in the US and elsewhere [3,4].

Previous work has examined the effects of water scarcity [5–8] and water quality [9,10] on irrigation behavior. However, it remains unclear whether irrigator perceptions of groundwater quantity and quality accurately align with real-world agricultural outcomes. For instance, evidence from drinking water [11] and outdoor recreation [12–14] suggest that perceptions of water quality may not accurately reflect objective measures of water quality. If irrigation choices are made based on perceptions, then such information is important to include in irrigation demand models. However, studies linking perceptions of water characteristics to water use behaviors are largely limited to the household drinking water [15–18,52] and outdoor recreation [19] literature.

In this paper, we examine how groundwater quality and quantity perceptions correlate with three measures of past agricultural irrigation behavior. Specifically, we examine correlations between irrigators' stated concerns and their behavioral history of water use and cropping decisions using a combination of survey data and field-level irrigation and cropping data for the Kansas portion of the High Plains Aquifer (HPA). We hypothesize that irrigators develop a level of concern over water quality or quantity through indicators

* Corresponding author.

E-mail addresses: grant.gardner@uky.edu (G. Gardner), gsampson@ksu.edu (G.S. Sampson).

such as well depth measurements, well pumping rates, water quality testing, crop yield impacts, or information exchange. The irrigator's level of concern is thus hypothesized to be linked to observed irrigation behavior.

Our empirical analysis draws on two primary datasets. First, we obtain information on stated levels of concern over the quality and quantity of local groundwater from a survey of 626 irrigators conducted in 2020. Second, we obtain field-level irrigation water use and cropping data for the years 2000–2019 from the Water Information Management and Analysis System (WIMAS) of the Kansas Division of Water Resources (DWR). We examine three margins of irrigation behavior: (i) total water use, (ii) the total number of irrigated acres, and (iii) the number of irrigated acres planted to corn. We match the field-level irrigation and cropping data to information obtained from the surveys on an irrigator-by-irrigator basis.

We detect a pattern where irrigators indicating elevated concern over groundwater quality or groundwater quantity tend to use less water overall, irrigate fewer total acres, and irrigate fewer acres of corn. Additionally, we find that concerns over groundwater quantity generally correlate with a greater reduction in water use along all water use margins compared to equal concerns over groundwater quality. Thus, issues of water quantity appear to be more impactful to irrigators than issues of water quality. This finding is consistent with previous estimates of irrigator willingness to pay for improvements in water quantity (e.g. Ref. [20]) and quality (e.g. Ref. [21]).

This paper makes two contributions. First, we directly compare concerns over water quality to concerns over water quantity by examining a rich set of field-level irrigation outcomes. Previous studies estimate irrigator response to predicted water quality [9,10] and pumping constraints presented by physical conditions (e.g., Ref. [22–24]) or regulations (e.g., Ref. [6,7,25]). Our findings provide insights linking irrigator perceptions to water use outcomes along multiple margins that are useful to water managers tasked with designing conservation and reclamation policies given stated concerns of their constituents.

Second, we establish a link between stated concerns over two measures of irrigation water attributes and past irrigation outcomes. Hypothetical bias is a prevalent concern in studies deploying survey techniques, whereby respondents indicate information that is not indicative of their real-world behaviors ([26] provides a review). Given a general lack of competitive water markets where attributes of irrigation water can be directly valued, researchers must frequently rely on survey techniques that indirectly reveal values. While we do not attempt to estimate willingness to pay, our findings do provide evidence that irrigator perceptions of their groundwater quality and groundwater quantity accurately reflect past outcomes that are likely to affect producer well-being through returns to crop production.

2. Background

The HPA spans eight states, but the largest portions overlie Texas, Kansas, and Nebraska. On average, the Kansas portion of the HPA supplies water to 2.6 million irrigated acres each year [27]. Using the relative difference in market value between irrigated and non-irrigated land, Edwards et al. [28] estimate that the HPA has contributed \$3.5 billion toward agricultural land values in western Kansas. However, decades of pumping that exceed the rate of recharge have led to speculation that future irrigated crop production in some parts of the HPA will not be possible without changes to groundwater management [29].

Groundwater for irrigation in Kansas is governed by a system of prior appropriation rights first established by the Kansas Water Appropriation Act of 1945. Any producer seeking to irrigate must first apply for a permit from DWR. Once granted, the permit defines the annual volume of water that may be pumped, the number of acres that can be irrigated, the location of the irrigation well, the

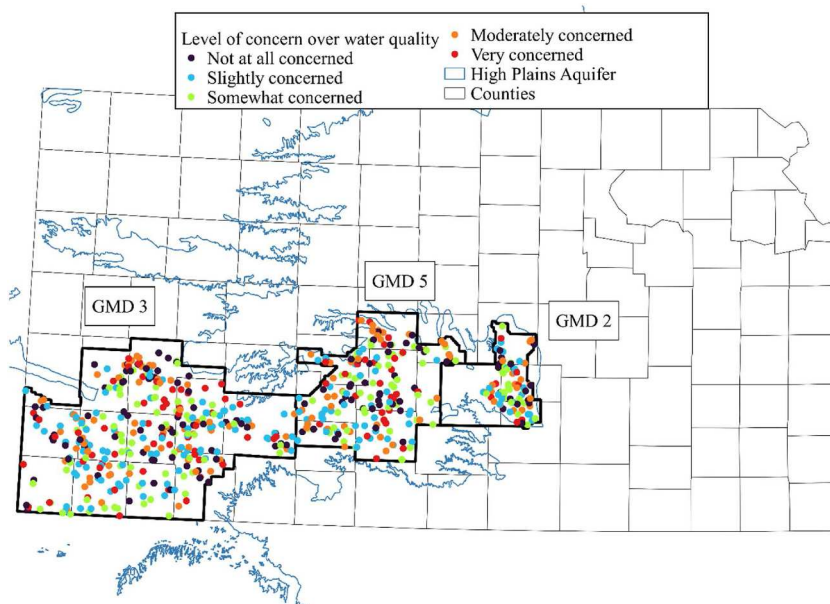


Fig. 1. Map of survey respondents and stated level of concern over irrigation water quality.

location where water may be applied (i.e., field), and the priority date of the permit (i.e., seniority ranking). In 1972, the Kansas Legislature authorized the Kansas Groundwater Management Districts Act, which led to the formation of five Groundwater Management Districts (GMDs). Fig. 1 provides a map of GMDs 2, 3, and 5, which are the focus of our study. Each GMD has the power to set local water governance and provide water use planning subject to the approval of the Chief Engineer of DWR.

Groundwater quality of the Kansas HPA has deteriorated in three ways. First, nitrogen and agricultural chemicals have entered the aquifer via leaching [30]. Secondly, the salt content of the aquifer has increased via intrusion of brackish waters from oil well drilling and water intrusion from saline surface waters such as the Arkansas River, which crosses portions of GMDs 3 and 5 [31,32]. Third, rapid withdrawals have accelerated upward movement of saline water present in the underlying geologic formations [10,33]. Using a survey of 622 irrigators in western Kansas, Gardner et al. [21] find that over 20 % of respondents indicated “moderate” or “major” perceived impacts of deteriorated groundwater quality on their crop yields.

Depletion of the HPA is a widespread concern among managers, irrigators, and the scientific community [3]. Steward et al. [34] estimate that recharge supports only 15 % of current pumping activity in the Kansas HPA. In a survey of 205 irrigators located in the Colorado and Nebraska portions of the HPA, Suter et al. [35] find an average level of concern over future groundwater availability ranging between “slightly concerned” and “moderately concerned.”

