texaswaterjournal.org

An online, peer-reviewed journal
published in cooperation with the
Texas Water Resources Institute

Texas Water Journal

Volume 9 Number 1 | 2018

Texas Water Journal

Volume 9, Number 1
2018
ISSN 2160-5319

texaswaterjournal.org

THE TEXAS WATER JOURNAL is an online, peer-reviewed journal devoted to the timely consideration of Texas water resources management, research, and policy issues. The journal provides in-depth analysis of Texas water resources management and policies from a multidisciplinary perspective that integrates science, engineering, law, planning, and other disciplines. It also provides updates on key state legislation and policy changes by Texas administrative agencies.

For more information on TWJ as well as TWJ policies and submission guidelines, please visit texaswaterjournal.org.

Editorial Board
Todd H. Votteler, Ph.D.
Editor-in-Chief
Collaborative Water Resolution LLC

Kathy A. Alexander, Ph.D.

Gabriel Collins, J.D.
Center for Energy Studies
Baker Institute for Public Policy

Robert L. Gulley, Ph.D.
Texas Comptroller of Public Accounts

Robert E. Mace, Ph.D.
Meadows Center for Water and the Environment
Texas State University

Ken A. Rainwater, Ph.D.
Texas Tech University

Rosario Sanchez, Ph.D.
Texas Water Resources Institute

Managing Editor
Kathy Wythe
Texas Water Resources Institute

Layout Editor
Sarah Richardson
Texas Water Resources Institute

Staff Editor
Kristina J. Trevino, Ph.D.

The Texas Water Journal is published in cooperation with the Texas Water Resources Institute, part of Texas A&M AgriLife Research, the Texas A&M AgriLife Extension Service, and the College of Agriculture and Life Sciences at Texas A&M University.

Texas Water Resources Institute
make every drop count

Cover photo: Sunrise over Coastal Bend Bays & Esturaries Program land. ©*2017* John Reuthinger. See winning photos at WildlifeinFocus.org

Texas Water Resources Institute
Texas Water Journal
Volume 9, Number 1, June 20, 2018
Pages 69–81

Seasonal changes of groundwater quality in the Ogallala Aquifer

Timothy S. Goebel[1], John E. Stout[1] and Robert J. Lascano[1]*

Abstract: The Ogallala Aquifer extends beneath eight states in the Great Plains region of North America. It stretches from Texas to South Dakota and is among the largest aquifers in the world. In Texas, extraction of groundwater, primarily for cropland irrigation, far exceeds recharge resulting in a significant decline of the water table. In the Texas High Plains, this decline prompted restrictions set by a local water conservation agency in 2009 stating that in 50 years about 50% of the saturated thickness of the Ogallala Aquifer should be preserved. However, this restriction only addressed the quantity and not the quality of the remaining water. The quality of water extracted from the Ogallala Aquifer has been observed to change over time, especially over the length of a crop's growing season. We measured water quality over a three-year period using an electrical conductivity sensor and measured depth to water at 20 locations across five counties in the Texas High Plains. Results show that when wells are actively pumping, water quality can change in complex and unpredictable ways. In some cases, water quality declined and in others water quality improved. This result has prompted us to further investigate the mechanisms involved in observed seasonal water quality changes.

Keywords: Ogallala Aquifer, water quality, groundwater, irrigation, conductivity

[1] Wind Erosion and Water Conservation Research Unit, Cropping Systems Research Laboratory, USDA-ARS#, 3810 4th Street, Lubbock, TX 79415

*Corresponding author: Robert.Lascano@ars.usda.gov

#USDA-ARS is an equal opportunity provider and employer.

Citation: Goebel TS, Stout JE, Lascano RJ. 2018. Seasonal changes of groundwater quality in the Ogallala Aquifer. Texas Water Journal. 9(1):69-81. Available from: https://doi.org/10.21423/twj.v9i1.7067.

© 2018 Timothy S. Goebel, John E. Stout, Robert J. Lascano. This work is licensed under the Creative Commons Attribution 4.0 International License. To view a copy of this license, visit https://creativecommons.org/licenses/by/4.0/ or visit the TWJ website.

Terms used in paper

Short name or acronym	Descriptive name
ARS	Agricultural Research Service
CP	center pivot
°C	degrees Celsius
EC	electrical conductivity
km^2	square kilometers
m	meter
mg/L	milligrams per liter
mL	milliliter
SDI	subsurface drip irrigation
THP	Texas High Plains
TDS	total dissolved solids
USDA	U.S. Department of Agriculture
µS/cm	micro-Siemens per centimeter

INTRODUCTION

The Ogallala Aquifer extends across an area of approximately 450,000 square kilometers (km^2) (173,746 square miles) and is among the largest aquifers in the world (http://water.usgs.gov/ogw/aquiferbasics/ext_hpaq.html). This vast aquifer extends across portions of eight states where it is the primary source of irrigation water for various crops, accounting for 27% of the irrigated land in the United States (Darton 1898; Gollehon and Winston 2013). In the Southern High Plains, the Ogallala formation was deposited by ancient rivers that once flowed west to east from the mountains of New Mexico. Remnant paleo-valleys such as the Winkler, Simanola, and Portales valleys have been identified and mapped by geologists that have studied the area (Holliday 1995). These valleys were sequentially abandoned as the Pecos Valley formed and provided a new path to the Rio Grande and ultimately to the Gulf of Mexico. The waters contained within the Ogallala sands and gravels deposited by these ancient streams were subsequently covered and preserved by aeolian deposits, such as the Blackwater Draw formation (Robbins 1941).

Today, the Ogallala Aquifer is being depleted at a rapid rate. Changes in the saturated thickness of an aquifer respond to changes in the balance between recharge and discharge. On the High Plains of the Llano Estacado, the only significant source of recharge is precipitation; however, hydrogeological studies have shown for decades that groundwater withdrawals exceed the amount of recharge by a large margin (Cronin 1969; McGuire 2014). Thus, despite its critical importance to irrigated agriculture, the Ogallala Aquifer is being depleted at a rapid rate (Dutton et al. 2001; Custodio 2002; Whitehead 2007; McGuire 2014). Depth-to-water measurements obtained each year by the High Plains Underground Water Conservation District indicated that the saturated thickness of the aquifer has dropped at an average rate of 0.3 meters (m), or 1 foot, per year since 1985 (McCain 1996; HPWD 2014). During drought conditions, the depletion of the aquifer can accelerate to nearly twice this long-term rate (Mullican 2013).

