texaswaterjournal.org

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

TEXAS WATER JOURNAL

Volume 6 Number 1
2015

TEXAS WATER JOURNAL

Volume 6, Number 1
2015
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*.

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: Anzalduas Dam in Hidalgo County. Photo courtesy of the Texas Water Development Board.

Table of Contents

Texas Water Resources Institute
Texas Water Journal
Volume 6, Number 1, Pages 1–10

Commentary:
The price Texas pays for Mexico's water debt

Carlos Rubinstein [1, 2]

Editor's Note: The opinion expressed in this commentary is the opinion of the individual author and not the opinion of the Texas Water Journal or the Texas Water Resources Institute.

Abstract: The Lower Rio Grande Valley of Texas is not only a cultural gem but also a significant contributor to our state's economy. Since the region is largely dependent upon the Rio Grande for its water supply, it is critical that those states and nations with which we share common borders comply with state, federal, and international agreements regarding the river. Since the early 1990s, Mexico has consistently failed to meet its obligations to the treaty signed in 1944 that allocates waters in the lower reach of the Rio Grande. Mexico's repeated failure to comply with the treaty has caused severe economic hardship to Texas communities and farmers. Despite numerous efforts, Mexico continues to resist entering into a productive discussion and commitment to honor the treaty. A meaningful resolution to this issue will require active participation from the U.S. Department of State, the White House, and Texas officials.

Keywords: Rio Grande, compact, Mexico, Lower Rio Grande Valley

[1] Chairman, Texas Water Development Board, and former Commissioner, Deputy Executive Director, and Rio Grande Watermaster of the Texas Commission on Environmental Quality

[2] The author wishes to extend special thanks to Kathleen B. Ligon, Senior Policy Analyst with the Texas Water Development Board, and Herman R. Settemeyer, Rio Grande Compact Commission Engineer Adviser with the Texas Commission on Environmental Quality, for their assistance with the article

*Corresponding author: kathleen.ligon@twdb.texas.gov

Citation: Rubinstein C. 2015. The price Texas pays for Mexico's water debt. Texas Water Journal. 6(1):1-10. Available from: https://doi.org/10.21423/twj.v6i1.7015.

Terms used in paper

Descriptive name	Short name or acronym
Lower Rio Grande Valley	Valley
Texas Water Development Board	TWDB
International Boundary and Water Commission	IBWC

INTRODUCTION

In Texas, we know that when it rains, it pours. And then sometimes it doesn't rain much at all for a very long time. Our notoriously variable weather and semiarid climate necessitate long-range planning and responsible conservation, management, and development of our water resources. An important component of these efforts is reasonable and reliable cooperation with those states and nations with which we share common borders and accompanying natural resources. Sustainable development of not only the United States and Mexico border region, but also the Western states of the United States and Northwest states in Mexico, demands such cooperation.

Because of our state's notoriously flashy precipitation patterns, we must utilize reservoirs—the cornerstone of surface water management in Texas—as an important means to provide reliable water supplies in times of scarcity (Ward 2011). The basin of the mighty Rio Grande is no exception. After the introduction of large-scale irrigation and the building of the railroad around the turn of the 20th century, the Lower Rio Grande Valley (Valley) of Texas experienced spectacular development (Vigness and Odintz 2015). Early settlers of Cameron, Hidalgo, and Starr counties in particular found that the natural, unregulated flows of the river were either too low to support irrigated agriculture or so high that heavy flooding damaged towns and irrigated lands. Agricultural development, along with serious flooding, continued through the 1930s and 1940s, increasing the sense of urgency to fairly allocate and regulate the waters of the lower reach of the Rio Grande (Jarvis 2005).

Reaching an agreement on the allocation of waters in both the upper reach—from the river's headwaters in Colorado to Fort Quitman, Texas—and the lower reach—from Fort Quitman to the Gulf of Mexico—took many years. Early agreements in the 1800s and in 1906 addressed the international boundary and flows in the upper reach, but it wasn't until 1944 that the United States and Mexico agreed on allocation of the waters in the lower reach[3].

The 1944 Treaty, "animated by the sincere spirit of cordiality and friendly cooperation," called for the construction of reservoirs along the international border and allocated water in the river based on a percentage of flows from each country's tributaries (Treaty Series 994, 1944). It stipulated that one-third of the flow of the Rio Conchos, Rio San Diego, Rio San Rodrigo, Rio Escondido, Rio Salado, and Las Vacas Arroyo in Mexico (Figure 1) was allotted to the United States and required a delivery from these named tributaries in Mexico to the United States of not less than an average of 350,000 acre-feet of water annually within cycles of 5 consecutive years[4]. The treaty specified that Mexico can only deliver less than this annual average amount during a 5-year cycle in the event of an "extraordinary drought." Like the earlier 1906 Convention, the International Boundary and Water Commission (IBWC) was given the responsibility for implementing the 1944 Treaty[5]. Many of the details of implementation were left to the U.S. Department of State and the Mexican Ministry of Foreign Relations (Jarvis 2005).

New reservoirs were a key component to this agreement, greatly enhancing the ability to deliver a dependable supply of water to users in both countries (RJ Brandes 1998). Construction of Amistad Dam and Reservoir, named for the Spanish word for "friendship," began in December 1964 and was completed in November 1969. The lake surface covers 89,000 acres in southern Val Verde County. With an original conservation storage capacity of 3.5 million acre-feet[6] (TWDB 2012), Amistad is the second largest reservoir in Texas.

Work on International Falcon Reservoir, bounded by Starr and Zapata counties, began in 1951 and was completed in April 1954. Like Amistad, Falcon is a very large reservoir, ranking number 5 in the state with an original conservation storage capacity of 2.8 million acre-feet (TWDB 2012). Both Amistad and Falcon are jointly owned by the United States and Mexico and operated as a system by the IBWC, with each country having storage capacity in both reservoirs. When Amistad and Falcon are at or below conservation capacity, the release of U.S. water is at the call of the Texas Rio Grande Watermaster. Like many Texas reservoirs, Amistad and Falcon have provided flood control benefits that far exceeded the costs of their construction. Falcon Dam retained a flood shortly after it was completed in 1954, preventing catastrophic flooding in the Valley (TBWE 1958).

The importance of the waters of the Rio Grande, both historically and today, cannot be overstated. The United States' share of the combined firm yield[7] of Amistad and Falcon reservoirs is more than 1 million acre-feet, with about 87% of the

[3] The treaties and various orders have also set forth operating and accounting procedures regarding reservoir storage, river diversions, flood control, and other matters (RJ Brandes 1998).

[4] In return, Mexico received 1.5 million acre-feet of water each year from the Colorado River, which drains into Mexico at the California-Arizona border.

[5] The Texas Commission on Environmental Quality Rio Grande Watermaster is responsible for water accounting and the day-to-day operation of the water delivery system in the middle and lower basin of the Rio Grande in Texas.

[6] An acre-foot is the volume of water needed to cover 1 acre to a depth of 1 foot; it equals 325,851 gallons.

[7] Firm yield represents the maximum water volume a reservoir can provide each year under a repeat of the state's drought of record, the period of time during recorded history when natural hydrological conditions provided the least amount of water supply. For Texas as a whole, the drought of record is generally considered to be from about 1950 to 1957.

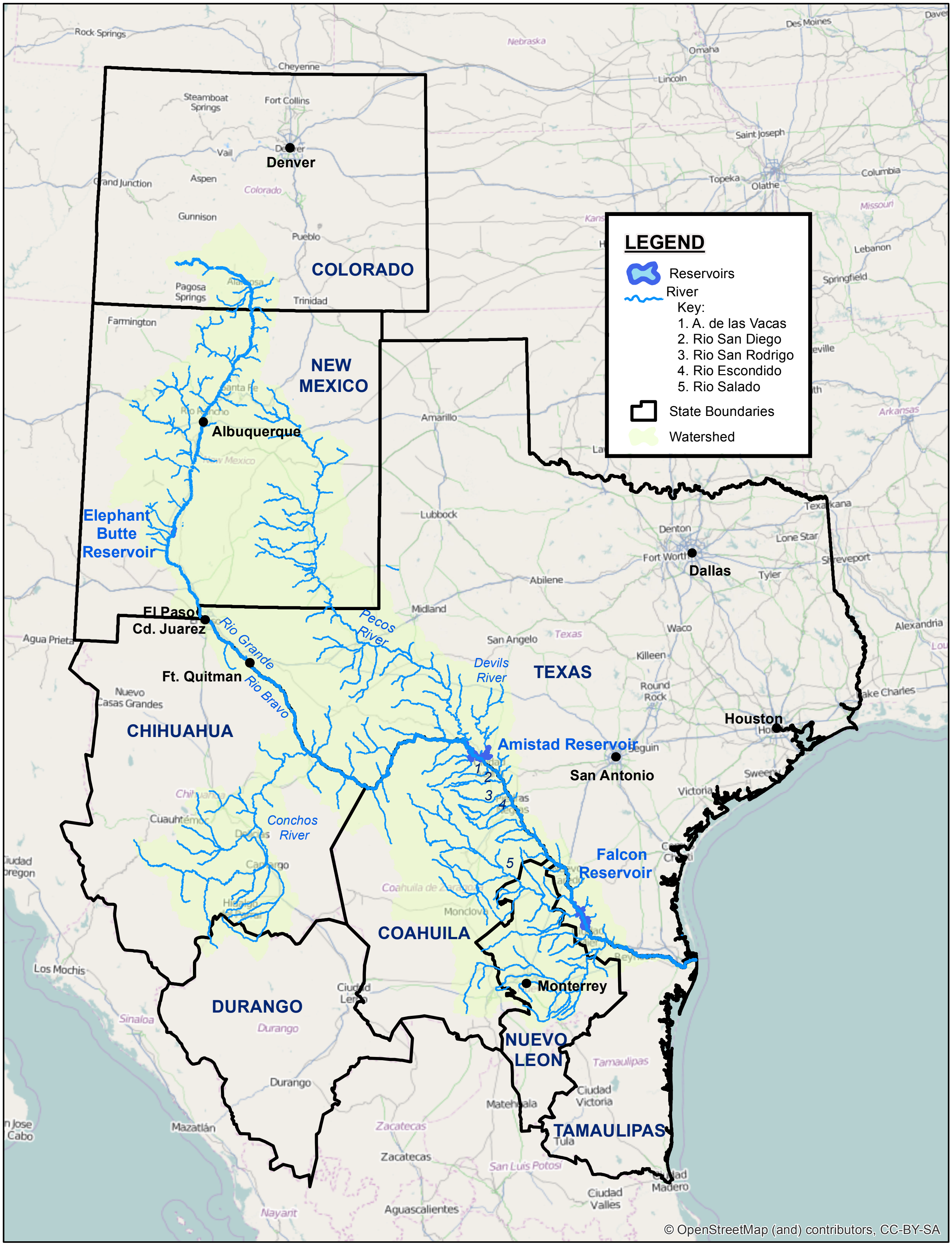


Figure 1. Rio Grande Basin.

United States' surface water rights going to Cameron and Hidalgo counties in the Valley. Surface water from the Rio Grande provides more than 90% of the region's water supply, with agricultural irrigation making up the largest share of water demands (TWDB 2012).

The Valley was a far different place in 1944 when the 2 international reservoirs were contemplated in the treaty. The total population of Starr, Cameron, Hidalgo, and Willacy counties in the 1940 census was only a little more than 200,000 (Texas Almanac 2015). Like in the early 1900s, and at the time the treaty was signed, the Valley developed around and relied upon the various irrigation districts to "lift" water from the Rio Grande and convey it to irrigated lands as well as developing municipal and industrial centers.

A notable change over the decades since the signing of the treaty is the method and extent that water supply planning is done in the state. In response to the drought of the 1950s, the Texas Legislature created the Texas Water Development Board (TWDB) in 1957 to plan to meet the state's future water needs and help communities develop adequate water supplies. In 1997, the legislature established a new water planning process based on a consensus-driven approach at the regional level.

The Rio Grande Regional Water Planning Area, delineated by the TWDB for regional water planning purposes, includes Starr, Cameron, Hidalgo, and Willacy counties in the Valley along with Jim Hogg, Maverick, Webb, and Zapata counties along the Texas-Mexico border. It is the fastest growing of the state's 16 planning regions, now home to more than 1.6 million Texans (Figure 2). The region's population is projected to increase to more than 4 million residents by 2070, with 3.2 million of those residing in the 4 counties of the Valley. As a true river delta, the Valley's economy has historically been based in agriculture but has seen recent growth in trade, services, manufacturing, and hydrocarbon production. Gross regional product quadrupled from $5.3 billion in 1970 to more than $20 billion in the 2000s (NRS Consulting Engineers 2010).

Without a reliable water supply, the region cannot sustain growth or support its current population. Since all planning is predicated on compliance with the law, it is critical that all states and nations comply with state, federal, and international agreements regarding the Rio Grande, or planning itself is futile. The following sections detail how the river is governed, how Mexico's failure to comply with the 1944 Treaty impacts this culturally and economically important region of our state, and what steps need to be taken to curb Mexico's current water deficit[8].

[8] While the focus on this paper is on Mexico's lack of compliance with the 1944 Treaty, New Mexico's lack of compliance with the Rio Grande Compact and the IBWC's water accounting practices at Fort Quitman are equally important issues in the Rio Grande Basin that demand attention.

GOVERNANCE OF THE RIO GRANDE

Governance of the Rio Grande is a complicated matter involving not only 2 nations but also 3 U.S. states. The Rio Grande originates in southwestern Colorado and northern New Mexico where it derives its headwaters from snow melt in the Rocky Mountains. The river flows southward through New Mexico and then forms the international boundary between Mexico and Texas. The Rio Grande's total length is almost 1,900 miles, with approximately 1,248 miles making up the international boundary.

The waters of the Rio Grande and its tributaries are used for recreational, agricultural, and municipal uses. In New Mexico, Elephant Butte Dam and Reservoir, approximately 125 miles north of El Paso, can store more than 2,000,000 acre-feet of water from the Rio Grande to meet irrigation demands in the Rincon, Mesilla, El Paso, and Juarez valleys. Below Elephant Butte Reservoir, flow in the river is somewhat controlled by releases from Caballo Reservoir (Caballo Reservoir can store more than 325,000 acre-feet of water), receiving water released from the upstream Elephant Butte Reservoir in southern New Mexico. The Rio Grande's flow above Fort Quitman, Texas, is diverted for irrigation purposes at Percha, Leasburg, and Mesilla dams in New Mexico and at American Dam in Texas. Water is also diverted at the International Dam to supply irrigation demand in Mexico as stipulated by the treaty.

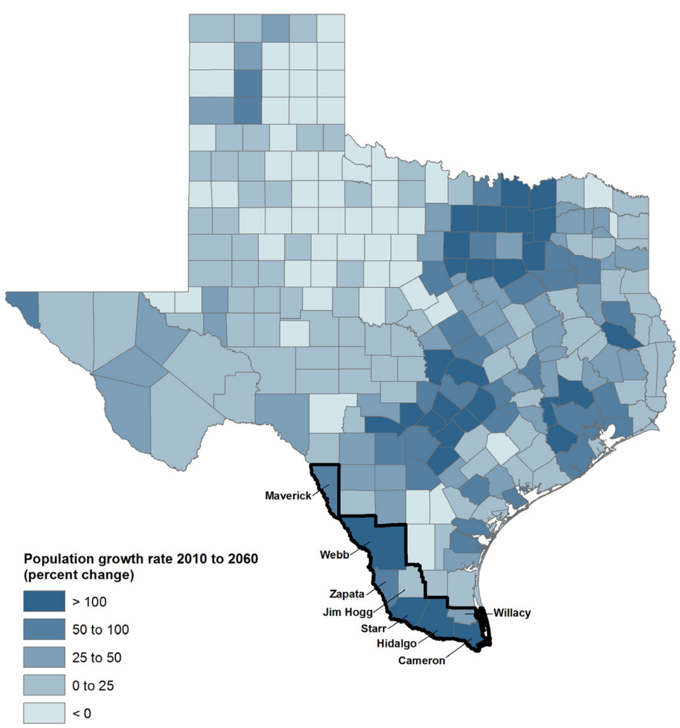


Figure 2. Projected population growth in the Rio Grande Regional Water Planning Area.

Downstream from El Paso to Fort Quitman, flow in the river consists mostly of treated municipal wastewater from El Paso, untreated municipal wastewater from Juarez, and irrigation return flow. Below the El Paso-Hudspeth county line, flow consists mostly of irrigation return flow and occasional floodwater and runoff from adjacent areas. The flow from Fort Quitman to Presidio is frequently intermittent and the section is often referred to as the "Forgotten River" reach of the Rio Grande. The river becomes a permanent stream when it is joined by the Mexican tributary, the Rio Conchos, just upstream of Presidio. From Presidio downstream until it reaches Amistad Reservoir near Del Rio, the Rio Grande often lacks sufficient flow to adequately support minimum recreational, environmental, or agricultural needs (NRS Consulting Engineers 2010).

Because its waters are shared between 3 U.S. states and Mexico, a system of federal, state, and local programs and agreements has been developed to oversee the management of the Rio Grande. In addition to the 1944 Treaty, the following provide a legal framework for its management:

1906 Convention between Mexico and the United States (1906 Convention): The 1906 Convention between the United States and Mexico obligates the United States to deliver 60,000 acre-feet of water annually from the Rio Grande to Mexico at no cost and in accordance with a monthly distribution schedule from February through November. The IBWC and the Comisión Internacional de Límites y Aguas are the designated bi-national agencies that oversee the yearly delivery of international waters to Mexico. The U.S. Bureau of Reclamation calculates the allocations in coordination with the IBWC. During times of reduced water allocations to the U. S. water users, Mexico's allocation is reduced proportionally. Article IV of the 1906 Convention stipulates that "…in consideration of such delivery of water, Mexico waives any and all claims to the waters of the Rio Grande for any purpose whatever between the head of the present Mexican Canal[9] and Fort Quitman, Texas…"

Rio Grande Compact: Signed in 1938 between the states of Colorado, New Mexico, and Texas, the compact was ratified by the U.S. Congress and approved by the President of the United States[10]. The purpose of the compact is to equitably apportion the waters of the Rio Grande Basin above Fort Quitman and to schedule deliveries of water. The Texas Rio Grande Compact Commission administers the compact to ensure that Texas receives its equitable share of quality water from the Rio Grande as apportioned. The interstate commission is composed of 1 representative from each state:

- the State Engineer of Colorado
- the State Engineer of New Mexico
- an appointee by the Governor of Texas

Rio Grande Project: The Rio Grande Project is a federal irrigation and storage reclamation project administered by the U.S. Bureau of Reclamation. The project's primary facilities are Elephant Butte and Caballo reservoirs in New Mexico and diversion dams at the headings of main canals. The project delivers water to the Elephant Butte Irrigation District and the El Paso County Water Improvement District No. 1. The Elephant Butte Irrigation District encompasses project lands in New Mexico south of Caballo Reservoir, and the El Paso County Water Improvement District No. 1 encompasses project lands in El Paso County, Texas. Since 1941, the water improvement district has delivered water to the city of El Paso for municipal and industrial use through contracts between the district, the city, and the U.S. Bureau of Reclamation. The project also delivers water to Mexico in accordance with the 1906 Convention. Thus, the Rio Grande Project, the Rio Grande Compact, and the 1906 Convention are inextricably linked.

1944 TREATY COMPLIANCE

The provisions of the 1944 Treaty worked well for more than 50 years, even throughout the drought of the 1950s (Jarvis 2005). Since a drought in the early 1990s, however, Mexico has repeatedly—and what would appear to be also systematically—failed to meet its obligations in the 2 treaty cycles between 1992 and 2002 and is currently behind on its water deliveries in the current cycle that began October 25, 2010 and will end October 24, 2015.

As of December 20, 2014, Mexico's deficit to the United States was 270,996 acre-feet (TCEQ 2015), an amount of water that exceeds the total net water use of the city of Dallas in 2012[11] (TWDB 2015). Earlier in the current cycle, Mexico's deficit to the Rio Grande was in excess of 480,000 acre-feet. Effective awareness and direct involvement by Texas' delegation in Congress, as noted below, and state leadership have contributed in reducing the deficit to its current level. While the 1944 Treaty allows for less than average deliveries by Mexico during periods of extraordinary drought, Mexico consistently

[9] Per Article 1 of the 1906 Convention, the Mexican Canal is where the head works of the Acequia Madre, known as the Old Mexican Canal, now exist above the city of Juarez, Mexico.

[10] The treaty was ratified by the U.S. Senate on April 18, 1944, and signed by President Harry S. Truman on November 27, 1945.

[11] Estimated total net water use includes municipal, industrial, and power water use as estimated annually by the TWDB Water Use Survey.

operates the basin to deliver less than the minimum, even when extraordinary drought conditions do not exist. The term "extraordinary drought" is not defined in the treaty; however, the North American Drought Monitor includes a designation of "extreme" as the highest form of drought—conditions that have not existed in Mexico's portion of the basin since 2012.

A fundamental issue is that Mexico does not recognize the United States as a user entitled to water from the tributaries named in the treaty. Mexico has constructed an extensive system of reservoirs, many within the basin of the Rio Conchos, with combined storage capacity approximately 2.5 times the country's available conservation storage in Amistad and Falcon reservoirs. All water in these reservoirs in the interior of Mexico is allocated solely to meet Mexico's demands (NRS Consulting Engineers 2010).

Additionally, Texas continues to challenge the way Mexico and, unfortunately, some at the U.S. State Department, choose to interpret Article IV(B)(c) and the closing statement under the same Article IV that references **annual** deliveries to the Rio Grande by Mexico under the 1944 Treaty as noted below (emphasis added):

> *…(c) One-third of the flow reaching the main channel of the Rio Grande (Rio Bravo) from the Conchos, San Diego, San Rodrigo, Escondido and Salado Rivers and the Las Vacas Arroyo,* ***provided that this third shall not be less, as an <u>average amount</u> in cycles of five consecutive years, than 350,000 acre-feet (431,721,000 cubic meters) <u>annually</u>.*** *The United States shall not acquire any right by the use of the waters of the tributaries named in this subparagraph,* ***in excess of the said 350,000 acre-feet (431,721,000 cubic meters) <u>annually</u>****, except the right to use one-third of the flow reaching the Rio Grande (Rio Bravo) from said tributaries, although such one-third may be in excess of that amount…*
> *… In the event of extraordinary drought or serious accident to the hydraulic systems on the measured Mexican tributaries,* ***making it difficult for Mexico to make available the runoff of 350,000 acre-feet (431,721,000 cubic meters) <u>annually,</u>*** *allotted in subparagraph (c) of paragraph B of this Article to the United States as the minimum contribution from the aforesaid Mexican tributaries, any deficiencies existing at the end of the aforesaid five-year cycle shall be made up in the following five-year cycle with water from the said measured tributaries…*

Texas interprets these treaty provisions as requiring a minimum annual delivery of 350,000 acre-feet, except when extraordinary drought conditions do in fact exist. To the extent that extraordinary drought conditions exist that "make it difficult" for Mexico to deliver the annual minimum contribution to the Rio Grande of at least 350,000 acre-feet, then average annual deliveries can be contemplated to make up such deficiencies. In other words, Mexico should operate its portion of the basin to deliver to the United States at least 350,000 acre-feet annually, not bet on periods of dry weather to excuse lack of compliance, and only periods of abundant rain to deliver the minimum required annual amount.

Texas has taken extraordinary steps to encourage the U.S. Department of State to engage in discussions regarding the water debt, including letters from me, former Governor Perry, Senator John Cornyn, the Texas congressional delegation, state Representative Eddie Lucio, III, and former Texas Agriculture Commissioner Todd Staples, requesting this issue be elevated to the highest levels of the federal government for resolution. During the 2013 Texas Legislative Session, House Concurrent Resolution 55 was adopted asking the federal government to resolve the issue. Congressman Filemon Vela and Senator Cornyn developed and gained adoption of additional legislation to require specific reporting from the Department of State on efforts to get Mexico to comply with the treaty.

Water officials from the United States, Texas, and Mexico have met on numerous occasions in El Paso, San Diego, and Mexico City to address these issues, but Mexico continues to resist entering into a productive and earnest discussion and commitment to honor the treaty and schedule delivery of at least the minimum amount of water on an annual basis. Members of the United States section of the IBWC and from the TWDB have developed a model based on naturalized flows that could be relied upon to better manage the basin and equitably distribute its waters. Mexico has refused to enter into any meaningful discussions regarding the model and has yet to enter into any delivery agreement or to set aside water for treaty compliance. Until the federal government engages in a more serious manner, it is expected that Mexico will continue to disregard the treaty[12].

IMPACTS OF THE WATER DEFICIT

Mexico's repeated failure to comply with the treaty has caused severe economic hardship not only to Texas farmers who rely on the river to irrigate their crops but also to cities in the Valley that rely on agricultural water deliveries to help carry drinking water to their communities. Opportunities for developing additional water supplies in the Valley are limited, mostly because few opportunities exist to increase the water supply yield of the Rio Grande. The 2006 Rio Grande Regional Water Plan recommended a number of water management strategies to meet shortages during drought, including conservation, wastewater reuse, groundwater development, and desalination; however, the river will remain an invaluable water supply resource over the 50-year water planning horizon.

[12] Previous water debt negotiations have involved not only the U.S. State Department but also presidents of the United States and Mexico.

Between 1992 and 2002, Mexico accumulated a debt of 1.5 million acre-feet of water that had a severe impact on Texas agriculture. As Mexico's water debt grew, irrigated agricultural acreage in the Valley decreased, with the number of acres of irrigated cropland in Cameron, Hidalgo, Starr, and Willacy counties falling by 14% (HRO 2002). Texas A&M University studies showed that the Valley lost nearly $1 billion in decreased economic activity and 30,000 jobs as a direct result of Mexico's failure to comply with its treaty obligations over the period from 1992 to 2002 (NRS Consulting Engineers 2010).

The impacts of the current water deficit are expected to have similar consequences, with ripple effects extending well beyond agriculture. A 2013 Texas A&M AgriLife study identified that a loss of irrigation water in the Valley endangers about 4,800 jobs and reduces agricultural output by about $395 million annually (Ribera et al. 2013).

The lack of water deliveries by Mexico has also already put the municipal water supply of several communities in Cameron, Hidalgo, and Willacy counties at risk, since transportation of raw surface water in the Valley from the Rio Grande to the end users occurs mostly through irrigation district conveyance systems. These conveyance systems are networks of mainly open canals or resacas[13] that need to be full or "charged" in order to move water through the system to both agricultural irrigation users and municipal users. When farmers are actively irrigating and irrigation water is available, this does not present any particular problem or concern. However, when irrigation water use is curtailed, many communities dependent on the Rio Grande system have to purchase "pushwater" to move water through the irrigation systems to their water treatment plants. The cost of pushwater, depending on the length and severity of conditions, can be extremely burdensome for communities. The TWDB and the Texas Department of Agriculture have recently provided financial assistance to several public water supply systems as a result of emergency water supply issues caused by drought and Mexico's lack of treaty compliance (Table 1, Figure 3)[14]. Some of these entities have come within less than a month of running out of water entirely[15].

CURBING THE DEFICIT

Allowing the current water deficit to continue and tolerating future non-compliance will have severe negative impacts on Texas. The United States has never failed to meets its obligation to deliver 1.5 million acre-feet from the Colorado River to Mexico under the same treaty; Texas is simply requesting that Mexico treat its obligation to the Rio Grande in the same manner.

There are ways to curb the deficit and for Mexico to begin meeting its delivery obligations, but such a resolution will require contributions from various sources, including direct, meaningful, and active participation from the U.S. Department of State, the White House, and Texas officials.

The following actions should be pursued:

- At minimum, Mexico should commit to not allowing the current deficit to grow beyond its current level. Mexico could ensure all of its tributaries to the Rio Grande collectively contribute an average of 958 acre-feet per day for allocation to the United States.
- Mexico needs to recognize the United States as a user of water under the treaty. Mexico should set water aside in its annual allocation processes and reservoir operation plans to deliver a minimum of 350,000 acre-feet per year on average to the United States.
- Mexico's internal and international reservoir operation plans should be modified and upstream reservoirs should be called on to address the demands of downstream reservoirs and users. While Mexico's deficit to the United States grew during the current cycle to more than 483,000 acre-feet at one point and remains at more than 270,000 acre-feet, Mexico allowed its lowermost reservoir on the Rio Conchos, the Luis Leon Reservoir, to store water well above conservation capacity. Mexico has also allowed other reservoirs on the Conchos to remain at or above conservation. A portion of this water coupled with the utilization of water from other sources, as described below, could help address the deficit and Mexico's annual average water obligation.
- Article IX of the treaty and a subsequently negotiated binding agreement called Minute 234 provide Mexico great flexibility in apportioning water to the United States. For example, the Rio San Juan, which enters the Rio Grande below Falcon Reservoir, is normally allocated 100 percent to Mexico. During the previous debt, Mexico allowed portions of this source to be allocated to the United States to the extent it could be beneficially used. This water was credited towards reducing the debt at that time. Such flexibility should continue to be pursued from this and other numerous Mexican tributaries to the Rio Grande to address the annual average delivery requirement and the current deficit. Recent actions by Mexico indicate that this flexibility remains a possibility but can only be considered if the "committed" water is reliably and predictably delivered to the Rio Grande to meet specific "called for" Texas water needs.

[13] Resacas are former channels of the Rio Grande commonly developed as reservoirs and channels for irrigation water.

[14] This list does not include projects funded through other mechanisms.

