A Meta-analysis of Water Conservation Policies in the Southern Ogallala Aquifer Region

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Abstract

To extend the economic life of the Ogallala Aquifer, policy makers and stakeholders have considered and implemented several water conservation policies. Starting with an empirical study by Segarra and Feng (1994), the inter-temporal dynamic approach has been adopted in literature to evaluate impacts of these policies in the region. To integrate the findings and make comparable evaluations, we conducted a meta-analysis of the literature. After a systematic identification and screening of relevant publications including journal articles, meeting papers and reports, the meta-analysis included 19 studies focusing on nine major water conservation polices, including irrigation technology adoption, water use restriction, biotechnology, permanent and temporary conversion to dryland production. The average number of policies analyzed by the literature was 3.33, and more than 60% of the studies included one or more counties in the Southern High Plains region of Texas. The average planning horizon was 52 years. The estimated average decrease of saturated thickness was 59 feet. The economic impacts of these policies were significantly different in each study.

Key words: Groundwater management, water conservation policy, Ogallala Aquifer, meta-analysis, effect size

JEL codes: R11, Q15, Q25, Q32

Introduction

With a semi-arid climate, the High Plains experience limited precipitation, and the scarce surface water is not reliable for agricultural irrigation in this region. Ogallala Aquifer supplies more than 90% of the water for farm irrigation in the High Plains area (Jensen, 2004). As a result, the groundwater table has declined rapidly in past decades because of intensive agricultural irrigation, especially in the Southern Ogallala Aquifer. The low recharge rate of the aquifer further aggravates water shortage in this region. Policy makers and stakeholders have proposed and implemented several groundwater conservation policies to extend the economic life of the aquifer.

Among the eight states overlying the aquifer, Texas and Kansas are most active to regulate water withdrawal. Bounded by dominating water allocation rules, water conservation policies oftentimes need to be tailored. In Texas, landowners have the right to withdraw and use groundwater beneath their land for beneficial use. While the rule of capture has been followed over more than 100 years by Texas courts, the Legislature is the overarching body of institutions and determines the regulation of groundwater (Kaiser & Skillern, 2001). Established in 1949, groundwater management districts are the preferred institutions for groundwater management in Texas (House Research Organization, 2000). The groundwater management districts can evaluate local water availability and design water policies to address priority areas. As one of the western states following Prior Appropriation doctrine to allocate water resources, Kansas has established its permit system to appropriate water since 1945. Since 1972 five Groundwater Management Districts were formed and intensive groundwater use control areas were established to reduce permissible groundwater withdrawal (Amosson et al., 2009).

Along with the establishment of management districts, multiple policies have been designed and/or implemented to achieve short- or long-run objectives. These policies include water use fee, water use restriction, biotechnology, enhanced irrigation technology, temporary and permanent conversion to dryland production (Amosson et al., 2009; Wang et al., 2015). Evaluation of these water conservation strategies has shown illuminating, but diverse hydrologic and economic outcomes. To aggregate the effects of these policies, this study investigates the empirical studies and provides insights for water policy design based on a systematic review and meta-analysis.

Policies to manage groundwater in the Ogallala Aquifer region

Several policies have been evaluated in the Ogallala Aquifer region and/or its sub-regions (Park, 2005). A survey conducted by Guerrero et al. (2008) found that five out of twelve selected water conservation policies in the Southern Ogallala Regions were ranked top choices by Texas farmers. These policies include water use restriction, biotechnology, irrigation technology, temporary and permanent conversion to dryland. In addition, water use fee has been used to regulate water demand in agriculture sector. Water demand has also been evaluated in various climate change and biophysical conditions, and under land use changes. These relevant policies and their implementation in the High Plains Aquifer are briefly introduced below.

Water use fee

Variations of water use fee and different pricing structures have been implemented in water management (Johansson et al., 2002; Wang et al., 2015). One of the most common type water fees is a mandatory per unit charge on the water amount pumped, also called water pumpage fee (Johnson et al., 2009). The Texas Legislature authorized groundwater management districts to manage groundwater withdrawals using alternative regulatory policies including water use fees (Texas Joint Committee on Water Resources, 2002).