The water quality research most related to this study are the works of Haw et al. [9] and Lee and Hendricks [10]. Haw et al. [9] survey perceptions of irrigation-induced soil salinity amongst farmers in the Trugowel Plains of Australia. Haw et al. [9] find that farmers are relatively less responsive to localized threats of resource degradation and relatively more responsive to chronic degradation at regional scales. Lee and Hendricks [10] estimate the impact of predicted groundwater quality on total water use, irrigated acres, and application depth in Kansas GMD 5. They find that irrigators located in areas with higher predicted chloride salt levels tend to irrigate fewer acres and use less water. However, Lee and Hendricks [10] do not gather information on irrigator awareness or perception of salinity threats to irrigated production.

3. Materials and methods

We obtain data from a variety of sources in estimating correlations between past irrigation behavior and stated concerns over groundwater quality and quantity. A summary of the different levels of concern along with irrigation outcomes are presented in Table 1. A summary of irrigation water use, planting, and all remaining data for groups responding and not responding to the survey are presented in Table 2. We describe each data source used in the regression models in detail below.

3.1. Survey data

The main variables of interest for this study are obtained from a mail survey sent to 3924 irrigators located in GMDs 2, 3, and 5 in Kansas (Figs. 1 and 2). Mailing addresses for 3924 registered holders of agricultural water rights in GMDs 2, 3, and 5 were obtained from DWR. We focus on GMDs 2, 3, and 5 because prior research has identified these as potential regions of deteriorated groundwater quality [10,36]. Advanced postcards were mailed on March 4, 2020. The full survey was mailed on March 10 and 11, 2020. A follow-up postcard was mailed on March 23, 2020. Of the 3924 surveys mailed out, 308 were returned as undeliverable. A total of 626 useable surveys were returned out of the 3616 delivered, for a response rate of 17 %. The survey contained questions on the perceived impact of groundwater quality on the respondent’s cropping practices and farm outcomes.

Of particular focus are two questions in the survey targeting the irrigator’s level of concern over groundwater quality and quantity. The first question of interest asked, “To what extent are you concerned about irrigation water quality in your area?” Response options were based on a five-point Likert scale, which included options for “not at all concerned,” “slightly concerned,” “somewhat concerned,” “moderately concerned,” and “very concerned.” The second question of interest asked, “To what extent are you concerned about well yields for irrigation wells in your area?” Response options were based on the same five-point Likert scale. The question on well yields was designed to capture concern about groundwater quantity, as measured by well yields. Well yields, which have been shown to affect irrigator behaviors and agricultural outcomes, measure the upper limit on the volumetric rate of water withdrawal and are typically modeled as a nonlinear function of the saturated thickness of the aquifer [22,51]. Additional details of the mail survey are documented in Gardner et al. [21].

3.2. Irrigation and cropping data

Information on annual water use, acreage, cropping decisions, and irrigation technology (e.g., flood, pivot) is obtained from WIMAS. As previously mentioned, a water right is necessary to irrigate in Kansas. One challenge to using the WIMAS data is that two or more water rights may spatially overlap in the location of the well or field. Because of this potential overlap, we aggregate water use and acreage up to the level of a “water right group.” The water right group is thus defined as the smallest legal combination of field and well location such that no two water right groups share a common field or well location (Earnhardt and Hendricks [7] provide an illustration in their appendix).

Correspondence information (i.e., mailing address) is obtained from WIMAS for the entity filing the annual water use reports. This information links the mailing address to the water right. Using the mailing address, we then link the survey information to the water right group. It is common in Kansas for an entity to hold multiple water rights, creating the potential for multiple water right groups to be linked to a single correspondent. We assign the survey information to all water right groups held by a common mailing address. In total, we match the 626 completed surveys to 1642 water right groups. Thus, each respondent in our sample holds 2–3 water right

Table 1

Count of different levels of concern over water quality and water quantity along with average water use.

<u>Level of concern over water quality</u>	<u>Count</u>	<u>Water use (acre-ft)</u>	<u>Total acres</u>	<u>Corn acres</u>
Not at all concerned	123	347.78	311.87	133.34
Slightly concerned	150	299.71	263.03	97.38
Somewhat concerned	134	275.20	227.10	84.93
Moderately concerned	125	259.29	237.39	87.16
Very concerned	85	301.60	258.69	95.24
<u>Level of concern over water quantity</u>				
Not at all concerned	90	388.69	338.95	155.85
Slightly concerned	105	292.08	270.10	89.31
Somewhat concerned	103	294.02	247.74	86.70
Moderately concerned	145	284.27	252.85	100.90
Very concerned	178	257.34	219.43	80.97

Table 2

Summary statistics and test of mean differences for survey respondents and non-respondents.

Variable	<u>Respondents</u>		<u>Non-Respondents</u>		<u>Difference</u>
	<u>N</u>	<u>Mean (se)</u>	<u>N</u>	<u>Mean (se)</u>	
Total water use	29,952	291.222 (2.641)	143,278	265.711 (1.222)	25.511***
Acres irrigated	29,952	250.424 (2.102)	143,278	223.037 (0.746)	27.388***
Irrigated corn acreage	29,952	102.638 (1.222)	143,278	91.703 (0.395)	10.935***
Annual authorized volume	29,952	492.890 (4.138)	143,278	430.328 (1.507)	62.562***
Annual authorized acreage	29,952	329.909 (2.761)	143,278	287.338 (0.997)	42.571***
Center pivot technology	29,952	0.116 (0.002)	143,278	0.131 (0.001)	−0.015***
Combined center pivot with drop nozzle	29,952	0.064 (0.001)	143,278	0.052 (0.001)	0.013***
Drop nozzle technology	29,952	0.700 (0.003)	143,278	0.714 (0.001)	−0.014***
Other technology	29,952	0.060 (0.001)	143,278	0.044 (0.001)	0.016***
Degree days between 10C and 34C	29,952	2359.01 (0.772)	143,278	2361.56 (0.342)	−2.551***
Water deficit	29,952	24.026 (0.046)	143,278	23.749 (0.022)	0.277***
Degree days over 34C	29,952	21.246 (0.087)	143,278	21.247 (0.040)	−0.002
Saturated thickness	29,952	152.106 (0.533)	143,278	147.619 (0.247)	4.487***
Hydraulic conductivity	29,952	83.083 (0.153)	143,278	84.793 (0.066)	−1.710***
Depth to water	29,952	112.522 (0.541)	143,278	113.698 (0.257)	−1.176*
Electricity price	29,952	21.132 (0.012)	143,278	21.137 (0.005)	−0.004
Natural gas price	29,952	6.164 (0.012)	143,278	6.162 (0.005)	0.002
Diesel price	29,952	17.880 (0.037)	143,278	17.890 (0.017)	0.010
Slope	29,952	2.000 (0.015)	143,278	2.194 (0.008)	−0.194***
Total clay	29,952	22.165 (0.055)	143,278	22.163 (0.026)	0.002
Total silt	29,952	35.595 (0.117)	143,278	35.467 (0.054)	0.128

Note: measurements averaged over 2000–2019.

groups on average.