[15] The projected number of days to run out of water is based on data self-reported by the water system to the Texas Commission on Environmental Quality.

Table 1: Emergency water supply projects in the Lower Rio Grande Valley.

Public Water Supply System	Population Served	Water Supplier	Project Cost	Project Description
City of Elsa	5,660	Hidalgo Water Control and Improvement District No. 9	$1.3 million	TWDB Drinking Water State Revolving Fund assistance for construction of an emergency interconnection with Engleman Irrigation District to provide a secondary source of raw water.
City of Raymondville	11,114	Delta Lake Irrigation District	$350,000 (TDA); $3,800,000 (TWDB)	Texas Department of Agriculture Disaster Relief funding to rehabilitate well; TWDB Drinking Water State Revolving Fund for reverse osmosis, wastewater reclamation, and raw water reservoir expansion.
City of Rio Hondo	2,356	Cameron County Irrigation District No. 2	$3,793,916	TWDB Drinking Water State Revolving Fund assistance for several emergency water supply measures, including purchasing push water from Cameron County Irrigation District No. 2, constructing an emergency interconnection with the City of Harlingen, and rehabilitating the ground and elevated storage tanks at the City's water treatment plant.
East Rio Hondo Water Supply Corporation	19,904	Cameron County Irrigation District No. 2	$1,970,000	TWDB Drinking Water State Revolving Fund assistance for construction of raw water pump station and water transmission line to transfer water from Cameron County Irrigation District No. 6, a new source. Also construction of water line to eliminate bottleneck between the east and west portions of distribution system.
City of Lyford	1,973	Delta Lake Irrigation District	$350,000	Texas Department of Agriculture Disaster Relief funding for new well.

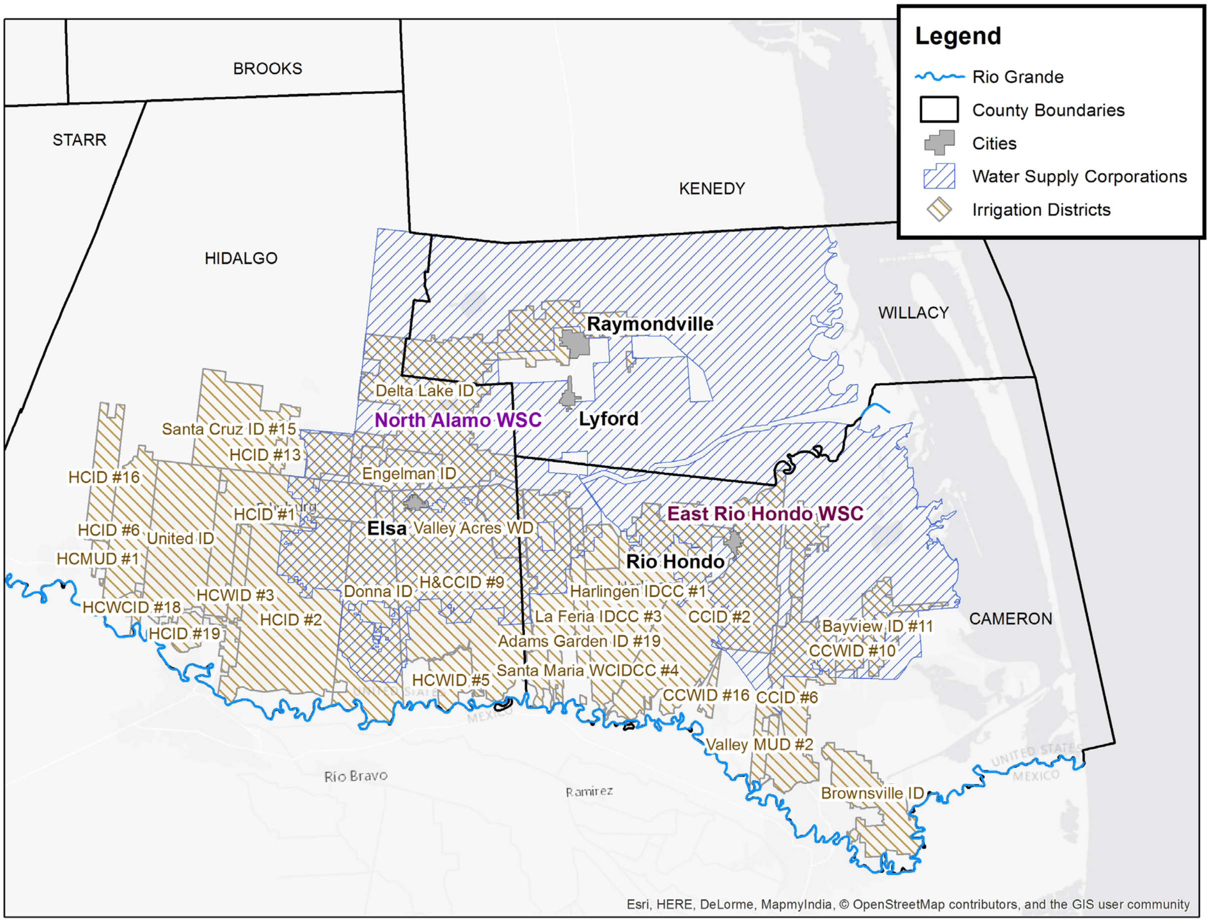


Figure 3. Water suppliers with emergency water supply projects in the Lower Rio Grande Valley.

- IBWC needs to recognize the valid challenge of how the water at Fort Quitman should be accounted. The current accounting by IBWC gives one-half of this water to Mexico, while the binding 1906 Convention clearly allocates 100% of these flows to the United States. Texas' position is that the 1944 Treaty does not grant Mexico any ownership of these flows.
- The U.S. representative of the IBWC must resolve and acquire the 78,000 acre-feet of water used to address water salinity issues created by Mexico's inadequate operation of El Morillo Drain. This is water Texas needs and has requested on numerous occasions with no resolution from the IBWC as of this writing.
- IBWC needs to take a stronger and more proactive management role in stopping illegal diversions of Texas water by Mexico in all reaches of the Rio Grande.

In the spirit of friendship and cooperation—highlighted as the original motivation of the 1944 Treaty—the highest levels of our 2 governments should come together to resolve this issue. Lack of compliance with the 1944 Treaty has become a significant bilateral irritant in the past and threatens to remain one in the future. Since water is certainly not the only natural resource to span the international border, and Mexico looks to soon begin development of its extensive oil and gas reserves, we hope that we can work cooperatively so that both of our countries can fairly share water and benefit economically from the development of our natural resources.

REFERENCES

RJ Brandes Company, Michael Sullivan & Associates, Inc. 1998. The international reservoirs operations and drought contingency planning study for the Middle and Lower Rio Grande. Prepared for the Texas Water Development Board. Austin (Texas). Contract No.: 95483142. Available from: http://www.twdb.texas.gov/publications/reports/contracted_reports/doc/95483143.pdf

[HRO]. House Research Organization. 2002. Mexico's water debt: behind the U.S.-Mexico water treaty dispute. (Interim News). Austin (Texas): Texas House of Representatives. Number 77-7.

Jarvis G. 2005. Legal and institutional aspects of international water allocation on the Rio Grande. In: Binational Rio Grande Summit, Cooperation for a Better Future, Proceedings: Reynosa (Tamaulipas) and McAllen (Texas) [Internet]. Available from: http://glennjarvis.com/water-rights-adjudication/Legal_and_InstitutionalAspectsofInternationalWaterAllocationontheRioGrande_2005.pdf

NRS Consulting Engineers. 2010. 2011 Rio Grande regional water plan [Internet]. Rio Grande Regional Water Planning Group. Prepared for the Texas Water Development Board. Austin (Texas). Available from: http://www.twdb.texas.gov/waterplanning/rwp/plans/2011/index.asp#region-m

Ribera LA, McCorkle D. 2013. Economic impact estimate of irrigation water shortages on the Lower Rio Grande Valley agriculture [Internet]. College Station (Texas): Texas A&M AgriLife Extension. Available from: http://www.twdb.texas.gov/newsmedia/water_deficit/doc/economic-impact-LRGV.pdf

Texas Almanac. 2015. Population history of counties from 1850-2010 [Internet]. Austin (Texas): Texas State Historical Association. Available from: http://www.texasalmanac.com/topics/population

[TBWE] Texas Board of Water Engineers. 1958. Texas water resources planning at the end of the year 1958, a progress report to the Fifty-Sixth Legislature. Austin (Texas): Texas Board of Water Engineers.

[TCEQ] Texas Commission on Environmental Quality. 2015. Water shortage issue related to the Mexican water deficit [Internet]. Austin (Texas): Texas Commission on Environmental Quality. Available from: http://www.tceq.texas.gov/border/water-deficit.html

[TWDB] Texas Water Development Board. 2012. Water for Texas 2012 State Water Plan [Internet]. Austin (Texas): Texas Water Development Board. Available from: http://www.twdb.texas.gov/waterplanning/swp/2012/index.asp

[TWDB] Texas Water Development Board. 2015. Water use summary estimates, 2012 [Internet]. Austin (Texas): Texas Water Development Board. Available from: http://www.twdb.texas.gov/waterplanning/waterusesurvey/estimates/index.asp

Treaty Series 994. Utilization of waters of the Colorado and Tijuana Rivers and of the Rio Grande, United States and Mexico. February 3, 1944 [Internet]. Washington D.C.: United States Government Printing Office. Available from: http://ibwc.state.gov/Files/1944Treaty.pdf

Vigness DM and Odintz M. Lower Rio Grande Valley. 2015. In: Handbook of Texas Online [Internet]. Austin (Texas): Texas State Historical Association. Available from: http://www.tshaonline.org/handbook/online/articles/ryr01

Ward GH. 2011 Water resources and water supply. In: North GR, Schmandt J, Clarkson J, editors. The impact of global warming on Texas. Austin (Texas): University of Texas.

Texas Water Resources Institute
Texas Water Journal
Volume 6, Number 1, Pages 11–32

Spatial and temporal effects of the Rincon Bayou Pipeline on hypersaline conditions in the Lower Nueces Delta, Texas, USA

Erin M. Hill [1*], Jace W. Tunnell [2], Brien A. Nicolau [3]

Abstract: The Rincon Bayou Pipeline became operational in 2007 and delivers Nueces River water to the Nueces Delta via the Rincon Bayou. Salinity was monitored during 3 pumping events to identify the spatial and temporal effects of the pumped freshwater to the Rincon Bayou Channel and to areas outside of the channel proper. The spatial extent of the pumped freshwater lowered salinity beyond the Rincon Bayou Channel to connecting marsh areas and salinities remained below hypersaline levels 8 to 16 days after pumping ceased. The results of this new and innovative way of delivering freshwater to the Nueces Delta has proved to be a valuable management tool for minimizing the duration of hypersaline conditions within the estuary. Water resource management decision-makers can use this information for developing strategies to optimize freshwater inflow needs to the estuary while balancing the freshwater demands for humans.

Keywords: freshwater management, freshwater inflow, hypersalinity, estuary

[1] Center for Coastal Studies, Texas A&M University-Corpus Christi, 6300 Ocean Drive, Suite 3200, Corpus Christi, Texas 78412
[2] Coastal Bend Bays & Estuaries Program, 1305 N. Shoreline Blvd., Suite 205, Corpus Christi, Texas 78401
[3] Center for Coastal Studies ,Texas A&M University-Corpus Christi, 6300 Ocean Drive, Suite 3200, Corpus Christi, Texas 78412
* Corresponding author: Erin M. Hill, Erin.Hill@tamucc.edu

Citation: Hill EM, Tunnell JW, Nicolau BA. 2014. Spatial and temporal effects of the Rincon Bayou Pipeline on hypersaline conditions in the Lower Nueces Delta, Texas, USA. Texas Water Journal. 6(1):11-32. Available from: https://doi.org/10.21423/twj.v6i1.6998.

Terms used in paper

Short name or acronym	Descriptive name
BOR	U.S. Bureau of Reclamation
NEAC	Nueces Estuary Advisory Council
NOC	Nueces River Outflow Channel
RBP	Rincon Bayou Pipeline
ROC	Rincon Bayou Overflow Channel
USGS	U.S. Geological Survey

INTRODUCTION

Restoring freshwater to the Nueces Delta and Nueces Estuary has continued to be an environmental challenge since the negative ecological and biological effects of hypersaline conditions were identified in the shrimp populations in the 1990s within the Nueces Estuary (Matthews and Mueller 1987; Whitledge and Stockwell 1995; Montagna et al. 2009; Hill et al. 2011; Nueces BBEST 2011; Nueces BBASC 2012). The lack of freshwater inflow into the Nueces Delta and Nueces Estuary, coupled with a semiarid climate and frequent drought conditions, has resulted in hypersaline conditions (Figure 1) (Montagna et al. 2002; Knowles 2002). The lack of freshwater inflows to the delta and estuary is the result of reservoir embankments, riverbank modifications, and increased urbanization and industrialization along the Nueces River. The state of Texas, alongside stakeholders, has worked rigorously toward finding solutions to increase flows into the estuary and delta through management of reservoir operations to include inflow requirements to the estuary and delta. The background and history of the establishment of inflow requirements to the Nueces Estuary follows in the next section.

History of management of freshwater inflows to the Nueces Estuary

Two reservoirs are located on the Nueces River: (1) Choke Canyon Reservoir (Choke Canyon Dam), built in 1982, is located on the Frio River approximately 16 kilometers above the Frio River's confluence with the Nueces River, and (2) Lake Corpus Christi (Wesley Seale Dam), built in 1958, is located on the Nueces River approximately 48 kilometers farther downstream (Figure 2). After Choke Canyon Reservoir was built, the state of Texas started to develop an inflow criterion in 1990s for freshwater inflows for the Nueces Estuary (BOR 2000; Montagna et al. 2002; Palmer et al. 2002).

The Texas Natural Resource Conservation Commission, now the Texas Commission on Environmental Quality, addressed the lack of freshwater inflows into the Nueces Estuary through a series of amendments to the initial May 1990 Agreed Order to manage inflows into the estuary. The May 1990 Agreed Order required inflows to the estuary for May and June 1990 and stated a Technical Advisory Committee would be established to assist in the development of a permanent inflow operation procedure for the estuary. The Agreed Order was

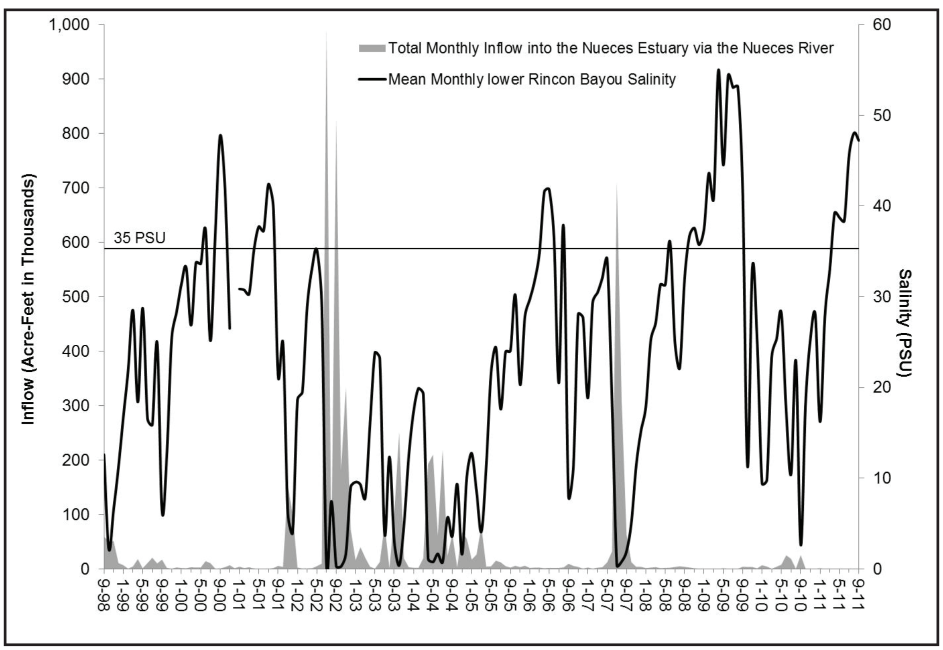


Figure 1. Total monthly inflow into the Nueces Estuary via the Nueces River and mean monthly salinity in the lower Rincon Bayou, September 1998–September 2011. Salinity data was collected monthly by the Center for Coastal Studies, Texas A&M University–Corpus Christi and flow data from USGS gauge (No. 08211500) at Calallen, Texas. Reference line showing 35 practical salinity units.

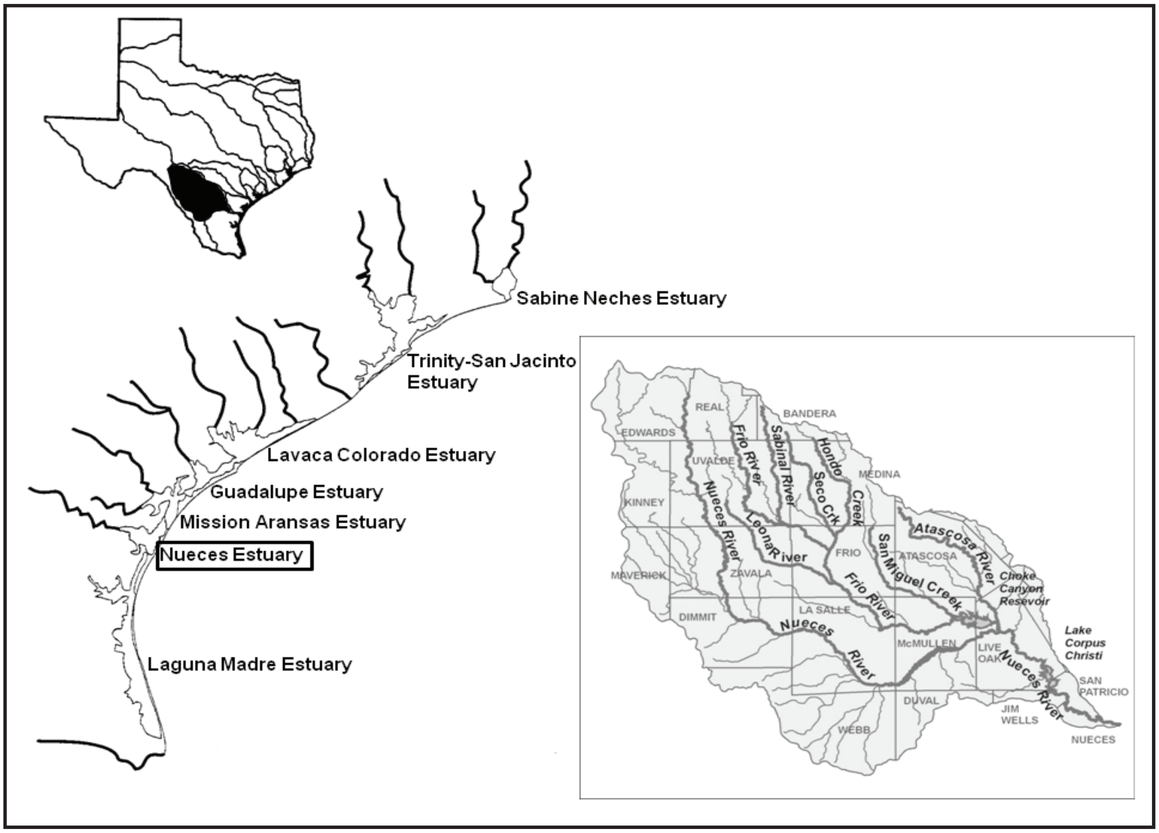


Figure 2. Main estuaries along the Texas coast with the shaded area indicating the Nueces River Basin, Texas USA (Hill et al. 2011).

amended again in August 1990 and expanded operations to now provide for monthly inflow requirements to the estuary (Ray Allen personal Communication; unreferenced).

The Agreed Order was amended again in 1992 and established (1) the Nueces Estuary Advisory Council (NEAC), (2) defined credits for monthly excess inflow and salinity, and (3) required the city of Corpus Christi to maintain at least 2 salinity monitoring stations in Nueces Bay (currently maintained by the Conrad Blucher Institute at Texas A&M University–Corpus Christi). The NEAC was created to provide recommendations for freshwater inflow management into the Nueces Estuary under the Special Condition 5.B, Certificate of Adjudication No. 21-3214 (TCEQ 1992).

The Agreed Order was amended again in 1995 to establish operational procedures relating to releases and spills from Lake Corpus Christi and Choke Canyon Reservoir. The 1995 Agreed Order changed the inflow requirements from mandatory to a pass-through plan based on inflows to the reservoir system. Pass-throughs during drought conditions were now contingent upon the city of Corpus Christi's implementation of the Drought Contingency Plan. The NEAC also began identifying areas in the delta where freshwater inflow would be most beneficial in increasing biological productivity.

The current Agreed Order, amended in April 2001, established specific monthly inflow targets for the estuary to maximize biological productivity. The monthly targets take in consideration the reservoir levels and drought contingency measures. Under the 2001 Agreed Order, the city was required to (1) re-open the Nueces River Overflow Channel, making it a permanent feature of the Rincon Bayou, (2) build and operate a system to deliver up to 3,000 acre-feet per month into the Upper Rincon Bayou, (3) continue the salinity monitoring stations in Nueces Bay, and (4) implement an on-going biological monitoring and assessment program for "adaptive management" for freshwater inflows into the Nueces Estuary.

The monthly inflow targets were developed by the Texas Water Development Board and Texas Parks and Wildlife Department and require the city of Corpus Christi to provide no less than 151,000 acre-feet per year (186,106 cubic meters) to the Nueces Estuary (TCEQ 1995). Each month the city is required to "pass through" inflow to the Nueces Estuary equal to the measured instream flows into the Choke Canyon Reservoir/Lake Corpus Christi Reservoir System up to a target amount (TCEQ 1995). The target amount varies by month and is calculated based on the combined storage volume of the reservoir system. The city receives 500 acre-feet per month return flow credits and may receive additional credits for excess inflow from the previous month or from relief credits based on salinity measured in Nueces Bay (Montagna et al. 2009).

The city addressed the lack of freshwater inflow and hypersaline conditions in the Nueces Delta by building the Rincon Bayou Pipeline (RBP) to deliver up to 3,000 acre-feet of water directly to the Rincon Bayou during a pass-through. The RBP is the conveyer system that delivers water to the interior delta to manage salinity levels. The Salinity Monitoring and Real Time Inflow Management program currently being developed uses salinity monitoring stations in Nueces Bay and Rincon Bayou for the management of water releases during high salinity periods.

Restoring freshwater to the Rincon Bayou

The first attempt to restore freshwater to the Nueces Delta was the Rincon Bayou Demonstration Project that was initiated in 1993 by the U.S. Bureau of Reclamation (BOR) (BOR 2000; Montagna et al. 2002; Palmer et al. 2002). Two man-made diversion channels were dug in 1995 to connect the delta to the Nueces River: (1) the Nueces River Overflow Channel (NOC), approximately 60 meters downstream of Interstate Highway 37, connects the Nueces River to the Rincon Bayou, and (2) the Rincon Bayou Overflow Channel (ROC) further downstream connects the Rincon Bayou to the NOC (Figure 3). Because land modifications were made to increase inflow into the delta, monitoring activities were conducted from October 1994 to December 1999 to measure biological productivity in response to the freshwater inflows (BOR 2000). Once the project was complete, in 2000 the NOC was filled in, due to project requirements and land easement contracts. However, the NOC was reopened in 2001 by the city of Corpus Christi prior to the RBP, which became operational in 2007 (Hill et al. 2012).

Figure 3. Map showing placement of the Nueces Overflow Channel and Rincon Overflow Channel on the Nueces River (BOR 2000).

Before the BOR project, the Nueces Delta only received inflows during locally heavy rainfall events or flood events that caused over-banking of the Nueces River (BOR 2000; Pulich et al. 2002; Hill et al. 2011). The overflow channels increased the chance of water reaching the delta when ample inflow could move through the man-made Rincon Bayou diversion channels. The 2 overflow diversion channels increased freshwater inflow to the historical river channel Rincon Bayou by lowering the minimum flood threshold of the upper Nueces Delta from 1.64 above meters mean sea level to approximately 0 meters mean sea level (BOR 2000).

The second attempt to restore freshwater to the Rincon Bayou was the RBP study funded by the city of Corpus Christi. The RBP study followed the 2001 Texas Commission on Environmental Quality Agreed Order requiring the construction and operation of a 1.5 meter-diameter pipeline to deliver up to 3.7 x 106 cubic meters per day (3000 acre-feet) of freshwater to the Rincon Bayou in accordance with the 1995 Texas Commission on Environmental Quality pass-through order (Hill et al. 2011).

This study evaluates the freshwater management effort of the RBP to alleviate hypersaline conditions in the Nueces Delta and its effectiveness in creating a typical estuarine salinity gradient where seaward-moving water transitions from fresh to saline. The spatial and temporal extent of freshwater coming into Rincon Bayou via the RBP was measured at salinity stations downstream of the pipeline and in areas adjacent to the main channel. Each RBP pumping event is described independently, with no salinity comparisons between events, since station locations were not fixed points outside the main channel. A descriptive analysis of the distribution of RBP freshwater inflows in the lower Nueces Delta for 3 RBP inflow events that occurred November 2011, March 2012, and June 2012 will be discussed.

STUDY SITE

Nueces Delta region

The Nueces Delta is located in the Texas Coastal Bend and is part of the Nueces Estuary. Historically, the Nueces River emptied into the delta via the Rincon Bayou Channel but now completely bypasses the delta and flows along the southern edge of the delta and empties into Nueces Bay (Figure 4).

The Nueces Delta is 75 square kilometers of vegetated marshes, mudflats, and open water habitats and is located in a convergence zone of subtropical and semiarid climates characteristic of the Texas Coastal Bend. Summers are hot and humid,

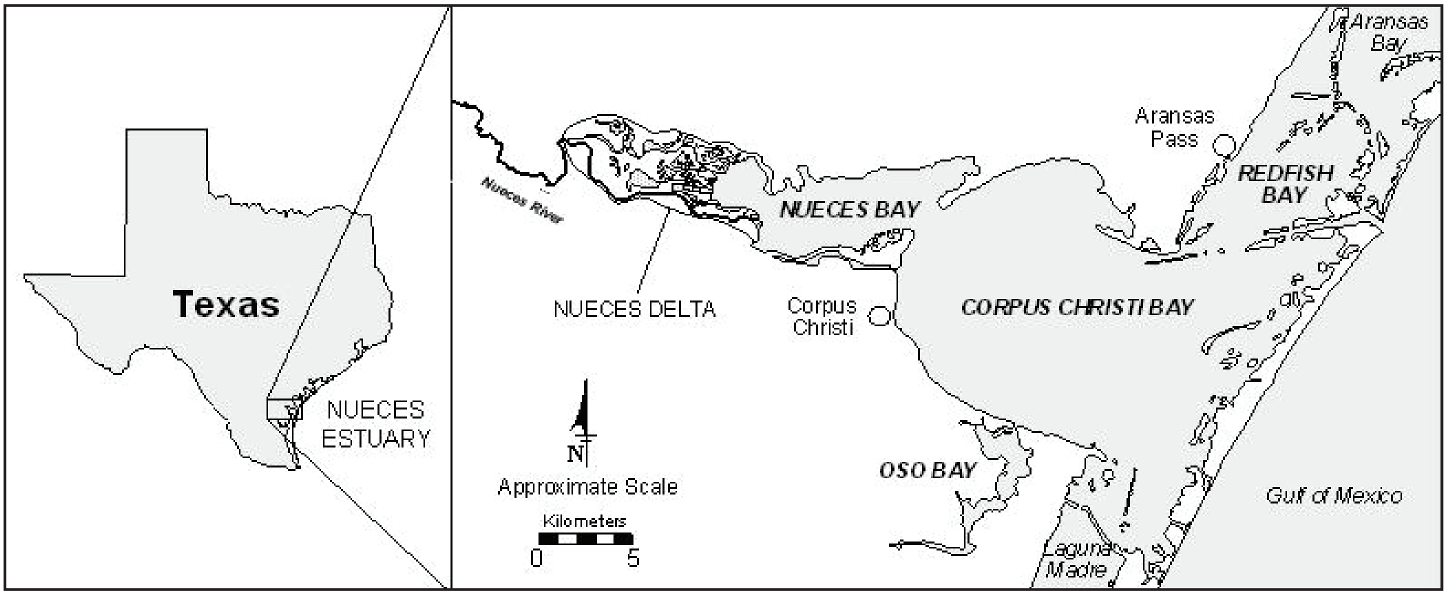


Figure 4. Nueces Estuary, Corpus Christi, Texas, USA (BOR 2000).

and winters are typically moderate with an occasional freeze following strong northerly fronts that pass through the area. Mean annual rainfall in the region is approximately 77.6 centimeters per year (NOAA 2010) with evaporation rates ranging from 90 to 115 centimeters per year but can be as high as 150 centimeters per year (TWC 1991). Wind direction is predominately southeast and is the primary source of atmospheric humidity. Tropical storms and hurricanes are possible during late summer and early fall, which brings substantial amounts of precipitation during these events.

Rincon Bayou Pipeline system

The RBP pump station is located on the Nueces River and diverts up to the first 3,000 acre-feet of required water "pass through" to the RBP outfall located in the man-made Rincon Bayou diversion channel (Figure 5). The RBP became operational in November 2007 and includes 3 350-horsepower mixed-flow submersible pumps capable of moving up to 60,000 gallons per minute with all 3 pumps operating (Table 1; Figure 6). The number of days to deliver a given volume of freshwater through the RBP depends on the number of pumps used.