Water use restriction

One of other regulatory policies the Texas Legislature authorized to manage groundwater is water use restriction (Texas Joint Committee on Water Resources, 2002). With water pumping quotas set for each water management unit, the amount of water pumped from the Ogallala Aquifer to irrigate croplands can be reduced. To enact a water use restriction in counties of the Southern Ogallala Aquifer, any sub-regions of the aquifer are projected to use more than 40% of saturated thickness over 60 years (Amosson et al., 2009). Applied to wells for irrigated farms, each irrigator is required to measure water withdrawal using an approved water meter, and report water usage to the local water authority. In the Southern Ogallala Aquifer, total groundwater withdrawal for agricultural irrigation is limited to 10% per decade on average (Amosson et al., 2009).

Biotechnology

As a voluntary incentive-based water conservation policy, the biotechnology policy encourages producers to adopt more crop varieties with high water efficiency. With seeds genetically engineered to tolerate water stress, the new crop varieties are expected to reduce water requirements, or increase crop yield per unit of water applied. Thus the biotechnology policy can potentially improve the long-run sustainability of agricultural production in the High Plains region (Tewari et al., 2010). Biotechnology helps increase or stabilize agricultural profitability when facing climate risks and uncertain socioeconomic changes (Middleton et al., 1999).

Irrigation technology

With a higher irrigation efficiency, enhanced irrigation technology, such as drip and sprinkler systems, is an effective way to slow down groundwater depletion. Irrigation technology adoption can reduce water use per unit of land, increase crop yield, thus achieving higher expected profits compared to traditional irrigation systems. As investigated by Amosson et al. (2001), drip, low elevation precision application (LEPA), and low elevation spray application (LESA) have a high application efficiency of 97%, 95%, and 88%, respectively. Comparatively, conventional furrow, surge flow, mid-elevation spray application (MESA) systems have 60%, 70%, and 78% application efficiency, as 22-40% of water is lost in delivery to the field and due to runoff, deep percolation or evaporation (Amosson et al., 2009).

Temporary conversion to dryland

As a voluntary incentive-based mechanism, temporary conversion to dryland production policy allows farmers to temporarily convert irrigated land to dryland for compensations. For a short period of time, landowners can choose to withdraw less water through temporarily retiring or leasing out their water rights (Amosson et al., 2009). With immediate curtailment of groundwater use, the temporary conversion policy is oftentimes utilized to address priority areas for certain environmental or social purposes. Typical programs of temporary dryland conversion policy include Environmental Quality Incentives Program (EQIP) and Conservation Reserve Enhancement Program (CREP). Both need efforts from agricultural landowners to implement conservation practices and require state and federal partnerships. Studies have evaluated the economic and hydrological effects of such policies or other similar temporary programs. For instance, Almas et al. (2017) simulated a program with 15 year duration assuming 2% of existing irrigated farmland was converted to dryland production each year for the first 5 years (a total of 10% by year 5). In year 16 the converted land could return to irrigated production again.

Permanent conversion to dryland

To compensate farmers to permanently convert irrigated land to dryland, the permanent dryland conversion policy is aimed to achieve a long-term reduction in water consumption. By buying out water rights from producers or allowing permanent retirement of water rights, this policy helps avoid over appropriation of limited water resource in the High Plains region (Amosson et al., 2009). The CREP purchases water rights in addition to the temporary mechanism mentioned above. To achieve reductions in groundwater withdrawal, purchasing water rights is more cost effective compared to other water conservation policies (Golden & Peterson, 2006; Supalla et al., 2006). As a typical example, the permanent conversion to dryland policy can switch 2% of existing irrigated land to dryland each year for the first 5 years. Starting from year 5, a total of 10% converted acreages remain for dryland production during the rest of the planning horizon (Almas et al., 2017)

Climate change scenarios

In much research, multiple climate scenarios have been incorporated in evaluating the hydrological and economic effects of other water conservation policies (Tewari et al., 2015). Climate change and weather conditions greatly influence the development and sustainability of the Ogallala Aquifer and the economy it supports (Antle & Capalbo, 2010). The agriculture-based economy in the High Plains heavily relies on groundwater resources. Since the precipitation and temperature change affect the recharge of the aquifer and availability of groundwater, impacts of future climate scenarios are profound. The effects of climate scenarios will be unevenly distributed with a potentially remarkable impact on the transitional areas like High Plains (IPCC, 2007). Results from Tewari et al. (2015) suggested decreased water availability and water consumption from multiple IPCC climate models and emission scenarios, while the effects on average agriculture income are varying across the models.