While conservation of the quantity of groundwater is important, the quality of the remaining groundwater is equally important (Chaudhuri and Ale 2014; Ledbetter 2014). It has been suggested that the impact of increased salinization of freshwater is a significant threat to global water resources (Williams 2001). Aqueous salinity is a measure of the dissolved mineral content of water and is reported in units of milligrams per liter (mg/L) total dissolved solids (TDS). The quality of water produced from the Ogallala Aquifer generally falls into the category of brackish (1,000–10,000 mg/L TDS) (Hanor 1994). The Dockum Aquifer, a second aquifer that underlies the Ogallala Aquifer, and is categorized as saline, typically has TDS values exceeding 10,000 mg/L (Hanor 1994). In general, water quality decreases in the lower sections of the saturated thickness of an aquifer (Hanor 1994; Druhan et al. 2008). This phenomenon is one of the causes of increased salinization of aquifers over time in agricultural regions above the Ogallala Aquifer, pumping of available groundwater for irrigation creates a situation where this common mechanism for groundwater salinization occurs (Druhan et al. 2008). Typically, there would be a diffuse mixing layer of variable thickness that would separate areas of higher and lower salinity. Pumping of groundwater induces the migration of poorer quality water (such as that in the Dockum), and if pumping rates are high enough, the saline water can enter the well's capture zone resulting in increased salinity of irrigation water (Kreitler 1993).

While it is commonly accepted that the deeper water in an aquifer is more saline (Hanor 1994; Druhan et al. 2008), of interest to agricultural producers in the Texas High Plains (THP) is the quality of the deeper and more saline water and its suitability for irrigation, which would be accessed in the later months of the growing season. On the THP and during the growing season there is a need for irrigation during the dry period from the end of July to early September. Irrigation wells are generally running at full capacity to compensate for the lack of rain during this critical period. The objective of this study was to sample the quality of the water in a number of irrigation wells across several counties in the THP during the growing season (1 April to 1 October) (Howell et al. 1996; Lascano 2000; Bordovsky et al. 2012; TAWC 2013). We hypothesized that as the cone of depression, caused by water extraction, expanded to deeper depths the water pumped for irrigation would become more saline. This assessment is needed to understand the long-term impact of lower quality water on crop irrigation.

METHODS

Well Sampling

Water samples were taken from all sites at approximately two-week intervals starting in spring of 2014 and continuing through 2016. When the wells were in operation, water samples were obtained from spigots on wells. If the wells were inactive, then pencil bailers (EcoBailer, ECOPVC 703, Mississauga, Ontario, Canada[1]) were used to obtain water samples. Water samples were placed in 60 milliliter (mL) vials (Thomas Scientific, pre-cleaned clear vial with 0.1 SEPTA cap, 9-093-2, Swedesboro, New Jersey). When the wells were not active, depth-to-water measurements were obtained with an "electric line" water level sensor (Solinst, Model 102, Georgetown, Ontario, Canada). Water samples were then filtered through a 0.2-millimeter filter and tested for pH (Mettler Toledo, MA235 pH/Ion Analyzer with InLab 413 pH Probe, Columbus, Ohio) and electrical conductivity (EC) was measured with a conductivity sensor (Thermo Orion, Model 105A with 011050 conductivity cell, Waltham, Massachusetts). Thereafter, remaining water samples were placed in a 20 mL vial (National EPA Vial Kit) and stored at 4 degrees Celsius (°C) (39 degrees Fahrenheit).

Site Description

A total of 20 irrigation wells were selected for sampling. The selected wells spanned five counties of the THP, which from south to north included Terry, Lubbock, Hockley, Cochran, and Lamb counties (Figure 1). Permission was obtained from producers to access the irrigation wells at sites shown on the map (Figure 2). Due to privacy and agreement with the landowners, the specific location of each irrigation well remains

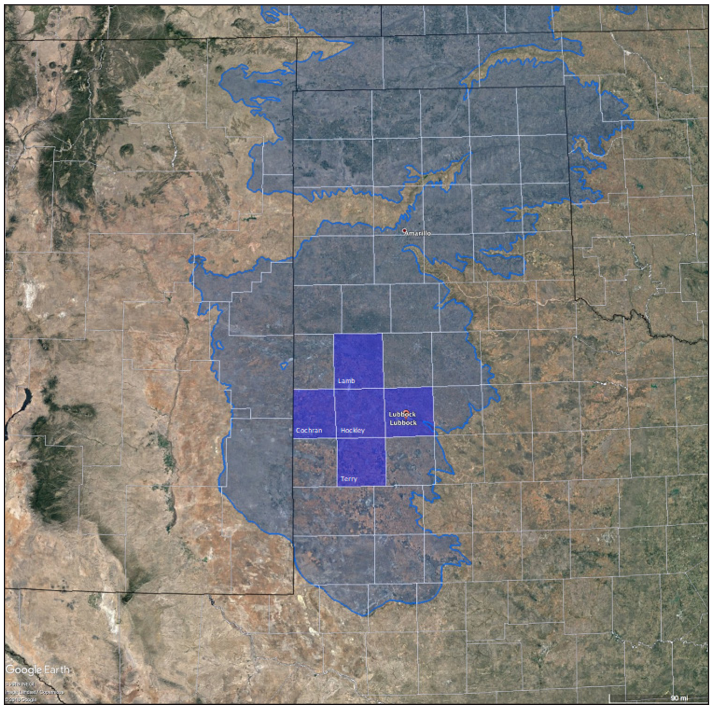

Figure 1. Location of the five counties where study was conducted with respect to the Texas border and the underlying Ogallala Aquifer (courtesy of Google Earth® using data from the USGA National Atlas).

---

[1] Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

Table 1. General description of the 20 irrigation wells located in five counties of the THP and used for sampling in our study.