METHOD

Salinity was measured during 3 events to determine spatial and temporal effects of RBP freshwater inflows to habitats connected to the main Rincon Bayou channel (i.e. small tidal channels, mudflats, and ephemeral ponds) (Figure 7; Table 2). Stations consisted of one 6920 YSI® datasonde attached to a PVC bipod and programmed to sample salinity (practical salinity unit) every 15 minutes *in situ*. Datasondes were deployed up to 3 weeks prior to the RBP release and recovered up to 3 weeks after the RBP stopped discharging water so temporal effects could be quantified. Field maintenance occurred every 2 weeks during the RBP release and included data downloads to a field computer. Calibration and post-calibration of datasondes were performed and all quality control forms were retained in the laboratory. Each RBP event is independent in this study, since no fixed stations occurred outside the main channel. For each RBP event, stations were randomly chosen to determine the extent of freshwater to adjacent.

Salinity data from the Conrad Blucher Institute for Surveying and Science at Texas A&M University–Corpus Christi were

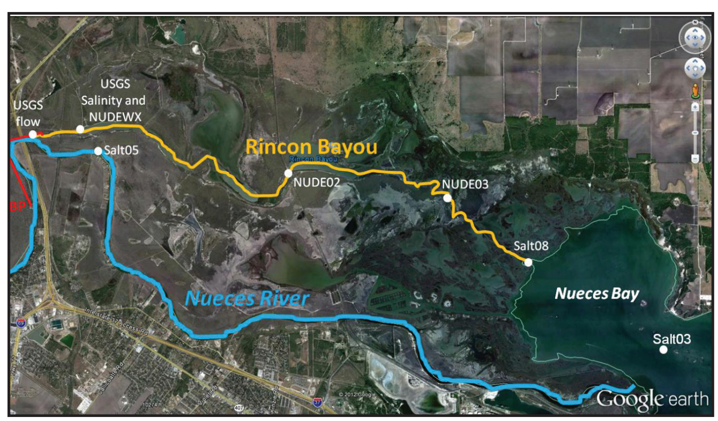


Figure 5. Map of the Nueces Delta and locations of Conrad Blucher Institute at Texas A&M University–Corpus Christi salinity monitoring stations and United States Geological Survey flow gauge.

Table 1. Capacity of the Rincon Bayou Pipeline.

	Rincon Bayou Pumps		
	1	2	3
Flow, gallons per minute	28,000	46,000	60,000
Flow, cubic feet per second	62	102	134
Flow, acre-feet per day	124	203	265
Total kilowatts	230	455	675

also used (http://www.cbi.tamucc.edu/cbi/data). Data from the following Conrad Blucher Institute stations were used in this study (see Figure 3): NUDE02, located in the middle reach of Rincon Bayou (27.888611°N, -97.569444°W); NUDE03 located in the lower tidally influenced reach of Rincon Bayou (27.883774°N, -97.533188°W); Salt08 located in the lower Rincon Bayou at the confluence of Nueces Bay (27.870428°N, -97.517090°W); Salt03 (27.851561°N, -97.482028°W) located in the middle of Nueces Bay near the mouth of the Nueces River and Salt05 (27.891601°N, -97.610684°W) located in the upper tidal reach of the Nueces River. Salt03 and Salt05 salinity data are used as references in this study to compare Nueces Bay and Nueces River salinity, respectively, to Rincon Bayou salinity. Data from the weather station NUDEWX located on Rincon Bayou downstream from the RBP outfall included rainfall (millimeters]).

Data analysis

Salinity data were binned based on the RBP pumping event period (n = days in period): Pre-RBP, During-RBP, and Post-RBP. IBM SPSS version 19 (IBM SPSS, 2012) was used to analyze salinity data. For each event, a one-way ANOVA was used to determine mean salinity differences between Pre-RBP, During-RBP, and Post-RBP to identify the spatial and temporal extent of the RBP in the Rincon Bayou and adjacent stations. A first-order variant of local polynomial interpolation method with barriers was used to determine salinity changes: Pre-RBP, During-RBP, and Post-RBP using ArcGIS software (version 10; ESRI, 2011). Refer to Figure 7 for station locations for each RBP release and Table 2 for the latitude and longitude for each station and station distance from Rincon Bayou. The distance was measured using instream distance from the closest inlet connecting to Rincon Bayou. Salt03 and Salt05 salinity data were included in tables as a reference to salinity in the middle of Nueces Bay and Nueces River, but these values were not included in statistical analyses. No salinity comparisons between RBP events were done since station locations changed for each event.

RESULTS

Event 1

A total of 2,031 acre-feet of water was pumped to the Rincon Bayou from 2 November 2011 through 22 November 2011. Widespread hypersaline conditions (> 35 practical salinity units) were observed in the Rincon Bayou and in areas outside of the channel prior to the RBP event (Table 3). A total of 8 millimeters of rainfall was recorded at the NUDEWX station

Figure 6a-b. a) RBP pumps located on the Nueces River above the Calallen Dam and b) RBP outfall in the Rincon Bayou.

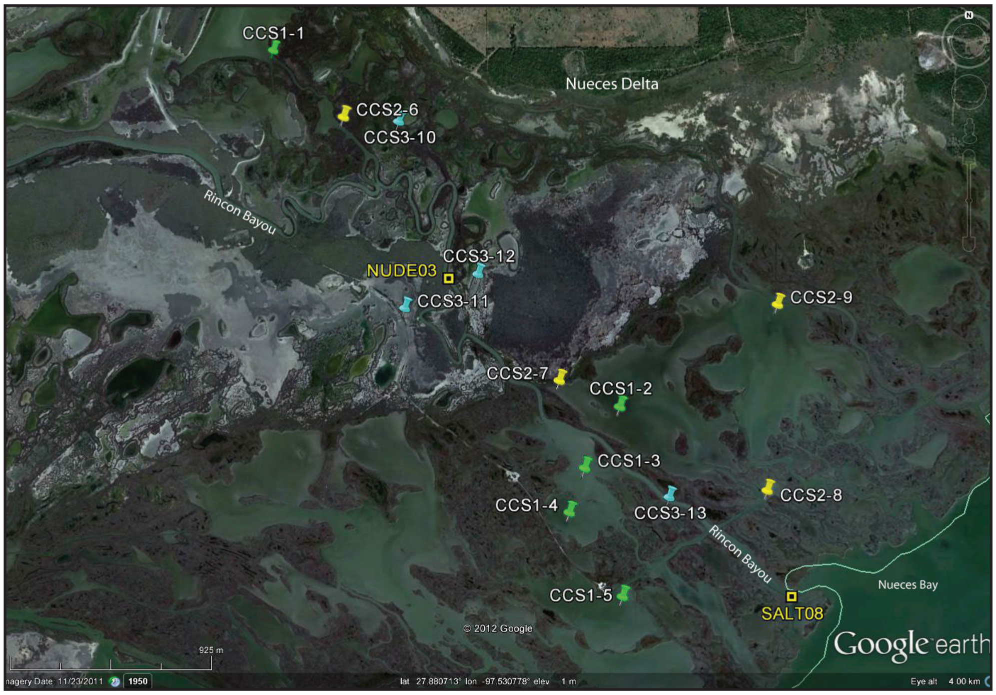


Figure 7. Location of Center for Coastal Studies (CCS) satellite stations, NUDE03, and Salt08. Green pins = Event 1, yellow pins = Event 2, and blue pins = Event 3 (Map modified from Google Earth 2012).

during Event 1. The lack of rainfall during the RBP event indicates salinity changes observed in the Rincon Bayou were likely a direct result from the RBP. The RBP freshwater signal was recognized at all stations in the Rincon Bayou during Event 1.

Once the RBP pumping event was complete, hypersaline conditions (>35 practical salinity units) were still observed at CCS5 and Salt08 in the Rincon Bayou (See Figure 7; Table 3). An ANOVA identified the significant decrease in salinity between Pre-RBP (n=8), During-RBP (n=21), and Post-RBP (n=24) conditions (Table 4). CCS1 was not included in the ANOVA analysis since Pre-RBP data does not exist. Mean

Table 2. Location of CCS stations and distance from the Rincon Bayou main channel by event.

Event	Station	Latitude	Longitude	Distance from Rincon Bayou Channel (m)
1	CCS1	27.89266°N	-97.54141°W	655
1	CCS2	27.87786°N	-97.52623°W	150
1	CCS3	27.87533°N	-97.52688°W	182
1	CCS4	27.87310°N	-97.52758°W	393
1	CCS5	27.87001°N	-97.52511°W	593
2	CCS6	27.88987°N	-97.53815°W	191
2	CCS7	27.87895°N	-97.52806°W	83
2	CCS8	27.87439°N	-97.51834°W	278
2	CCS9	27.88208°N	-97.52672°W	4043
3	CCS10	27.88966°N	-97.53556°W	361
3	CCS11	27.88195°N	-97.5353°W	104
3	CCS12	27.88335°N	-97.53186°W	110
3	CCS13	27.87411°N	-97.52293°W	555

Table 3. Pre-RBP, During-RBP, and Post-RBP mean salinity, Event 1.

Mean Practical Salinity Units	CCS1	CCS2	CCS3	CCS4	CCS5	NUDE2	NUDE3	Salt08	Salt03	Salt05
Pre-RBP		51.63	50.25	50.07	46.48	63.83	41.63	49.06	45.76	11.00
During-RBP	32.35	41.24	37.81	40.00	40.87	21.11	30.70	41.33	45.50	8.74
Post-RBP	30.37	33.44	30.28	31.89	37.86	23.05	31.35	38.58	44.13	7.39

salinity During-RBP and Post-RBP were significantly lower compared to the Pre-RBP conditions. Tukey HSD tests identified Pre-RBP mean salinity statistically significantly higher compared to During-RBP and Post-RBP at all CCS stations. Salt08 mean salinity was not statistically different from Pre-RBP, During-RBP, and Post-RBP salinity. Overall, the volume of freshwater released was not enough to offset the hypersaline conditions in the lower Rincon Bayou during this event.

Spatial interpolation of salinity in the Rincon Bayou Pre-RBP identified a classic negative estuarine system with salinity increasing as you move upstream from Nueces Bay (Figure 8). Once the 21-day RBP release started, salinity began decreasing in the channel. Even though salinity measured outside the channel proper During-RBP decreased by 10 practical salinity units, Rincon Bayou remained hypersaline. Post-RBP mean salinity in the channel ranged from 23.05 practical salinity units at NUDE2 to 38.58 practical salinity units at Salt08 located at the mouth of Nueces Bay. Mean salinity outside the channel was below hypersaline conditions except at CCS5 located closest to Nueces Bay (mean 37.86 practical salinity units). After pumping was complete, hypersalinity returned within 10 days at stations CCS1, CCS2, CCS3, and CCS4. Salinity at CCS5 had no temporal change during Event 1. See Appendix I for all salinity data.

Event 2

A total of 1,309 acre-feet of water was pumped to the Rincon Bayou from 7 March through 19 March 2012. Salinity in the Rincon Bayou channel ranged from 20 to 30 practical salinity units, and ranged from 24 to 36 practical salinity units at stations outside of the Rincon Bayou channel prior to the March 2012 RBP event. A total of 40 millimeters of rainfall was recorded at NUDEWX during Event 2, with most of the rainfall during the Post-RBP period (39.0 millimeters). Rainfall coupled with the RBP event lowered salinity to below hypersaline conditions establishing a typical estuarine salinity gradient.

Mean salinities in the Rincon Bayou channel and adjacent stations were not hypersaline prior to the RBP March 2012 event (Table 5). An ANOVA identified a significant difference in salinity means between Pre-RBP (n=5), During-RBP (n=13), and Post-RBP (n=22) conditions (Table 6). Mean salinity During-RBP and Post-RBP were significantly lower compared to the Pre-RBP conditions. Because Pre-RBP salinity in the Rincon Bayou was not hypersaline, the changes between event periods at CCS7, NUDE3, and Salt08 were not significant.

Spatial interpolation of salinity in the Rincon Bayou Pre-RBP identified an estuarine salinity gradient, atypical of the Rincon Bayou (Figure 9). Once the 13-day RBP event ended, salinity remained lower than seen in the pre-pumping at all stations. The CCS9 station was not included in the inter-

Table 4. ANOVA salinity analysis for Event 1 RBP pumping event. Tukey HSD means are arranged from low (left) to high (right); ns = not significant.

Station	df	F	p	TukeyTest
CCS2	2, 49	24.34	<0.001	PostRBP RBP PreRBP
CCS3	2, 51	13.21	<0.001	PostRBP RBP PreRBP
CCS4	2, 50	10.26	<0.001	PostRBP RBP PreRBP
CCS5	2, 51	22.39	<0.001	PostRBP RBP PreRBP
NUDE02	2, 35	13.42	<0.001	RBP PostRBP PreRBP
NUDE03	2, 44	1.56	0.222	ns
Salt08	2, 47	3.51	0.38	ns

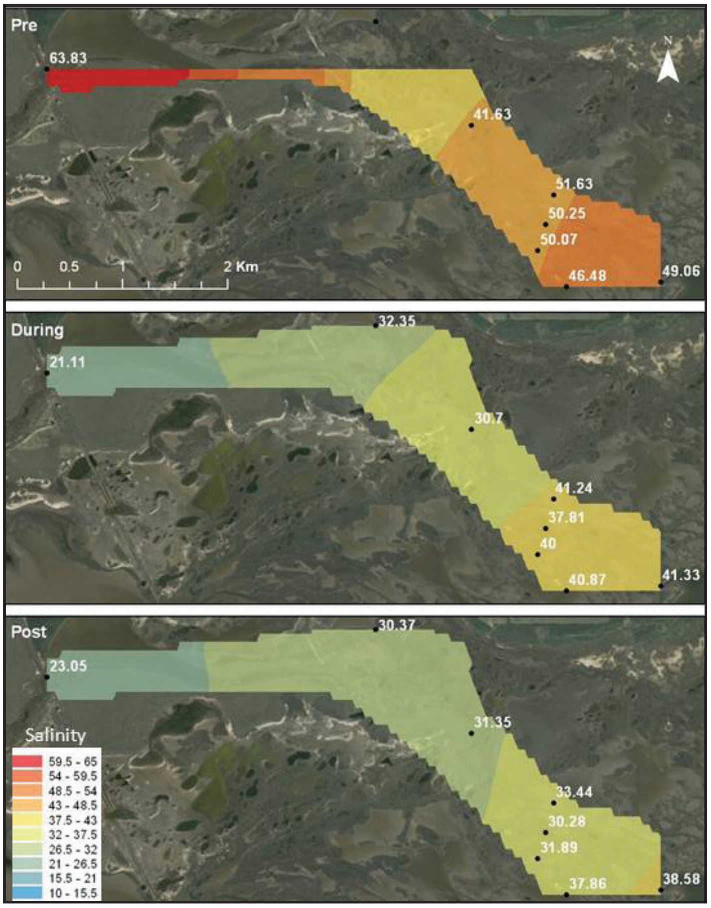


Figure 8. Spatial interpolation using the mean salinity of Pre-RBP, During-RBP, and Post-RBP for Event 1.

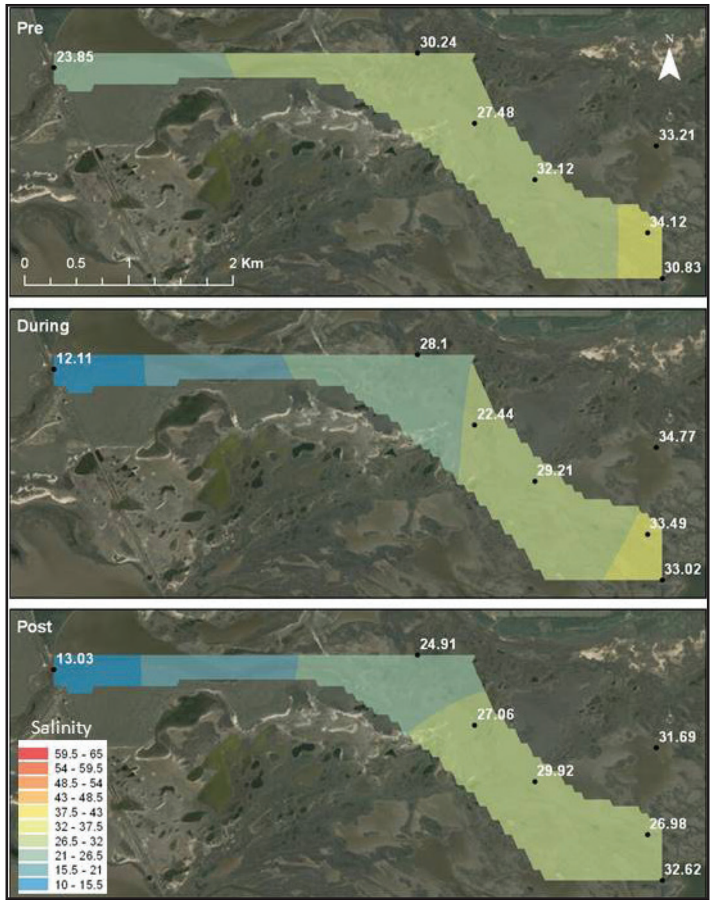


Figure 9. Spatial interpolation using the mean salinity of Pre-RBP, During-RBP, and Post-RBP for Event 2.

Table 5. Pre-RBP, During-RBP, and Post-RBP mean salinity, Event 2.

Mean Practical Salinity Units	CCS6	CCS7	CCS8	CCS9	NUDE2	NUDE3	Salt08	Salt03	Salt05
Pre-RBP	30.24	32.12	34.12	33.21	23.85	27.48	30.83	31.78	5.90
During-RBP	28.10	29.21	33.49	34.77	12.11	22.44	33.02	33.68	6.68
Post-RBP	24.91	29.92	26.98	31.69	13.03	27.06	32.62	34.35	7.90

Table 6. ANOVA salinity analysis for Event 2 RBP pumping event. Tukey HSD means are arranged from low (left) to high (right); ns = not significant.

Station	df	F	p	Turkey HSD Test
CCS6	2, 39	4.46	<0.05	PostRBP RBP PreRBP
CCS7	2, 39	0.49	0.62	ns
CCS8	2, 39	142.33	<0.001	PostRBP RBP PreRBP
CCS9	2, 39	7.51	<0.05	PostRBP PreRBP RBP
NUDE02	2, 27	2.80	0.08	RBP PostRBP PreRBP
NUDE03	2, 25	1.20	0.32	ns
Salt08	2, 31	1.28	0.29	ns

polation because of the distance from Rincon Bayou. Salinity at CCS9 fluctuated likely from rainfall during the event period and was not a result of the RBP. Overall, a typical estuarine salinity gradient was achieved Post-RBP in the Rincon Bayou. Temporal changes in salinity Post-RBP could not be quantified due to changes in salinity likely being from both rainfall and pumping. See Appendix II for all salinity data.

Event 3

A total of 2,354 acre-feet of water was pumped to the Rincon Bayou from 21 June through 13 July 2012. Salinity in the Rincon Bayou channel prior to the release ranged from 20 to 38 practical salinity units and from 2 to 119 practical salinity units at 4 stations outside of the channel prior to the June 2012 RBP event. The rain gauge on NUDEWX station failed 19 May 2012 resulting in no rain data being collected during Event 3.

Mean salinity in the Rincon Bayou and adjacent stations prior to the RBP March 2012 event was below hypersaline conditions except at CCS12 (Table 7). The RBP event lasted 23 days and Post-RBP mean salinity in the channel ranged from 14.57 practical salinity units at NUDE2 to 26.53 practical salinity units at Salt08. An ANOVA identified a significant difference in salinity means between Pre-RBP (n=15), During-RBP (n=23), and Post-RBP (n=16) conditions (Table 8). Mean salinity During-RBP and Post-RBP were significantly lower compared to Pre-RBP conditions for all stations, except at Salt08, which had significantly lower salinity Pre-RBP compared to Post-RBP. After pumping was complete, hypersalinity did not return during the Post-RBP sampling period (16 days) at stations CCS10, CCS11, and CCS13; however, CCS12 remained hypersaline during Post-RBP.

Spatial interpolation of salinity in the Rincon Bayou Pre-RBP identified a negative estuarine system with salinity increasing moving upstream from Nueces Bay, as seen in Event 1; hypersalinity was not observed at CCS13 (Figure 10). The RBP decreased salinity, relieving the reverse estuarine conditions in the channel and areas outside the channel. The area that remained hypersaline (CCS12) throughout most of Event 3 was a tidal pool cut off from exchange to the main Rincon Bayou because of water level and dry conditions. The decrease in salinity at CCS12 was likely due to rainfall; however, conditions remained hypersaline throughout the event. Tidal ponds and creeks located at higher elevations (e.g. CCS12) are restricted from the benefits of the reduced salinity in the Rincon Bayou Channel during RBP pumping events. The RBP inflows can only reach these elevated adjacent areas when water level in the channel proper breaches the threshold allowing for inundation. Overall, a typical estuarine salinity gradient in areas connected to the main Rincon Bayou channel Post-RBP was achieved during this event. See Appendix III for all salinity data.

Table 7. Pre-RBP, During-RBP, and Post-RBP mean salinity, Event 3.

Mean Practical Salinity Units	CCS10	CCS11	CCS12	CCS13	NUDE2	NUDE3	Salt08	Salt03	Salt05
Pre-RBP	29.68	30.94	78.02	16.21	33.75	24.06	23.29	26.68	0.61
During-RBP	21.70	26.85	45.63	18.17	10.33	18.22	23.47	29.33	0.68
Post-RBP	18.00	24.25	58.27	12.42	14.57	26.44	26.53	30.73	0.68

Table 8. ANOVA salinity analysis for Event 3 RBP pumping event. Tukey HSD means are arranged from low (left) to high (right).

Station	df	F	p	Tukey HSD Test
CCS10	2, 53	26.76	<0.001	PostRBP RBP PreRBP
CCS11	2, 53	9.29	<0.001	PostRBP RBP PreRBP
CCS12	2, 53	13.89	<0.001	RBP PostRBP PreRBP
CCS13	2, 53	6.98	<0.05	PostRBP PreRBP RBP
NUDE02	2, 41	54.68	<0.001	RBP PostRBP PreRBP
NUDE03	2, 36	6.32	<0.05	RBP PreRBP PostRBP
Salt08	2, 48	4.83	<0.05	PreRBP RBP PostRBP

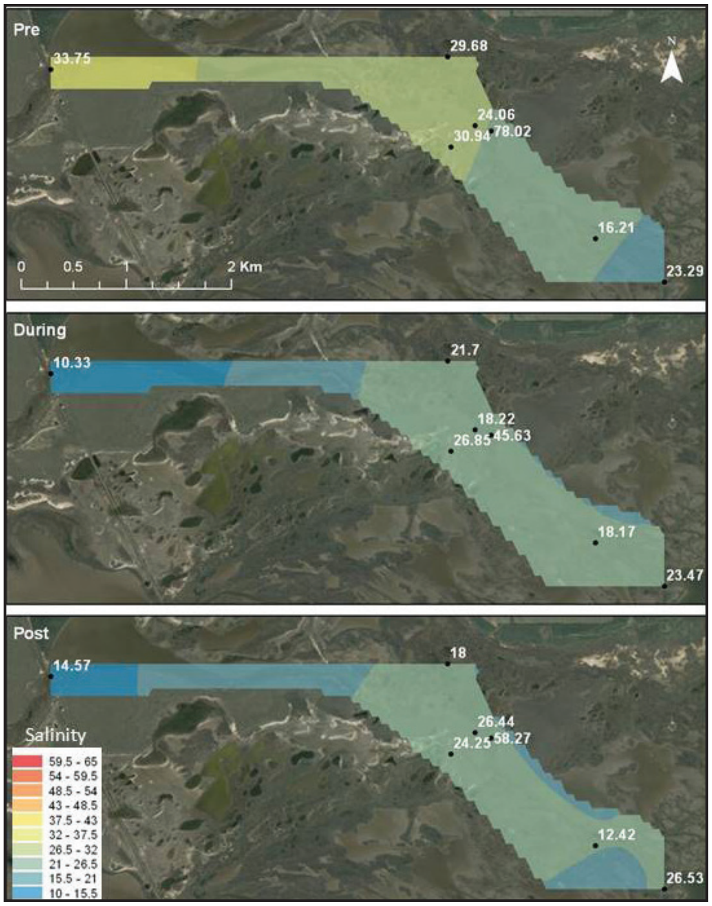


Figure 10. Spatial interpolation using the mean salinity of Pre-RBP, During-RBP, and Post-RBP for Event 3.

SUMMARY OF RINCON BAYOU PUMPING EVENTS

Nine pumping events have taken place since the RBP became operational in late 2007. During the 4-year pumping period, 14,709 acre-feet of water has been pumped into the upper Rincon Bayou (Table 9). Drought conditions occurred in late 2008 and persisted until fall 2009, which did not permit RBP pumping events to occur in Year 1. In Year 2, the RBP pumped a total of 6,017 acre-feet to the Rincon Bayou. Year 3 a total of 2,997 acre-feet was passed through and in Year 4 a total of 5,695 acre-feet was released into the Rincon Bayou. Figure 11 shows all 9 pumping events and their impact on salinity within the Rincon Bayou.

The Rincon Bayou has no distinct elevation gradient at the RBP outfall so water naturally flows both downstream to the Rincon Bayou and upstream back to the Nueces River. As cited in Tunnell and Lloyd (2011), during RBP operational testing phases the city installed a swing gate to prevent upstream flow. A U.S. Geological Survey (USGS) gauge (No. 08211503) has been in operation since 1996 and is located upstream of the RBP outfall. This gauge measures discharge rates of the RBP and natural flows through the Rincon Bayou. Data from this gauge were used to calculate the percentage of RBP backflow to the Nueces River and total water flowing downstream to the Rincon Bayou for each of the 3 pumping events during this study (Figure 12).

Table 9. RBP pumping events by water-year (1 September to 31 August) including pumping dates, duration, and acre-feet pumped.

Year	Pumping Event	Dates of Event	Duration (days)	Acre-Feet Pumped
1	-	No pumping occurred	-	-
2	1	28 September to 21 October 2009	24	2,987
2	2	6 January to 14 January 2010	9	742
2	3	10 May to 31 May 2010	21	2,288
3	4	21 March to 30 March 2011	10	1,001
3	5	3 May to 12 May 2011	10	1,002
3	6	13 June to 22 June 2011	10	994
4	7	2 November to 22 November 2011	21	2,031
4	8	7 March to 19 March 2012	13	1,310
4	9	21 June to 13 July 2012	23	2,354

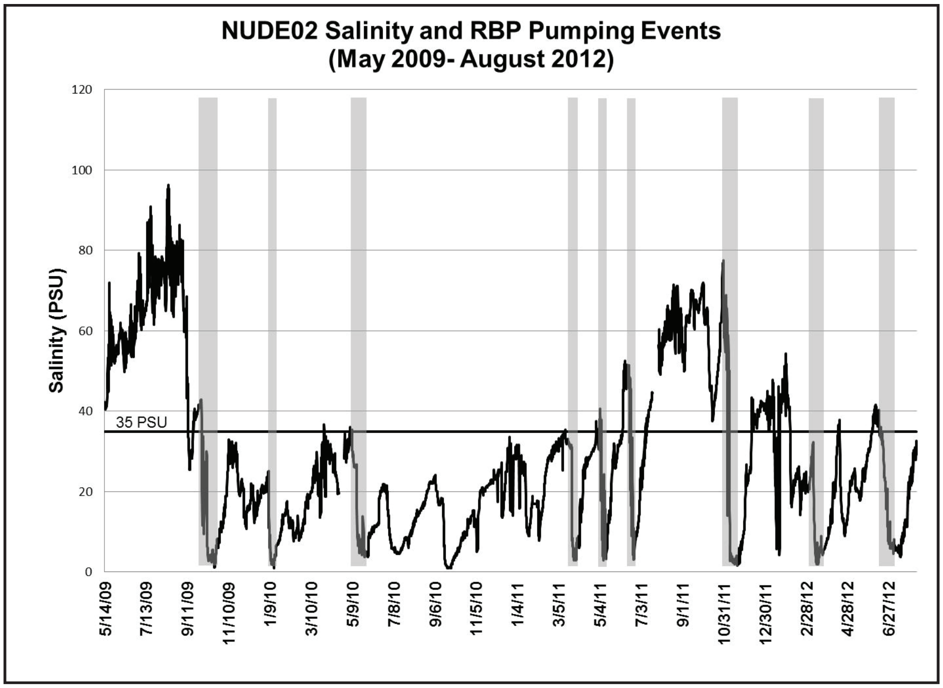


Figure 11. Upper Rincon Bayou salinity at NUDE02 during the 9 pumping events. Gray-shaded areas denote the 9 events that have occurred during the period of May 2009 to August 2012. Thickness of each shaded area represents days of pumping. Reference line showing 35 practical salinity units.