The WIMAS data provides annual field-level information on the amount of water used, the number of acres irrigated, the type of crop(s) planted, and the irrigation technology used. In Kansas, irrigation is regularly applied to five cash crops: corn, soybean, alfalfa, sorghum, and wheat. Irrigated corn generally provides the greatest net return per acre [37] but also has a low salinity tolerance. In

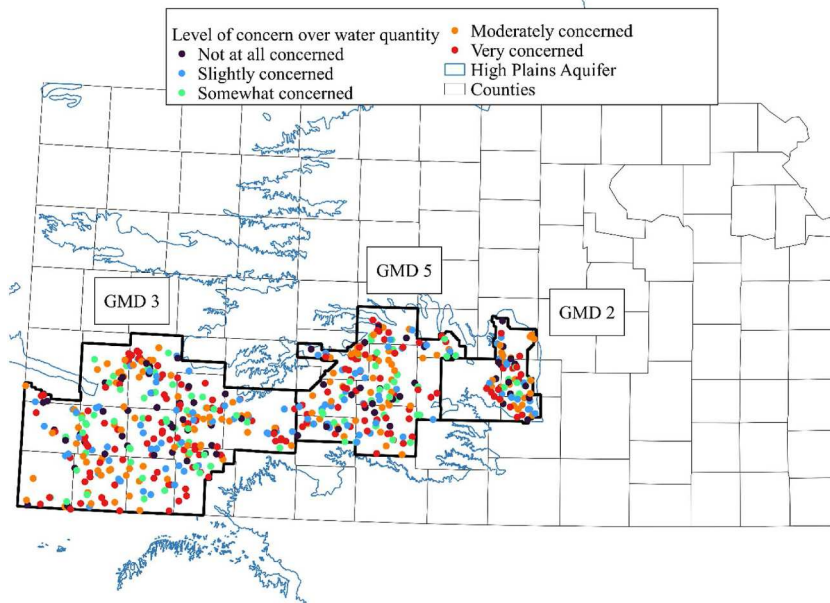


Fig. 2. Map of survey respondents and stated level of concern over irrigation water quantity.

some cases, multiple crop types are indicated for a single field in WIMAS. However, the WIMAS data does not specify the number of acres within the field planted to each crop type. We assume that if $n > 1$ crop types are indicated for a given field, then the proportion of the field used for each crop type is $\frac{1}{n}$. Double cropping is indicated for less than 3 % of the observations in the WIMAS data. However, WIMAS does not indicate which crops are double cropped, so we omit this category.

We focus our analysis on three irrigation outcomes: total water use, total irrigated acreage, and corn irrigated acreage. Table 1 and Fig. 3 present summary information for these three outcomes for each of the five concern categories on the survey. We match WIMAS data for the years 2000–2019 to the survey information. Thus, we obtain up to 20 years of irrigation and cropping data prior to the survey being sent to irrigators.¹ In total, we obtain 29,952 water right group-year observations.

3.3. Hydrology

We include measures of aquifer saturated thickness and depth to water as independent variables in the regressions. These data are derived from a set of 1002 monitoring wells operated by the Kansas Geological Survey as described in Sampson et al. [38]. Winter well measurements are obtained for the years 1990–2020. A 3-year average is computed for each monitoring well at 5-year intervals. We spatially interpolate water table elevations using inverse distance weighting for each of the 5-year intervals. The resulting data is clipped to Public Land Survey System (PLSS) sections, which are then merged to the WIMAS data. Years between the 5-year intervals are imputed using linear interpolation. We also obtain information on hydraulic conductivity from the Kansas Geological Survey.

3.4. Climate

Weather data are obtained from PRISM at the grid cell level. We construct three climate variables: the number of degree days between 10C and 34C during the growing season (April–September), the number of degree days above 34C during the growing season, and a measure of the growing season water deficit, which we define as the difference between reference evapotranspiration and precipitation. Reference evapotranspiration is calculated using the method described in Hargreaves and Samani [39]. The PRISM data are linked to PLSS sections which are then merged to the WIMAS data.

3.5. Soils

Soils characteristics are obtained from the SSURGO soil survey of the USDA Natural Resource Conservation Service. The SSURGO map units are merged to the WIMAS data at the PLSS section. These characteristics include land slope and total soil texture classified as clay or silt. Soil texture in SSURGO is classified as either clay, silt, or sand. We exclude sand to avoid perfect collinearity. We choose these independent variables to control for drainage and water storability on irrigated lands.

¹ While development of water rights slowed after 1980 due to basin closures, there are still some newly developed water rights observed post-2000 [54]. For rights that were developed post-2000 we include irrigation and cropping data for 2019 back to the year the right was perfected.

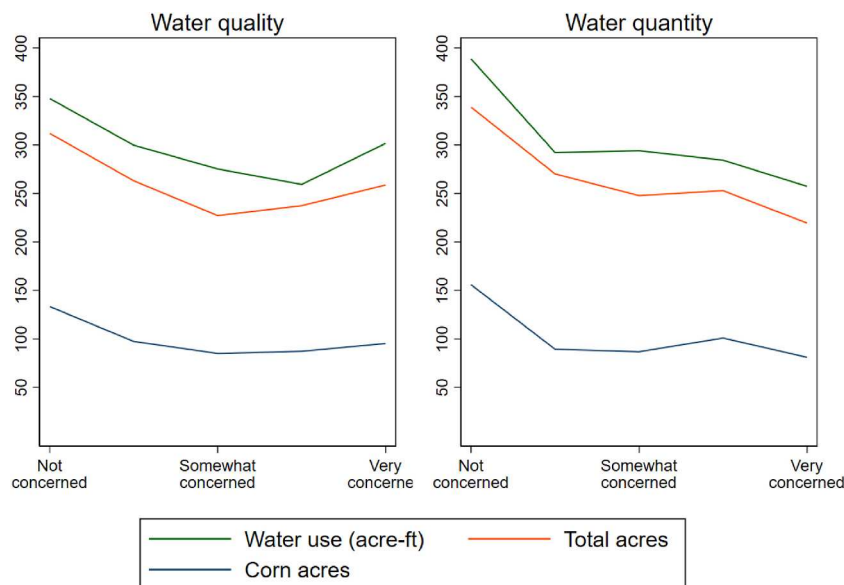


Fig. 3. Average total water use, total irrigated acres, and corn irrigated acres by level of concern over water quality (left) and water quantity (right). Note: axis labels for “slight concern” and “moderate concern” are hidden due to space.

3.6. Energy prices

The WIMAS data do not indicate energy sources. Irrigation pumping plants in GMDs 2, 3, and 5 use diesel, electricity, and natural gas [40]. We obtain annual bulk diesel prices from the Nebraska Energy Office. We obtain annual industrial-sector electricity and natural gas price information for Kansas from the Energy Information Administration. All energy prices are converted to dollars per million btu and are adjusted to 2019 dollars using the Consumer Price Index. Correlations between the prices for the three energy sources are less than 0.7 in absolute magnitude. Following Brill and Burness [50], Burness and Brill [41], Hendricks and Peterson [42], and Quintana Ashwell et al. [43], we conceptualize pumping cost as a function of energy prices and lift height.

3.7. Summary statistics and analysis

Our regression analysis contains 29,952 water right group-year observations for 1642 water right groups. The data span the years 2000–2019. Table 2 presents a balance table of mean values for water right groups responding to the survey and water right groups not responding. Tables A1–A3 present this information for each GMD specifically.

While our survey was sent to the full population of water right groups in GMDs 2, 3, and 5, there are some differences in mean characteristics for water right groups that chose to respond to the survey relative to those that did not. On average, groups that responded to the survey use more water (291 acre-ft vs. 266 acre-ft), irrigate more acreage (250 acres vs. 223 acres), and possess greater annual authorized allowances for pumping volume and acreage from DWR. There are also differences in irrigation technology, with respondents less likely to use conventional center pivot or drop nozzle, but more likely to use combined center pivot with drop nozzle. Respondents, on average, have greater saturated thickness and depth to water. Thus, we cannot say that our survey sample strictly represents all groundwater irrigators in GMDs 2, 3, and 5.