County	Well #	General Use	Well Depth in Meters (feet)	Irrigation System	Crops Irrigated	Soil Series	Sampling Period
Lubbock	1	Irrigation	51 (167)	SDI & CP[1]	Cotton, Sorghum & Peanuts	Amarillo	Nov 2012–Sep 2016
	2	Abandoned	49 (161)				
Terry	1	Residential	52 (171)				Nov 2013–Dec 2016
	2	Residential	50 (164)				
	3	Irrigation	50 (164)	CP	Cotton & Peanuts	Patricia & Amarillo	
	4	Irrigation	52 (171)	CP	Cotton & Peanuts	Patricia & Amarillo	
Hockley	1	Irrigation	46 (151)	SDI	Cotton	Amarillo & Ranco	Nov 2013–Dec 2016
	2	Irrigation	45 (148)	CP	Cotton	Amarillo & Ranco	
	3	Irrigation	47 (154)	CP	Cotton	Amarillo & Ranco	
	4	Irrigation	76 (249)	CP	Cotton	Amarillo & Ranco	
	5	Irrigation	65 (213)	CP	Cotton	Amarillo & Ranco	
Lamb	1	Irrigation	53 (174)	SDI	Cotton, Sorghum & Wheat	Amarillo, Midessa & Olton	June 2014–Dec 2016
	2	Irrigation	62 (203)	CP	Cotton, Sorghum & Wheat	Amarillo, Midessa & Olton	
	3	Irrigation	52 (171)	CP	Cotton, Sorghum & Wheat	Amarillo, Midessa & Olton	
	4	Irrigation	51 (167)	CP	Cotton, Sorghum & Wheat	Amarillo, Midessa & Olton	
Cochran	1	Storage – Fracking	N/A			Patricia & Amarillo	July 2014–Dec 2016
	2	Irrigation	73 (240)	SDI & CP	Cotton, Sorghum & Peanuts	Patricia & Amarillo	
	3	Irrigation	76 (249)	SDI & CP	Cotton, Sorghum & Peanuts	Patricia & Amarillo	
	4	Irrigation	75 (246)	SDI & CP	Cotton, Sorghum & Peanuts	Patricia & Amarillo	
	5	Irrigation	71 (233)	SDI & CP	Cotton, Sorghum & Peanuts	Patricia & Amarillo	

[1] Subsurface drip irrigation (SDI) and center pivot (CP) irrigation.

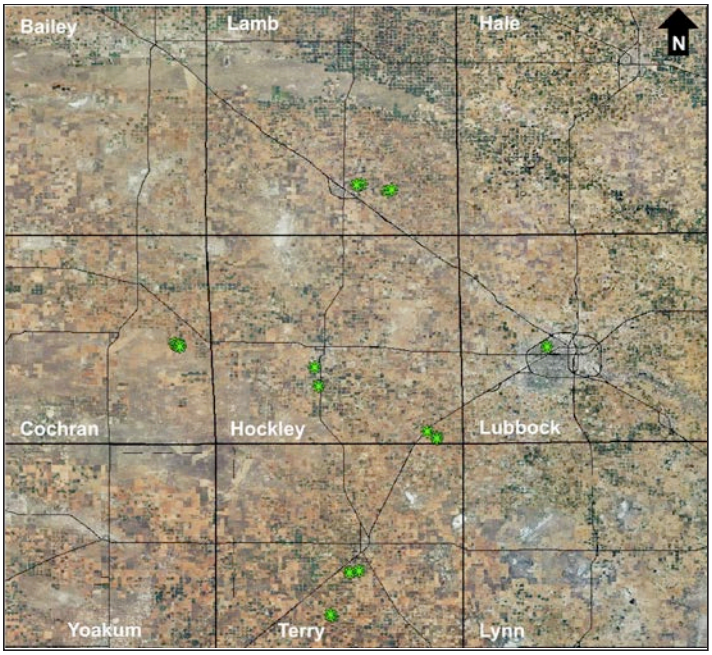

Figure 2. Location of 20 irrigation wells sampled in Terry, Hockley, Lubbock, Cochran, and Lamb counties in the Texas High Plains. (From: Esri®ArcMap™10.2.0.3348).

confidential. A general description of the irrigation wells used in our study is provided in Table 1.

Lubbock County

Two wells were located in Lubbock County separated by approximately 100 m (328 feet) (Figure 2). One well is actively used for irrigation while the other is an abandoned well that was converted to an observation well. The well that is actively used for crop irrigation is located at the U.S. Department of Agriculture (USDA) Agricultural Research Service (ARS) Plant Stress and Water Conservation Laboratory and is used to irrigate several different crops including cotton (*Gossypium hirsutum* L.), sorghum (*Sorghum bicolor* L.), and peanuts (*Arachis hypogaea* L.) using subsurface drip irrigation (SDI) as well as a two-span center pivot (CP) irrigation system. The soil type is classified as Amarillo soil series (fine-loamy, mixed, thermic Aridic Paleustalf). These wells were part of our initial assessment and they have been sampled since November 2012.

Terry County

Four irrigation wells were selected in Terry County (Figure 2). Two of these wells are for residential use only and were permanently in operation while the other two were used to irrigate cotton and peanuts using CP irrigation. The soil types are Patricia (fine-loamy, mixed, superactive, thermic Aridic Paleustalf) and Amarillo loamy fine sands. These wells were sampled starting in November 2013.

Hockley County

We sampled five irrigation wells in Hockley County (Figure 2). All of these wells were used to irrigate a cotton crop. One well supplied water to a SDI and the other four fed into CP irrigation systems. The soil types being irrigated were Amarillo fine sandy loam and Ranco (very-fine, smectitic, thermic Ustic Epiaquerts) clay. These wells were sampled starting in November 2013.

Lamb County

Four irrigation wells were sampled in Lamb County (Figure 2). All of these wells were used for irrigation of crops including cotton, sorghum, and winter wheat (*Triticum aestivum* L.). Three wells were used for SDI and one well was used for CP irrigation. The soil types being irrigated were Amarillo fine sandy loam, Midessa (fine-loamy, mixed, superactive, thermic Aridic Calciustepts) fine sandy loam, and Olton (fine, mixed, superactive, thermic Aridic Paleustolls) loam. These wells were sampled starting in June 2014.

Cochran County

A total of five irrigation wells were sampled in Cochran County (Figure 2). These wells are part of a corporate farm that, in addition to using water for agricultural irrigation, was also selling water for oil-field operations, such as hydraulic fracturing. The result was that while most irrigation wells were not in operation during the winter some of the wells were operational to provide water to a storage tank (~75,000 liters, or ~19,800 gallons) until it was transported off site. The first irrigation well on this site was taken from a valve on the above-mentioned storage tank. The rest of the irrigation wells fed both CP as well as SDI systems. The irrigated crops are primarily cotton, sorghum, and peanuts. The surface soil types in this area include Patricia and Amarillo loamy fine sands. These wells were sampled starting in July 2014.