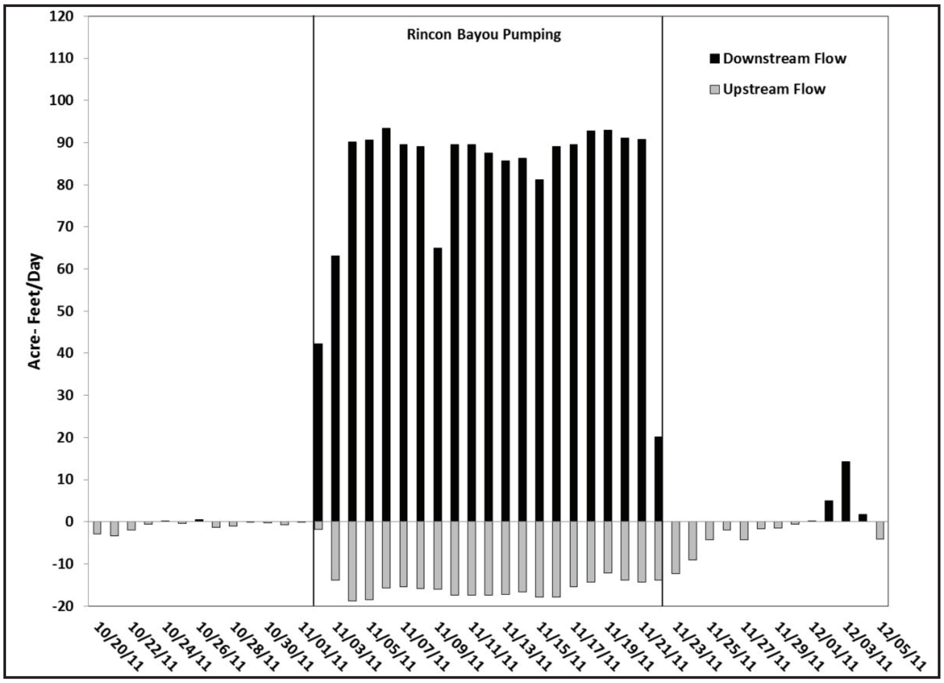


Figure 12a. Discharge rates of freshwater through the RBP during the a) November 2011 pumping event, b) March 2012 pumping event, and c) June-July 2012 pumping event showing the amount of water following downstream (black) through the Rincon Bayou or the loss (gray) upstream to the Nueces River measured at USGS gauge No. 08211503. Area between the thin lines depicts the RBP Event. (Figure 12b-c continued on next page.)

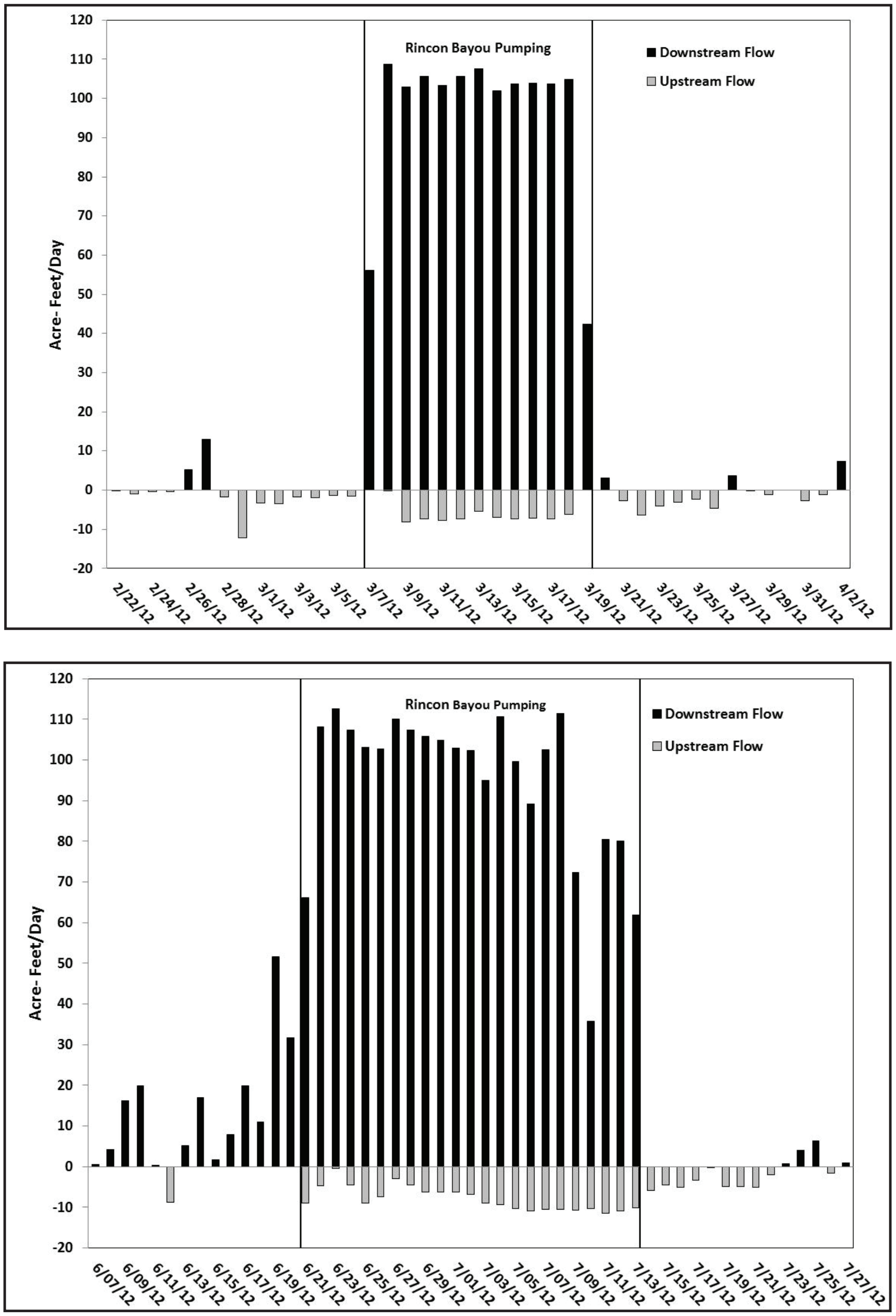


Figure 12b-c. Discharge rates of freshwater through the RBP during the a) November 2011 pumping event (Figure 12a on previous page.), b) March 2012 pumping event, and c) June-July 2012 pumping event showing the amount of water following downstream (black) through the Rincon Bayou or the loss (gray) upstream to the Nueces River measured at USGS gauge No. 08211503. Area between the thin lines depicts the RBP Event.

DISCUSSION

The physical, chemical, and biological behavior of the Nueces Delta is defined by its connectivity to the Gulf of Mexico and its river source, the Nueces River. The freshwater inflows from the Nueces River are the most significant factor of the 2 sources affecting water quality in the Nueces Delta and Nueces Estuary (BOR 2000). The Nueces River provides salinity relief as well as sediment and nutrients from processes occurring upstream in the watershed. Salinity fluctuations provide a useful index in determining estuarine system interactions as salinity affects water chemistry and influences equilibrium and constant rates as well as diversity and survivability of estuarine fauna and flora (Knowles 2002).

The timing and volume of freshwater inflow to the Rincon Bayou is vital to system functioning (Montagna et al. 2002). The RBP can help manage salinity variability within the delta by reducing extreme salinity fluctuations during periods of low flow. The reduction in salinity variability and restoring the salinity gradient to the estuary should create conditions more favorable for biological productivity.

Salinity in the lower Nueces Delta during the 3 pumping events showed the RBP freshwater reduced salinity beyond the Rincon Bayou channel proper to the lower connecting marsh areas. Additional environmental factors influencing the spatial coverage and flow of the RBP include: quantity of freshwater pumped through the RBP, wind speed and direction, tide level, and rainfall. Management of the RBP pumping events must consider these factors when scheduling a release. Temporal effects on salinities outside the Rincon Bayou showed a reduction in salinity between 8 and 16 days after pumping had ceased. As with spatial coverage, other environmental factors, including wind, tide, and rainfall influenced these changes.

This project accomplished the goal of determining if freshwater from the RBP influences the lower Nueces Delta. The hot and dry climate of the Nueces Delta coupled with variable rainfall patterns often creates a negative estuary. The RBP pumping events relieved the hypersalinity conditions and created an estuarine salinity gradient in the Rincon Bayou Channel proper and in connecting habitats. This information will help to further refine the freshwater inflow management plan for the Nueces Delta and in developing an operational and scheduling plan for the RBP.

ACKNOWLEDGMENTS

We would like to thank the Coastal Bend Bays & Estuaries Program for funding this project. We particularly thank Aaron Baxter and Robert "Bobby" Duke from the Center for Coastal Studies for their role in conducting field work and Larry Lloyd, Sara Ussery, Dominic Burch, Amelia Everett, and other Conrad Blucher Institute personnel for help in the field and laboratory for this project. We thank Terry Palmer from the Harte Research Institute, who provided GIS support to this paper.

REFERENCES

[BOR] Bureau of Reclamation. 2000. Concluding report: Rincon Bayou demonstration project [Internet]. Volume II: Findings. Austin (Texas): United States Department of the Interior, Bureau of Reclamation, Oklahoma-Texas Area Office; [cited 2015 January 06]. Available from: https://archive.org/download/rinconbayoudemon00unit/rinconbayoudemon00unit.pdf.

ESRI. 2011. ArcGIS Desktop 10. Redlands (California): Environmental Systems Research Institute.

Hill EM, Tunnell, JW, Lloyd L. 2012. Spatial effects of Rincon Bayou Pipeline inflows on salinity in the Lower Nueces Delta, Texas [Internet]. Corpus Christi (Texas): Coastal Bend Bays & Estuaries Program. 29p. Available from: http://www.cbbep.org/publications/publication1202.pdf

Hill EM, Nicolau BA, Zimba PV. 2011. Habitat management history of the Nueces Estuary, Texas, USA. Texas Water Journal. (2)1: 97-111.

IBM SPSS 19.0. 2012. Chicago (Illinois): IBM SPSS Inc.

Knowles N. 2002. Natural and management influences on freshwater inflows and salinity in the San Francisco Estuary at monthly to interannual scales. Water Resources Research. 12:1-11.

Matthews GA, Mueller AJ. 1987. Freshwater inflow requirements of a Texas estuary. Coastal Zone 1987. Seattle (Washington): American Society of Civil Engineers. 15 p.

Montagna PA, Alber M, Doering P, Connor MS. 2002. Freshwater inflow: science, policy, management. Estuaries. 25:1243-1245.

Montagna PA, Hill EM, Moulton B. 2009 Role of science-based and adaptive management in allocating environmental flows to the Nueces Estuary, Texas, USA. In: Brebbia, C.A. and E. Tiezzi, editors. Ecosystems and Sustainable Development VII. Southampton (United Kingdom): WIT Press, p. 559-570.

[Nueces BBEST] Nueces River and Corpus Christi and Baffin Bays Basin and Bay Expert Science Team. 2011. Environmental flows recommendations report [Internet]. 285 p. [cited 2015 January 06]. Available from: http://www.tceq.state.tx.us/assets/public/permitting/watersupply/water_rights/eflows/20111028nuecesbbest_recommendations.pdf

[Nueces BBASC] Nueces River and Corpus Christi and Baffin Bays Basin and Bay Area Stakeholder Committee. 2012. Environmental flow standards and strategies recommendations report [Internet]. 112 p. Available from: http://www.tceq.state.tx.us/assets/public/permitting/watersupply/water_rights/eflows/nuecesbbasc_recommendationsreport.pdf

Palmer TE, Montagna PA, Kalke RD. 2002. Downstream effects of restored freshwater inflow to Rincon Bayou, Nueces Delta, Texas, USA. Estuaries. 1448-1456.

Pulich Jr. WJ, Tolan J, Lee WY, Alvis W. 2002. Freshwater inflow recommendation for the Nueces Estuary [Internet]. Austin (Texas): Texas Parks and Wildlife Department. 69 p. Available from: http://www.tpwd.state.tx.us/landwater/water/conservation/freshwater_inflow/nueces/media/nueces.pdf

[TCEQ] Texas Commission on Environmental Quality. Agreed order establishing operational procedures pertaining to Special Condition B, No. 21-3214, City of Corpus Christi, et al. (April 28, 1995).

[TCEQ] Texas Commission on Environmental Quality. 1992. Agreed order establishing Advisory Council to Special Condition B, Certificate of Adjudication, No. 21-3214, City of Corpus Christi, et al. [Internet]. (March 4, 1992). Available from: http://tceq.com/assets/public/implementation/water/1992_agreedorder.pdf

[TWC] Texas Water Commission. 1991. Choke Canyon/ Lake Corpus Christi Technical Advisory Committee recommendations for a Reservoir System Operation Plan. Austin (Texas).

Tunnell JW, Lloyd L. 2011. Effects of Rincon Bayou Pipeline inflows on salinity structure within the Nueces Delta, Texas [Internet]. Corpus Christi (Texas): Coastal Bend Bays & Estuaries Program project 1106. CBBEP-76. 23 p. Available from: http://www.cbbep.org/publications/virtuallibrary/1106.pdf

Whitledge TE, Stockwell DA. 1995. The effects of mandated freshwater releases on the nutrient and pigment environment in Nueces Bay and Rincon Delta: 1990-1994. In: Jensen R, editor. Proceedings of the 24th Water for Texas Conference. 1995 Jan 26-27; Austin. College Station (Texas): Texas Water Resources Institute. p. 47-51.

Appendix I. Rincon Bayou Pipeline Event 1 daily mean salinity (practical salinity units). For reference, stations Salt05 located in the Nueces River and Salt03 located in Nueces Bay are included. Shaded areas: gray = time period of the RBP release and bold type = salinity < 35 practical salinity units.

Rain mm	RBP Date	RBP Flow Acre-feet	Date	CCS1	CCS2	CCS3	CCS4	CCS5	NUDE2	NUDE3	Salt 08	Salt 03	Salt 05
0			10/25/11		51.8	49.7	48.7	46.9	55.8	41.9	46.3	44.7	10.9
0			10/26/11		51.5	48.8	48.7	45.9			47.3	44.6	11.2
0			10/27/11		52.0	48.9	49.5	44.3					
0			10/28/11		51.6	53.2	50.6	47.2	75.6		53.9	46.5	11.1
0			10/29/11		53.1	53.8	52.6	48.4	75.4	43.3	49.3	46.3	11.1
0			10/30/11		51.1	50.8	50.6	47.4	61.3	41.2	47.9	46.2	11.3
0			10/31/11		51.2	48.9	50.0	46.8	60.2		49.6	46.0	11.2
0			11/1/11		50.7	47.9	49.8	44.9	54.7	40.1	49.1	46.0	10.2
0	11/2/11	44	11/2/11		48.9	46.5	49.2	42.5	57.4	39.0	47.4		9.9
1.0	11/3/11	77	11/3/11		48.7	49.8	48.9	41.9	64.0	42.8	54.5	45.6	8.9
0	11/4/11	109	11/4/11		37.1	52.4	54.2	45.0	62.2	44.8	51.0	45.8	9.1
0	11/5/11	109	11/5/11		**32.5**	50.9	51.1	44.3	40.5	42.3	48.4	45.8	9.0
0	11/6/11	109	11/6/11	43.9	35.6	44.2	48.3	44.1	54.2	38.8	46.3	45.5	9.1
0	11/7/11	105	11/7/11	44.6	44.5	44.8	47.7	41.1	49.5	37.6	46.1	45.0	9.1
0	11/8/11	105	11/8/11	45.7	46.3	46.9	47.2	45.7	**11.5**	39.1	45.8	44.0	8.6
0	11/9/11	81	11/9/11	47.8	47.0	41.1	46.6	41.8	**4.1**	**30.7**	44.2	46.1	
0	11/10/11	107	11/10/11	40.7	46.5	**27.0**	**33.3**	39.1		17.5			
0	11/12/11	105	11/11/11	**31.5**	44.9	**30.4**	**27.4**	38.7	**3.6**	**17.0**	44.0	45.0	8.7
0	11/13/11	103	11/12/11	**34.9**	41.8	39.6	39.9	39.3	**2.9**	**22.1**	43.6	46.5	8.8
0	11/14/11	103	11/13/11	**32.7**	40.2	40.1	41.2	40.4	**2.8**	**19.7**	38.8	46.1	8.0
0	11/15/11	99	11/14/11	**30.5**	39.5	41.1	41.3	40.5	**3.0**		**34.4**	45.6	8.7
4.0	11/16/11	107	11/15/11	**29.0**	39.5	**31.4**	39.7	40.7		**12.5**	**17.1**	45.4	5.9
0	11/17/11	105	11/16/11	**25.2**	39.3	**19.3**	**24.0**	40.1	**3.5**	**9.9**	**12.3**	45.5	6.5
0	11/18/11	107	11/17/11	**12.9**	38.7	**13.5**	**12.8**	**30.0**	**4.0**		**34.9**	46.3	11.6
0	11/19/11	105	11/18/11	**9.2**	37.0	**23.5**	**22.0**	37.9	**3.0**	**23.9**	41.5	46.3	9.3
0	11/20/11	105	11/19/11	**28.1**	38.6	36.9	40.3	41.7	**3.7**	43.2	45.2	45.1	
0	11/21/11	105	11/20/11	**32.1**	39.5	38.8	42.2	40.9	**4.0**	41.6	44.1	44.7	8.8
0	11/22/11	34	11/21/11	**28.9**	38.8	37.7	42.8	42.0	**6.0**	**30.1**	45.6	44.7	8.6
0			11/22/11	**30.4**	38.5	**32.0**	36.4	42.5	**2.5**	**14.0**	43.8	45.1	6.8
0			11/23/11	**30.9**	38.5	**16.4**	**19.7**	38.7	**4.6**	**9.2**	39.8	45.4	8.4
0			11/24/11	**29.3**	**34.1**	**13.7**	**13.0**	36.1	**7.2**	**10.0**	39.7	45.1	8.7
0			11/25/11	**20.0**	**34.5**	**33.6**	**34.5**	37.6	**6.5**	**12.4**	36.6	45.1	8.5
0			11/26/11	**29.8**	**27.4**	**33.7**	38.1	39.2	**7.5**	**18.0**	**32.5**	45.5	5.1
0			11/27/11	**14.2**	**18.5**	**11.1**	**18.0**	36.8		9.9		47.1	6.5
0			11/28/11			8.0	11.9	34.1		**11.5**	**13.8**	45.8	4.2
0			11/29/11			14.6		30.5				45.9	
0			11/30/11		**22.2**	**32.8**	**19.7**	37.3		**27.5**	40.3	44.7	
0			12/1/11	**33.9**	41.8	40.5	39.5	40.4		43.9	43.3	44.5	6.4

Appendix I (Continued). Rincon Bayou Pipeline Event 1 daily mean salinity (practical salinity units). For reference, stations Salt05 located in the Nueces River and Salt03 located in Nueces Bay are included. Shaded areas: gray = time period of the RBP release and bold type = salinity < 35 practical salinity units.

Rain mm	RBP Date	RBP Flow Acre-feet	Date	CCS1	CCS2	CCS3	CCS4	CCS5	NUDE2	NUDE3	Salt 08	Salt 03	Salt 05
0			12/2/11	41.7	42.1	42.3	42.2	40.0		41.9	43.0	43.7	6.5
0			12/3/11	40.9	40.1	42.2	42.4	37.1		42.3	42.9	43.7	6.2
0			12/4/11	40.1	41.1	42.1	42.4	36.0		42.7	42.7	42.8	
0			12/5/11	42.2	**27.6**	37.5	35.5	36.1		37.5	42.2	43.2	4.6
0			12/6/11	**29.9**	**19.5**	**24.2**	**23.0**	**30.6**		**34.6**	39.2		
0			12/7/11	**8.5**	**15.0**	**23.3**	**15.4**	**33.6**	**25.5**	**31.7**	44.2	43.8	
0			12/8/11	**5.5**	**20.2**	**24.1**	**15.3**	39.2	**25.8**	37.4	44.4	43.3	6.3
0			12/9/11	**29.5**	37.8	35.4	**34.9**	41.0		43.3	44.1	43.4	7.3
2.0			12/10/11	41.7	42.0	36.7	42.7	42.5	41.7	42.7	44.1	43.1	
1.0			12/11/11	40.6	40.0	37.8	42.3	41.7	39.4	43.7	43.7	42.9	11.3
0			12/12/11	39.8	39.3	36.4	41.7	40.4	38.8	42.2	42.2	42.4	10.3
0			12/13/11	38.7	38.5	35.9	41.1	41.1	38.2	41.0	41.4		
0			12/14/11	38.9	38.1	**34.3**	41.8	39.0	38.9	40.8	41.3	42.0	11.2
0			12/15/11	38.7	38.8	38.1	42.3	37.3		42.9	42.2	42.4	

Appendix II. Rincon Bayou Pipeline Event 2 daily mean salinity (practical salinity units). For reference, stations Salt05 located in the Nueces River and Salt03 located in Nueces Bay are included. Shaded areas: gray = time period of the RBP release and bold type = salinity < 35 practical salinity units.

Rain mm	RBP Date	RBP Flow Acre-feet	Date	CCS6	CCS7	CCS8	CCS9	NUDE2	NUDE3	Salt 08	Salt 03	Salt 05
0			3/2/12	**30.4**	35.9	**33.3**	35.1	**20.5**	26.9	30.9	30.8	
0			3/3/12	**29.7**	35.7	**33.5**	**24.4**	**23.1**	**25.4**	**28.6**	**31.9**	5.4
0			3/4/12	**26.3**	**29.6**	**34.1**	37.1	**23.7**		31.8	32.0	5.0
0			3/5/12	**29.0**	**30.6**	**34.6**	**33.0**		26.2		32.1	
0			3/6/12	35.7	**28.8**	35.0	36.5	**28.1**	**31.4**	**32.0**	**32.1**	7.3
0	3/7/12	52	3/7/12	35.2	37.2	**34.8**	36.8	**31.1**				
0	3/8/12	109	3/8/12	35.3	37.3	**34.8**	36.8	**32.3**		31.8	32.6	7.5
1.0	3/9/12	111	3/9/12	38.3	**8.0**	**31.8**	**29.9**	**17.9**		32.6		
0	3/10/12	113	3/10/12	**30.0**	**23.6**	**32.7**	36.2		21.7	**32.8**	**33.1**	6.6
0	3/11/12	111	3/11/12	**26.5**	**26.6**	**33.7**	35.1	5.3	27.2		33.1	
0	3/12/12	113	3/12/12	**25.5**	**27.1**	**33.5**	35.1	**3.5**		31.3	32.9	
0	3/13/12	113	3/13/12	**25.9**	**23.1**	32.2	34.1	3.1	27.5	31.5	32.6	
0	3/14/12	109	3/14/12	**27.7**	29.1	32.5	34.3	7.3	28.9	33.2	34.1	
0	3/15/12	111	3/15/12	26.4	33.9	33.7	34.8	1.9	22.9	33.8	34.1	
0	3/16/11	111	3/16/12	**23.9**	**33.8**	**34.4**	35.2		14.7	34.0	34.3	
0	3/17/12	111	3/17/12	**22.7**	**33.6**	**34.1**	35.0			34.4	34.5	
0	3/18/11	111	3/18/12	**16.8**	**33.5**	**33.6**	35.0		9.3	**34.1**	**34.7**	4.8
0	3/19/12	34	3/19/12	**31.2**	**33.1**	**33.6**	**33.8**	**6.6**	**27.3**	**33.7**	**34.5**	7.8
17.0			3/20/12	**30.5**	**31.4**	**32.1**	**33.1**			**31.9**	**34.3**	
0			3/21/12	**27.5**	**28.4**	**29.5**	**31.9**	**5.2**	**14.8**	**22.4**	**34.7**	5.2
0			3/22/12	**27.8**	**22.7**	**24.9**	**32.0**	**4.8**	**13.1**	**30.4**	**33.8**	
0			3/23/12	**21.2**	**23.9**	**27.2**	**32.3**			**32.0**	**34.4**	
0			3/24/12	**19.5**	**24.2**	**27.3**	**34.2**	**6.1**	**18.9**	**31.7**	**34.4**	
0			3/25/12	**19.4**	**24.2**	**27.2**	**33.5**		**19.3**	**31.5**		
0			3/26/12	**20.0**	**28.0**	**26.5**	**32.9**		**19.8**	**31.8**	**34.2**	

Appendix II. (Continued) Rincon Bayou Pipeline Event 2 daily mean salinity (practical salinity units). For reference, stations Salt05 located in the Nueces River and Salt03 located in Nueces Bay are included. Shaded areas: gray = time period of the RBP release and bold type = salinity < 35 practical salinity units.

Rain mm	RBP Date	RBP Flow Acre-feet	Date	CCS6	CCS7	CCS8	CCS9	NUDE2	NUDE3	Salt 08	Salt 03	Salt 05
0			3/27/12	**22.3**	**31.8**	**27.8**	**33.1**	**7.1**		**34.7**		
6.0			3/28/12	**24.0**	**30.9**	**28.0**	**33.6**	**8.1**	**32.5**	**34.5**	**35.1**	
4.0			3/29/12	**23.5**	**29.9**	**27.1**	**32.6**	**8.3**		**33.8**	**34.1**	
0			3/30/12	**22.6**	**29.3**	**26.2**	**32.0**	**9.0**			**34.1**	
0			3/31/12	**24.0**	**25.5**	**26.4**	**32.7**	**9.8**				
0			4/1/12	**24.5**	**27.0**	**26.5**	**31.5**	**10.7**			**34.1**	
12.0			4/2/12	**27.5**	**32.6**	**26.1**	**30.8**				**34.0**	8.0
0			4/3/12	**28.3**	**34.1**	**25.9**	**31.4**	**14.8**	**32.0**	**35.0**	**34.7**	
0			4/4/12	**27.2**	**35.5**	**26.1**	**31.2**		**32.9**	**34.7**	**34.4**	
0			4/5/12	**26.7**	**35.9**	**26.4**	**30.8**		**30.5**	**34.7**	**34.5**	8.1
0			4/6/12	**26.4**	**36.4**	**26.5**	**31.0**	**20.9**	**30.3**		**33.8**	
0			4/7/12	**27.5**	**33.9**	**26.5**	**29.8**	**21.6**	**34.4**	**33.8**	**34.3**	
0			4/8/12	**26.7**	**33.2**	**26.6**	**29.3**	**21.4**	**33.2**	**34.1**	**34.6**	
0			4/9/12	**25.6**	**31.6**	**26.4**	**29.2**	**23.1**	**32.7**	**33.7**	**34.4**	9.0
0			4/10/12	**25.3**	**27.7**	**26.5**	**28.3**	**24.6**	**34.5**	**33.9**	**34.8**	9.2

Appendix III. Rincon Bayou Pipeline Event 3 daily mean salinity (practical salinity units). For reference, stations Salt05 located in the Nueces River and Salt03 located in Nueces Bay are included. Shaded areas: gray = time period of the RBP release and bold type = salinity < 35 practical salinity units.

Rain mm	RBP Date	RBP Flow Acre-feet	Date	CCS 10	CCS 11	CCS 12	CCS 13	NUDE 2	NUDE 3	Salt 08	Salt 03	Salt 05
			6/6/12	**32.2**	36.8	74.5	**2.7**	38.8	**28.3**	**28.0**	**30.2**	
			6/7/12	**33.2**	38.6	76.8	**8.3**	38.9	**27.3**		**30.5**	**0.7**
			6/8/12	**33.9**	36.4	80.0	**17.3**	36.9		**26.4**	**29.2**	
			6/9/12	**31.2**	**33.3**	83.2	**16.3**	38.4	**25.2**	**24.1**		**0.6**
			6/10/12	**26.0**	**29.0**	87.4	**15.7**	36.3	**27.0**	**26.7**	**27.2**	**0.6**
			6/11/12	**28.9**	**32.1**	90.5	**16.0**		**27.6**	**25.7**	**22.4**	
			6/12/12	**32.9**	**34.0**	94.0	**15.4**	34.0		**23.5**	**24.5**	
			6/13/12	**33.7**	**34.4**	102.2	**14.9**	33.7	**24.3**	**22.3**	**25.5**	**0.6**
			6/14/12	**28.4**	**29.4**	111.1	**13.7**	34.7		**20.9**	**23.1**	**0.6**
			6/15/12	**27.9**	**26.6**	118.5	**17.5**	**32.9**	**23.0**	**21.3**	**24.2**	
			6/16/12	**29.5**	**27.8**	119.8	**19.1**	**32.5**	**20.2**	**19.5**	**25.5**	**0.6**
			6/17/12	**26.5**	**24.3**	67.9	**20.9**	**31.6**	**20.4**	**20.4**	**28.2**	**0.6**
			6/18/12	**23.8**	**26.2**	**1.9**	**21.6**		**20.9**	**21.5**		**0.6**
			6/19/12	**26.3**	**27.5**	**13.1**	**21.4**	**26.5**	**20.5**	**22.3**		**0.6**
			6/20/12	**30.8**	**27.6**	49.5	**22.2**	**23.5**		**23.4**	**29.7**	**0.6**
	6/21/12	75	6/21/12	**27.6**	**24.3**	51.7	**21.3**	**22.4**		**21.6**	**29.5**	
	6/22/12	113	6/22/12	**23.9**	**23.2**	51.2	**21.0**	**20.4**	**20.1**	**21.7**	**29.0**	**0.6**
	6/23/12	113	6/23/12	**23.6**	**23.2**	47.0	**21.4**		**18.9**	**22.2**	**30.2**	
	6/24/12	112	6/24/12	**25.1**	**23.8**	46.7	**21.8**	**20.7**		**22.4**	**28.1**	**0.6**
	6/25/12	112	6/25/12	**25.3**	**25.9**	45.6	**23.4**			**22.4**	**28.1**	**0.6**
	6/26/12	110	6/26/12	**24.3**	**26.1**	44.1	**23.0**	**8.3**		**22.9**	**28.3**	**0.6**
	6/27/12	113	6/27/12	**24.4**	**24.6**	43.7	**23.1**	**12.3**	**21.4**	**23.3**	**29.2**	
	6/28/12	112	6/28/12	**25.2**	**27.5**	42.8	**23.6**	**12.5**	**26.8**	**26.4**	**28.9**	**0.7**
	6/29/12	112	6/29/12	**25.7**	**27.1**	43.5	**23.9**		**26.3**	**27.2**		**0.7**
	6/30/12	111	6/30/12	**24.7**	**25.2**	42.4	**22.0**	**7.0**	**24.4**		**30.3**	**0.7**
	7/1/12	109	7/1/12	**23.1**	**24.7**	41.0	**20.6**	**7.3**	**24.2**		**29.3**	**0.7**
	7/2/12	109	7/2/12	**22.4**	**24.7**	40.9	**20.9**	**6.6**	**24.8**	**25.9**	**29.9**	**0.7**
	7/3/12	104	7/3/12	**21.9**	**24.5**	41.5	**20.5**	**8.1**	**24.0**	**27.6**	**30.7**	**0.7**
	7/4/12	120	7/4/12	**21.1**	**23.8**	42.5	**19.9**	**6.7**	**23.2**	**27.3**	**30.0**	**0.7**
	7/5/12	110	7/5/12	**20.7**	**23.3**	43.4	**19.2**	**5.7**	**23.9**	**29.5**		**0.7**
	7/6/12	100	7/6/12	**18.4**	**22.0**	44.2	**17.7**	**5.9**		**26.9**	**29.7**	**0.7**
	7/7/12	113	7/7/12	**16.7**	**23.8**	45.4	**15.8**		**11.3**	**27.6**	**29.6**	
	7/8/12	122	7/8/12	**14.4**	**24.3**	46.7	**14.9**					

Appendix III. (Continued) Rincon Bayou Pipeline Event 3 daily mean salinity (practical salinity units). For reference, stations Salt05 located in the Nueces River and Salt03 located in Nueces Bay are included. Shaded areas: gray = time period of the RBP release and bold type = salinity < 35 practical salinity units.