We also estimated a linear probability model of participation, where we regressed an indicator for survey response on average annual water use, total aquifer depletion from 2000 to 2019, a dummy variable for whether there were two or more filers for the annual water use reports to DWR during 2000–2019, and GMD dummies (see Table A4 in the supplementary appendix). Net of the GMD effects, we do not detect any evidence of average water use, aquifer depletion, or change in filer being a statistically significant predictor of survey participation.

Table 1 and Fig. 3 present summary measures of the three irrigation outcomes for each of the five concern categories. We observe a pattern where total water use, total irrigated acres, and irrigated corn acres decline as the level of concern over water quality or water quantity increases. For groundwater quality, the average for the “very concerned” response amounts to 46 acre-ft less water use than the average for “not at all concerned” (i.e., a 13 % reduction). For groundwater quantity, the average for the “very concerned” response amounts to 131 acre-ft less water use than the average for the “not at all concerned” (i.e., a 34 % reduction).

We also examine how differences in water use behavior across water right groups having different levels of concern evolve through time in Figs. A1–A3. For total irrigated acres and corn irrigated acres, we observe some evidence that the differences between water right groups having “no concern” and elevated levels of concern have been growing over time (Figs. A2 and A3). In contrast, we do not observe any clear evidence of a trend in either direction for total water use (Fig. A1).

As mentioned above, water rights in Kansas are limited in their annual volumes and acreage allowances by DWR. One potential

concern is that irrigators who indicate elevated concern over groundwater quality or quantity were systematically granted lower total water and acreage allowances when their water rights were perfected with DWR. This scenario would produce spurious correlation between irrigation outcomes and indicated level of concern. We explore this possibility by conducting one-way analysis of variance of annual authorized water use and irrigated acreage by each category of concern for groundwater quality and quantity for the water right groups participating in the survey. In short, we do not obtain any statistically significant evidence that the average authorized water use and acreage is different across the five categories of concern for water right groups who participated in the survey.

Table 1 and Fig. 3 provide preliminary evidence of elevated water quality and water quantity concerns correlating with past water use and cropping decisions. Our regression analysis in the next section will provide a more detailed estimate of these correlations.

3.8. Empirical approach

We hypothesize that concerns over groundwater quality and quantity can be formed in three ways. First, irrigators may directly observe changes over time to their well yields or crop yields that are indicative of groundwater quantity or quality issues, respectively. Such observations might influence which crops they choose to plant, the number of acres they irrigate, or their total water use. Second, irrigators might conduct testing (either themselves or via a technician) of the chemical quality of the water in their wells or the volumetric flow rates of their wells. Third, concern over groundwater quality or quantity may arise from information dissemination through irrigator peer networks, extension presentations, interactions with crop consultants, or irrigation equipment suppliers. Previous research has documented peer networks affecting adoption rates of irrigation technologies in Kansas [1], so it seems intuitive that information on groundwater quality or quantity might be similarly exchanged over such networks.

Irrigators have several adaptation strategies available when problems of groundwater quality are present. Two of these options relate to water irrigation depth: reducing the depth of water applied to limit salt accumulation in the soil or, conversely, over-applying irrigation to move salts past the root zone, defined as the ‘intrusion’ and ‘washing’ effects respectively by Lee and Hendricks [10]. A third strategy is to reduce the number of acres irrigated. The producer could then irrigate different portions of their acreage over time to mitigate the presence of salts across their total managed land area. The fourth strategy is for the producer to plant fewer acres to crops that are sensitive to low water quality. Of the prominent cash crops in Kansas, corn is the most water intensive and the most sensitive to salinity [44].

With respect to well yield, irrigators again have different adaptation strategies available. First, irrigators can reduce the number of acres they irrigate. With low well yields, irrigators may not be able to fully meet crop water demand across the entire field. Decreasing the number of acres irrigated is expected to attenuate this problem [23]. Second, irrigators may choose or be forced to reduce the irrigation depth. Third, irrigators can adjust away from water-intensive crops such as corn [22,23,51,53].

Using the suite of possible adaptation strategies described above, we develop three testable hypotheses:

Hypothesis 1. Irrigators indicating concern over groundwater quality or quantity have a history of lower total irrigated acreage.

Hypothesis 2. Irrigators indicating concern over groundwater quality or quantity have a history of lower irrigated corn acreage.

Hypothesis 3. Total irrigation water use is a product of total acreage and depth of water applied. Using this logic and following Hypothesis 1, irrigators indicating concerns over groundwater quantity have a history of lower total water use. Conversely, the opposing “intrusion” and “washing” adaptation strategies to water quality could either increase or decrease past total water use.

3.9. Estimating equations

We use regressions to estimate correlations between the five categories of concern over groundwater quality and quantity and the three irrigation outcomes: total water use (W_{it}), total irrigated acreage (A_{it}), and corn irrigated acreage (C_{it}). Regression models for each of the three irrigation outcomes are specified as functions of irrigation technology, marginal pumping cost, hydrologic factors, soil factors, weather characteristics, and concern over groundwater quality and quantity. We estimate the following models:

$$W_{it} = \beta_1^W \text{quality}_i + \beta_2^W \text{quantity}_i + \mathbf{x}_{it}\boldsymbol{\theta}^W + \mathbf{z}_i\boldsymbol{\alpha}^W + \lambda_g^W + \tau_{g,t}^W + e_{it} \quad (1)$$

$$A_{it} = \beta_1^A \text{quality}_i + \beta_2^A \text{quantity}_i + \mathbf{x}_{it}\boldsymbol{\theta}^A + \mathbf{z}_i\boldsymbol{\alpha}^A + \lambda_g^A + \tau_{g,t}^A + e_{it} \quad (2)$$

$$C_{it} = \beta_1^C \text{quality}_i + \beta_2^C \text{quantity}_i + \mathbf{x}_{it}\boldsymbol{\theta}^C + \mathbf{z}_i\boldsymbol{\alpha}^C + \lambda_g^C + \tau_{g,t}^C + e_{it} \quad (3)$$

where quality_i and quantity_i are categorical variables for the stated level of concern for groundwater quality and groundwater quantity for water group i , respectively. Additionally, $\mathbf{x}_{it}$ is a vector of observable characteristics that vary over time for each water right group (e.g., weather, hydrology), and $\mathbf{z}_i$ is a vector of characteristics that vary over water right groups but do not vary through time (e.g., soils). Spatial dummy variables, λ_g , are included at the GMD-level to control for unobserved heterogeneity in water governance and agronomic conditions that might exist between GMDs and affect irrigation outcomes. GMD by year dummies, $\tau_{g,t}$, are included to control for unobserved spatio-temporal factors influencing irrigation outcomes (e.g., commodity prices). With GMD and GMD-year dummies specified, the effect of quality or quantity concern on irrigation outcomes is obtained through cross-sectional variation in survey responses within a GMD. Controlling for unobserved differences that are stable across GMDs is important because GMDs in Kansas are empowered to set rules regarding groundwater use that might affect irrigation behavior and irrigator concerns [45,46].

We estimate equations (1)–(3) as a multivariate regression. As we are only able to exploit cross-sectional variation in levels of concern and lack an obvious instrument, we are unable to make any claims about causal relationships between stated levels of concern and irrigation behavior. Thus, we view the results of this study as correlational rather than strictly causal.