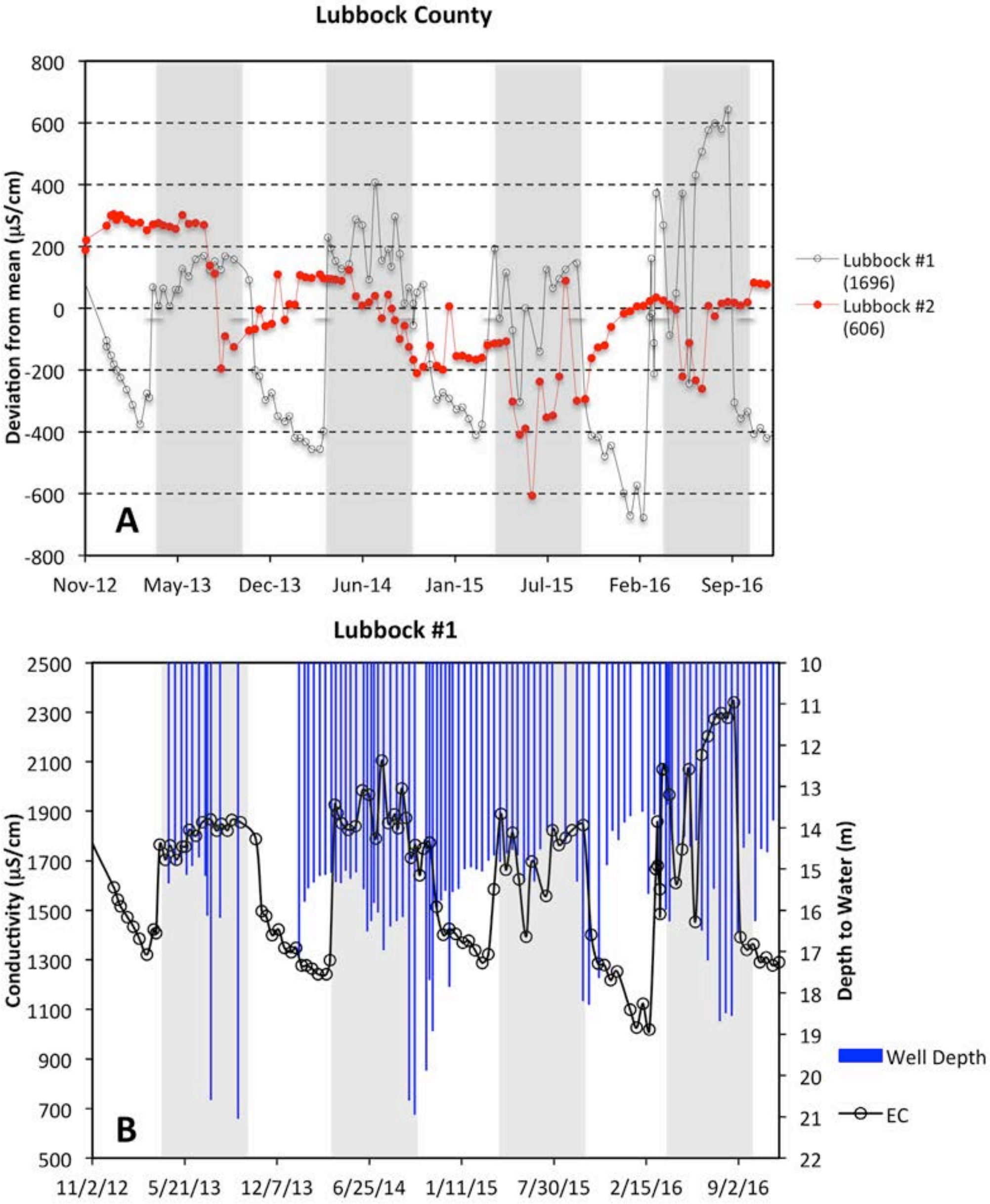

Figure 3. (a) Deviation from the mean value of electrical conductivity (µS/cm) measured throughout the sampling period for four irrigation wells in Lubbock County. (b) Electrical conductivity (µS/cm) and depth (m) to water table of Well #1 in Lubbock County. The shaded area denotes the crop-growing season for the year.

RESULTS AND DISCUSSION

Lubbock County

The initial phase of our investigation focused on the quality of irrigation water within two wells located at the Plant Stress and Water Conservation Laboratory in Lubbock County (Figure 2). During the first two years, seasonal changes in EC (peak to trough) was as high as 30% (Figure 3a), and it was this unexpected result that led us to further investigate possible seasonal variations of groundwater water quality. We wanted to evaluate if the seasonal change in water quality was common on the high plains of Texas or if this was simply a local anomaly. The measured EC of the water in these two irrigation wells was quite different (Figure 3a) considering that these wells were spaced only 100 m (328 feet) from each other. The values of EC are shown as a deviation from the mean EC for all sampled wells and this comparison reveals significant seasonal changes

Table 2. The mean electrical conductivity (µS/cm) of the water sampled at each of the 20 irrigation wells in Lubbock, Terry, Hockley, Lamb, and Cochran counties in the THP. Also given is the calculated average slope over time.

County	Well #	Slope	Mean Electrical Conductivity (µS/cm)
Lubbock	1	–0.57	1,696
	2	–1.34	606
Terry	1	–0.18	2,037
	2	0.15	1,346
	3	–0.42	2,788
	4	–0.76	2,423
Hockley	1	0.71	1,044
	2	0.38	1,249
	3	0.79	1,329
	4	–0.80	1,011
	5	0.37	1,167
Lamb	1	–0.27	2,884
	2	–0.02	3,528
	3	–0.41	1,183
	4	0.10	1,503
Cochran	1	–0.18	1,348
	2	–0.01	1,344
	3	–0.01	1,767
	4	–0.03	1,761
	5	–0.04	1,201

in EC (Figure 3a). The mean EC, over a five-year span, was 1,696 micro-Siemens per centimeter (µS/cm) at the active irrigation well identified as Lubbock #1 and 606 µS/cm at the inactive observation well (Lubbock #2), and this difference of 1,090 µS/cm represents an increase of 180% (Table 2). Irrigation Well #1 showed an increase in EC during the growing season when it was actively pumping (Figure 3a). Both of the wells trended toward improved water quality, i.e., lower EC over the course of five years, and more noticeably towards the end of each growing seasons. For these particular two irrigation wells, the results suggest that this trend repeats each year; however, the extent of the increase of EC within the growing season and decrease thereafter is not well defined.