Heterogeneous land uses and aquifer characteristics

In addition to the hydrologic modeling of aquifer depletion, the heterogeneity of land use patterns and aquifer characteristics have been considered in economic production models.

The spatial variability in land use practices could determine water withdrawal and aquifer depletion. As a result, the variable costs, including pumping costs, and profits are influenced. Furthermore, the spatial heterogeneity in aquifer characteristics also affects the costs and benefits of agricultural production. Evaluation of other water policies generally assume homogenous land use and aquifer characteristics (except for several aspects in consideration, like varying saturated thickness and lift of water). Results from hydro-economic models incorporating heterogeneous land uses and aquifer characteristics can help policy makers target specific water uses and geographic regions to achieve most cost-effective policy implementation (Willis et al., 2010).

Meta-analysis and procedures

Data collection

To evaluate the effectiveness of water conservation policies in the Ogallala Aquifer region, it's critical to conduct systematic and comprehensive literature searches. In April - October 2017, extensive literature searches and identification were conducted using major search engines, including Elsevier, Emerald, Springer, Wiley, Google Search, and Google Scholar. Starting with two publications, a dissertation by Feng (1992) and a journal article by (Segarra & Feng, 1994)[1], which analyzed adoption of irrigation technology and its effect on groundwater use, we located all studies citing the two publications. More studies were found from the reference lists of identified publications.

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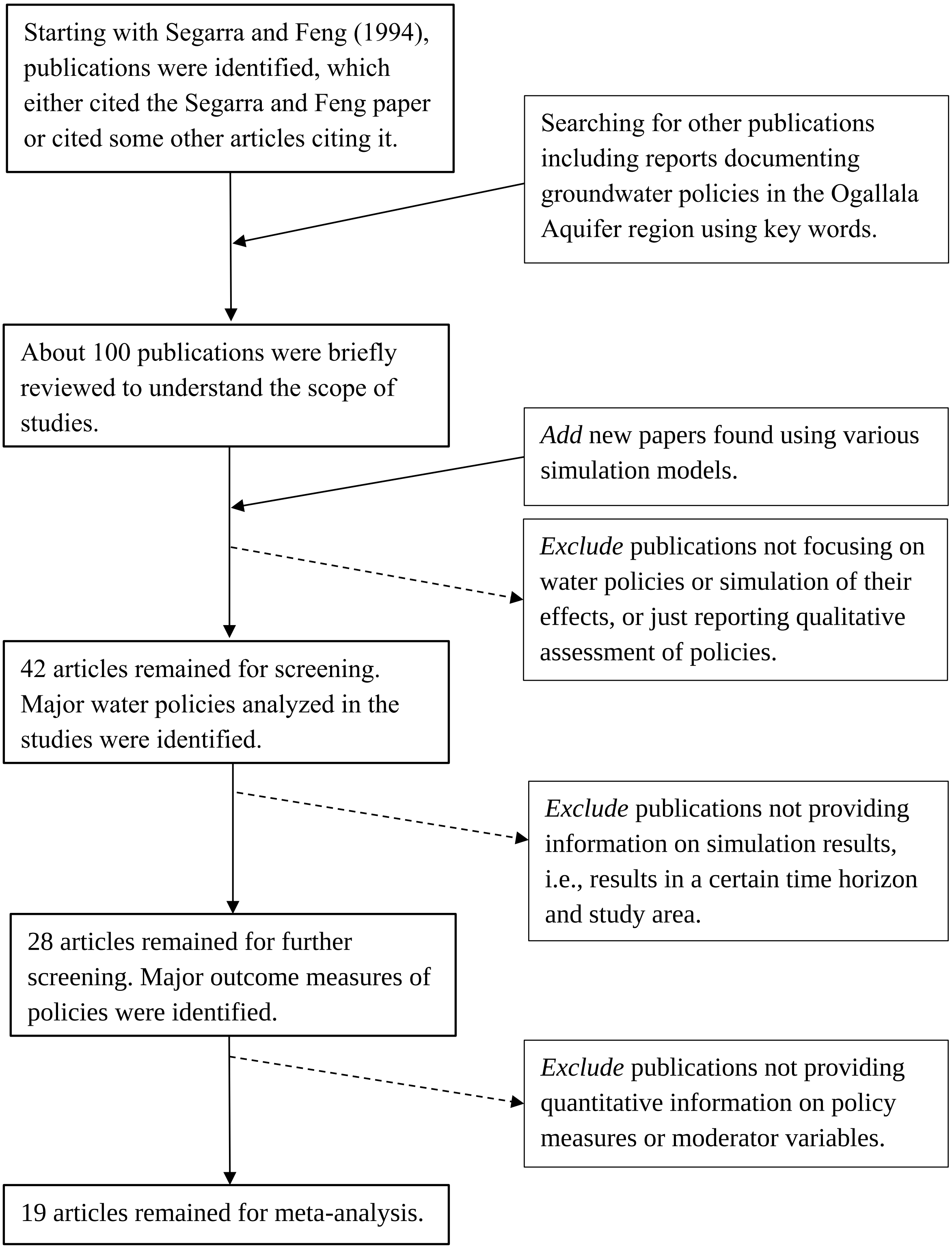
[1] The journal article Segarra and Feng (1994) is one part of the dissertation by Feng (1992). Some publications adopting the optimization model cited one or the other.