4. Results and discussion

The results of estimation of equations (1)–(3) for the key variables of interest are presented in Table 3. Column 1 provides the change in total water use for irrigators indicating “slightly concerned,” “somewhat concerned,” “moderately concerned,” or “very concerned” responses to groundwater quality and quantity relative to water right groups indicating “not concerned at all.” Column 2 reports estimates for total irrigated acreage. Column 3 reports estimates for corn irrigated acreage. The full set of regression coefficients, including the controls, are provided in Table A5 of the supplementary appendix.

4.1. Groundwater quality

We first focus on regression results relating to groundwater quality. Looking across the columns of Table 3, we find strong evidence of elevated groundwater quality concerns correlating with all three measures of past irrigation outcomes. We find that concerned water right groups use less total water per year on average than water right groups that have no concern. Specifically, irrigators indicating “slightly,” “somewhat,” “moderately,” or “very” concerned use on average about 49.8, 32.2, 37.4, and 29.0 acre-ft less water per year than irrigators indicating “not at all concerned,” respectively. Thus, somewhat surprisingly, irrigators indicating “slightly concerned” use the least amount of water per year on average. Table 4 shows pairwise comparisons amongst all the concern categories. Using pairwise comparisons, we find that the differences in marginal effects between “slightly” and all other categories are statistically significant at 0.10 or better. The pairwise difference in the remaining marginal effects are not statistically significant.

Looking next at the total irrigated acreage effect, we observe negative and statistically significant coefficients on all levels of concern relative to no concern, in support of Hypothesis 1. Specifically, irrigators indicating “slightly,” “somewhat,” “moderately,” or “very” concerned irrigate 33.8, 28.4, 26.3, and 13.1 fewer acres per year than irrigators indicating “not at all concerned,” respectively. Again, somewhat surprisingly, the coefficient on “very concerned” is the smallest in magnitude relative to no concern. Examining Table 4, the pairwise difference between “very concerned” and all other levels of concern is statistically significant at 0.05 or better. The pairwise differences between the remaining categories for total acreage are not statistically significant. By comparison, Lee and Hendricks [10] estimate that a predicted chloride concentration in the base of the aquifer in excess of 5000 mg/L correlates with a 10 acre decrease in irrigated acres when compared to the base case (<500 mg/L), which is close in magnitude to our estimated acreage reduction for the “very concerned” category.

Looking next at corn irrigated acreage, we observe that irrigators having elevated concern over groundwater quality tend to irrigate fewer corn acres per year on average relative to irrigators that have no concern. Specifically, irrigators indicating “slightly,” “somewhat,” “moderately,” or “very” concerned irrigate 31.2, 28.6, 21.1, and 21.4 fewer acres of corn per year than irrigators indicating “not at all concerned,” respectively. These results support Hypothesis 2 that irrigators concerned over groundwater quality adapt by planting fewer acres to saline sensitive crops. Again, the pattern of acreage reduction is not necessarily monotonic across concern categories. Using pairwise comparison of the average marginal effects in Table 4, we find statistically significant differences between “slightly concerned” and “moderately concerned” and “very concerned” at 0.01 or better. Likewise, the pairwise difference between “somewhat concerned” and “moderately concerned” and “very concerned” is statistically significant at 0.01. By comparison, Lee and

Table 3

Regression results for total water use, total acres, corn acres, and depth of water applied.

	Total water use (acre-feet)	Total acres	Corn acres
<u>Water quality concern level</u>			
Slightly concerned	−49.806*** (6.545)	−33.820*** (5.571)	−31.211*** (3.754)
Somewhat concerned	−32.209*** (6.517)	−28.423*** (5.137)	−28.551*** (3.595)
Moderately concerned	−37.348*** (7.865)	−26.287*** (6.126)	−21.045*** (3.700)
Very concerned	−29.011*** (7.457)	−13.140** (6.068)	−21.438*** (4.216)
<u>Water quantity concern level</u>			
Slightly concerned	−47.661*** (11.863)	−18.450* (9.817)	−29.064*** (6.499)
Somewhat concerned	−68.050*** (11.520)	−51.077*** (9.486)	−37.360*** (6.528)
Moderately concerned	−44.601*** (10.908)	−34.541*** (8.992)	−25.605*** (6.298)
Very concerned	−69.675*** (11.541)	−59.063*** (9.493)	−50.645*** (6.570)
Observations	29,952	29,952	29,952
R-squared	0.182	0.164	0.070

Table 4

Pairwise comparisons between all concern categories.

	Total water use	Total acres	Corn acres
	Water quality		
Slightly concerned			
vs. somewhat concerned	−17.597***	−5.397	−2.660
vs. moderately concerned	−12.458***	−7.533	−10.167***
vs. very concerned	−20.796***	−20.680***	−9.773***
Somewhat concerned			
vs. moderately concerned	5.139	−2.136	−7.507***
vs. very concerned	−3.198	−15.283***	−7.113**
Moderately concerned			
vs. very concerned	−8.338	−13.149**	0.394
	Water quantity		
Slightly concerned			
vs. somewhat concerned	20.390***	32.627***	8.296***
vs. moderately concerned	−3.060	16.091***	−3.459
vs. very concerned	22.014***	40.613***	21.581***
Somewhat concerned			
vs. moderately concerned	−23.450***	−16.536***	−11.755***
vs. very concerned	1.625	7.986	13.285***
Moderately concerned			
vs. very concerned	25.074***	24.522***	25.039***

Hendricks [10] estimate that a predicted chloride concentration in the base of the aquifer in excess of 5000 mg/L correlates with a 8.9 % reduction (~9.4 acres) in irrigated acres planted to corn when compared to the base case (<500 mg/L).

In sum, we detect evidence that irrigators indicating no concern over groundwater quality tend to use more water, irrigate a larger number of total acres, and irrigate a larger number of corn acres than irrigators having elevated concerns over groundwater quality. Our findings support Hypotheses 1 and 2 outlined above. However, we find evidence that water use and irrigated acreage does not necessarily decrease monotonically with increasing level of concern over groundwater quality. In fact, irrigators indicating “very concerned” tend to use more total water, irrigate more total acres, and irrigate more corn acres than irrigators indicating “slightly concerned.”

4.2. Groundwater quantity

We next examine the regression results relating to groundwater quantity. Looking across columns of Table 3, we find clear correlations between irrigators having elevated concern over well yields and using less water and irrigating fewer acres per year. Focusing on total water use, we find that irrigators indicating “slightly,” “somewhat,” “moderately,” or “very” concerned use about 47.7, 68.1, 44.6, and 69.7 less acre-ft of water per year than irrigators indicating no concern, respectively. These findings support Hypothesis 3 that concern correlates with a history of lower water use. The pairwise difference in marginal effects are presented in Table 4. The difference between “slightly concerned” and “somewhat concerned” and “very concerned” is statistically significant at 0.01. Additionally, the difference between “moderately concerned” and “very concerned” is statistically significant at 0.01. Thus, those irrigators stating the highest level of concern generally tend to use the least amount of water per year.

Table 5 presents linear hypothesis tests of coefficients on water quantity and water quality concerns. We detect a general pattern where concern over groundwater quantity correlates with lower past total water use when compared to the equivalent category of concern over groundwater quality (i.e., a negative difference). For example, the coefficient on “somewhat concerned” for groundwater quantity is approximately twice as large as it is for groundwater quality, with the difference statistically significant at 0.01. The same is true for the “very concerned” category.