Rain mm	RBP Date	RBP Flow Acre-feet	Date	CCS 10	CCS 11	CCS 12	CCS 13	NUDE 2	NUDE 3	Salt 08	Salt 03	Salt 05
	7/9/12	83	7/9/12	**14.4**	**28.2**	48.0	**13.8**		**9.2**	**26.3**	**29.1**	**0.7**
	7/10/12	46	7/10/12	**19.3**	37.0	48.8	**8.5**	**6.7**	**7.7**	**15.2**	**28.9**	
	7/11/12	92	7/11/12	**23.3**	36.8	49.2	**6.3**		**7.7**	**11.3**	**29.2**	
	7/12/12	91	7/12/12	**21.5**	38.7	49.6	**6.4**	**4.4**	**8.7**	**21.7**	**29.3**	**0.7**
	7/13/12	72	7/13/12	**12.1**	**34.8**	49.9	**8.7**		**7.2**	**19.9**		**0.7**
			7/14/12	**9.4**	**28.4**	50.4	**10.3**	**4.4**	**13.4**	**24.1**	**29.2**	**0.6**
			7/15/12	**10.6**	**27.8**	51.0	**11.8**	**8.6**		**24.8**	**29.0**	**0.6**
			7/16/12	**10.5**	**23.1**	51.7	**12.3**	**7.2**		**24.9**		**0.6**
			7/17/12	**11.2**	**22.7**	52.5	**13.1**	**7.6**		**24.9**	**30.5**	**0.6**
			7/18/12	**14.0**	**23.5**	53.1	**14.1**	**8.6**		**27.7**	**31.3**	**0.6**
			7/19/12	**15.4**	**23.9**	53.8	**14.5**	**9.0**		**26.2**	**29.9**	**0.6**
			7/20/12	**15.3**	**23.7**	54.2	**10.7**	**11.1**	**25.6**	**26.2**	**29.7**	**0.7**
			7/21/12	**15.7**	**24.3**	55.3	**8.3**	**12.7**	**25.1**	**25.9**	**29.4**	
			7/22/12	**17.1**	**19.7**	56.7	**9.4**					
			7/23/12	**20.7**	**17.6**	58.1	**12.0**	**18.8**	**26.8**	**27.1**		
			7/24/12	**22.3**	**20.6**	60.1	**12.5**	**22.3**	**26.8**	**27.5**		0.8
			7/25/12	**24.0**	**24.1**	62.6	**13.2**	**19.0**		**28.7**	**31.3**	
			7/26/12	**24.5**	**25.9**	65.3	**13.6**	**23.9**	**28.5**	**28.3**		
			7/27/12	**25.0**	**26.9**	66.8	**14.0**		**29.9**	**27.3**	**32.7**	**0.8**
			7/28/12	**26.2**	**27.5**	68.9	**14.4**	**25.4**	**31.0**	**27.2**	**32.9**	
			7/29/12	**26.0**	**28.2**	71.7	**14.4**	**25.4**	**30.9**	**27.2**	**32.1**	**0.9**

Texas Water Resources Institute
Texas Water Journal
Volume 6, Number 1, Pages 33–44

Estimating *E. coli* and *Enterococcus* loads in a coastal Texas watershed

Kyna Borel[1], R. Karthikeyan[2], Troy A. Berthold[3], Kevin Wagner[4]

Abstract: Pathogens are the principal cause of water body impairment for 303(d) listed waters in Texas and across the United States with 10,654 impairments nationally (TCEQ 2012; USEPA 2013). In Texas, 45% of 568 total impairments are caused by elevated bacteria levels (TCEQ 2012). Models such as the Soil and Water Assessment Tool (SWAT) and Hydrological Simulation Program-FORTRAN (HSPF) have been used for assessing bacterial sources and loading. Other simplistic microbial models, such as the Potential Nonpoint Pollution Index (PNPI), Spatially Explicit Delivery MODel (SEDMOD), and Spatially Explicit Load Enrichment Calculation Tool (SELECT), have been developed to rank potential pollution impacts from nonpoint sources and identify critical areas primarily using land use and geomorphology.

Keywords: water quality modeling, TMDL, GIS, coastal watershed protection

[1] Former Graduate Research Assistant, Department of Biological and Agricultural Engineering, Texas A&M University, College Station, Texas 77843

[2] Associate Professor, Department of Biological and Agricultural Engineering, Texas A&M University, College Station, Texas 77843

[3] Research Scientist, Texas Water Resources Institute, College Station, Texas 77843

[4] Associate Director, Texas Water Resources Institute, College Station, Texas 77843

* Corresponding author: kynaborel@gmail.com

Citation: Borel K, Karthikeyan R, Berthold TA, Wagner K. 2014. Estimating *E. coli* and *Enterococcus* loads in a coastal Texas watershed. Texas Water Journal. 6(1):33-44. Available from: https://doi.org/10.21423/twj.v6i1.7008.

Terms used in paper

Short name of acronym	Descriptive name
AU	animal unit
BMPs	best management practices
CFU	colony forming units
HSPF	Hydrological Simulation Program-FORTRAN
HUC	hydrologic unit code
MGD	million gallons per day
OSSFs	on-site sewage facilities
PNPI	Potential Nonpoint Pollution Index
SEDMOD	Spatially Explicit Delivery MODel
SELECT	Spatially Explicit Load Enrichment Calculation Tool
SWAT	Soil and Water Assessment Tool
TPWD	Texas Parks and Wildlife Department
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
USDA-NRCS	U.S. Department of Agriculture-Natural Resources Conservation Service
WWTFs	wastewater treatment facilities

INTRODUCTION

Pathogens are the principal cause of water body impairment for 303(d) listed waters in Texas and across the United States with 10,654 impairments nationally (TCEQ 2012; USEPA 2013). In Texas, 45% of 568 total impairments are caused by elevated bacteria levels (TCEQ 2012). Models such as the Soil and Water Assessment Tool (SWAT) and Hydrological Simulation Program-FORTRAN (HSPF) have been used for assessing bacterial sources and loading. Other simplistic microbial models, such as the Potential Nonpoint Pollution Index (PNPI), Spatially Explicit Delivery MODel (SEDMOD), and Spatially Explicit Load Enrichment Calculation Tool (SELECT), have been developed to rank potential pollution impacts from nonpoint and point sources and identify critical areas primarily using land use, geomorphology, and potential sources in the watershed (Borel et al. 2012; Fraser et al. 1998; Munafo et al. 2005; Riebschleager et al. 2012; Teague et al. 2009).

The SELECT methodology was developed to characterize *E. coli* sources from point and nonpoint pollution in watersheds where watershed protection plans or total maximum daily loads (TMDLs) are developed to address bacterial contamination (Teague et al. 2009). Automated SELECT contains a graphic user interface within ArcGIS, whereby the user can adjust project parameters to develop watershed-specific pollutant loading scenarios using source and area characteristics (Riebschleager et al. 2012).

STUDY WATERSHED

The Copano Bay watershed (Figure 1) is located in the San Antonio-Nueces Coastal Basin and contains 3 water bodies impaired for bacteria: the tidal classified segments of the Aransas and Mission rivers and Aransas Creek, an unclassified water body. Both the rivers discharge to Copano Bay. This 485,073-hectare (1,198,641 acre) rural watershed contains both fresh and tidal waters. The Aransas River watershed totals 217,068 hectares (536,387 acres), of which 45% is used for cultivated crops (Figure 2). The largest municipality within the Aransas River watershed is Beeville with a population of 13,101 (USCB 2013). The Aransas River watershed encompasses portions of Bee, San Patricio, and Refugio counties with less than 1% of the watershed within Aransas and Live Oak counties. The Mission River watershed is predominantly comprised of range and pasture land – 73% shrub/scrub and pasture hay out of the total 267,807 hectare (661,765 acre) land area (Figure 2). The watershed contains only 2 munici-

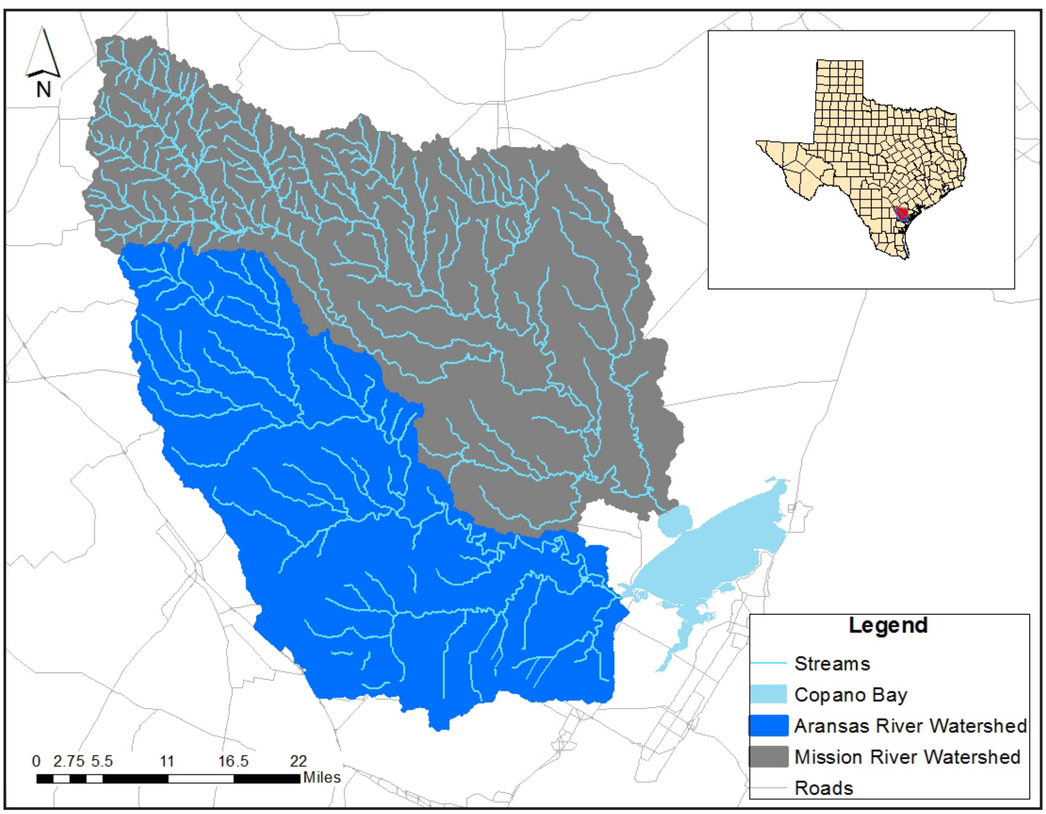


Figure 1. Copano Bay watershed location in Texas.

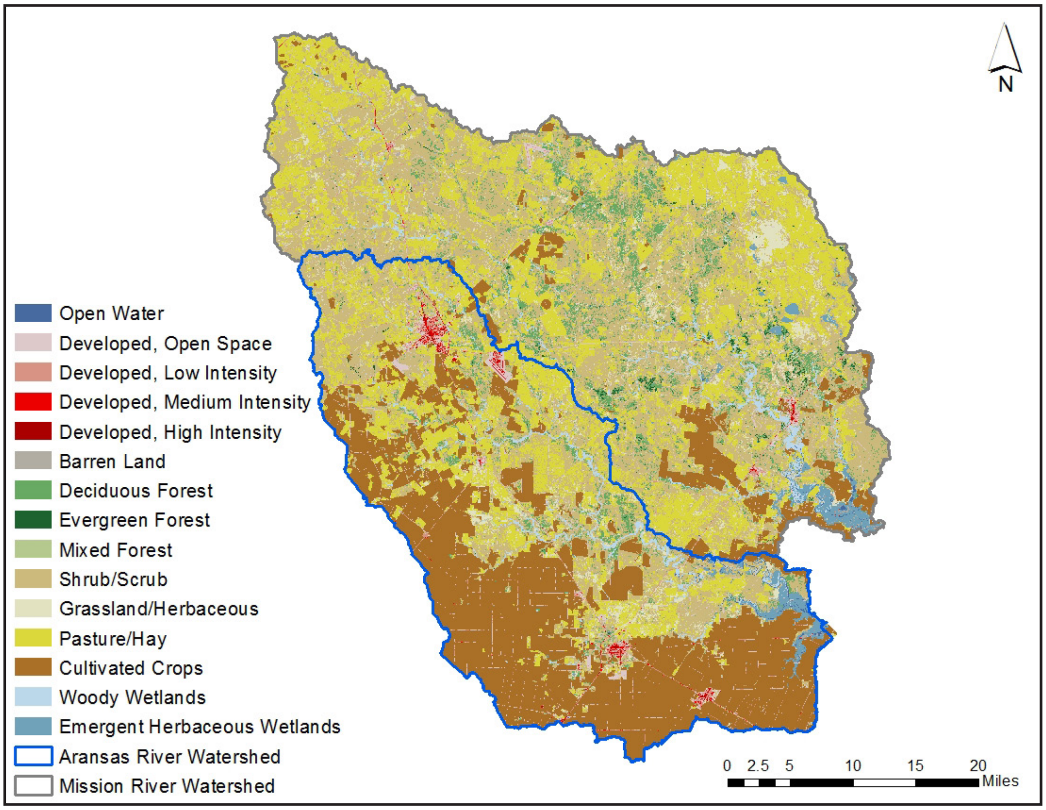


Figure 2. Copano Bay watershed land use.

palities, Refugio, population 2,840, and Woodsboro, population 1,484 (USCB 2013), spanning across portions of Karnes, Goliad, Bee, and Refugio counties.

SPATIAL ANALYSES

The spatially explicit methodology, developed at Texas A&M University by the Department of Biological and Agricultural Engineering and Spatial Sciences Laboratory, was used to identify contributing potential bacteria sources and to estimate daily potential from indicator bacteria, *E. coli* and *Enterococcus,* loads in the Aransas River and Mission River watersheds. All birds and mammals are potential sources of bacteria, and those present in the watershed contribute *E. coli* or *Enterococcus* to the tidal and freshwater portion of the Aransas and Mission rivers. However, each watershed is different and not all sources are likely to contribute significant amounts of bacteria to the water bodies. Additionally, sufficient information on species populations, *E. coli* and *Enterococcus* concentrations, and feces production rates are often unavailable, thus precluding the ability to effectively assess potential *E. coli* or *Enterococcus* contributions from respective sources. Data from government agencies and local stakeholders on the number and distribution of contributing sources, in combination with National Land Cover Database 2006 (NLCD 2006) land use classification data were entered into a GIS software program. Each watershed was also divided into 4,047 to 16,187 hectares (10,000 and 40,000 acres) 12-digit hydrologic unit code (HUC) subwatersheds acquired from U.S. Geological Survey (USGS) and U.S. Department of Agriculture-Natural Resources Conservation Service (USDA-NRCS) (2012). Bacterial sources were examined at this subwatershed level, as opposed to the entire watershed of each river, to identify and target the areas in each subwatershed where the sources were likely to impact water quality.

The 2 factors considered when determining the potential contribution for each source were the abundance of a particular source in the watershed and whether sufficient information is available to effectively predict bacteria loadings from that source. The methodology developed by Wagner and Moench (2009) to estimate animal population was applied here to update population densities. Wagner and Moench (2009) included cattle, horses, goats, sheep, domestic hogs, poultry, deer, and feral hogs in their estimation protocol. With the exception of domestic hogs and poultry, all of these sources, with the addition of on-site sewage facilities (OSSFs), wastewater treatment facilities (WWTFs), and pet dogs, warranted modeling and had sufficient information to model using SELECT.

POTENTIAL *E. COLI* AND *ENTEROCOCCUS* LOAD ESTIMATION

The analysis was performed at a 30 meter by 30 meter resolution. Each source was distributed to appropriate land uses in the watershed, and then the potential *E. coli* and *Enterococcus* loads were calculated using the equations in Tables 1 and 2, respectively. *E. coli* and *Enterococcus* bacteria are indicator bacteria and are generally not pathogenic but indicators of potential fecal contamination. The daily fecal coliform production rates for the livestock, wildlife, and feral hog sources were estimated per animal unit (AU) from Wagner and Moench (2009). The highest fecal coliform production values in U.S. Environmental Protection Agency (USEPA) guidelines document (2001) were used for OSSF and dog sources. *E. coli* and *Enterococcus* loads were calculated

Table 1. Calculation of potential *E. coli l*oads from various sources.

Source	*E. coli* load calculation
Cattle	$EC = \# \ Cattle * 1 \ AU * 8.55 \times 10^{9} \ cfu/AU/day * 0.63$
Horses	$EC = \# \ Horses * 1.25 \ AU * 2.91 \times 10^{8} \ cfu/AU/day * 0.63$
Goats	$EC = \# \ Goats * 0.17 \ AU * 2.54 \times 10^{10} \ cfu/AU/day * 0.63$
Sheep	$EC = \# \ Sheep * 0.2 \ AU * 2.90 \times 10^{11} \ cfu/AU/day * 0.63$
Deer	$EC = \# \ Deer * 0.112 \ AU * 1.50 \times 10^{10} \ cfu/AU/day * 0.63$
Feral Hogs	$EC = \# \ Hogs * 0.125 \ AU * 1.21 \times 10^{9} \ cfu/AU/day * 0.63$
OSSFs	$EC = \# \ OSSFs * Failure\ Rate * \frac{10 * 10^{6}}{100\ mL} * \frac{70\ gal}{\frac{person}{day}} * \frac{Avg\ \#}{Household} * \frac{3758.2\ mL}{gal} * 0.63$
Dogs	$EC = \# \ Households * \frac{1\ dog}{household} * 5 \times 10^{9} \ cfu/day * 0.63$
WWTFs	$EC = Permitted\ MGD * \frac{126\ cfu}{100\ mL} * \frac{10^{6}\ gal}{MGD} * \frac{3758.2\ mL}{gal}$

Table 2. Calculation of potential *Enterococcus* loads from various sources.

Source	*Enterococcus* load calculation
Cattle	$EC = \# \ Cattle * 1 \ AU * 8.55 \times 10^{9} \ cfu/AU/day * 0.175$
Horses	$EC = \# \ Horses * 1.25 \ AU * 2.91 \times 10^{8} \ cfu/AU/day * 0.175$
Goats	$EC = \# \ Goats * 0.17 \ AU * 2.54 \times 10^{10} \ cfu/AU/day * 0.175$
Sheep	$EC = \# \ Sheep * 0.2 \ AU * 2.90 \times 10^{11} \ cfu/AU/day * 0.175$
Deer	$EC = \# \ Deer * 0.112 \ AU * 1.50 \times 10^{10} \ cfu/AU/day * 0.175$
Feral Hogs	$EC = \# \ Hogs * 0.125 \ AU * 1.21 \times 10^{9} \ cfu/AU/day * 0.175$
OSSFs	$EC = \# \ OSSFs * Failure\ Rate * \frac{10 * 10^{6}}{100\ mL} * \frac{70\ gal}{\frac{person}{day}} * \frac{Avg\ \#}{Household} * \frac{3758.2\ mL}{gal} * 0.175$
Dogs	$EC = \# \ Households * \frac{1\ dog}{household} * 5 \times 10^{9} \ cfu/day * 0.175$
WWTFs	$EC = Permitted\ MGD * \frac{35\ cfu}{100\ mL} * \frac{10^{6}\ gal}{MGD} * \frac{3758.2\ mL}{gal}$

from fecal coliform loads using a ratio of 0.63 fecal coliform to *E. coli* and 0.175 fecal coliform to *Enterococcus*, based on 2010 Texas Surface Water Quality regulatory standards in recreational waters. The geometric mean regulatory standard for primary contact recreational use for freshwater (Segments 2002 and 2004) is 126 organisms per 100 milliliter for *E. coli*, and for high saline inland waters (Segments 2001 and 2003) 35 organisms per 100 milliliter for *Enterococcus* (TCEQ 2010). After the potential *E. coli* or *Enterococcus* loads were calculated, the results were aggregated to the subwatershed level to identify areas of potential concern.

Cattle

Cattle were uniformly applied according to 4 separate stocking rates derived from 2004 to 2008 *Texas Agricultural Statistics* (USDA-NASS 2004–2008) and USDA-NRCS estimates from Wagner and Moench (2009). The 4 stocking rates were: 20 acre/AU for the land use classifications of deciduous forest, evergreen forest, and mixed forest, 30 acre/AU for the shrub/scrub land use classification, 15.4 acre/AU for the land use classification grasslands/herbaceous, and 7.7 acre/AU for the pasture/hay classification. A total of 3,152 AUs were evenly distributed to all of the forested lands. 13,153 AUs of cattle were uniformly applied over shrub/scrub classifications. 3,148 AUs were evenly distributed over grassland/herbaceous land use classifications and 40,052 AUs were distributed over pasture/hay lands. The total cattle potential loads were estimated by adding together the results from the 4 separate stocking rate distributions. A fecal coliform production rate of 8.55×10^9 colony forming units (CFU) per AU per day (Wagner and Moench 2009) was used in the model and converted from fecal coliform to *E. coli* using a conversion ratio. The total potential *E. coli* and *Enterococcus* loads for cattle were estimated using the distributed cattle density production rate, fecal coliform production rate, and conversion ratios.

Horses

A total of 2,772 AUs of horses were evenly distributed over developed open space, grassland/herbaceous, and pasture/hay. This number was derived from the 2007 USDA Census of Agriculture (USDA-NASS 2007) county estimates multiplied by the percentage of the county in the Aransas River and Mission River watersheds and the AU conversion of 1.25 (Wagner and Moench 2009). The percentage of a county in a watershed was adjusted from Wagner and Moench (2009) because the watershed boundary differed from the original report, causing the estimated animal populations to adjust as well. The fecal coliform production rate used in the model was 2.91×10^8 CFU per AU per day (Wagner and Moench 2009). The total potential *E. coli* and *Enterococcus* loads for horses were estimated using the distributed horse density, fecal coliform production rate, and conversion ratios.

Goats

A total of 565 AUs of goats were evenly distributed over developed open space, shrub/scrub grassland/herbaceous, and pasture/hay. Wagner and Moench (2009) estimated the goat numbers by using the 2005–2008 *Texas Agricultural Statistics* for Bee, Goliad, and Karnes counties and district numbers for Aransas, Refugio, and San Patricio counties. The numbers were updated from Wagner and Moench (2009) by using an adjusted percent in watershed number because the Aransas River and Mission River watersheds boundaries differed from the original report. The fecal coliform production rate used in the model was 2.54×10^{10} CFU per AU per day (Wagner and Moench 2009), and total potential *E. coli* and *Enterococcus* loads for goats were estimated using the distributed goat density, fecal coliform production rate, and conversion ratios.

Sheep

A total of 111 AUs of sheep were evenly distributed over developed open space, shrub/scrub, grassland/herbaceous, and pasture/hay. This number was derived from the *2007 USDA Census of Agriculture* county estimates multiplied by the percentage of the county in the watershed and the AU conversion of 0.2 (USDA-NASS 2007; Wagner and Moench 2009). The fecal coliform production rate used in the model was 2.90×10^{11} CFU per AU per day (Wagner and Moench 2009) and total potential *E. coli* and *Enterococcus* loads for sheep were estimated using the distributed sheep density, fecal coliform production rate, and conversion ratios.

Deer

A total of 9,951 deer AUs were evenly applied over the entire watershed. This is the population estimate produced by applying Wagner and Moench (2009) county densities calculated from Texas Parks and Wildlife Department (TPWD) surveys. Deer were evenly distributed across the Aransas River and Mission River watersheds to best reflect the surveying techniques used by the TPWD. The densities were multiplied by the number of acres of the county in the watershed and the AU conversion of 0.112 to determine the number of deer AUs in each county. The fecal coliform production rate used was 1.50×10^{10} CFU per AU per day (Yagow 2001; Cox et al. 2005; Wagner and Moench 2009), and total potential *E. coli* and *Enterococcus* loads for deer were estimated using the distributed deer density, fecal coliform production rate, and conversion ratios.

Feral hogs

A total of 4,198 feral hog AUs were applied uniformly across deciduous forest, evergreen forest, mixed forest, shrub/scrub, grassland/herbaceous, pasture/hay, cultivated crops, and woody wetlands. This population estimate was derived by Reidy (2007) using a density of 33.3 acre/hog and an AU conversion of 0.125 (Wagner and Moench 2009). The fecal coliform production rate used was 1.21×10^9 CFU per AU per day (Cox et al. 2005; Mukhtar 2007; Wagner and Moench 2009), and total potential *E. coli* and *Enterococcus* loads for feral hogs were estimated using the distributed feral hog density, fecal coliform production rate, and conversion ratios.

On-site sewage facilities

OSSFs were modeled using spatially distributed point data of each household obtained from residential 911 address data gathered from the Coastal Bend Council of Governments and the Golden Crescent Regional Planning Commission. 2010 census data (USCB 2010) was used for Karnes County because 911 address data was unavailable for this county. Households within Certificate of Convenience and Necessity areas (PUC 2013) were removed to exclude households being serviced by a WWTF. The total number of households with OSSFs in the watershed was estimated to be 10,047, and the average persons per household for a census block were calculated by using 2010 Census data (USCB 2010). A fecal coliform concentration of raw sewage 10×10^6 CFU per 100 milliliters (USEPA 2001) was used to model failing OSSFs with a constant sewage discharge of 70 gallons per person per day. OSSF failure rate was estimated by applying the soil drainfield limitation classes as follows: very limited with 15% failing, somewhat limited with 10% failing, not limited with 5% failing, and not rated with 15% failing (USDA-NRCS 2004). The percentage of *E. coli* and *Enterococcus* contributing to the Aransas River and Mission River watersheds due to OSSF failures were calculated by multiplying the OSSF household densities, average person per household, fecal coliform concentration of raw sewage, sewage discharge, failure rate, and conversion ratios.

Dogs

A dog density of 1 dog per household was an updated density as reported by the American Veterinarian Medical Association and used in the Geronimo Creek watershed analysis (AVMA 2002; Geronimo and Alligator Creeks Watershed Partnership 2012). The density was applied to the residential 911 addresses, resulting in an estimated dog population of 10,065. The fecal coliform production rate of 5×10^9 CFU per dog per day (USEPA 2001) multiplied by the conversion ratios was used to determine the potential *E. coli* and *Enterococcus* loads resulting from dogs.

Wastewater treatment facilities

There are 12 WWTFs in the Aransas River and Mission River watersheds. Three WWTFs are within the Mission River watershed: town of Refugio, town of Woodsboro, and Pettus Municipal Utility District with permitted discharges of 0.576, 0.25, and 0.105 million gallons per day (MGD) respectively. Nine WWTFs are within the Aransas River watershed including 2 for the city of Beeville with permitted discharges of 3 and 2.5 MGD as well as, 2 for the city of Sinton with permitted discharges of 0.015 and 0.8 MGD. The remaining WWTFs in the Aransas River watershed are: city of Taft, Skidmore Water Supply Corporation, St. Paul Water Supply Corporation, Tynan Water Supply Corporation, and Texas Department of Transportation with permitted discharges of 0.9, 0.131, 0.05, 0.045, and 0.00038 MGD, respectively. Each WWTF was modeled at its daily maximum permitted discharge and, if applicable, its effluent limitation of either an *E. coli* concentration of 126 CFU or most probable number per 100 milliliters or an *Enterococcus* concentration of 35 CFU per 100 milliliters, to estimate the potential bacteria loads from WWTFs.

In total, 9 potential sources were modeled using SELECT in both the Aransas River and Mission River watersheds. Since the 2 watersheds are part of the entire Copano Bay watershed, the potential source contribution population densities applied were the same for both the Aransas River and Mission River watersheds.