Also shown in Figure 3b is the measured depth to the water table for Lubbock Well #1. Note that depth to water increased toward the end of each growing season, e.g., 20 m (66 feet) in 2013 and 2014 and 18 m (59 feet) in 2015 and 2016. In between growing seasons, the depth to water stabilized at around 15 m (49 feet).

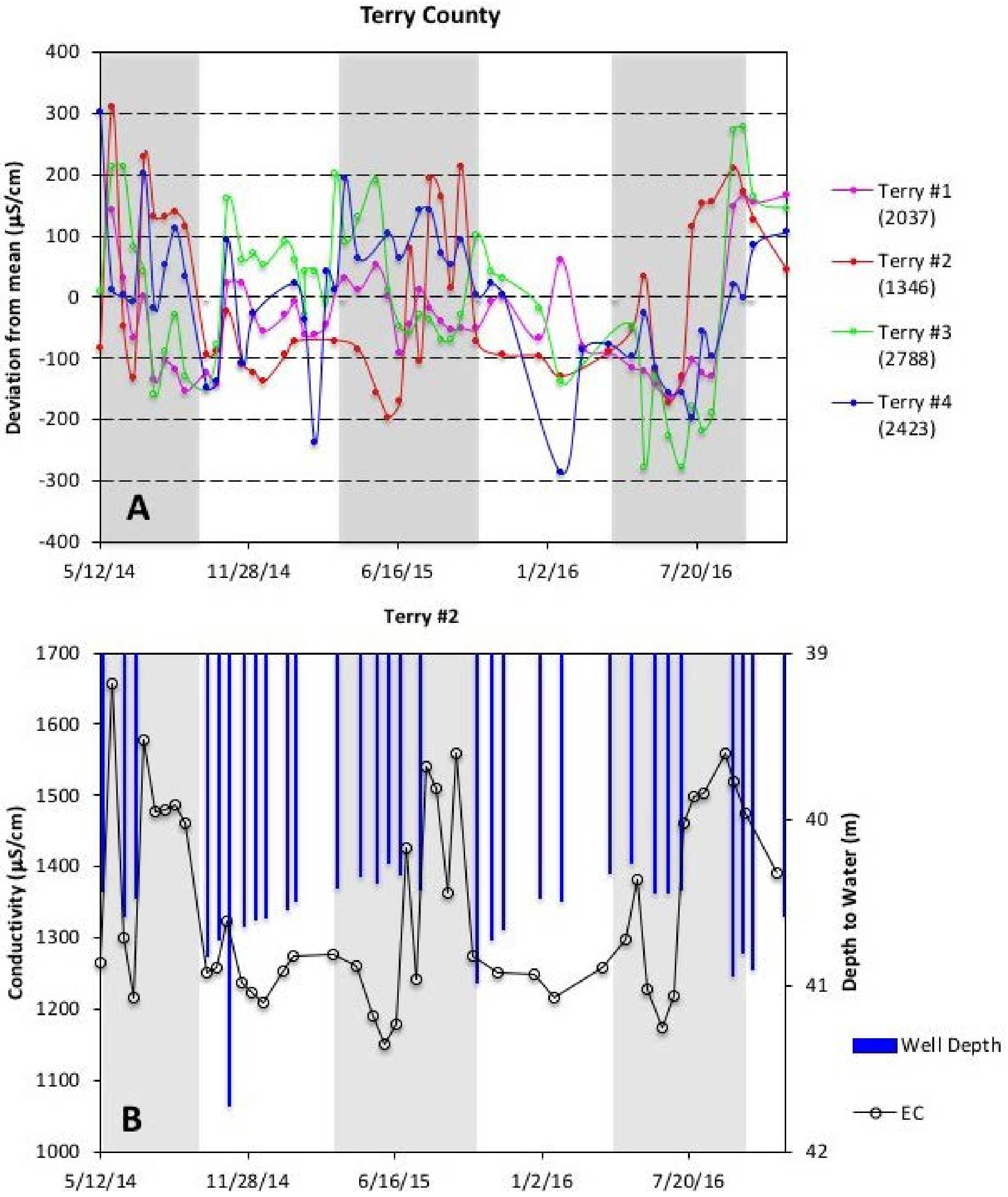

Figure 4. (a) Deviation from the mean value of electrical conductivity (µS/cm) measured throughout the sampling period for four irrigation wells in Terry County. (b) Electrical conductivity (µS/cm) and depth (m) to water table of Well #2 in Terry County. The shaded area denotes the crop-growing season for the year.

Terry County

In general, the four sampled irrigation wells in Terry County did show some evidence of changes in EC relative to the mean value during the growing season (Figure 4a), and three of the four wells tended to show improved water quality, i.e., a negative slope, over the course of the three growing seasons (Table 2). In fact, irrigation well Terry #2 showed an increase in EC from 1,150 µS/cm to 1,560 µS/cm during the active irrigation period in 2015 (Figure 4b). Observations made at irrigation well Terry #2 showed that in each growing season, when the wells were actively pumped, EC increased by as much as 28%. The depth to the water table for Terry #2 showed a value of 41 ± 1 m (135 ± 3.3 feet) over the three growing seasons (Figure 4b).