Turning next to total irrigated acreage, we again detect a pattern where irrigated acreage levels decline as the level of concern increases, supporting Hypothesis 1. Specifically, irrigators indicating “slightly,” “somewhat,” “moderately,” or “very” concerned irrigate about 18.5, 51.1, 34.5, and 59.1 fewer acres per year than irrigators indicating no concern, respectively. Again, the reduction in acreage across categories of concern is not necessarily monotonic (Table 4). For example, the “very concerned” category has the coefficient of largest absolute magnitude but is not statistically different from the “somewhat concerned” category. We also note that the effect magnitude for groundwater quantity tends to exceed the effect magnitude for groundwater quality (Table 5). For instance, an

Table 5

Comparison of regression coefficients for water quantity concern and water quality concern.

Difference in water quantity coefficient and water quality coefficient	Total water use (acre-feet)	Total acres	Corn acres
Slightly concerned	2.145	15.371*	2.147
Somewhat concerned	−35.841***	−22.654***	−8.809*
Moderately concerned	−7.253	−8.254	−4.561
Very concerned	−40.664***	−45.922***	−29.206***

irrigator indicating “very concerned” with regards to groundwater quantity reduces their total acreage by 59.1 acres, while an irrigator indicating “very concerned” with regards to groundwater quality reduces their total acreage by only 13.1 acres, with the difference being statistically significant.

Looking next at corn irrigated acreage, we observe that irrigators indicating “slightly,” “somewhat,” “moderately,” or “very” concerned irrigate about 29.1, 37.4, 25.6, and 50.7 fewer acres of corn per year than irrigators indicating no concern, respectively. These findings support [Hypothesis 2](#). Using pairwise comparison of the average marginal effects, we find that irrigators indicating “very concerned” tend to irrigate the fewest number of corn acres overall, with the difference between all other groups statistically significant at 0.01 ([Table 4](#)). Corn provides the highest net returns to irrigated production but is also the most irrigation intensive. Thus, we find correlational evidence that irrigators having concern over their ability to pump adequate quantities of water tend to choose crops providing less downside risk to crop water deficits. The coefficient on “very concerned” for water quantity is over twice as large as the “very concerned” coefficient for water quality, with the difference statistically significant at 0.01 ([Table 5](#)).

In sum, we detect those irrigators having elevated concern over groundwater quantity, as measured by well yield, tend to use less total water, irrigate fewer total acres, and irrigate fewer acres of corn than irrigators that have no concern over groundwater quantity. We detect a general pattern where the “very concerned” category correlates with the largest reductions in water use or acreage. However, the relationship between stated category of concern and irrigation outcomes is not necessarily monotonic in each and every case. Additionally, holding the category of concern fixed for water quantity and water quality, concerns over water quantity tend to correlate with larger absolute reductions in water use and irrigated acreage than concerns over water quality (e.g., [Table 5](#)). One possible explanation for larger reductions in water use and acreage correlating with water quantity concerns is that groundwater quantity concerns correlate with well depletion, which could place constraints on pumping through local ordinances, pumping costs, or simply lack of water.

4.3. Robustness checks

We conduct several robustness checks to our main models estimates and report in [Tables A6–A11](#) in the supplementary appendix. [Table A6](#) limits the analysis to 2010–2019 with results similar to those in [Table 3](#). [Table A7](#) controls for unobserved spatial heterogeneity using county dummies instead of GMD dummies. We do note some attenuation to some of the concern categories for water quality relative to [Table 3](#), which may be the result of having limited within-county variation in survey responses. The coefficients on water quantity concerns increase slightly relative to [Table 3](#). [Table A8](#) restricts the analysis to respondents who conducted a chemical water quality test within the last 10 years. We generally find coefficients of larger absolute magnitude on the water quality concern categories for total water use and total acreage relative to [Table 3](#). [Tables A9 and A10](#) restrict the analysis to water rights groups that did not have a change in the legal person or correspondent filing the annual water use reports to DWR. A change in filer might result in disconnect between survey information and past irrigation outcomes. The results in [Tables A9 and A10](#) provide estimates that are similar to those in [Table 3](#) but with some loss of precision due to a smaller sample size. [Table A11](#) pools together the “slightly” and “somewhat” and the “moderately” and “very” concerned categories. The pooled categories produce coefficients that are similar in magnitude.

5. Conclusions

We find that irrigators indicating elevated concern over groundwater quality or groundwater quantity correlates with a history of lower water use, lower total irrigated acreage, and lower irrigated corn acreage when compared to irrigators indicating no concern. Irrigators indicating concern over groundwater quality correlates with 29–50 less acre-ft of water per year and 13 to 34 fewer acres per year than irrigators having no concern. We detect a stronger relationship between groundwater quality concerns and total water use and irrigated acreage when we restrict the analysis to respondents having knowledge of test results for the chemical quality of their water. With respect to irrigated corn acreage, irrigators indicating concern over groundwater quality correlates with 21–31 fewer acres per year than irrigators indicating no concern. We also find that concern over groundwater quantity tends to correlate with larger overall reductions in past water use or irrigated acreage than equivalent levels of concern over groundwater quality. For instance, irrigators indicating concern over groundwater quantity correlates with 45–70 less acre-ft of water per year than irrigators indicating no concern. Taken together, our results suggest that public expenditures toward improving issues related to water quantity are likely to be more impactful than expenditures toward issues of water quality.

From a welfare perspective, less water use, irrigated acreage, and corn acreage are likely to result in lower producer wellbeing. As irrigated corn generally provides the greatest net return per acre in Kansas [[37](#)], less water use could cause foregone economic returns through lower yields [[47](#)]. Additionally, smaller irrigated acreage or irrigated corn acreages are likely to result in lost welfare; however, precise loss estimates require the use of explicit assumptions regarding replacement crops, crop rotations, and whether ground is fallowed.

Water use and irrigated acreage do not necessarily decrease monotonically with increasing levels of concern over groundwater quality or quantity. Although irrigators indicating “very concerned” use less water and irrigate less than the unconcerned, they do not necessarily irrigate the least. As our study is correlational instead of causal, this could be indicative that concerns over water quality or quantity are dependent on an unobserved variable such as operation or risk preferences. For example, irrigators that are “very concerned” with water quality or quantity could be more dependent on irrigation (e.g., continuous corn) or apply more water to mitigate risk. While we cannot identify specifically why a level of concern arises, our results suggest that irrigator perception is reflective of behavior. Water managers may therefore benefit from detailed information on irrigators’ perceptions including operation and risk

preference to inform water conservation and reclamation policy.

Recent nonmarket valuation studies of groundwater quantity and quality in the HPA indicate that irrigators generally place greater valuation on improvements in groundwater quantity. Suter et al. [20] estimate a median willingness to pay of \$77/well for a marginal increase in well yields using data for several states overlying the HPA. By comparison, Gardner et al. [21] estimate a median willingness to pay of \$39/well for a marginal decrease in the salt content of groundwater using data for the Kansas HPA. Consistent with the willingness to pay information from these studies, we generally find that groundwater quantity concerns correlate with greater overall reductions in past water use and irrigated acreage than groundwater quality concerns.

Previous research reveals that individuals who perceive water quality to be poor are willing to pay more for marginal improvements than individuals who perceive water quality to be good [11,48]. However, individual perceptions of water quality attributes do not always match up with the actual water quality [11,14]. When we restrict the sample to irrigators having knowledge of the chemical quality of their irrigation water, we find stronger evidence of elevated concern over water quality correlating with reductions in water use and irrigated acreage. While we do not estimate willingness to pay for water quality improvements in this study, our results are consistent with previous valuation studies in that irrigators who knew their water quality and expressed elevated concerns tend to also have a history of substantially reduced water use and acreage.