RESULTS AND DISCUSSION

The watershed spatial analysis performed by SELECT highlights subwatersheds within the individual Aransas River and Mission River watersheds that have the highest potential to contribute *E. coli* and *Enterococcus* based on land use distribution and potential source contributions. The analysis highlights subwatersheds of concern for particular sources and for total potential *E. coli* and *Enterococcus* loads, taking into account all of the potential sources modeled. Conclusions can be made about which sources have the highest potential to contribute *E. coli* and *Enterococcus* and pinpoint subwatersheds where those contributions are in the Aransas River and Mission River watersheds by using SELECT results.

Spatially explicit *E. coli* and *Enterococcus* load estimation

Tables 3 and 4 illustrate the source specific *E. coli* and *Enterococcus* ranges used to estimate the contribution of each source

Table 3. Daily potential *E. coli* load ranges.

Potential Sources	**Daily Potential *E. coli* Load (cfu/day)**	
	Mission River Watershed	Aransas River Watershed
Cattle	$7.42 \times 10^{11} – 1.81 \times 10^{13}$	$2.86 \times 10^{11} – 1.25 \times 10^{13}$
Horses	$1.43 \times 10^{9} – 2.39 \times 10^{10}$	$3.47 \times 10^{9} – 2.17 \times 10^{10}$
Goats	$7.13 \times 10^{9} – 5.43 \times 10^{11}$	$2.14 \times 10^{10} – 5.43 \times 10^{11}$
Sheep	$0 – 1.68 \times 10^{12}$	$0 – 1.68 \times 10^{12}$
Deer	$8.56 \times 10^{11} – 3.23 \times 10^{12}$	$8.56 \times 10^{11} – 4.25\ 10^{12}$
Feral Hogs	$1.87 \times 10^{10} – 1.15 \times 10^{11}$	$9.87 \times 10^{10} – 1.15 \times 10^{11}$
OSSF	$0 – 5.13 \times 10^{12}$	$0 – 5.13 \times 10^{12}$
Dogs	$3.15 \times 10^{9} – 3.39 \times 10^{12}$	$3.15 \times 10^{9} – 3.39 \times 10^{12}$
WWTF	$0 – 1.43 \times 10^{10}$	$0 – 1.43 \times 10^{10}$

Table 4. Daily potential *Enterococcus* load ranges.

Potential Sources	**Daily Potential *Enterococcus* Load (cfu/day)**	
	Mission River Watershed	Aransas River Watershed
Cattle	$2.08 \times 10^{11} – 5.06 \times 10^{12}$	$8.00 \times 10^{10} – 3.51 \times 10^{12}$
Horses	$3.99 \times 10^{8} – 6.70 \times 10^{9}$	$9.71 \times 10^{8} – 6.05 \times 10^{9}$
Goats	$2.00 \times 10^{9} – 1.52 \times 10^{11}$	$5.98 \times 10^{9} – 1.52 \times 10^{11}$
Sheep	$0 – 4.72 \times 10^{11}$	$0 – 4.72 \times 10^{11}$
Deer	$2.40 \times 10^{11} – 9.06 \times 10^{11}$	$9.98 \times 10^{11} – 1.19 \times 10^{12}$
Feral Hogs	$5.23 \times 10^{9} – 3.23 \times 10^{10}$	$8.90 \times 10^{9} – 3.23 \times 10^{10}$
OSSF	$0 – 1.44 \times 10^{12}$	$0 – 1.44 \times 10^{12}$
Dogs	$8.82 \times 10^{8} – 9.50 \times 10^{11}$	$8.82 \times 10^{8} – 9.50 \times 10^{11}$
WWTF	$0 – 3.99 \times 10^{9}$	$0 – 3.99 \times 10^{9}$

for both the Mission River and Aransas River watersheds. The source-specific ranges for both watersheds are identical or similar because sources were distributed similarly. The source exhibiting highest daily potential *E. coli* and *Enterococcus* loads in both the Aransas River and Mission River watersheds was cattle, while OSSFs, dogs, and deer were the next highest contributors, respectively. Sources with moderate potential contributions were sheep, feral hogs, and goats. The lowest contributors were horses and WWTFs.

Figures 3 and 4 illustrate the total potential *E. coli* and *Enterococcus* loads, or combined load, which includes the loading potentials of all of the modeled sources applied in the Mission and Aransas River watersheds. Subwatersheds in red indicate areas with the highest potential for *E. coli* contributions to the river, while the darkest green represents areas with the lowest potential. The highest contributing subwatersheds either had a dominant land use of pasture/hay or urban land uses generally due to the high numbers of cattle, OSSFs, and dogs associated with these land uses. The lowest contributing subwatersheds contained areas of mostly cultivated crop land.

Potential Issues

SELECT provides a daily snapshot of fecal and bacterial deposition based on conditions inputted into the model, and as such, fecal buildup or bacteria die-off and re-growth are not taken into account. Fecal buildup over the land surface before a rainfall event as well as bacteria die-off can cause the actual *E. coli* or *Enterococcus* production rates to vary widely compared to those in the model.

SELECT does not take into account direct deposition of fecal material into the stream. Direct deposition significantly affects the bacteria concentrations present in a water body more so than land deposition. Larsen et al. (1994) found that manure deposited 0.6 meters (2 feet) from a stream contributed 83% less bacteria and manure deposited at 2.1 meters (7 feet) contributed 95% less than manure deposited directly into a stream. The timing of fecal deposition is also not taken into account. If fecal matter is deposited shortly before a rain event, then the bacteria will more likely end up in the water body

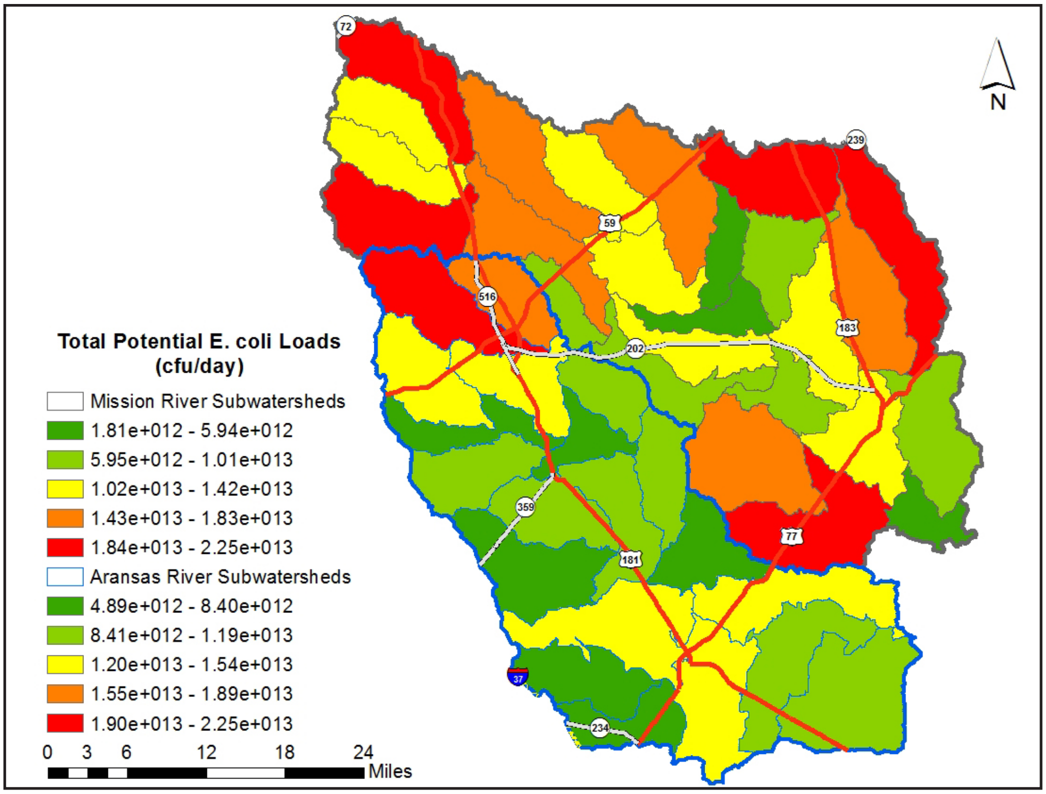


Figure 3. Total daily potential *E. coli* loads from all considered sources in the Mission River and Aransas River watersheds.

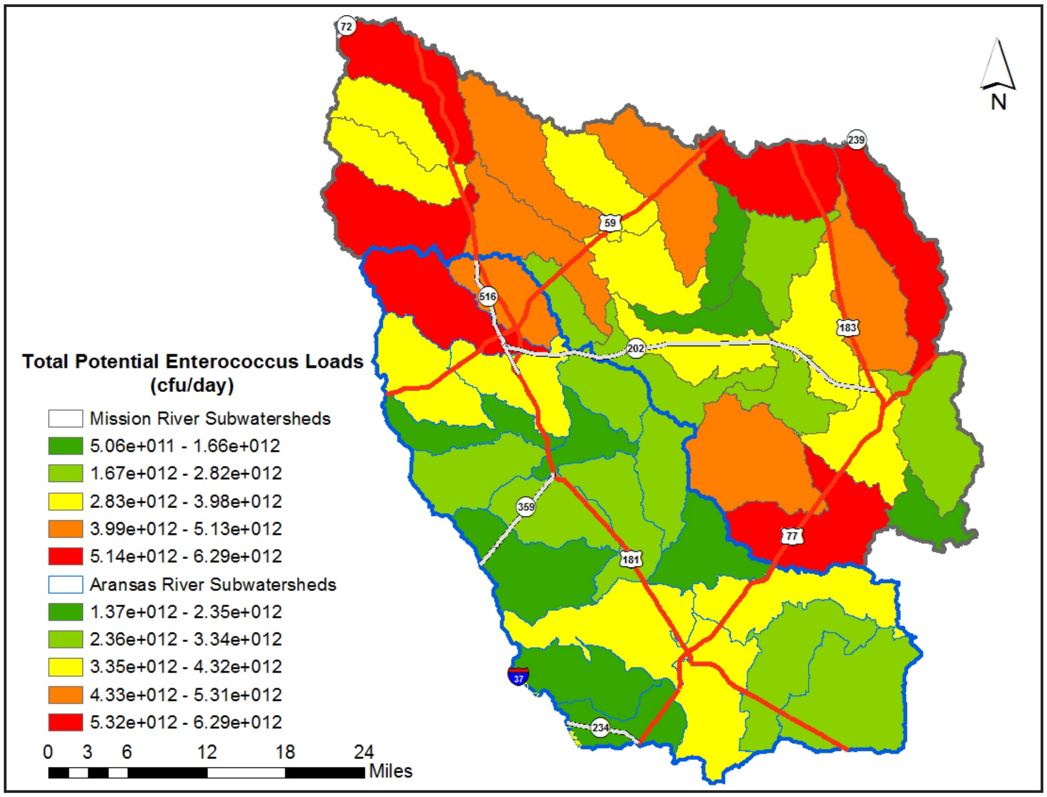


Figure 4. Total daily potential *Enterococcus* loads from all considered sources in the Mission River and Aransas River watersheds.

via surface runoff. A significant factor found by Wagner et al. (2012) is when runoff occurred more than 2 weeks following grazing (and fecal matter deposition), *E. coli* levels were 88% lower compared to runoff during or soon after grazing. SELECT does not take into account the distance of the fecal deposition from the water body. As found by Larsen et al. (1994), bacteria from fecal deposition have a much higher potential to impact water quality when deposited at closer distances compared to farther distances from a water body.

In addition, the animal densities used in the model can vary. Animal densities can change drastically from season to season and from year to year, particularly in response to worsening drought conditions that often affect many areas of Texas. Further, with the exception of feral hogs and deer, estimates of wildlife numbers are impracticable to evaluate. These issues can impact the watershed planning process, particularly because SELECT results show cattle as the top contributors of bacteria into the water bodies. In comparison, bacterial source tracking conducted in the Buck Creek, Little Brazos River, and Big Cypress Creek watersheds suggest that wildlife contributions range from 42–65%, while cattle and other domestic animal contributions range from only 14–29% (Di Giovanni et al. 2013). The fecal material from cattle may not be reaching and contaminating the water body, but other sources could be contaminating the water more directly or not integrated into the model. As a result, the best management practices (BMPs) chosen to be implemented would be influenced by these issues with the model, and their overall impact of projected loadings would be greatly affected.

CONCLUSIONS

The SELECT methodology was applied to the entire Copano Bay watershed, comprised of the Aransas River and Mission River watersheds, to calculate potential *E. coli* and *Enterococcus* loads occurring in the watersheds and identify priority areas for implementing management practices. The SELECT methodology was adapted to the Copano Bay watershed to include the perceived potential contributors with data availability. The model is unable to reflect the true potential loading of the watershed as not all contributing sources are taken into account due to the availability of data. Once data is collected, the SELECT model can be adapted and additional sources can easily be added to the model. In both the Aransas River and Mission River watersheds, cattle were determined to be the largest potential contributor. This suggests that BMPs supporting good grazing management will yield the most improvements and be the most effective at lowering the bacteria contamination in the water body. The SELECT methodology was able to highlight areas of highest concern, which provides guidance for individuals and entities that implement BMPs where practices would be the most effective. The SELECT methodology can easily be adapted and applied to watersheds to reflect stakeholder concerns.

The next steps for the SELECT methodology are to account for sources that are currently not able to be modeled, such as mesomammals, birds, and other background sources. Potential integration of bacterial source tracking results with SELECT could also be evaluated to address these issues. Future SELECT methodology could also include fecal buildup and bacteria die-off and re-growth to improve the model. SELECT outputs could be combined with another model to determine the *E. coli* and *Enterococcus* loads reaching the water bodies either through surface runoff or through soils.

REFERENCES

[AVMA] American Veterinary Medical Association. 2002. U.S. pet ownership and demographics source book. Schaumberg (Illinois): Center for Information Management American Veterinary Medical Association.

Borel KE, Karthikeyan R, Smith PK, Gregory LF, Srinivasan R. 2012. Estimating daily potential *E. coli* loads in rural Texas watersheds using spatially explicit load enrichment calculation tool (SELECT). Texas Water Journal. 3(1):42-58.

Cox P, Griffith M, Angles M, Deere D, Ferguson C. 2005. Concentrations of pathogens and indicators in animal feces in the Sydney watershed. Applied and Environmental Microbiology. 71(10):5929-34.

Di Giovanni GD, Casarez EA, Gentry TJ, Martin EC, Gregory L, Wagner K. 2013. Support analytical infrastructure and further development of a statewide bacterial source tracking library [Internet]. College Station (Texas): Texas Water Resources Institute. TR-448. 74 p. Available from: http://twri.tamu.edu/reports/2013/tr448.pdf

Fraser RH, Barten PK, Pinney DA. 1998. Predicting stream pathogen loading from livestock using a geographical information system-based delivery model. Journal of Environmental Quality. 27:935-945.

Geronimo and Alligator Creeks Watershed Partnership. 2012. Geronimo and Alligator Creeks watershed protection plan [Internet]. College Station (Texas): Texas AgriLife Extension Service; [cited 2015 January 11]. 174 p. Available from: http://www.geronimocreek.org/documents/wpp/FinalDraftGACWPP.pdf

Larsen R, Miner J, Buckhouse J, Moore JA. 1994. Water-quality benefits of having cattle manure deposited away from streams. Bioresource Tech. 48(2):113-118.

Mukhtar S. 2007. Manure production and characteristics: Its importance to Texas and animal feeding operations [Internet]. College Station (Texas): Texas AgriLife Extension Service, Texas A&M System; [cited 2015 January

11]. L-5489. Available from: http://agrilifecdn.tamu.edu/tammi/files/2014/04/manureproductionSM-5489.pdf

Munafo M, Cecchi G, Baiocco F, Mancini L. 2005. River pollution from non-point sources: a new simplified method of assessment. Journal of Environmental Management. 77:93-98.

[NLCD] National Land Cover Database. 2006. NLCD 2006 land cover (2011 edition) [Internet]. Washington (District of Columbia); National Land Cover Database Multi-Resolution Land Characteristics Consortium; [cited 2015 January 11]. Available from: http://www.mrlc.gov/nlcd06_data.php

[PUC] Public Utility Commission of Texas. 2013.Water & Sewer Certificates of Convenience and Necessity Service Areas & Facility Lines[Internet]. Austin (Texas): Public Utility Commission of Texas; [cited 2015 January 11]. Available from: https://www.puc.texas.gov/industry/water/utilities/gis.aspx

Reidy MM. 2007. Efficacy of electric fencing to inhibit feral pig movements and evaluation of population estimation techniques[thesis]. [Kingsville (Texas)]: Texas A&M University-Kingsville.

Riebschleager KJ, Karthikeyan R, Srinivasan R, McKee K. 2012. Estimating potential *E. coli* sources in a watershed using spatially explicit modeling techniques. Journal of the American Water Resources Association. 48(4):745-761.

Teague A, Karthikeyan R, Babbar-Sebens M, Srinivasan R, Persyn RA. 2009. Spatially explicit load enrichment calculation tool to identify potential *E. coli* sources in watersheds, Transactions of the ASABE. 52(4):1109-1120.

[TCEQ] Texas Commission on Environmental Quality. 2012. 2012 Texas integrated report [Internet]. Austin (Texas): Texas Commission on Environmental Quality; [cited 2015 January 11]. Available from: http://www.tceq.texas.gov/waterquality/assessment/waterquality/assessment/12twqi/twqi12

[TCEQ] Texas Commission on Environmental Quality. 2010. Chapter 307 – Texas surface water quality standards [Internet]. Austin (Texas): Texas Commission on Environmental Quality; [cited 2015 January 30]. 217 p. Available from: https://www.tceq.texas.gov/assets/public/waterquality/standards/TSWQS2010/TSWQS2010_rule.pdf

[USCB] U.S. Census Bureau. 2010. 2010 TIGER/Line Shapefiles [Internet]. Washington (District of Columbia): U.S. Census Bureau; [cited 2015 January 11]. Available from: ftp://ftp2.census.gov/geo/pvs/tiger2010st/

[USCB] U.S. Census Bureau. 2013. Annual estimates of the resident population: April 1, 2010 to July 1, 2012 [Internet]. Washington (District of Columbia): U.S. Census Bureau, Population Division; [cited 2015 January 11]. Available from: http://factfinder.census.gov/faces/tableservices/jsf/pages/productview.xhtml?pid=PEP_2012_PEPANNRES&prodType=table

[USDA-NASS] U.S. Department of Agriculture National Agricultural Statistics Service. 2004–2008. Texas agricultural statistics [Internet]. Austin (Texas): U.S. Department of Agriculture National Agricultural Statistics Service Texas Field Office; [cited 2015 January 11]. Available from: http://www.nass.usda.gov/Statistics_by_State/Texas/Publications/Annual_Statistical_Bulletin/

[USDA-NASS] U.S. Department of Agriculture National Agricultural Statistics Service. 2007. 2007 Census of agriculture [Internet]. Washington (District of Columbia): U.S. Department of Agriculture National Agricultural Statistics Service; [cited 2015 January 11]. Available from: http://www.agcensus.usda.gov/Publications/2007/index.php

[USDA-NRCS] U.S. Department of Agriculture-Natural Resources Conservation Survey. 2004. Soil Survey Geographic (SSURGO) Database [Internet]. Washington (District of Columbia): U. S. Department of Agriculture National Resource Conservation Service; [cited 2015 January 11] Available from: http://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx

[USEPA] U.S. Environmental Protection Agency. 2001. Protocol for developing pathogen TMDLs: Source Assessment, 5-1-5-18 1st edition [Internet]. Washington (District of Columbia): U.S. Environmental Protection Agency; [cited 2015 January 11]. 132 p. Available from: http://www.epa.gov/owow/tmdl/pathogen_all.pdf

[USEPA] U.S. Environmental Protection Agency. 2013. Causes of impairment for 303(d) listed waters [Internet]. Washington (District of Columbia): U.S. Environmental Protection Agency; [cited 2015 January 11]. Available from: http://iaspub.epa.gov/waters10/attains_nation_cy.control?p_report_type=T#status_of_data

[USGS and USDA-NRCS] U.S. Geological Survey and U.S. Department of Agriculture Natural Resources Conservation Service. 2012. Federal standards and procedures for the national watershed boundary dataset (WBD) (3rd edition): U.S. Geological Survey Techniques and Methods 11–A3 [Internet]. Reston (Virginia): U.S Geological Survey; [cited 2015 January 11]. 63 p. Available from: http://pubs.usgs.gov/tm/tm11a3/

Wagner K, Moench E. 2009. Education program for improved water quality in Copano Bay: Task two report [Internet]. College Station (Texas): Texas Water Resources Institute; [cited 2015 January 11]. TR-347. 33 p. Available from: http://twri.tamu.edu/reports/2009/tr347.pdf

Wagner K, Redmon L, Gentry T, Harmel R. 2012. Assessment of cattle grazing effects on *E. coli* runoff. Transactions of the ASABE. 55(6):2111-2122.

Yagow G. 2001. Fecal coliform TMDL, Mountain Run watershed, Culpeper County, Virginia [Internet]. Richmond (Virginia): Virginia Tech Department of Biological Systems Engineering, Department of Environmental Quality, and Department of Conservation and Recreation; [cited 2015 January 11]. Available from: http://www.deq.virginia.gov/portals/0/DEQ/Water/TMDL/apptmdls/rapprvr/mtrnfec.pdf

Texas Water Resources Institute
Texas Water Journal
Volume 6, Number 1, Pages 45–63

Who regulates it? Water policy and hydraulic fracturing in Texas

Margaret A. Cook[1*], Karen L. Huber[2], Michael E. Webber[3]

Abstract: Hydraulic fracturing, the injection of a pressurized fluid mixture of mostly water, sand and a small amount of chemicals (frac fluids), increases extraction rates and recovery of oil or gas. The technique has become increasingly popular when used in combination with horizontal drilling, especially in Texas shale formations. Hydraulic fracturing often requires thousands of cubic meters of water per well. Access to water might be challenging due to water scarcity, allocation policies, price, location, and competition for water. In this policy analysis, we conducted a detailed bottom-up survey for each groundwater conservation district to catalog and assess the prevailing policies and practices related to water and hydraulic fracturing, focusing on the ways in which the State of Texas regulates the use of fresh and non-freshwater for hydraulic fracturing. We find that policies are inconsistent statewide with great variability from district to district in regulations and potential solutions to the challenge of freshwater use. From this analysis, we provide information on the practice of hydraulic fracturing and examine strategies for reducing freshwater use through recycling and use of non-freshwater. In this report, we present the current water policy framework and alternative solutions.

Keywords: Hydraulic fracturing, water policy, groundwater, produced water, brackish water

[1]Department of Civil, Architectural and Environmental Engineering, The University of Texas at Austin, Austin, TX 78712-1173

[2]Lyndon B. Johnson School of Public Affairs, The University of Texas at Austin, Austin, TX 78713-8925

[3]Department of Mechanical Engineering, The University of Texas at Austin, Austin, TX 78712-1591

*Corresponding author: margaretcook@utexas.edu

Citation: Cook MA, Huber KL, Webber ME. 2015. Who regulates it? Water policy and hydraulic fracturing in Texas. Texas Water Journal. 6(1):45-63. Available from: https://doi.org/10.21423/twj.v6i1.7021.

Terms used in paper

Short name or acronym	Descriptive name
NPDES	National Pollutant Discharge Elimination System
TDS	total dissolved solids

INTRODUCTION AND SCOPE

The interconnection between energy and water has become increasingly apparent as both resources are stretched to provide for growing populations. Hydraulic fracturing, the injection of a pressurized fluid mixture of mostly water and sand and a small amount of chemicals (frac fluids), increases extraction rates and recovery of oil or gas. This technique has become increasingly popular when used in combination with horizontal drilling, especially in Texas shale plays (Pacsi et al. 2014). Hydraulic fracturing encompasses less than 2% of overall state water supplies but sometimes results in much higher water use on the local scale (Nicot and Scanlon 2012; Vaughan et al. 2012). Moreover, 2 of the most active areas, the Permian Basin and Eagle Ford Shale, are located in water-scarce areas and have grown substantially since current water availability data was assessed and made public. As the use of hydraulic fracturing has increased, public concerns have been raised over the water quantity used in the hydraulic fracturing process, the source of that water, the proper management and disposal of wastewater, and seismic activity potentially resulting from wastewater disposal. This policy analysis provides information on hydraulic fracturing and examines ways in which the State of Texas regulates the use of fresh and non-freshwater for hydraulic fracturing. We present a case for increased use of alternative water resources, particularly recycling produced water. We outline recommended strategies for reducing freshwater use in favor of non-freshwater use.

BACKGROUND

Water availability in Texas

The 2010 U.S. census revealed that, over the last 10 years, Texas received the largest increase in population of any state (U.S. Census Bureau 2012). In the same period, Texas also suffered more weeks of exceptional drought—the worst drought classification given by the National Drought Mitigation Center—than any other state (National Drought Mitigation Center 2013). Between 2011 and 2014, water supplies in Texas dwindled. Surface water levels reached their 20-year low between February and October 2013 and again in 2014 as shown in Figure 1. Similarly, water levels in the Ogallala Aquifer in Texas have sharply decreased over the past 60 years (USGS 2014). The U.S. Geological Survey reports depletion of 45 to 122 meters across the Texas portion of the aquifer (USGS 2014). In the Winter Garden region of South Texas, in the Eagle Ford Shale area, groundwater levels have declined over 60 meters over an area of 6.5 × 10^3 square kilometers (Deeds et al. 2003). This increased water scarcity is the motivation for the research presented in this manuscript.

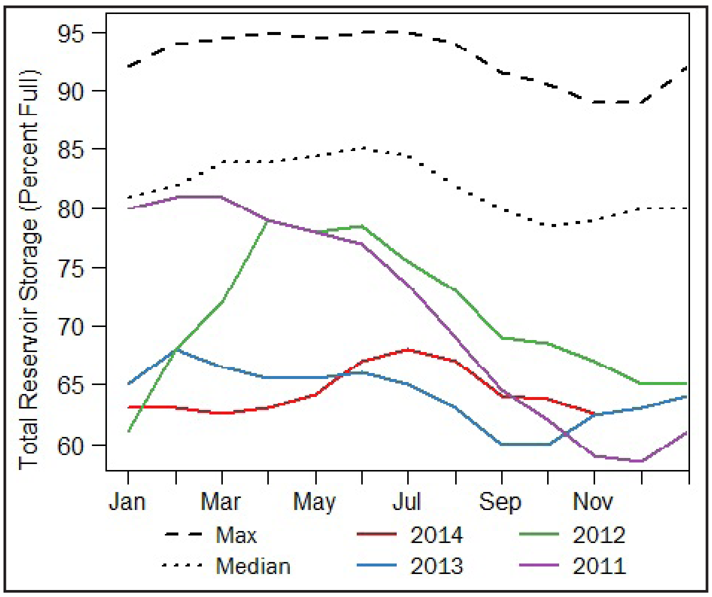


Figure 1. Surface water reservoir levels across the State of Texas remained below median levels between 2011 and 2014. Between February and October 2013, water levels remained at the lowest levels in 20 years. Water levels in 2014 then dipped lower between January and June. (Map created by the author based on data from Water Data for Texas.)

Water use for hydraulic fracturing in Texas

Hydraulic fracturing is often used alongside horizontal drilling, particularly in Texas shale plays. Shale deposits are thin, sometimes relatively impermeable, layers of rock that contain significant quantities of natural gas or petroleum liquids and often cover a large area underground. A horizontal well is developed by drilling a vertical well thousands of feet into the ground then turning the drill horizontally into the zone from which the operator would like to produce hydrocarbons, as shown in Figure 2.

The lateral portion will often extend many thousands of meters. The total length of the vertical and lateral portions of the horizontal well depends on the depth of the shale and the horizontal distance to the intended production zone. Within the aquifer, the wells are cased in concrete and steel to protect freshwater. Using a horizontal well rather than the traditional vertical well allows the well to be fractured at multiple points, or stages, along the horizontal line of the well instead of just along the vertical. By fracturing multiple points along the horizontal line, the operator is able to access a much wider area of shale. Thus, a horizontal well can be more productive in accessing the unconventional resource than a vertical well. Hydraulic fracturing in combination with horizontal drilling uses more water per well than conventional production does, though the ultimate ratio of water to energy extracted is similar to conventional production (Scanlon et al. 2014a).

Because the technologically advanced process of hydraulic fracturing allows access to oil and gas in shale rock previously considered too impervious for economic extraction, production has increased significantly. Many of these areas had some historical production, but production has increased in areas where little to no oil or gas activity occurred previously. These areas are now experiencing increased water demands from increased or new exploration. Some of these areas already experience high water demands from other water use sectors, such as irrigation for agriculture. Thus, the rise in the number of unconventional shale wells puts pressure on existing water resources, especially in the arid and drought-prone areas of Texas.

Texas has several shale plays, as shown in Figure 3. The Energy Information Administration estimates the Eagle Ford Shale holds about 4.3% of the nation's total natural gas reserves and about 7% of the nation's total oil reserves (US EIA 2011). As shown in Figure 4, Texas experienced increased levels of oil production and volatile gas production between 2007 and 2014. Some analysts expect continued long-term growth (US EIA, 2014a).