More online searches were conducted in English using key words including Ogallala (High Plains) Aquifer and its combinations with one or more terms-water (conservation) policy, farm irrigation, saturated thickness, water withdrawal, economic impacts, agriculture, production. All types of publications reporting empirical analysis of water policies were identified, including journal articles, conference proceedings, meeting papers, project reports, dissertation, thesis, and other unpublished materials. Duplicate versions of publications were identified, and the latest version was finally used for the meta-analysis. For example, a journal article was selected if it's one part of a thesis or dissertation, or if it's a newer version of a previous meeting paper.

A general process to choosing empirical studies for meta-analysis was followed (Fan et al., 2018). Figure 1 shows the literature searching process. About 100 publications were located, including those citing Feng (1992), and Segarra and Feng (1994), as well as those found from the initial online literature searches. These studies were briefly reviewed; the scope of studies was identified as well as their suitability to be included in the meta-analysis. We added some papers found using various simulation models focusing on the Ogallala Aquifer. After the initial screening, a majority of publications were excluded, for example, some older or duplicate versions of studies, those papers not focusing on water policies or simulation of water policy effects, or just reporting the qualitative assessment of water policies. The initial screening gives us 42 articles reporting major water conservation policies.



Starting with Segarra and Feng (1994), publications were identified, which either cited the Segarra and Feng paper or cited some other articles citing it.

Searching for other publications including reports documenting groundwater policies in the Ogallala Aquifer region using key words.

About 100 publications were briefly reviewed to understand the scope of studies.

Add new papers found using various simulation models.

Exclude publications not focusing on water policies or simulation of their effects, or just reporting qualitative assessment of policies.

42 articles remained for screening. Major water policies analyzed in the studies were identified.

Exclude publications not providing information on simulation results, i.e., results in a certain time horizon and study area.

28 articles remained for further screening. Major outcome measures of policies were identified.

Exclude publications not providing quantitative information on policy measures or moderator variables.

19 articles remained for meta-analysis.

Figure 1. Literature searching and screening process for the meta-analysis.

Then a second round of screening further excluded some papers without clear simulation information, or time horizon. Twenty-eight articles remained, and major outcome measures of policies were identified. A final review of the studies excluded publications which didn't provide clear quantitative information on policy effects or other moderator variables. Finally, nineteen empirical studies were selected for the meta-analysis.

Although the literature searches were conducted systematically and exclusively, the number of selected publications providing complete and comparative information relating to major water conservation policies was limited. Many qualitative policy studies or those without complete or comparable information were unfortunately excluded. Even though limited empirical studies were analyzed, given the representativeness of the Ogallala Aquifer, we believe the insights from aggregating and analyzing typical groundwater conservation policies will be useful to water management in other aquifers worldwide.

Variable identification

As one of the most important components, several types of variables were identified in the literature screening and review process, including dependent variables, moderator variables and policy predictor variable. The latter two are independent variables.

Dependent variables

The hydro-economic models evaluating water conservation policies in the Ogallala Aquifer typically present results on saturated thickness, water use (or withdrawal, application), irrigated acres, and profits (or costs and benefits, income, etc.). To prepare for comparable analysis, conversions between units (i.e., meter to feet), transformations between measures (initial and final saturated thickness vs. change of saturated thickness) are needed.