Our work also relates to the literature on stated preference and hypothetical bias. Hypothetical bias occurs when information elicited from hypothetical scenarios exceed values that would be obtained from binding real-world outcomes ([49] review the literature). For instance, over 15 % of respondents in the survey of Gardner et al. [21] report that water quality problems impact their cropping decisions. Here we provide correlational evidence that irrigators expressing concern over groundwater in a survey tend to have a history of lower overall water use and irrigated acreage than their counterparts expressing no concern. To the extent that lower annual water use and irrigated acreage affects irrigator wellbeing through reduced annual crop returns, it is reasonable to believe that estimated valuations of groundwater quantity and quality improvements obtained from survey methods that are conditioned on farmer perceptions accurately reflect the real-world.

Lastly, there are some limitations to the analysis worth mentioning. First, as noted in Section 3.9, we are not able to identify strictly causal relationships between stated levels of concern and irrigation behavior given the available data. For instance, an irrigator may be aware of the water quality or water quantity limitations present at their operation, this information influences the formulation of their concern, which then influences their irrigation decisions [16,48]. Conversely, an irrigator may perceive a trend in their water use or cropping, and this influences the formulation of their concern. Second, the available data do not include information specific to the producer, such as risk preferences or various measures of agronomic skill, which might influence irrigation behavior and outcomes. Additionally, while we can compare certain irrigation and land characteristics across the sample and full population of irrigators in our study region, we cannot compare socioeconomic characteristics to test for representativeness.

Authorship

Gabriel Sampson designed research, performed research, analyzed data, and wrote the paper. Grant Gardner designed research, performed research, analyzed data, and wrote the paper.

Financial support

This work was supported by the USDA National Institute of Food and Agriculture (Hatch project 1017720 and multi-state project 1020662), National Science Foundation (award #2316295), and by a financial gift from John and Della Hodler. John and Della Hodler had no role in the design, analysis, or writing of this article.

CRediT authorship contribution statement

Grant Gardner: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Gabriel S. Sampson:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.wre.2024.100246>.

References

- [1] G.S. Sampson, E.D. Perry, Peer effects in the diffusion of water-saving agricultural technologies, *Agric. Econ.* 50 (6) (2019) 693–706, <https://doi.org/10.1111/agec.12518>.
- [2] A. Hrozencik, M. Aillery, Trends in irrigated agriculture reveal sector's ability to adapt to evolving climatic, resource, and market conditions, *Amber Waves: The Economics of Food, Farming, Natural Resources, and Rural America* 2022 (2022), 1490–2022–276.
- [3] B.R. Scanlon, C.C. Faunt, L. Longuevergne, R.C. Reedy, W.M. Alley, V.L. McGuire, P.B. McMahon, Groundwater depletion and sustainability of irrigation in the US High Plains and central valley, *Proc. Natl. Acad. Sci. USA* 109 (24) (2012) 9320–9325.
- [4] E.C. Edwards, T. Guilfoos, The economics of groundwater governance institutions across the globe, *Appl. Econ. Perspect. Pol.* 43 (4) (2021) 1571–1594, <https://doi.org/10.1002/aep.13088>.
- [5] D. Rey, I.P. Holman, J.W. Knox, Developing drought resilience in irrigated agriculture in the face of increasing water scarcity, *Reg. Environ. Change* 17 (5) (2017) 1527–1540, <https://doi.org/10.1007/s10113-017-1116-6>.
- [6] K.M. Drysdale, N.P. Hendricks, Adaptation to an irrigation water restriction imposed through local governance, *J. Environ. Econ. Manag.* 91 (2018) 150–165.
- [7] D. Earnhart, N.P. Hendricks, Adapting to water restrictions: intensive versus extensive adaptation over time differentiated by water right seniority, *Am. J. Agric. Econ.* 105 (5) (2023) 1307–1570, <https://doi.org/10.1111/ajae.12361>.
- [8] L. Soltani, T. Mellah, Exploring farmers' adaptation strategies to water shortage under climate change in the Tunisian semi-arid region, *Environ. Manag.* 71 (1) (2023) 74–86, <https://doi.org/10.1007/s00267-022-01604-z>.
- [9] M. Haw, C. Cocklin, D. Mercer, A pinch of salt: landowner perception and adjustment to the salinity hazard in Victoria, Australia, *J. Rural Stud.* 16 (2) (2000) 155–169.
- [10] J. Lee, N.P. Hendricks, Irrigation decisions in response to groundwater salinity in Kansas, *J. Agric. Resour. Econ.* 47 (3) (2022) 616–S618.
- [11] J. Orgill, A. Shaheed, J. Brown, M. Jeuland, Water quality perceptions and willingness to pay for clean water in peri-urban Cambodian communities, *J. Water Health* 11 (3) (2013) 489–506, <https://doi.org/10.2166/wh.2013.212>.
- [12] P.J. Poor, K.J. Boyle, L.O. Taylor, R. Bouchard, Objective versus subjective measures of water clarity in hedonic property value models, *Land Econ.* 77 (4) (2001) 482–493.
- [13] Y. Jeon, J.A. Herriges, C.L. Kling, The role of water quality perceptions in modelling lake recreation demand, in: *The International Handbook on Non-market Environmental Valuation*, Edward Elgar Publishing, 2011.
- [14] J. Artell, H. Ahtiainen, E. Pouta, Subjective vs. objective measures in the valuation of water quality, *J. Environ. Manag.* 130 (2013) 288–296, <https://doi.org/10.1016/j.jenvman.2013.09.007>.
- [15] M.d.F. Doria, N. Pidgeon, P.R. Hunter, Perceptions of drinking water quality and risk and its effect on behaviour: a cross-national study, *Sci. Total Environ.* 407 (21) (2009) 5455–5464, <https://doi.org/10.1016/j.scitotenv.2009.06.031>.
- [16] C. Bontemps, C. Nauges, The impact of perceptions in averting-decision models: an application of the special regressor method to drinking water choices, *Am. J. Agric. Econ.* 98 (1) (2016) 297–313, <https://doi.org/10.1093/ajae/aav046>.
- [17] A. Javidi, G. Pierce, U.S. Households' perception of drinking water as unsafe and its consequences: examining alternative choices to the tap, *Water Resour. Res.* 54 (9) (2018) 6100–6113, <https://doi.org/10.1029/2017WR022186>.
- [18] C.J. Wright, J.M. Sargeant, V.L. Edge, J.D. Ford, K. Farahbakhsh, I. Shiwak, C. Flowers, A.C. Gordon, S.L. Harper, How are perceptions associated with water consumption in Canadian Inuit? A cross-sectional survey in Rigolet, Labrador, *Sci. Total Environ.* 618 (2018) 369–378, <https://doi.org/10.1016/j.scitotenv.2017.10.255>.
- [19] K.J. Egan, J.A. Herriges, C.L. Kling, J.A. Downing, Valuing water quality as a function of water quality measures, *Am. J. Agric. Econ.* 91 (1) (2009) 106–123, <https://doi.org/10.1111/j.1467-8276.2008.01182.x>.
- [20] J.F. Suter, M. Rouhi Rad, D.T. Manning, C. Goemans, M.R. Sanderson, Depletion, climate, and the incremental value of groundwater, *Resour. Energy Econ.* 63 (2021) 101143, <https://doi.org/10.1016/j.reseneeco.2019.101143>.
- [21] G. Gardner, G. Sampson, D. Presley, Irrigator perceptions and the value of groundwater quality in the High Plains Aquifer, *J. Soil Water Conserv.* 76 (4) (2021) 329–339.
- [22] T. Foster, N. Brozović, A.P. Butler, Analysis of the impacts of well yield and groundwater depth on irrigated agriculture, *J. Hydrol.* 523 (2015) 86–96.
- [23] M. Rouhi Rad, A. Araya, Z.T. Zambreski, Downside risk of aquifer depletion, *Irrigat. Sci.* 38 (5) (2020) 577–591, <https://doi.org/10.1007/s00271-020-00688-x>.
- [24] T. Mieno, M.R. Rad, J.F. Suter, R.A. Hrozencik, The importance of well yield in groundwater demand specifications, *Land Econ.* 97 (3) (2021) 672–687, <https://doi.org/10.3368/wple.97.3.030320-0031R1>.
- [25] S.M. Smith, K. Andersson, K.C. Cody, M. Cox, D. Ficklin, Responding to a groundwater crisis: the effects of self-imposed economic incentives, *Journal of the Association of Environmental and Resource Economists* 4 (4) (2017) 985–1023.
- [26] J. Loomis, WHAT'S TO KNOW about hypothetical bias in stated preference valuation studies? *J. Econ. Surv.* 25 (2) (2011) 363–370, <https://doi.org/10.1111/j.1467-6419.2010.00675.x>.
- [27] J.L. Lanning-Rush, Irrigation water use in Kansas, 2013, Data Series 981 (2016), <https://doi.org/10.3133/ds981>. U.S. Geological Survey.
- [28] E. Edwards, N.P. Hendricks, G.S. Sampson, *The Capitalization of Incomplete Property Rights to the Groundwater Commons*, Available at: SSRN 4509363, 2023.
- [29] E.M.K. Haacker, A.D. Kendall, D.W. Hyndman, Water level declines in the High Plains aquifer: predevelopment to resource senescence, *Groundwater* 54 (2) (2016) 231–242, <https://doi.org/10.1111/gwat.12350>.
- [30] J.J. Gurdak, P.B. McMahon, K. Dennehy, S.L. Qi, Water quality in the High Plains aquifer, Colorado, Kansas, Nebraska, New Mexico, Oklahoma, south Dakota, Texas, and Wyoming, 1999–2004, *US Geol. Surv. Circular* 1337 (2009) 63.
- [31] D.O. Whittemore, Geochemical differentiation of oil and gas brine from other saltwater sources contaminating water resources: case studies from Kansas and Oklahoma, *Environ. Geosci.* 2 (1) (1995) 15–31.
- [32] D.O. Whittemore, Ground-water quality of the Arkansas river corridor in southwest Kansas, *Kansas Geological Survey Open-File Report* 73 (2000) 109.
- [33] T.S. Ma, M. Sophocleous, Y.-S. Yu, R. Buddemeier, Modeling saltwater upconing in a freshwater aquifer in south-central Kansas, *J. Hydrol.* 201 (1–4) (1997) 120–137.
- [34] D.R. Steward, P.J. Bruss, X. Yang, S.A. Staggenborg, S.M. Welch, M.D. Apley, Tapping unsustainable groundwater stores for agricultural production in the High Plains Aquifer of Kansas, projections to 2110, *Proc. Natl. Acad. Sci. USA* 110 (37) (2013) E3477–E3486.
- [35] J. Suter, T. Guilfoos, K. Schoengold, Seasons, stress, salience, and support for cooperative groundwater management, *Journal of the Agricultural and Applied Economics Association* (2023) 1–15, <https://doi.org/10.1002/jaa2.78>.
- [36] D. Whittemore, E. Grieve, D. Young, B. Wilson, Water Quality in the High Plains Aquifer and the Cimarron River in Seward and Meade Counties, Kansas. KGS Open File Report 2005-27, Kansas Geological Survey, Lawrence, KS, 2005.
- [37] G. Ibendahl, 2023 Farm Management Guides for Irrigated Crops, Farm Budgets, 2023. Retrieved May 10, 2023, from, <https://agmanager.info/farm-budgets/2023-farm-management-guides-irrigated-crops>.
- [38] G.S. Sampson, N.P. Hendricks, M.R. Taylor, Land market valuation of groundwater, *Resour. Energy Econ.* 58 (2019) 101120, <https://doi.org/10.1016/j.reseneeco.2019.101120>.
- [39] G.H. Hargreaves, Z.A. Samani, Estimating potential evapotranspiration, *J. Irrigat. Drain. Div.* 108 (3) (1982) 225–230.
- [40] J. Aguilar, J. Thompson, Status of Irrigation Systems in Kansas: Road Survey Report, 2023, 2023 Governor's Water Conference. Manhattan, KS.
- [41] H.S. Burness, T.C. Brill, The role for policy in common pool groundwater use, *Resour. Energy Econ.* 23 (1) (2001) 19–40.
- [42] N.P. Hendricks, J.M. Peterson, Fixed effects estimation of the intensive and extensive margins of irrigation water demand, *J. Agric. Resour. Econ.* 37 (1) (2012) 1–19. <http://www.jstor.org/stable/23243046>.
- [43] N.E. Quintana Ashwell, J.M. Peterson, N.P. Hendricks, Optimal groundwater management under climate change and technical progress, *Resour. Energy Econ.* 51 (2018) 67–83, <https://doi.org/10.1016/j.reseneeco.2017.10.005>.