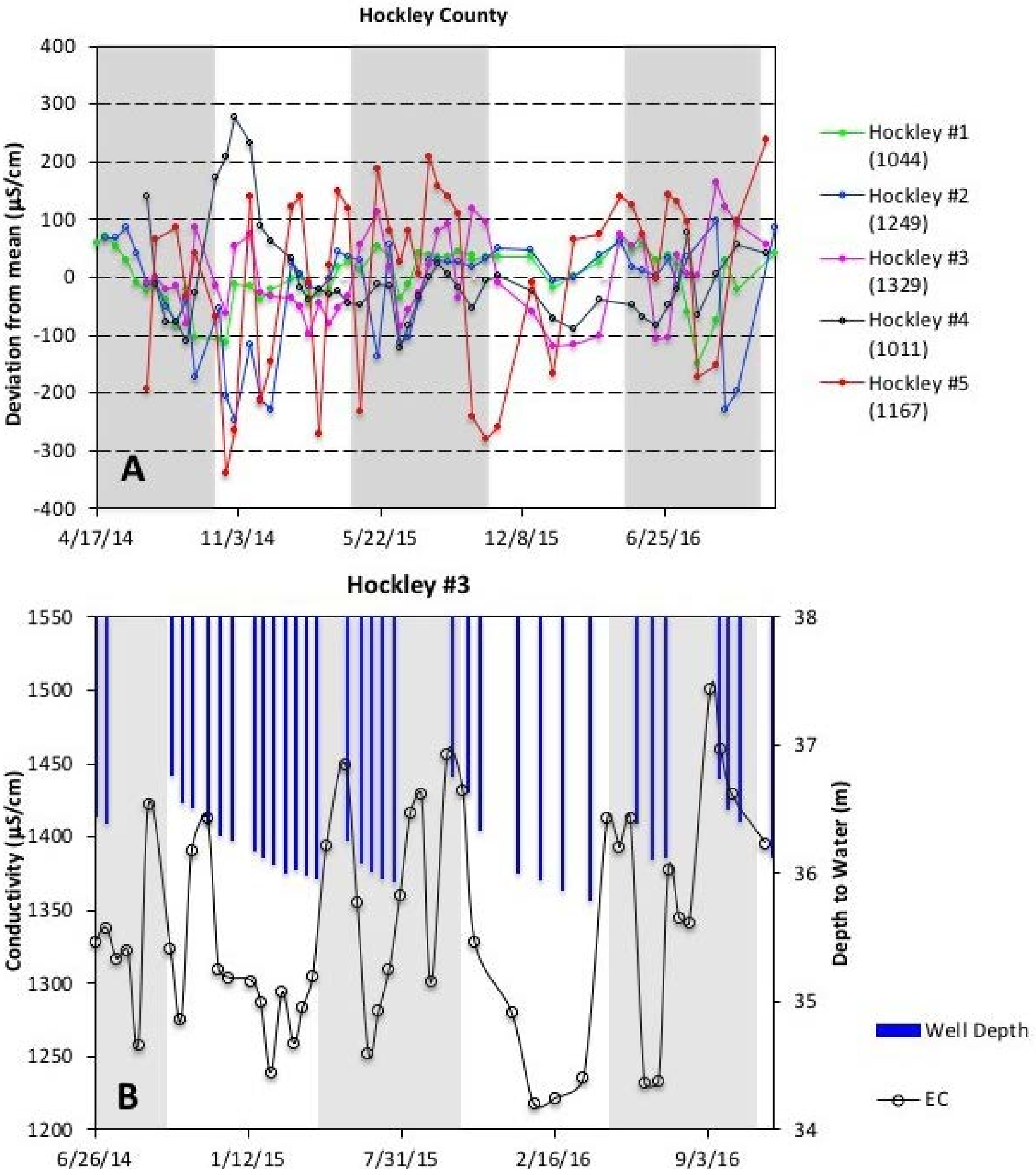

Figure 5. (a) Deviation from the mean value of electrical conductivity (µS/cm) measured throughout the sampling period for five irrigation wells in Hockley County. (b) Electrical conductivity (µS/cm) and depth (m) to water table of Well #3 in Hockley County. The shaded area denotes the crop-growing season for the year.

Hockley County

The EC of the five-sampled irrigation wells over three growing seasons for Hockley County is shown in Figure 5a. The values of EC are shown as a deviation from the mean EC for all sampled wells, and this comparison reveals significant seasonal changes in EC (Figure 5a). Four of the five wells trended toward higher EC over the three-year period (Table 2). One well, Hockley #3, did show some response to active pumping during the growing season where in the off-season the EC would gradually drift to lower values, ultimately changing as much as 17% (peak to trough) (Figure 5b). During the growing season, it would quickly become more saline and recover within two to four weeks after the wells were turned off due to rain. The depth-to-water values showed a consistent pattern of increasing about 1 m (3.3 feet) from the start to the end of the irrigation period for each of the growing seasons (Figure 5b).