Hydraulic fracturing requires thousands of cubic meters of frac fluids per well. However, the specific amount of water and the specific frac fluid formula varies based on many factors, including the geology of the shale play. In the Barnett Shale, water use per well is on average 1.06×10^4 cubic meters. (2.8 $\times 10^6$ gallons) while in the Eagle Ford Shale, water use per

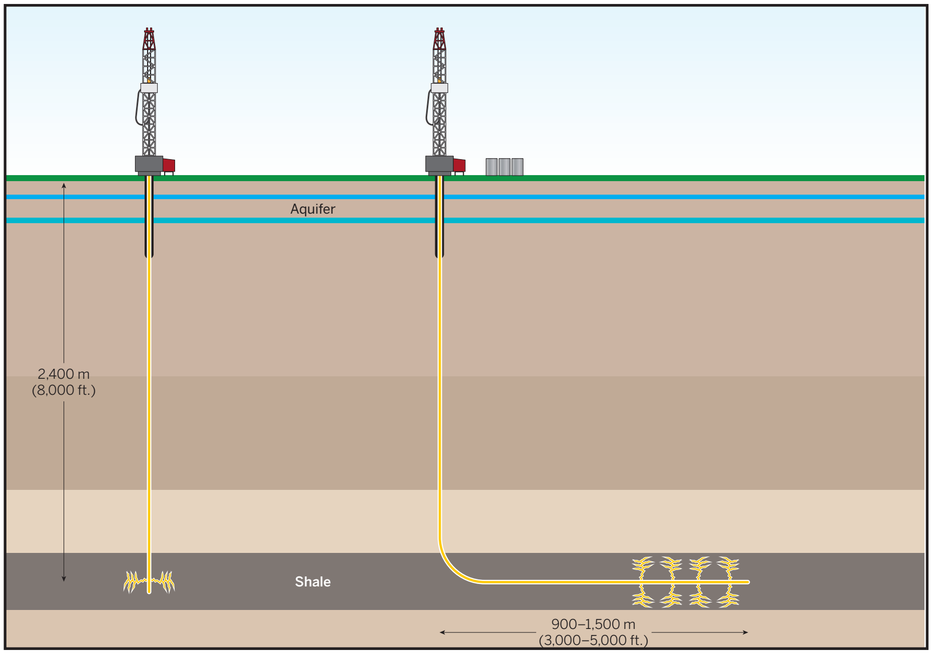


Figure 2. The figure shows examples of horizontal and vertical wells. A horizontal well is developed by drilling a vertical well thousands of meters into the ground then turning the drill horizontally into the zone from which the operator would like to produce hydrocarbons. The graphic is not to scale. (Graphic created by Jeff Phillips.)

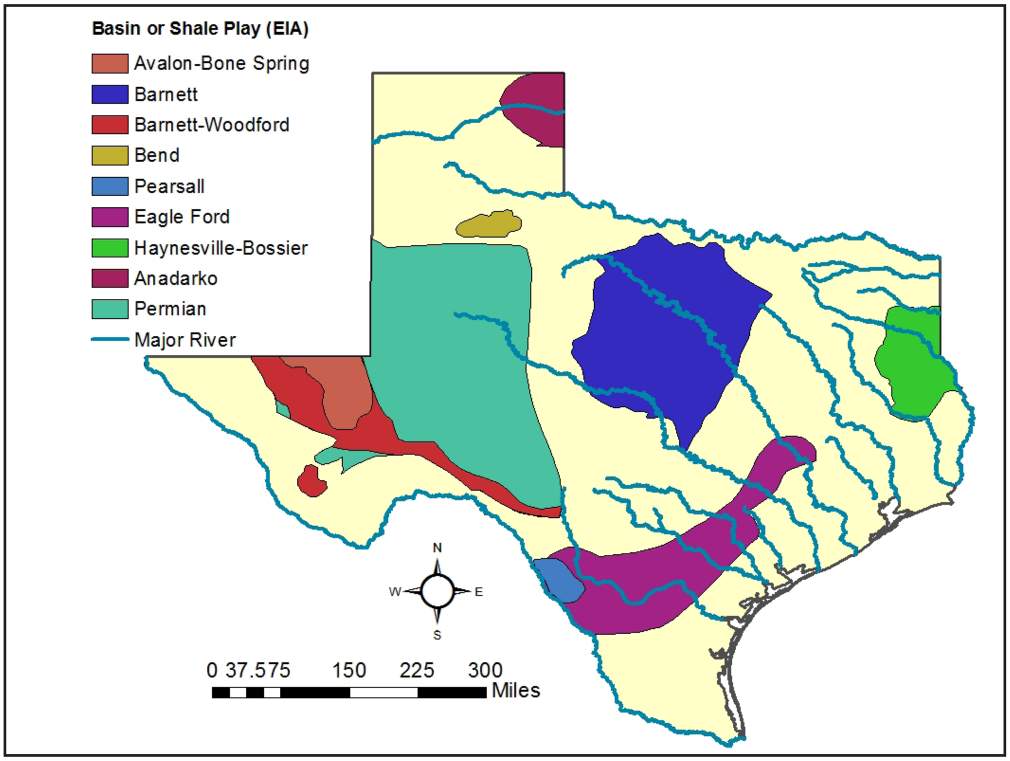


Figure 3. The map shows shale plays and major rivers in Texas. Surface water could be used in hydraulic fracturing operations when it is available physically and legally. (Map created by the author based on data from the Texas Water Development Board and EIA.)

well is on average 1.61×10^4 cubic meters (4.3×10^6 gallons) (Nicot and Scanlon 2012). In the Eagle Ford Shale, water use is equivalent to the water used for conventional oil production on a water-to-oil produced basis (Scanlon et al. 2014a). That water use amounts to less than 2% of state water use in Texas but could be significantly higher at the county or regional level (Nicot and Scanlon 2012; Vaughan et al. 2012). For example, oil and gas water use in Wise County was 40% of total water use in 2010 (Nicot and Scanlon 2012). In La Salle County, water use for oil and gas is expected to reach 89% of total water use by 2019, and in San Augustine County, oil and gas water use is expected to reach 136% of total water use by 2017 (Nicot and Scanlon 2012). In the United States, 48% of shale oil and gas wells are located in areas of high or extremely high

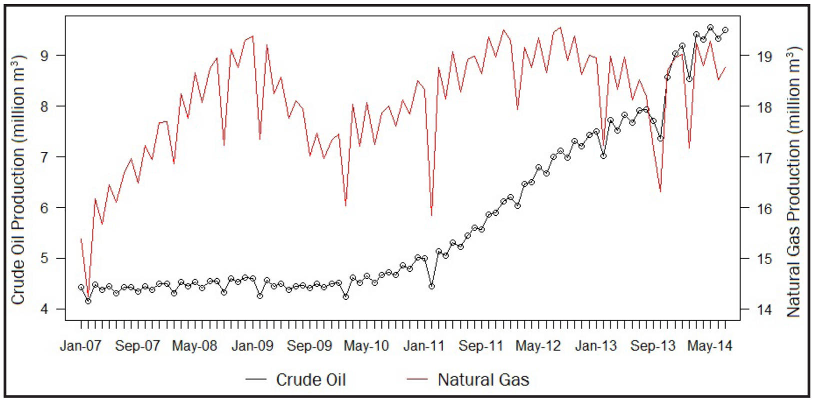


Figure 4. Between 2007 and 2013 natural gas production in Texas has fluctuated between 6 and 9×10^6 cubic meters, increasing from 2007 to 2009 and peaking in 2012 at close to 10×10^6 cubic meters. (Graph created by the authors based on data from RRC 2014a.)

water stress (Freyman 2014). In Texas, 28% of Eagle Ford wells are located in areas of high or extremely high water stress, while 87% of wells in the Permian Basin region are in areas of high or extreme water stress (Freyman 2014). Moreover, oil and gas production in these regions has also led to increased population growth, further taxing water availability and use (Freyman 2014).

In the area surrounding the Eagle Ford Shale formation, total water consumption is expected to increase from 7.15×10^6 cubic meters in 2010 to 5.5×10^7 cubic meters in 2020 due to oil and gas drilling (Nicot and Scanlon 2012). In a 2012 report, the Bureau of Economic Geology reported that groundwater provides approximately 100% of the water used for oil and gas in the Permian Basin, about 90% in the Eagle Ford, about 80% in the Anadarko Basin in the Texas Panhandle, and about 20% in the Barnett Shale (Nicot et al. 2012). In the Eagle Ford, operators mainly use groundwater from the Carrizo Aquifer, though some rely on surface water from the Rio Grande (Nicot and Scanlon 2012).

Past groundwater depletion from agricultural use already limits water availability in certain areas (Nicot and Scanlon 2012). These projections for high water use introduce a vulnerability and potential hindrance to increased hydraulic fracturing in Texas because the water might not be available due to prior allocation of surface water for other purposes, such as irrigation. This concern is most prevalent in areas where surface water resources are used for hydraulic fracturing. In areas where groundwater is used, water might not be available due to prior uses or water restrictions mentioned later in this paper. In certain areas of the state, water use for hydraulic fracturing has been banned or restricted. In August 2011, in the Barnett Shale region, the city of Grand Prairie banned the use of municipal water for hydraulic fracturing (Lee 2011). Similarly, in the Texas Panhandle the Board of Directors of the High Plains Underground Water Conservation District Number 1, which governs water use in the Ogallala Aquifer in its district, included limits on water use for hydraulic fracturing when it approved restrictions in July 2011 (Lee 2011). In 2014, citizens of the Denton voted to ban hydraulic fracturing from the city's limits. The ban was triggered partially by concerns over water (Dropkin and Henry 2014).

Significant volumes of flowback water—water that flows back to the surface from the well in the period immediately following hydraulic fracturing—and produced water,—water that originated in the production zone of the shale—return to the surface with the oil and gas after water is injected during the hydraulic fracturing process. These volumes vary by location. In the Permian Basin, the volume ratio of flowback and produced water to hydraulic fracturing water injected is 50-100% over the life of the well in the Midland Basin, the eastern portion of the Permian Basin, and 100% over the first year and about 200% over the life in the Delaware Basin, the western portion of the Permian Basin in Texas and New Mexico (Nicot et al. 2012). The volume ratio is much lower in the Eagle Ford—about 20% over the life of the well (Nicot et al. 2012). In the Barnett Shale area, the ratio is 10-20% in the first month and could reach 150% after 5 years (Nicot et al. 2012).

The significant volumes of flowback water and produced water are collected at the surface. Oil and gas are primarily disposed of in a different underground location via injection wells, removing it from the region's hydrologic cycle. According to the U.S. Environmental Protection Agency, "When states began to implement rules preventing disposal of brine to surface water bodies and soils, injection became the preferred way to dispose of this waste fluid" in the United States (US EPA 2014a). More discussion on injection and disposal is included later in this paper in the section "Disposal of production waste." Because much of the water used for unconventional oil and gas production is either sequestered in the shale formation during hydraulic fracturing or subsequently injected for disposal, most of the water used over the life of the well is considered consumed and is no longer part of the original hydrologic cycle. More discussion on how to reduce that consumption is included later in this paper in the section "Produced water reuse and recycling."

EXISTING POLICIES FOR WATER USE FOR HYDRAULIC FRACTURING IN TEXAS

An oil and gas operator has many choices in the selection of a water source, the essential ingredient in unconventional shale production. This section outlines the various policies associated with the water sources used in hydraulic fracturing operations.

Freshwater allocation policies in Texas

Freshwater is the most commonly used water source for hydraulic fracturing operations (Lyons and Tintera 2014). Surface water or groundwater is often located in close proximity to hydraulic fracturing operations, but Texas treats its surface water and groundwater differently from a regulatory perspective.

Price and location are major drivers in choosing the water source. Freshwater costs approximately \$0.35–\$1.50 for 1.6×10^{-1} cubic meters of water (a barrel of 42 gallons of water), according to estimates from various sources (Cook and Webber 2014; Galbraith 2013; Paul 2014). This price can be compared with the price of other source water that will also require minimal on-site treatment. If treatment is required, it is often helpful to compare total water costs, including the cost of source water, any required treatment for source water after purchase, transportation to and from the site, and storage, as well as disposal, reuse, or recycling for beneficial use. Total water costs vary by local market prices, by volume of water, and by distance and time in transit during transportation and often amount to several dollars per barrel of source water.

Surface water: prior appropriation

Access to water is exacerbated by water scarcity as well as water allocation policies. Texas surface water is allocated under the doctrine of prior appropriation, where a permit to withdraw water is based not on land ownership but on the point in time at which the permit, or "water right," was acquired from the Texas Commission on Environmental Quality or its predecessor agencies (Getches 2009). The system is often simplified as "first in time, first in right." Upon application, a permitting authority gives a water right holder a priority date and an allocation amount that resides with the water right as long as it remains valid. Thus, water shortages fall on those who last obtained a legal right to use the water. This is unlike under riparian water law, common in eastern states, where shortages are shared equally among landowners adjacent to the water source (Getches 2009). The Texas Commission on Environmental Quality can issue a priority call in times of drought, restricting users with permits after a certain priority date. In Texas, water users who seek to use less than 1.2×10^4 cubic meters (10 acre-feet or 3.25×10^6 gallons) can apply for a temporary permit for less than 1 year from the Texas Commission on Environmental Quality (TCEQ 2009). The commission may suspend all temporary permits in times of drought (TCEQ 2009). The commission, based on priority calls, can also restrict junior permit rights to withdraw in times of drought. Because appropriative rights exist separate from land ownership, they can be bought, sold, leased, or transferred, forming the basis for a surface water market.

In the Barnett Shale, about 80% of water used for oil and gas is surface water (Nicot et al. 2012). The Brazos River Authority has contracts to provide water to hydraulic fracturing operations while the Trinity River Authority does not supply water to oil and gas operations through such water contracts (Nicot et al. 2014). One of the major irrigation districts in the Lower Rio Grande, Hidalgo County Irrigation District No. 2, has added diversion points in the Middle Rio Grande, further upstream from its original diversion, where water can be easily delivered to energy entities that need water in the southern Eagle Ford Shale (Doherty and Smith 2012).

Groundwater: rule of capture and groundwater conservation districts

In contrast to its ownership and direct governance of surface water, the State of Texas does not incorporate permitting or judgments on reasonable use of water into its groundwater policy. Groundwater in Texas is owned by the landowner and follows the rule of capture. The rule of capture gives the right to withdraw groundwater to the landowner residing above that water and, absence trespassing, negligence, malice, or willful waste, landowners can withdraw as much water as they want without incurring liability, even if that withdrawal will inhibit access to water by neighboring landowners (Potter 2004). However, such rights are subject to groundwater conservation districts where present. Groundwater conservation districts are authorized by the Texas Legislature to protect and manage groundwater resources to maintain supplies in the area (Mittal and Gaffigan 2009). These districts have the ability to require permits and to place reasonable restrictions on water withdrawals or well location (Mittal and Gaffigan 2009). Some areas of the state are not within the boundaries of a groundwater conservation district, and therefore, water withdrawals are unregulated.

Because groundwater is a property right, it can be bought, sold, or traded. However, under the rule of capture, groundwater is an open-access good. Unless restricted by a groundwater conservation district or other authority, landowners may withdraw as much water as they need and are not prevented from over-exploiting it. No single user has an incentive to reduce exploitation due to knowledge that neighbors might exploit or sell water (Holland and Moore 2003).

On the other hand, regulations by groundwater conservation districts limit over-exploitation of groundwater while still allowing necessary water use and potential water marketing. Groundwater conservation districts have the authority to permit wells, require water withdrawal reporting and metering, and limit production. Figure 5 shows the groundwater conservation districts in which hydraulic fracturing operations are occurring as of December 2014 as recorded by the Texas Alliance of Groundwater Districts (TAGD 2014). There are hydraulic fracturing operations occurring outside of these areas where a groundwater conservation district is not present.

Figure 6 shows the groundwater conservation districts that require permits for wells used to supply water to hydraulic fracturing operations. As of December 2014, many districts that do not require permits are contemplating requiring them. Water restrictions for hydraulic fracturing are not uniform across the state, shale plays, or aquifers.

Part of the lack of uniformity and clarity is because wells for oil and gas drilling and exploration are exempt from groundwater conservation district permitting, but there is confu-

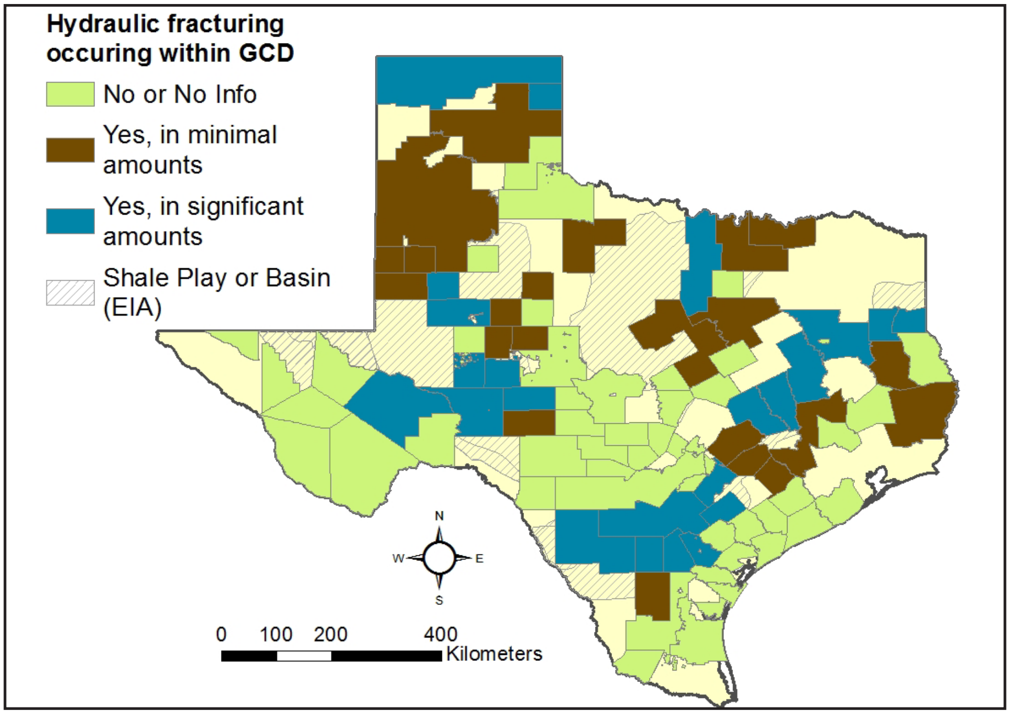


Figure 5. The map shows groundwater conservation districts in which hydraulic fracturing is occurring as of December 2014. There are parts of the state in which there is a groundwater conservation district but no hydraulic fracturing, conveyed by the "No or No Info" category. There are parts of the state in which hydraulic fracturing is occurring as of December 2014 but there is no groundwater conservation district regulating water withdrawals, conveyed with blank space. (Map created by the author based on data from TAGD 2014.)

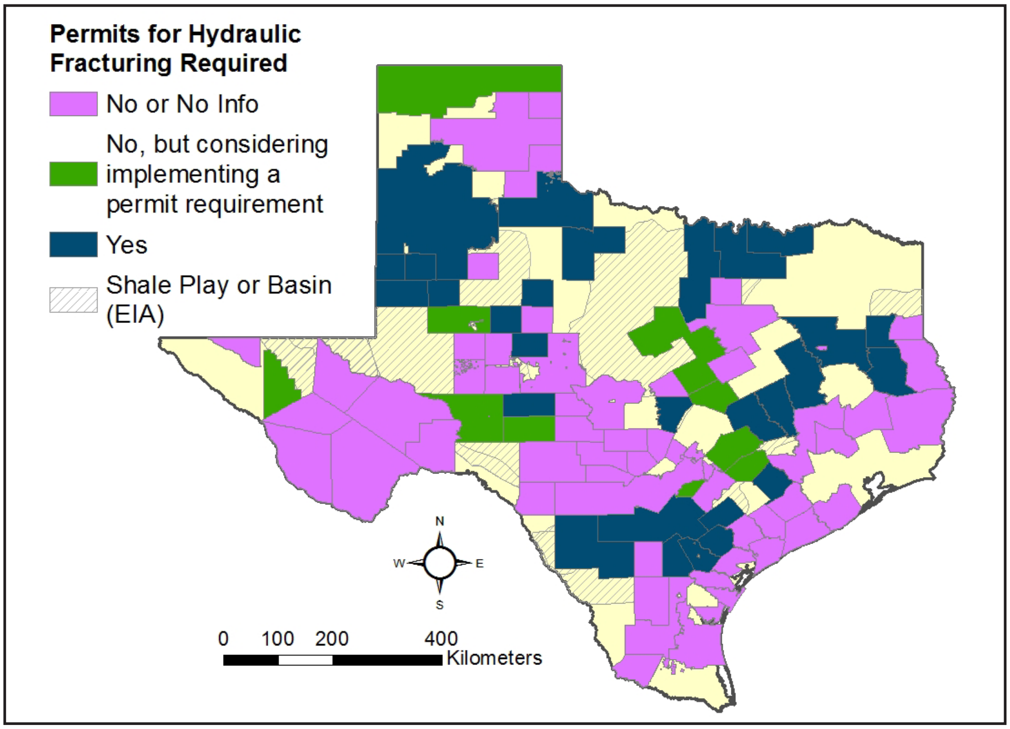


Figure 6. The map shows the groundwater conservation districts that require permits for wells to be used to provide water for use in hydraulic fracturing operations. Not all groundwater conservation districts with hydraulic fracturing operations present as of December 2014 (shown in Figure 5) require permits for wells that provide water for hydraulic fracturing. (Map created by the author based on data from TAGD 2014.)

sion among operators over whether water used for hydraulic fracturing applies to that exemption and whether groundwater conservation district can permit water wells used for hydraulic fracturing. Section 36.117 of the Texas Water Code outlines these exemptions. Under this section, a groundwater conservation district may not require a permit for "rig supply wells." If the well no longer serves as a rig supply well, the groundwater conservation district could require a permit. The Railroad Commission of Texas, the regulating authority for oil and gas operations, understands a "rig actively engaged in drilling or exploration operations for an oil or gas well" permitted by the railroad commission to include drilling rigs and hydraulic fracturing operations (Lyons and Tintera, 2014). However, there is still debate over whether water produced for hydraulic fracturing, a completion technique, qualifies as exploration or production (Scanlon et al. 2014b). In any case, exempt wells must still abide by other groundwater conservation district requirements like registration, well spacing, casing, and reporting.

Figure 7 shows the annual production limitations in groundwater conservation districts across the state. The limits shown might have other stipulations based on the type of water use or the amount of land owned. Many groundwater conservation districts have non-numeric production limitations on all wells, such as total aquifer limits, beneficial use, reasonable use, available water, or service area limitations. Some groundwater conservation districts limit production per well with use of formulas, permits, or studies. For non-exempt wells used to provide water to hydraulic fracturing, these production limitations could restrict the amount of water that can be used in a hydraulic fracturing operation or the rate at which water can be extracted from a well to provide water to an operation.

Figure 8 shows the groundwater conservation districts that allow groundwater export out of the district. In these groundwater conservation districts, water can be extracted from the aquifer and transported to another location, potentially for use in hydraulic fracturing. For other groundwater conservation districts in Texas, export is not allowed. Water extracted in that groundwater conservation district must be used in that groundwater conservation district.

Landowner role in regulating water use

Under the rule of capture, landowners own the water under their land. This rule applies whether the landowners own the surface rights only, which includes groundwater, or the surface and mineral rights (the rights to the oil and gas under their land) but does not apply if the groundwater rights have been

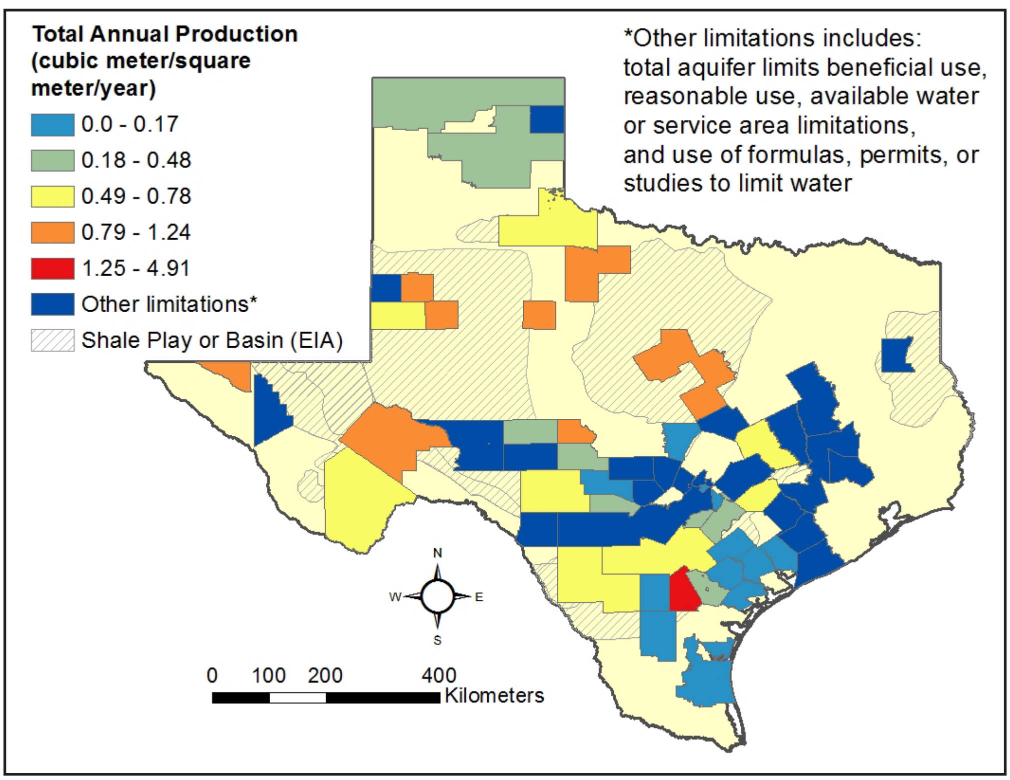


Figure 7. The map shows basic annual production limitations in volume of water per area of land per year (cubic meters/square meters/year) for non-exempt wells in Texas groundwater conservation districts. Some districts with annual production limitations have other stipulations associated with these limits. (Map created by the author based on data from TAGD 2014.)

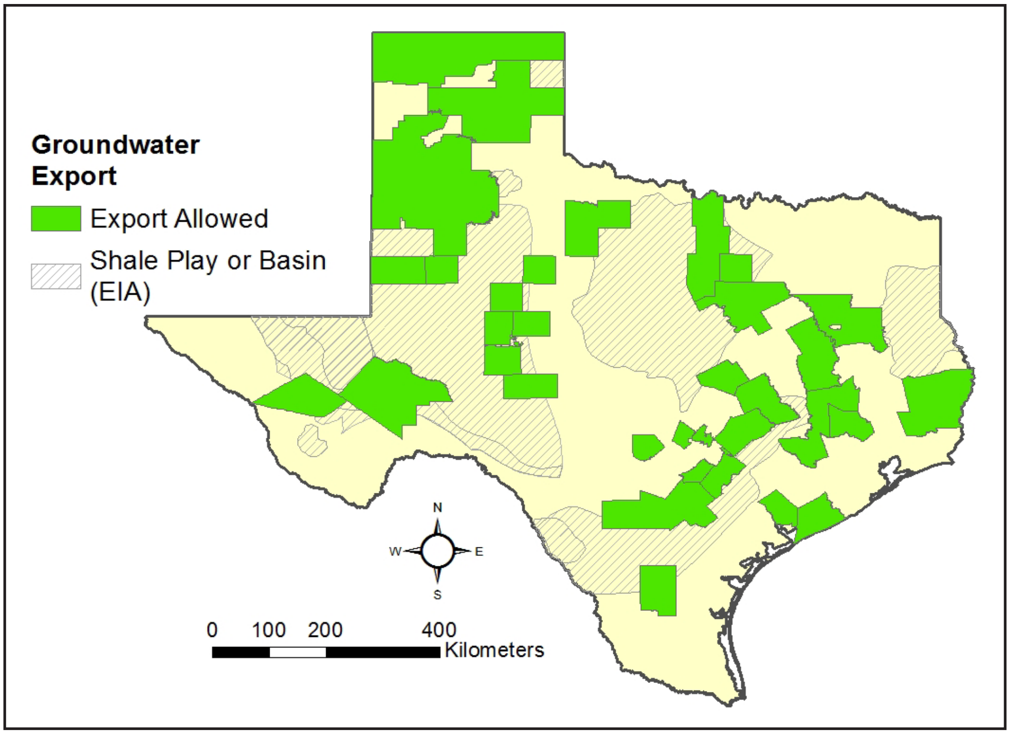


Figure 8. The map shows groundwater conservation districts that allow groundwater export outside of the groundwater conservation district. Groundwater from these groundwater conservation districts could be exported for use for hydraulic fracturing in other areas of the state. (Map created by the author based on data from TAGD 2014.)

severed from the surface estate (The City of Lubbock, Texas v. Coyote Lake Ranch, LLC 2014). If a landowner owns rights to the groundwater, s/he can sell the water to the operator to produce hydrocarbons.

When landowners own both the surface rights and mineral rights, they can play a key role in water allocation decisions. When negotiating a contract with operators for use of their mineral rights, landowners can also negotiate use of their water resources. In this contract, landowners can prohibit use of their water and restrict water use on their land to brackish water, effluent, or recycled water. Though some use of brackish water may be in question, if their land resides over brackish water resources, landowners can currently capitalize on selling that water for hydraulic fracturing. Conversely, landowners can prohibit use of alternative water resources on their land, requiring the use of only their freshwater resources. Landowners might not want recycled water brought onto their property because it might displace water they could sell to oil and gas operators (Lyons and Tintera 2014). To fully capitalize on their resources, some landowners require the oil and gas operator to drill a water well and purchase and use only that water for the hydraulic fracturing on that land (Galbraith 2013). Such contract negotiation, though legal, is a barrier to reducing freshwater use for hydraulic fracturing. In the current framework, both the landowner and the operator are economically motivated to exploit the groundwater resource.