The change of saturated thickness was identified or calculated with data presented in studies following:

$$Change\ of\ ST = ST_{time\ t} - ST_{time\ 0\ or\ 1} \tag{1}$$

where ST refers to saturated thickness with the unit foot. Time t represents the last year of simulation horizon, and time 0 or 1 represents the initial year with data presented in a study. The change of water use per irrigated acre or conserved water was identified or calculated following:

$$Change\ of\ WU = WU_{time\ t} - WU_{time\ 0\ or\ 1} \tag{2}$$

where WU refers to water use or withdrawal with the unit inch.

The change of irrigated acres was identified or calculated following:

$$Change\ of\ IA = IA_{time\ t} - IA_{time\ 0\ or\ 1} \tag{3}$$

where IA is county-level irrigated acreage with the unit acre.

The economic outcome can be represented by the net present values of returns at the county level.

$$NPV = \sum_{t=1}^{T} NR_t\ (1 + r)^{-t} \tag{4}$$

where NPV is the net present value of net returns, r is the discount rate, and NR_t is the net revenue at time t. NR_t is defined the difference between total revenue and total costs at time t:

$$NR_t = TR_t - TC_t \tag{5}$$

The net present value can be a region or county-level average value with the unit dollar/acre.

Moderator variables

Moderator variables include measures of estimate's precision, measures relating to a publication, authors, models employed, and data used in a study (Stanley et al., 2008). In this study, affiliation of the first author was identified (Texas Tech=1, otherwise=0). The publication type was used as a proxy of the quality of the study (journal article=1, otherwise=0). The methods employed in a study were used to distinguish research using a comprehensive socioeconomic database from those with simulations of direct agricultural production (IMPLAN=1, otherwise=0). The scope of a study was identified to differentiate region vs. one or several counties (North Texas Plains or larger=1, otherwise=0).

Predictor variables

The predictor variables are explanatory variables that we were primarily interested in. They include the major policies as mentioned above, converted to dummy variables (yes=1, no=0).

Analytical procedures

The analysis of the meta-data and presentation of the findings were conducted in three steps. First, for each outcome variable the effect size relating to each empirical study was calculated, and forest plots were drawn. Second, basic summary statistics for all variables corresponding to each outcome variable were calculated. Third, econometric models were run for each of the outcome variable and statistic tests were conducted. The effect size was calculated, and econometric models were run using Stata version 14.2. The forest plots were drawn using an Excel spreadsheet developed by Neyeloff et al. (2012).

Results and discussion

Meta-data overview

A summary of all selected empirical studies included for the meta-analysis is presented in Table 1. Totally 19 publications were used; they were published from 2001 to 2017 with number of authors from 1 to 10. Regarding the affiliation of the first author, Texas Tech University accounts for 7 publications, Western Texas A&M University 4, and other affiliations are Clemson University, Kansas State University, Texas A&M AgriLife, and The University of Tennessee at Martin. Twelve out of 19 studies were published in journal articles, including agricultural economics journals, i.e., Journal of Agricultural and Applied Economics, and journals addressing water management and policies, i.e., Water Policy, and Texas Journal of Agriculture and Natural Resource. The rest 7 studies were reports and agricultural economics meeting papers.

Regarding the methods, several packages were used in the empirical studies. IMpact analysis for PLANning (IMPLAN) was an input-output model to evaluate impacts of alternative scenarios, and it was used in five of the 19 publications. General Algebraic Modeling Systems (GAMS) was used alone or together with a production-risk management model CroPMan, accounting for nine studies. CroPMan were used in other 4 publications

Table 1. Summary of all selected studies included for the meta-analysis.