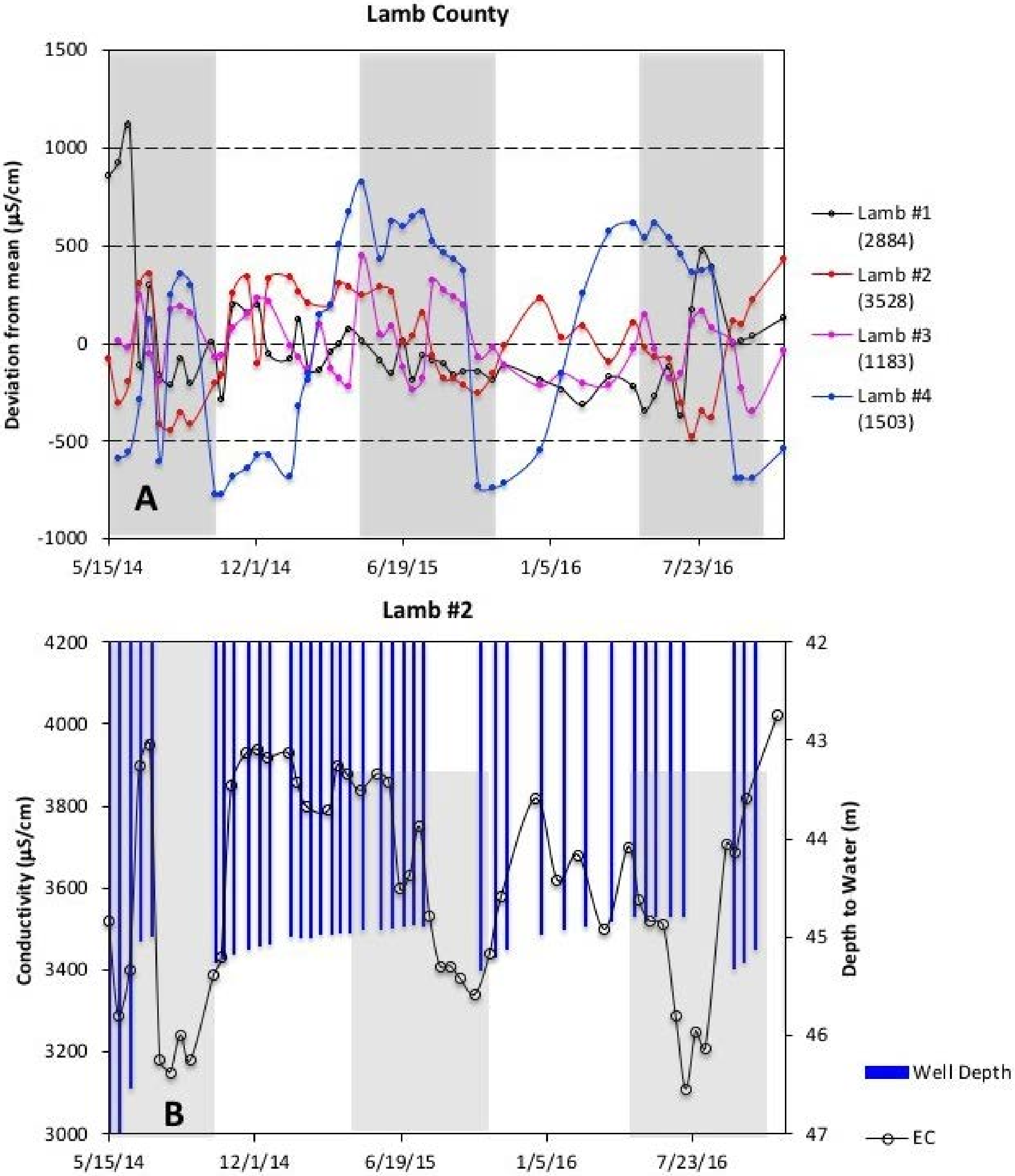

Figure 6. (a) Deviation from the mean value of electrical conductivity (µS/cm) measured throughout the sampling period for four irrigation wells in Lamb County. (b) Electrical conductivity (µS/cm) and depth (m) to water table of Well #2 in Lamb County. The shaded area denotes the crop-growing season for the year.

Lamb County

In Lamb County two of the four wells showed a seasonal change in EC while the other two wells did not (Figure 6a). In addition, three of the irrigation wells trended to lower values of EC over the three-year period while one well drifted in the opposite direction of increasing EC (Table 2). Lamb #4 showed a response similar to that of other wells in other counties, i.e., an increase in EC when the wells were actively pumping during the growing season. However, Lamb #2 responded to active pumping in the opposite direction (Figure 6b). For example, in 2014 EC decreased to 3,200 µS/cm during the irrigation period and increased to about 4,000 µS/cm in the winter. The same trend was measured during the 2015 growing season, with an EC of 3.400 µS/cm during the growing season and increasing to about 3.800 µS/cm thereafter (Figure 6b). There was no discernible pattern on the measured values of depth to water (Figure 6b).

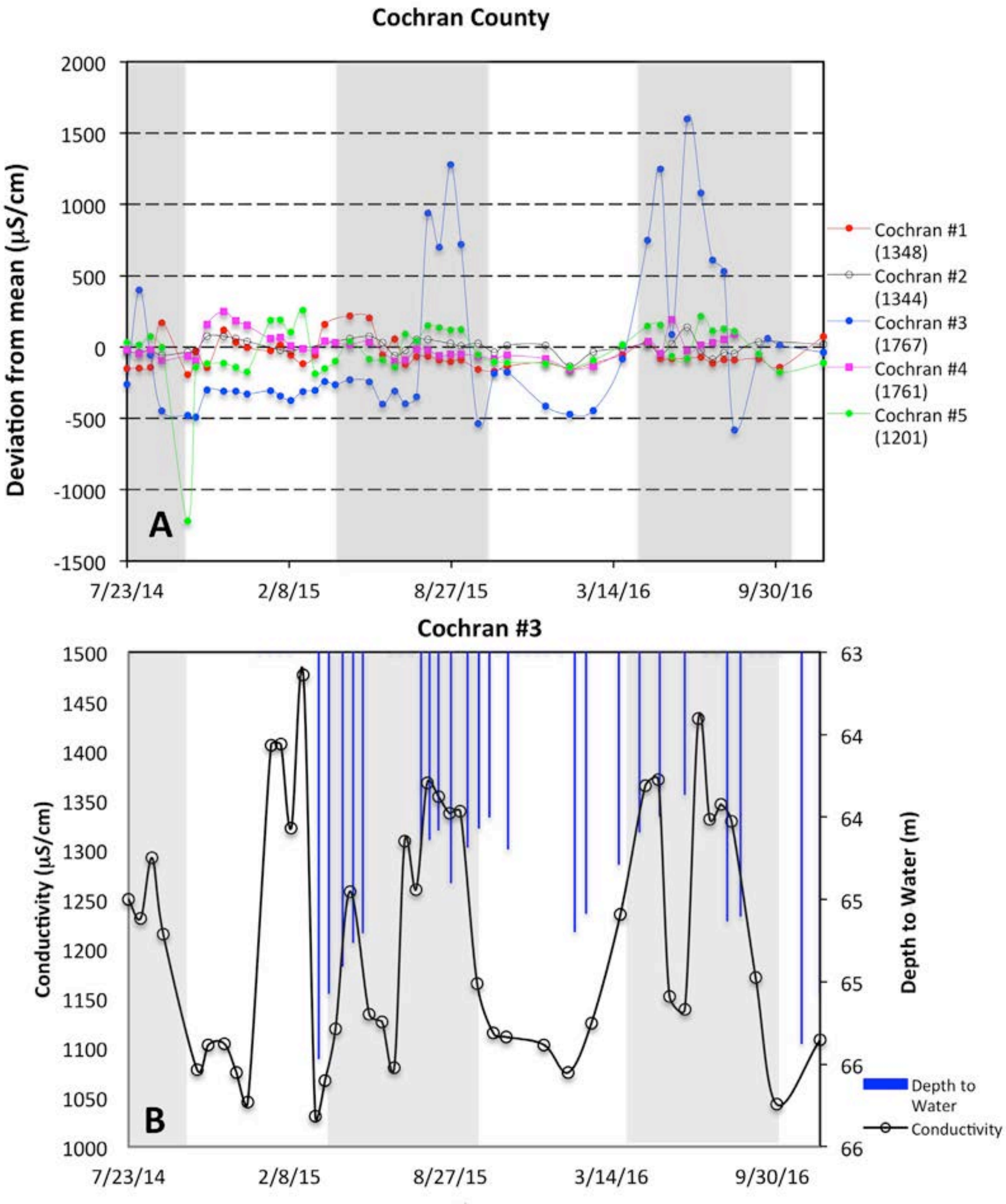

Figure 7. (a) Deviation from the mean value of electrical conductivity (µS/cm) measured throughout the sampling period for five irrigation wells in Cochran County. (b) Electrical conductivity (µS/cm) and depth (m) to water table of Well #3 in Cochran County. The shaded area denotes the crop-growing season for the year.