- [44] C. Brouwer, M. Heibloem, Irrigation water management: irrigation water needs, Training manual 3 (1986) 1–5. Rome, Food and Agriculture Organization.
- [45] E.C. Edwards, What lies beneath? Aquifer heterogeneity and the economics of groundwater management, *Journal of the Association of Environmental and Resource Economists* 3 (2) (2016) 453–491.
- [46] A. Hrozencik, G. Gardner, N. Potter, S. Wallander, Irrigation organizations: groundwater management, US Department of Agriculture Economic Research Service 34 (2023). Economic Brief Number.
- [47] C.A. Norwood, Water use and yield of limited-irrigated and dryland corn, *Soil Sci. Soc. Am. J.* 64 (1) (2000) 365–370, <https://doi.org/10.2136/sssaj2000.641365x>.
- [48] J.C. Whitehead, Improving willingness to pay estimates for quality improvements through joint estimation with quality perceptions, *South. Econ. J.* 73 (1) (2006) 100–111.
- [49] J. Penn, W. Hu, Cheap talk efficacy under potential and actual Hypothetical Bias: a meta-analysis, *J. Environ. Econ. Manag.* 96 (2019) 22–35, <https://doi.org/10.1016/j.jeem.2019.02.005>.
- [50] T.C. Brill, H.S. Burness, Planning versus competitive rates of groundwater pumping, *Water Resour. Res.* 30 (6) (1994) 1873–1880.
- [51] T. Foster, N. Brozović, A.P. Butler, Why well yield matters for managing agricultural drought risk, *Weather Clim. Extrem.* 10 (2015) 11–19, <https://doi.org/10.1016/j.wace.2015.07.003>.
- [52] H. March, X. Garcia, E. Domene, D. Sauri, Tap water, bottled water or in-home water treatment systems: insights on household perceptions and choices, *Water* 12 (5) (2020) 1310. <https://www.mdpi.com/2073-4441/12/5/1310>.
- [53] M. Rouhi Rad, N. Brozović, T. Foster, T. Mieno, Effects of instantaneous groundwater availability on irrigated agriculture and implications for aquifer management, *Resour. Energy Econ.* 59 (2020) 101129, <https://doi.org/10.1016/j.reseneeco.2019.101129>.
- [54] G.S. Sampson, E.D. Perry, The role of peer effects in natural resource appropriation – the case of groundwater, *Am. J. Agric. Econ.* 101 (1) (2019) 154–171, <https://doi.org/10.1093/ajae/aay090>.