Source	# author	Affiliation of 1st author	Publication type	Method	Time horizon	Baseline year	Study region/county
Almas et al. (2008)	3	West Texas A&M University	SAEA meeting	GAMS, CroPMan	60	2001	Oklahoma Panhandle
Almas et al. (2017)	6	West Texas A&M University	Journal of Water Resource and Protection	GAMS, CroPMan	60	2004	North Texas Plains
Amosson et al. (2009)	7	Texas A&M AgriLife	Report	IMPLAN	60	2000	West Kansas, East Colorado, West Oklahoma, North Texas, East New Mexico
Arabiyat et al. (2001)	3	Texas Tech University	Resources, Conservation and Recycling	IMPLAN	25	1995	Hale County
Das et al. (2010)	3	Kansas State University	Journal of Agricultural & Applied Economics	CROPMAN, MODFLOW	50	2004	Southern High Plains Region of Texas
Golden et al. (2008)	3	Kansas State University	Report	IMPLAN	60	2005	Northwest Kansas
Johnson et al. (2009)	5	Texas Tech University	Water Policy	IMPLAN	50	2001	Southern High Plains Region of Texas
Luitel et al. (2015)	5	Texas Tech University	Environmental Management and Sustainable Development	GAMS, CroPMan	50	2004	Hale County
Terrell et al. (2002)	3	Texas Tech University	Water Policy	IMPLAN	30	1995	Southern High Plains region of Texas
Tewari et al. (2010)	5	West Texas A&M University	SAEA meeting	GAMS	50	2010	Region A of Texas Panhandle

Tewari et al. (2014)	6	University of Tennessee at Martin	Texas Water Journal	GAMS	60	2008	Region A of Texas Panhandle
Tewari et al. (2015)	10	University of Tennessee at Martin	Journal of Water and Climate Change	GAMS	90	2010	Hale County
Vestal et al. (2017)	4	West Texas A&M University	Journal of Water Resource and Protection	MATLAB	50	2015	Southwest Kansas
Weinheimer et al. (2013)	4	Texas Tech University	Natural Resources	GAMS, CroPMan	10	2008	Floyd, Lubbock, Yoakum Counties
Wheeler et al. (2008)	4	Texas Tech University	Journal of Agricultural & Applied Economics	GAMS, CroPMan	60	2006	Terry, Floyd Counties
Wheeler-Cook et al. (2008)	5	Texas Tech University	Texas Journal of Agriculture and Natural Resource	GAMS, CroPMan	60	2006	Southern High Plains of Texas, and Eastern New Mexico
Willis (2008)	1	Clemson University	AAEA meeting	CroPMan	50	2004	Southern High Plains region of Texas
Willis et al. (2010)	5	Clemson University	AAEA meeting	CroPMan; MODFLOW	60	2008	Castro-Lamb, Gaines-Terry, Hale-Floyd
Willis et al. (2011)	7	Clemson University	SAEA meeting	CroPMan; MODFLOW	60	2008	Castro-Lamb, Gaines-Terry, Hale-Floyd

with a hydrologic model MODFLOW. In addition, simulation software Matlab was also used in one study.

The average time horizon for simulations was 52 years with a shortest period of 10 years and longest period of 90 years. The baseline year for research was from 1995 to 2015 with a median year 2005. For the scope of water policy studies, most focused on a region, for example, Southern High Plains of Texas, while some other just did simulations for one or several counties, for instance, Hale County, or several counties in Northwest or Southwest Kansas, or in North Texas.

Due to limitations, the following sections only present results on saturated thickness. A summary of policies evaluated by selected empirical studies is presented in Table 2. Totally 13 articles documented effects of water conservation policies on saturated thickness, and total number of observations identified from all articles was 177, with the fewest 2 observations, and the most 30 observations. Among the nine policies, water use restriction was reported five times; irrigation technology adoption, and permanent conversion to dryland were reported four times.

Effect size

Eight studies were included in the calculation of the overall effect size of water policy affecting saturated thickness relative to the baseline scenario. Table 3 presents the effect sizes for each study, the overall effect size, and 95% confidence intervals, under the fixed effect model. The forest plot on the right depicts all the individual and overall effect sizes. Compared to the baseline scenario (i.e., no policy intervention), the overall effect size

Table 2. Summary of policies evaluated by selected studies focusing on saturated thickness (N=177).