Cochran County

In Cochran County most of the irrigation wells showed small deviations from the mean value of EC, except for Cochran Well #3 (Figure 7a). All of the sampled irrigation wells trended toward improved water quality (lower EC values) over the course of the study (Table 2). Cochran #3 is used for irrigation and showed variation with the growing season. The largest variation in EC was 17% (Figure 7b). To supply water for oil-field operations, the well was often operating outside of the growing season, as shown in Figure 7b. Of the sampled wells in our study, Cochran Well #3 had the deepest depth-to-water of 66 m (217 feet) (Figure 7b).

CONCLUSIONS

While it is common for water deeper in an aquifer to have a higher salinity, the pressure of irrigation during the growing season has not caused a marked increase in salinity for most of the wells sampled in this study. Over the course of the study, the EC for roughly half of the sampled wells increased and the other half decreased. At least one well per county did have a change in water quality when the wells were actively pumped. Four of those wells showed an increase in EC while the wells were active, suggesting the possibility that more saline water from the depths of the aquifer were being drawn upward. In one case in Lamb County, the water quality actually improved when the well was actively pumped. This specific case does not follow the trend that is normally seen and is likely due to a unique local geologic condition at that location. The results presented here suggest that in the short term, a change in water quality over the growing season does not present a significant challenge to producers in this region. However, some wells are responding to the continued extraction of water from the aquifer, and likely the rest of the wells will begin to show similar trends at some point in the future as the aquifer continues to be depleted and more of the deeper, more saline water is accessed. This study will continue and future attempts will be made to better define possible salinity gradients within our observation wells so that we may ultimately reach a better understanding of possible future water quality conditions.

ACKNOWLEDGMENTS

This research was supported in part by the Ogallala Aquifer Program, a consortium between USDA-ARS, Kansas State University, Texas A&M AgriLife Research, Texas A&M AgriLife Extension Service, Texas Tech University, and West Texas A&M University.

The USDA prohibits discrimination in all its programs and activities on the basis of race, color, national origin, age, disability, and where applicable, sex, marital status, familial status, parental status, religion, sexual orientation, genetic information, political beliefs, reprisal, or because all or part of an individual's income is derived from any public assistance program.

REFERENCES

Bordovsky JP, Porter D, Johnson J. 2012. Effects of variable in-season irrigation capacity on cotton. Annual Report. Texas A&M AgriLife Research Project. 33 p. Project 11-811.

Chaudhuri S, Ale S. 2014. Long term (1960–2010) trends in groundwater contamination and salinization in the Ogallala aquifer in Texas. Journal of Hydrology. 513:376-390. Available from: https://doi.org/10.1016/j.jhydrol.2014.03.033.

Cronin JG. 1969. Ground water in the Ogallala Formation in the southern High Plains of Texas and New Mexico. Washington (District of Columbia): U.S. Department of the Interior Geological Survey. Hydrologic Atlas 330.

Custodio E. 2002. Aquifer overexploitation: what does it mean? Hydrogeology Journal. 10(2):254–277. Available from: https://doi.org/10.1007/s10040-002-0188-6.

Darton NH. 1898. Underground waters of a portion of southeastern Nebraska. Govt. Print. Off.

Druhan JL, Hogan JF, Eastoe CJ, Hibbs BJ, Hutchinson WR. 2008. Hydrogeologic controls on groundwater recharge and salinization: a geochemical analysis of the northern Hueco Bolson aquifer, Texas, USA. Hydrogeology Journal. 16 (2):281-296. Available from: https://doi.org/10.1007/s10040-007-0222-9.

Dutton AR, Reedy RC, Mace RE. 2001. Saturated thickness in the Ogallala aquifer in the Panhandle Water Planning Area: simulation of 2000 through 2050 withdrawal projections. Final Contract Report. Austin (Texas): Bureau of Economic Geology, University of Texas at Austin.

Gollehon N, Winston B. 2013. Groundwater irrigation and water withdrawals: the Ogallala Aquifer initiative. US Department of Agriculture-Natural Resources Conservation Service. Economic Series Number 1.

Hanor JS. 1994. Origin of saline fluids in sedimentary basins. Geological Society, London, Special Publications. 78 (1):151-174. Available from: doi: 10.1144/GSL.SP.1994.078.01.13.

[HPWD] High Plains Water District. 2014. HPWD management plan 2014–2024. High Plains Underground Water Conservation District No. 1. 49 p.

Holliday VT. 1995. Stratigraphy and paleoenvironments of late Quaternary valley fills on the Southern High Plains. Geological Society of America Memoirs. 186:1-131. Available from: https://doi.org/10.1130/0-8137-1186-X.1

Howell TA, Evett SR, Tolk JA, Schneider AD, Steiner JL. 1996. Evapotranspiration of corn - Southern High Plains. In: Camp CR, Sadler EJ, editors. Evapotranspiration and Irrigation Scheduling. Proceedings of the International Conference; San Antonio (Texas): American Society of Agricultural Engineers. p. 158-166.

Kreitler CW. 1993. Geochemical techniques for identifying sources of ground-water salinization: CRC Press. 272 p.

Lascano RJ. 2000. A general system to measure and to calculate daily crop water use. Agronomy Journal. 92:821-832. Available from: doi:10.2134/agronj2000.925821x.

Ledbetter K. 2014. Salinity of growing concern for Ogallala Aquifer. Southwest Farm Press. 41(10):16-18.

McCain C. 1996. Average decline of 1.91 feet recorded in District observation wells in 1995. The Cross Section. 42(4):1.

McGuire VL. 2014. Water-level changes and change in water in storage in the High Plains aquifer, predevelopment to 2013 and 2011–13. U.S. Geological Survey Scientific Investigations Report 2014-5218. 14 p. Available from: https://doi.org/10.3133/sir20145218.

Mullican WF 3rd. 2013. The rate of groundwater level decline. The Cross Section. 59(5):1.

Robbins HW. 1941. The Pleistocene geology of Portales valley, Roosevelt County, New Mexico, and certain adjacent areas. University of Nebraska (Lincoln Campus). 92 p.

[TAWC] Texas Alliance for Water Conservation. 2013. An integrated approach to water conservation for agriculture in the Texas Southern High Plains. Texas Alliance for Water Conservation (TAWC) Project Summary 2005–2012. 30 p.

Whitehead BP. 2007. Investigating depletion of the Southern High Plains (Ogallala) Aquifer [thesis]. [Mankato (Minnesota)]: Minnesota State University.

Williams WD. 2001. Anthropogenic salinisation of inland waters. Hydrobiologia. 466(1-3):329-337. Available from: https://doi.org/10.1023/A:1014598509028.