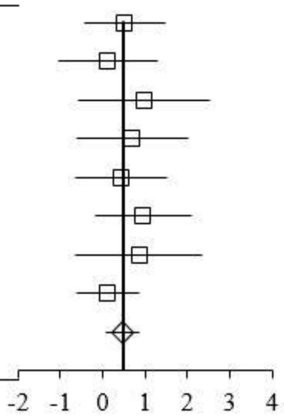
		Policies									
Source	**n**	**Baseline**	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**
Almas et al (2008)	3							Y			
Almas et al (2017)	30	Y		Y	Y	Y	Y	Y			
Amosson et al (2009)	21	Y		Y	Y	Y	Y	Y			
Arabiyat et al (2001)	4	Y			Y	Y					
Johnson et al (2009)	3	Y	Y	Y							
Luitel et al (2015)	2	Y	Y								
Terrell et al (2002)	20					Y					
Tewari et al (2014)	16	Y		Y							
Tewari et al (2015)	8								Y		
Vestal et al (2017)	12	Y						Y			
Wheeler et al (2008)	6	Y		Y							
Wheeler-Cook et al (2008)	24	Y									
Willis et al (2010)	28	Y								Y	Y

Notes: A: Water fee policy; B: Water use restriction; C: Biotechnology; D: Irrigation technology; E: Temporary conversion to dryland; F: Permanent conversion to dryland; G: Climate change scenarios; H: Heterogeneous land uses; I: Heterogeneous aquifer characteristics.
Y denotes such a policy was evaluated in a study.

Hedge's g is 0.47 (95% CI [0.9, 0.86]), which indicates water conservation policies were effective than no intervention, and the overall effect size is almost medium (Cohen, 1992). Significant heterogeneity between studies was not observed (Q(7)=2.72, p>0.10). While the overall effect is important, effects of each individual policy and moderator variables can be specifically estimated using econometric models while holding others constant.

Table 3. Effect size (Hedge's g) and forest plot for changes of saturated thickness in each study (95% confidence interval (CI)) (using an Excel spreadsheet provided in Neyeloff et al, 2012).

Source	Hedge's g	Standard Error	CI lower	CI upper
Almas et al (2017)	0.523	0.484	-0.426	1.471
Amosson et al (2009)	0.118	0.600	-1.057	1.293
Arabiyat et al (2001)	0.993	0.793	-0.562	2.548
Johnson et al (2009)	0.705	0.680	-0.628	2.039
Tewari et al (2014)	0.442	0.556	-0.647	1.532
Vestal et al (2017)	0.957	0.583	-0.186	2.101
Wheeler et al (2008)	0.855	0.772	-0.658	2.368
Willis et al (2010)	0.119	0.377	-0.619	0.857
Summary	0.474	0.197	0.087	0.860



Meta-regression analysis

Descriptive statistics of variables relating to saturated thickness

Table 4 presents the description of variables and summary statistics. The dependent variable, change of saturated thickness, has a mean value of 59 feet. This suggests a reduction of saturated thickness was estimated to be 59 feet in Southern Ogallala Aquifer region over the average simulation horizon.

A third of the studies have their first author from Texas Tech, and 71% of the studies were published in journals. About 27% of the studies employed IMPLAN, compared to other model combinations. About 38% of publications use South High Plains of Texas or a larger area as the study area, while more studies just use one or several counties.

Regarding the policy variables, irrigation technology, and water use restriction are the major policies, accounting for 17%, and 14%, respectively, followed by permanent conversion to dryland, heterogeneous land use and aquifer characteristics, accounting for about 8%.

Results from meta-regression analysis

Before running regressions using a subset of the meta-data for the saturated thickness, correlations between all independent variables were estimated. The absolute values of correlation coefficients for each pair was smaller than 0.40. The average variance inflation factor (VIF) was 1.72 with all VIF values smaller than 4, where a VIF of greater than 8 suggests a variable may show a linear relation with other independent variables in the model (Fan et al., 2017). The low VIF indicates no multicollinearity problem. Since the dependent variable is continuous, we use OLS to estimate the parameter. The adjusted R^2 is 0.68, suggesting 68% of the total variation of change in saturated thickness is explained by the independent variables. The F value ($p<0.001$) indicates the overall OLS model is significant in predicting the dependent variable.

The estimation results from OLS are also presented in Table 4. The first author's affiliation shows a negative effect, suggesting simulation results by Texas Tech authors tend to show significant water conservation because of policy implementation. Published as a

Table 4. Summary statistics of variables related to saturated thickness and estimates from ordinary least squares (OLS).

Variable	Description	Mean (SE)	Coef. (SE)
Dependent variable			
ST_Change	Change of saturated thickness at time t and time 0 or 1 (feet)	59.158 (2.654)	
Independent variable			
Moderator variable			
Affiliation	1st author affiliation (Texas Tech=1, otherwise=0)	0.333 (0.036)	−72.122*** (5.591)
Journal	Published in a journal (yes=1, otherwise=0)	0.706 (0.034)	35.400*** (5.639)
Method	Method is IMPLAN (yes, otherwise=0)	0.271 (0.034)	9.373 (6.672)
Region	Study area is South High Plains of Texas or larger (yes=1, one or several counties=0)	0.384 (0.037)	−5.062 (5.670)
Policy variable (reference category=baseline)			
WaterFee	Water fee policy (yes=1, no=0)	0.011 (0.008)	9.292 (14.873)
WaterUseRe	Water use restriction (yes=1, no=0)	0.141 (0.026)	−9.523* (5.142)
Biotech	Biotechnology (yes=1, no=0)	0.056 (0.017)	−18.670** (7.297)
IrrigationTech	Irrigation technology (yes=1, no=0)	0.169 (0.028)	−16.187*** (6.246)
TemporaryCon	Temporary conversion to dryland production (yes=1, no=0)	0.045 (0.016)	−10.559 (7.955)
PermanentCon	Permanent conversion to dryland production (yes=1, no=0)	0.079 (0.020)	−22.256*** (6.402)
ClimateChange	Climate change scenarios (yes=1, no=0)	0.045 (0.016)	−53.143*** (7.983)
HeterLandUse	Heterogeneous land uses (yes=1, no=0)	0.079 (0.020)	0.320 (9.041)
HeterAquiferChar	Heterogeneous aquifer characteristics (yes=1, no=0)	0.079 (0.020)	−3.846 (9.041)
Constant			67.559*** (4.802)
R-sq			0.70
Adj R-sq			0.68
F			29.73
Prob > F			<0.0001
Average VIF			1.72
N			177

Notes: ***significant at 1%; ** significant at 5%; * significant at 10%.

journal article shows a positive effect on the change of saturated thickness. Surprisingly, the variables relating to method and region are not significant.

For policy variables, compared to the reference category, baseline scenario (i.e., no policy implemented), water use restriction, biotechnology, irrigation technology adoption, permanent conversion to dryland, and climate change scenarios show significant effects on the change of saturated thickness. The negative sign indicates a decrease of the change, in other words, less change means water conservation. Surprisingly, the climate change scenarios show the largest effect with an absolute value of 53. In addition, permanent dryland conversion, biotechnology, and irrigation technology conserves water withdrawal with an estimated change of saturated thickness of 22 feet, 19 feet, and 16 feet, respectively.

The robustness of the OLS model has been evaluated using all policy variables only in the regression. Due to the limited observations for some of the variables and the embedded nature of the meta-data, more analyses will be conducted to explore possible improvements in model specification, variable selection and construction.

Conclusion and implications

To investigate water conservation policies and evaluate their effects in the Ogallala Aquifer region, a systematic literature search and review identified 19 publications including journal articles, conference papers, and project reports. Extracting data relating to the nine major water policies and moderator variables allows us to analyze policy effects on saturated thickness, water use, irrigated acreage, and economic returns in an aggregated manor using meta-analysis. With increasing applications of meta-analytical techniques, the effect size and regression coefficients estimated in this study focusing on policy effects on saturated thickness provide helpful insights for water policy design and programs to address regional priorities.

The negligible heterogeneity between studies reporting saturated thickness outcomes may be due to several aspects. Most studies adopted the non-linear dynamic optimization models developed in Segarra and Feng (1994) which incorporate hydrologic conditions, major agricultural production, and economic outcomes. Major simulation methods are not significantly different in predicting saturated thickness. The study areas in the selected studies are in the Southern Ogallala region, with more than half focusing on South High Plains region of Texas. More importantly, the local water authorities of groundwater management districts help achieve cost effective implementation of policies in coordination with stakeholders.

The insignificant effect of water use fee indicates pricing irrigation water is not effective in arid and semi-arid High Plains where agricultural production highly relies on groundwater. Water price is ineffective to regulate extraction when water demand is inelastic (Wang & Segarra, 2011). Compared with permanent conversion to dryland, the temporary conversion is not effective in a long-run to reduce water withdrawal. Thus, incentives to encourage farmers to participate dryland conversions not only emphasize short-run outcomes on water use reduction and revenue, but also the sustainability of environment and the underlying aquifer.

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