Alternative water allocation policies in Texas

With freshwater supplies stretched across various water use sectors and long-term drought further constraining supplies, alternative water sources could be a good option for oil and gas operators seeking water for hydraulic fracturing operations. However, there could be additional costs associated with using an alternative source of water (Lyons and Tintera 2014). The price of water plays a role, but other factors associated with alternative water, such as quality, also determine cost and feasibility. Often, the alternative source of water is a degraded quality compared to freshwater. Due to improved technology and chemistry, more saline water and water of degraded quality can be used with the addition of additives. However, if the increase in chemical needs is not offset by the reduction in cost of water, the total cost at the well could increase. This study does not assess the changes in cost associated with degraded quality water, but they should be evaluated when determining water source for hydraulic fracturing operations.

There are other considerations to keep in mind when choosing whether to use an alternative source of water. A study conducted through the Atlantic Council determined conditions that support or challenge using alternative, non-freshwater sources (Jester et al. 2013; Lyons and Tintera 2014). According to that study, conditions that support using alternative water sources are

- limited availability of high-quality source water, such as fresh groundwater;
- high quality and availability of produced water, brackish water, municipal effluent, or other alternative water source;
- reduction in costs associated with use of alternative, non-freshwater, such as for logistics or transportation;
- high compatibility with frac fluid chemistry or easily treated to compatibility with frac fluid chemistry; and
- high compatibility with the production zone of the reservoir (Jester et al. 2013).

According to the same study, challenges to non-freshwater use are related to logistics, costs,and contamination risks associated with

- transportation and gathering of non-freshwater, including but not limited to:
  – truck accidents
  – pipeline leaks
  – spills in loading or unloading the fluid
- treatment of non-freshwater,
- storage of non-freshwater,
  – pond or storage tank leaks
  – birds landing in uncovered ponds
- blending of water from different sources,
- compatibility with frac fluid chemistry resulting in consistent and predictable frac fluid performance,
- impacts on reservoir and fracture conductivity, and
- impacts on short- and long-term field production (Jester et al. 2013).

There are multiple options for using alternative, non-fresh sources of water. This study characterizes the potential for use of brackish water, effluent, and produced water and the policies that influence whether these choices are viable options for use in hydraulic fracturing.

Brackish water

Freshwater is often defined as water with salinity less than 1,000 milligrams per liter total dissolved solids (TDS). Brackish water does not have an exact definition, but typically water that is 1,000–10,000 milligrams per liter TDS is considered brackish. Within that category is water that is slightly saline (1,000–3,000 milligrams per liter TDS), and water that is moderately saline (3,000–10,000 milligrams per liter TDS) (Godsey). Highly saline water contains over 10,000 milligrams per liter TDS (Godsey). Seawater contains greater than 35,000 milligrams per liter TDS (Godsey). Texas is estimated to have 3.3×10^{12} cubic meters (8.8×10^{8} gallons or 2.7×10^{9} acre-feet) of brackish water (Kalaswad et al. 2005). That water is more abundant in the Gulf Coast near the Eagle Ford Shale and in West Texas near the Permian Basin (Kalaswad et al. 2005). In the Permian Basin, 30% of water used for hydraulic fracturing is brackish (Nicot and Scanlon 2012). At least 2 companies, Fasken Oil & Ranch and Apache Corporation, use brackish water from the Santa Rosa Aquifer for their frac jobs (Buchele 2013). In other shale plays, brackish water is used less frequently (Nicot and Scanlon 2012).

Improvements in efficiency of chemical additives to the frac fluid allow for use of more saline waters (Nicot and Scanlon 2012). However, friction reducers used in frac fluid might not work properly in water with high TDS (Nicot and Scanlon 2012). The dissolved solids might cause corrosion (Nicot and Scanlon 2012). In addition, handling costs for brackish water might be higher than those costs for freshwater (Lyons and Tintera, 2014). If brackish water resources are connected to freshwater resources as in the Carrizo-Wilcox Aquifer, there is a potential drawback in negatively impacting freshwater formations by drawing down brackish water (Lyons and Tintera 2014). If brackish water resources are below freshwater aquifers, drilling deeper into the earth to access the brackish water will increase the cost of accessing that water (Buchele 2013).

There is competition among operators as well as across water use sectors for brackish water resources. Agricultural operations in Gonzales County use water at 3,700 milligrams per liter TDS (Ritter and Fazio 2014). Municipalities looking to augment their water supplies by desalinating brackish water might be competing for the same supplies. The city of Gonzalez uses water of 2,800 milligrams per liter TDS for public supply, blending it with freshwater from the Guadalupe River (Ritter and Fazio 2014). As the salt content of brackish water increases, more energy is required to remove it if water is not available for dilution, and there is a higher cost to do so. Thus, cities will be looking to use slightly saline water to keep their energy and costs down. The Gonzales County Underground Water Conservation District has had reports of oil and gas companies using brackish water at 26,000 milligrams per liter TDS for hydraulic fracturing (Ritter and Fazio 2014).

There are policy hurdles to using brackish water that might increase the total cost. Water used for hydraulic fracturing is sometimes piped and stored in pits. However, if brackish water is used, it must be transported in no-leak transfer lines and held in containment suitable for salt water (Lyons and Tintera 2014; Nicot and Scanlon 2012). There is increased liability to producers that store and/or transfer large volumes of salt water (Lyons and Tintera 2014; Nicot and Scanlon 2012). A bird landing in the brackish water pit or a spillage of water creates environmental liabilities where use of freshwater would not (Lyons and Tintera 2014; Nicot and Scanlon 2012).

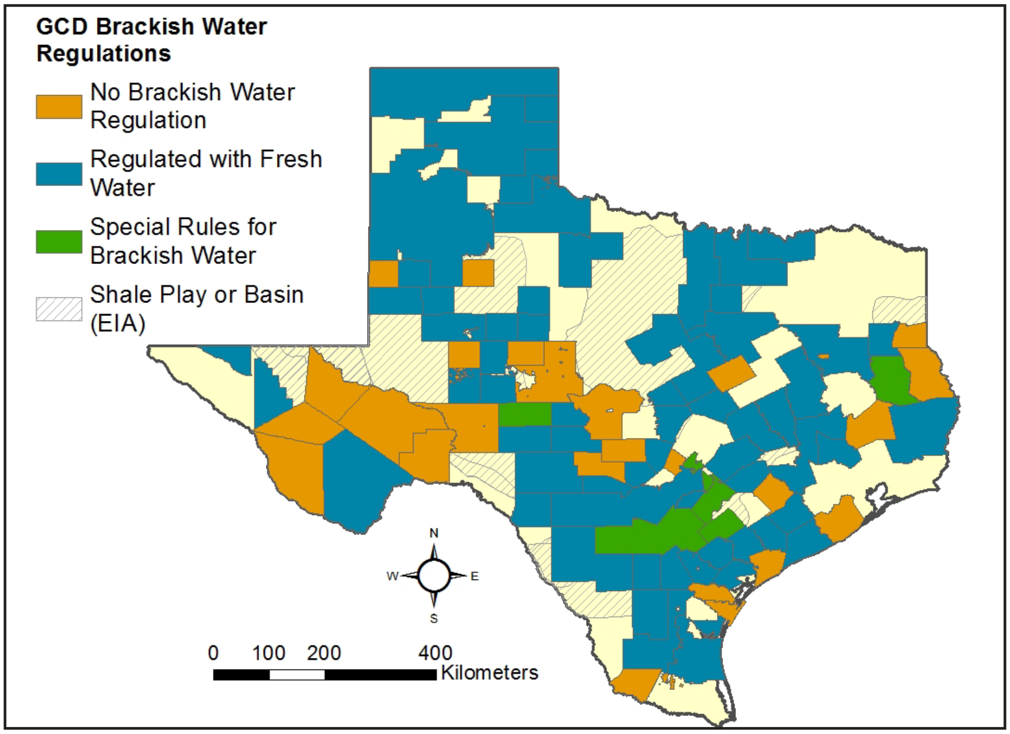


Figure 9. Brackish water is often regulated as if it is freshwater. Certain groundwater conservation districts have specific rules for brackish water, as shown in green in the figure. Some groundwater conservation districts do not regulate brackish water, and some areas of the state do not have a groundwater conservation district and are unregulated. In these areas, withdrawal of brackish water would follow the rule of capture. (Map created by the author based on data from TAGD 2014.)

Some groundwater conservation districts regulate brackish water use in the same way they regulate freshwater use. Some have specific policies for brackish water use. There are a few areas of the state where brackish water use is unregulated by a groundwater conservation district. Overall, the regulatory structure for brackish water is yet undeveloped but is at the forefront of issues for the 84th Texas Legislative Session. Figure 9 shows the difference in brackish water regulation in groundwater conservation districts across Texas. This difference in regulation could mean brackish water is easier to access in some areas than other areas.

Effluent reuse

Use of effluent is another option for an alternative water source that is becoming more common. Effluent could originate at a municipal wastewater facility, from an industrial process, or as irrigation tailwater. Each has its own considerations to maintain.

Municipal reclaimed water

There are 2 types of treated municipal wastewater (hereafter referred to as "municipal reclaimed water" or "municipal effluent"), Type I and Type II, which are defined according to whether people are likely to have contact with the municipal effluent during its use (TCEQ 2014). Type I water is that which public contact is likely (TCEQ 2014). This water requires more treatment and thus requires more energy and costs more to produce (TCEQ 2014). To reuse either type of municipal reclaimed water, the Texas Commission on Environmental Quality must give written approval to the provider of the water (TCEQ 2014). The water must then be sampled and analyzed before distribution (TCEQ 2014). To convey reclaimed water using waters of the state, the water provider must obtain a water-right authorization from the commission (TCEQ 2014). Reuse of untreated wastewater is prohibited.

Municipal reclaimed water is already commonly used by oil and gas operators in Texas. In the northern Eagle Ford Shale, Apache Corporation has a \$5 $\times 10^6$ 2-year agreement to use 1.1 $\times 10^4$ cubic meters (3 $\times 10^6$ gallons) per day of municipal effluent from Carter's Creek Wastewater Treatment Plant in College Station (Adger 2014). The water represents about half of the treated water produced in College Station (Apache Corporation 2014). Pioneer Natural Resources has a similar deal to purchase wastewater in Odessa. The \$1 $\times 10^8$ dollar agreement will provide Pioneer with about 5.7 $\times 10^6$ cubic meters (1.5 $\times 10^9$ gallons) of water per year for the next 10 years from the Bob Derrington Water Reclamation Plant (Paul 2014). Companies such as Alpha Reclaim Technologies LLC and PTP LP have emerged to function as intermediaries between wastewater treatment facilities and oil and gas operators. In 2013, Alpha Reclaim Technologies LLC collected water from more than 20 municipal wastewater facilities to sell for hydraulic fracturing operations (Hiller 2013). PTP LP contracted to purchase effluent water from Carrizo Springs, Eagle Pass, Pearsall, Pleasanton, and Shiner for the same purpose (Hiller 2013).

Municipal reclaimed water is often competitively priced with freshwater, and selling reclaimed water gives cities a new source of revenue (Eagle Ford Shale 2013). However, there is competition for use of municipal reclaimed water as Type I water can be used to water public parks, school yards, residential lawns, and athletic fields and can also be used for fire protection, food-crop irrigation, and application to pastures grazed by milking animals (TCEQ 2014). Type II water can be used for irrigation water that is not likely to contact edible portions of a crop, animal feed-crop irrigation that does not involve milking operations, supply to non-recreational water bodies, soil compaction, dust control, cooling tower makeup water, and certain applications at wastewater treatment facilities (TCEQ 2014). Moreover, water users including communities downstream of wastewater treatment plants rely on the discharged return flows for their water needs. In addition, water-stressed communities, such as Big Spring and Wichita Falls, have begun treating their wastewater many times over for municipal use, in a process known as "direct potable reuse" (Lawler 2014). In addition to increasing competition for municipal reclaimed water, use of this effluent in oil and gas operation does not decrease the amount of water consumed by the industry. The same amount of water injected in hydraulic fracturing that would normally be consumed if the water was fresh is still consumed when it originates as municipal reclaimed water.

Industrial reclaimed water use

To reuse industrial effluent water, the Texas Commission on Environmental Quality must give written approval before the water can be used off-site (TCEQ 2014). There are 2 levels used to assess treated industrial water, Level I and Level II (TCEQ 2014). The levels are classified according to "how they are generated and whether they will be used on-site or off-site" (TCEQ 2014). Both Level I and II water can be used off-site with written approval (TCEQ 2014). Level II water must be sampled to certify that it applies as reclaimed water before it can be used (TCEQ 2014).

Agricultural tailwater use

The runoff or "tailwater" from agricultural irrigation could also provide an option for non-freshwater. Because that water would normally soak into the earth or run into waters of the state, it is an unregulated effluent and does not require a permit for reuse. However, irrigation tailwater can have additional quality concerns during reuse in hydraulic fracturing. If there are bacteria in the tailwater, they would need to be removed prior to use in a hydraulic fracturing operation. The use of this water could jeopardize downstream flows or aquifer recharge depending on the location in which the agricultural tailwater would normally have gone.

Produced water reuse and recycling

While other user groups, including municipalities, compete for brackish water and effluent, there is little competition for reused (little to no treatment) or recycled (with treatment) produced, or flowback, water from oil and gas production. Also, in contrast to replacing freshwater use with another source such as brackish water or effluent, recycling produced water can offset multiple pieces in the chain of water use for oil and gas production. Recycling water replaces the need to dispose of most of the water as the treated water can then be reused. There is some disposal of waste from treatment, though. If that water is reused by the same company, recycling also replaces the need to find and purchase more water to hydraulically fracture a new well. If that new well is on the same well pad, recycling on-site could replace the need to transport (via truck or pipe) wastewater to disposal or water from a water source. Disposal and trucking are discussed further later in this paper in the sections "Trucking water and wastewater" and "Disposal of production waste."

Recycling, like use of other water sources, is limited by cost, policy, and technology. While recycling and reusing water offsets freshwater use and disposal, it also carries risks. For example, spillage from human error in waste handling or leaks from pipes could create environmental issues. Thus, the railroad commission regulates the process through Statewide Rule 8, which was amended in 2013. The amendments to the rule eliminate the need for a permit to recycle water on-lease under the authority of the oil and gas operator, allows recycling on another operator's lease, and distinguishes between commercial and non- commercial recycling (Lyons and Tintera 2014). The railroad commission also authorizes reuse via permit-by-rule, allowing reuse of treated or recycled water in the wellbore of an oil or gas well (Lyons and Tintera 2014). Amendments to the Natural Resources Code in 2013 (via Texas House Bill 2767in 2013) establish ownership of oil and gas waste transferred for treatment and subsequent beneficial use (NRC). When the fluid waste is transferred to a person for treatment and beneficial use, that person owns the fluid and the treated water until either is transferred to another person (NRC). In the event of a transfer, the person to which the fluid or treated water is transferred would own the fluid or treated water (NRC).

Wastewater from hydraulic fracturing can be recycled and reused as long as that water is not returned to the waters of the state (surface water) (TAC § 3.8). If that water is used as makeup water for another hydraulic fracturing operation, no permit is required, as that reuse is regulated via permit-by-rule (TAC § 3.8). If the water is reused in any other manner, a permit is required from the state or federal agency that regulates that water use (TAC § 3.8). If that wastewater is treated to distilled water quality, no permit is required to reuse it in any other manner, but the water still cannot be discharged into waters of the state (TAC § 3.8).

Recycling is also complicated because the quality of water that returns to the surface after hydraulic fracturing varies between formations and wells depending on the constituents in the geology and in the frac fluids (Lyons 2014). Flowback and produced water might contain hydrocarbons, salts, toxic natural inorganic and organic compounds, chemical additives, naturally occurring radioactive materials, oil and grease associated with production, high TDS, suspended solids, iron, boron, or oil residue (Lyons 2014). The produced water quality determines the technology needed and the cost of treatment before the water can be reused. However, recycling and reusing produced water might still be a cost-effective option. With the combined use of brackish water and produced water, 1 operator is able to eliminate the need for freshwater in its hydraulic fracturing operations in Irion County in the Permian Basin (Buchele 2013).

Recycling is estimated to provide about 2.5 million cubic meters or 2,000 acre-feet of water use for hydraulic fracturing across Texas, which is about 3% of total water use for the process statewide. Recycling and reuse amounts vary by operator and basin or shale play (Ritter and Fazio 2012). In 2011, recycled or reused water provided 2% of water used for hydraulic fracturing in the Permian Basin, 20% in the Anadarko Basin, and 0% in the Eagle Ford Shale (Nicot et al. 2012). In 2012, in the Barnett Shale, recycling and reuse ranged from 5% to 10% and was about 0% of total water use in the Texas portion of the Haynesville Shale (Nicot and Scanlon 2012).

The amount of freshwater that can be offset by use of recycled and reused produced water depends on the volumes of produced water that returns to the surface. While almost 100% of water is recycled or reused in the Marcellus Shale in the Northeastern United States, the water accounts for only 10-30% of the water required for hydraulic fracturing in that shale play (Scanlon et al. 2014b). Moreover, small flowback and produced water volumes generally do not support reuse/recycling requirements as the small volume makes it difficult to collect enough water to support economic reuse or recycling. According to a report from the Bureau of Economic Geology, "there is limited potential for reuse or recycling of flowback or produced water because of small volumes" of water returned to the surface after hydraulic fracturing, less than 5% of water required to hydraulically fracture wells in the Eagle Ford Shale (Scanlon et al. 2014b).

Operational areas, policies that could affect the price of water

Total water costs, including water acquisition, storage, transfer, and waste disposal services associated with the initial hydraulic fracturing of a new well, can represent approximately 10% of the total cost of a new well (IHS 2014). Cost of transporting water is a major component of total water costs for a well (Eaton 2014). In the Eagle Ford and Permian Basins, at rates of $70–$110 per hour for trucks carrying 100–130 barrels of water, cost of transporting water by truck might be $0.50 to several dollars per barrel of oil produced (Eaton 2014). Disposal costs approximately $0.60 to several dollars per barrel. Increases in these costs caused by fees or taxes can increase total water costs for oil and gas operations.

Trucking water and wastewater

Trucking water or wastewater is often the most expensive piece in the chain of total water costs in extraction of oil and gas. The use of trucks also causes damage to roads. In 2012, the Texas Department of Transportation estimated the cost for rebuilding the infrastructure damaged by increased energy-related activities at approximately $4 billion per year on the state highway system, city streets, and county roads (TXDOT 2012). In the 83rd Texas legislative session in 2013, Rep. Drew Darby proposed increasing vehicle registration fees to pay for state highways (Texas House Bill 3664 2013). The increase in registration fees would be used in the following manner:

> "One-third dedicated to the payment of existing voter authorized transportation debt until such debt is retired; and the remaining amount may be used only for acquiring rights-of-way and planning, designing, and constructing non-tolled improvements to the state highway system."

The bill was not passed, but such a bill would increase the cost for all vehicles in the state to pay for roads. An increase in the cost of transportation increases the cost for trucking water and, thus, increases the total cost of water for an oil and gas operation.

Following the 83rd Texas legislative session, in September 2014, Rep. Tryon Lewis explained that a similar fee on gas use instead of vehicles would be a good mechanism to pay for road improvements as it invoked a "user pay" principle (Lewis 2014). These fees on vehicle registration or gas help pay for necessary road improvements. However, they also increase the cost of transportation. Where trucking is the main method for transporting water, increases in transportation cost could significantly increase the total cost of water and make recycling more affordable in comparison. When possible, use of piping instead of water trucking reduces total water costs as well as road damage. However, there are risks associated with piping, including potential for leaks. Pipes should be monitored, especially when carrying non-freshwaters.

Disposal of production waste

There are options for managing produced water that flows to the surface during hydraulic fracturing operations, including (Jester et al. 2013; Lyons and Tintera 2014)

- use of on-site evaporation pits (not in Texas).
- discharge with National Pollutant Discharge Elimination System (NPDES) permit (not allowed in Texas or for most cases of onshore facilities).
- disposal via injection.
  - disposal into on-site injection or disposal wells
  - disposal at a centralized off-site underground injection site like a Underground Injection Control Class II well
- recycling or reuse.
  - transportation to and then treatment at a treatment plant
  - on-site treatment by a mobile unit for oilfield reuse
  - on-site mixing of produced water and freshwater for reuse in hydraulic fracturing, and
- treatment for beneficial use.

Underground injection in Underground Injection Control Class II disposal wells is the preferred option by the U.S. Environmental Protection Agency because the waste stream is trapped underground (US EPA 2014a). Risk and cost is relatively low in Texas. Class II wells are specifically permitted for injecting "brines and other fluids associated with oil and gas production, and hydrocarbons for storage" (US EPA 2014a). For operators, the economics also tend to favor disposal since Texas has approximately 35,000 Class II injection and disposal wells and over 295,000 producing oil and gas wells (RRC 2014b). In Texas, the railroad commission regulates oil and gas waste and permits 3 types of underground disposal:

1. *Enhanced Recovery Wells:* The wastewater can be returned to the reservoir from which it originated for secondary or enhanced oil recovery (RRC 2014b). These wells are called "injection wells" or wells involved in "secondary recovery/injection wells" (RRC 2014b; US EPA 2014a).
2. *Hydrocarbon Storage Wells:* If the wastewater is returned to the production zone without secondary recovery, it is referred to as "disposal into a productive zone" (RRC 2014b; US EPA 2014a. These wells are often used for Strategic Petroleum Reserve or for gas storage, not for waste disposal.
3. *Disposal Wells:* Wastewater can also be disposed of by injection into rock formations that do not produce oil or gas but are isolated from usable quality groundwater and "sealed above and below by unbroken and impermeable strata." These injection wells are called "disposal wells" or wells involved in "disposal into a non-productive zone" (RRC 2014b; US EPA 2014a). There are approximately 7,500 disposal wells in Texas (RRC 2014b). Nationally, disposal wells represent about 20% of Class II wells (US EPA 2014a).

In recent years, questions have been raised surrounding induced seismicity caused by underground injection (Folger and Tiemann 2014). The railroad commission held a town hall in Azle in January 2014 to discuss this issue and amended the rules later that year. The rule amendments, effective November 17, 2014, require applicants for new disposal wells to search for earthquakes within a circular area of 100 square miles around the proposed site. The amendments also clarify the commission's authority to modify, suspend, or terminate a disposal well permit and allow railroad commission staff to require operators to disclose disposal volumes on a more frequent basis and to require an applicant to provide additional information about the well site (16 Texas Administrative Code § 3.46; 16 Texas Administrative Code § 3.9; Fox 2014).

The rule amendments serve a purpose in protecting human health, but they could lead to slow development of new disposal wells relative to the creation of new wastewater from oil and gas production. A limit in supply of injection sites relative to the demand could result in increased disposal well costs or increased truck waiting times like those in Pennsylvania and Canada, another increase in the total cost of water.

As of December 2014, Pennsylvania had 7 active deep injection wells for oil and gas waste and over 5.7×10^4 producing natural gas wells (NPR 2014; US EIA 2014b). Without adequate disposal methods in close proximity, operators in Pennsylvania truck their waste to Ohio. However, the cost of trucking has pushed operators to instead recycle and reuse their produced water in future operations.

In Texas, at least 2 bills filed in the 83rd legislative session in 2013 would have limited wastewater disposal in commercial injections wells. Texas House Bill 2992 by Rep. Tracy King would have prohibited disposal unless the wastewater could not be treated.

> "Flowback and produced water from an oil or gas well on which a hydraulic fracturing treatment has been performed using groundwater may not be dis- posed of in an oil and gas waste disposal well unless the fluid is incapable of being treated to a degree that would allow the fluid to be:

- used to perform a hydraulic fracturing treatment on another oil or gas well;
- used for another beneficial purpose; or
- discharged into or adjacent to water in the state."

The bill did not pass. Texas House Bill 379 by Rep. Lon Burnam would have imposed a fee on the volume of water disposed of in commercial injection wells, the proceeds of which would go to the Oil and Gas Regulation and Cleanup Fund.

> "An oil-field cleanup regulatory fee is imposed on oil and gas waste disposed of by injection in a commercial injection well permitted by the railroad commission under this chapter in the amount of 1 cent for each barrel of 42 standard gallons," or 1.6×10^{-1} cubic meters of water."

The bill did not pass. A fee on disposal could significantly increase the cost of disposal, thereby increasing the total cost of water and making recycling more affordable in comparison.

POLICY ALTERNATIVES

There are many policy options available to help reduce freshwater use for hydraulic fracturing. Some are listed below:

- *Improve public outreach*: By engaging the public in discussions about water use for hydraulic fracturing, the public could become aware of technological innovations in the industry and water policy decisions and help encourage more efficient use of water.
- *Reporting*
  - *Water source reporting*: Operators should report whether their water is freshwater, brackish water, municipal reclaimed water, recycled or reused produced water, or another source. This reporting could be collected with current water volume and chemical content reporting sent to the railroad commission. Operators could also report their water source in the existing reporting on FracFocus.com.
  - *Water recycling reporting*: By reporting water recycling, in particular, either voluntarily or by requirement, companies could gain recognition from the public and potentially encourage other companies to recycle more water. Operators could report their water source in reporting sent to the railroad commission or to FracFocus.com.
- *Mandates*
  - *Reduce underground injection and disposal*: Such a policy would artificially increase the price of underground injection and disposal by reducing the amount of disposal available for use and cause oil and gas operators to search elsewhere for disposal methods like recycling. An example of a policy that limits disposal and mandates recycling is included previously in this paper in the section "Disposal of production waste."
  - *Reduce water or wastewater trucking*: Such a policy would artificially increase trucking costs through limiting the availability of it. In areas where pipelines are unavailable—perhaps because landowners refuse to allow pipelines on their property—limitations on trucking increase the total cost of water.
  - *Increase reuse/recycling*: Such a policy could increase the amount of recycling without decreasing the cost of treatment or reuse. Although, with more volumes recycled and more use of technology, economies of scale could result in reducing the total cost of recycling. An example of a policy that limits disposal and mandates recycling is included previously in this paper in the section "Disposal of production waste."
- *Fees:* Unlike mandates, fees serve as an economic tool to change behavior, in this case, in underground injection and disposal and in trucking water or wastewater. The fees collected could be used in many ways, including funding a program for reporting water recycling.
  - *Underground injection and disposal*: Such a policy would increase the cost of disposal, making recycling more competitive in comparison. An example of a disposal fee policy is included in the section "Disposal of production waste" where the funds collected would have been used for oil field cleanup.
  - *Trucking water or wastewater*: Such a policy would increase the trucking costs, thereby increasing the total cost of water. An example of a fee on trucking is included in the section "Trucking water and wastewater" where the funds collected would have been used to improve road conditions.
- *Incentives for recycling*: Incentives could encourage innovation and could be applied when an operator recycles water, when a service company recycles water, toward economically efficient recycling research at universities, for pilot-scale programs, or for construction of larger scale recycling facilities to be used by multiple companies. Incentives for reducing freshwater use would need to come from the Texas Legislature, as the Legislature sets the state budget. Incentives could include a tax credit for developing new freshwater sources to replace those depleted by production use or for using a non-freshwater source such as brackish water, reused or recycled produced water, or wastewater effluent. Potential disincentives that could also reduce total freshwater consumption are fees set on produced water disposal or on freshwater use. A water use fee on freshwater use would be difficult to impose without water monitoring. In 2006, oil and gas accounted for 99.6% of state subsidies, a total of $\$1.4 \times 10^9$ (Combs 2014). Examples of

existing incentives for oil and gas include (Lyons and Tintera 2014)
– special tax credits
– deductions
– exemptions
– allowances
– property tax incentives
– franchise tax exemptions
– property tax exemption for energy producers

- *Regulated water market*: A regulated water market can help bring transparency to water prices for fresh and non-fresh resources, make alternative water sources more competitive in the market, and give incentive to reduce wasteful use of water. A regulated market could allow reallocation of water resources to beneficial uses while maximizing the utility of both the original owner of the water and the end users. Landowners could be made aware of the potential to profit off of brackish, agricultural reuse water, or conserved resources (after installing more efficient irrigation technologies), potentially reducing the tendency to over-exploit freshwater aquifers (Cook and Webber 2014).
- *Transparent groundwater restrictions*: Groundwater conservation districts in the same aquifer have differing policies for freshwater and brackish water, production limits, exporting, and other issues that could create confusion among oil and gas operators. To reduce that confusion, these regulations could be made more transparent. Further, water does not follow the political boundaries of groundwater conservation districts. Wells drilled outside of a district, though unregulated by the district, could still affect the water supply within that district. The regulations could also be amended to promote cohesion between groundwater conservation districts in the same aquifer, allowing regulations to follow aquifer boundaries rather than political ones. In addition, much of the groundwater in the state is not regulated by a groundwater conservation district. The Legislature should develop a plan to limit groundwater exploitation outside of the boundaries of current groundwater conservation districts.
- *Beneficial use of recycled water*: The NPDES permit allocation for treated produced water could be reviewed to allow beneficial use of treated water for purposes other than reuse in another hydraulic fracturing operation while still ensuring environmental protection (Lyons and Tintera 2014).

CONCLUSIONS

With freshwater supplies already stretched across water use sectors, use of alternative water supplies for hydraulic fracturing such as brackish water, effluent, and recycled produced water should be made a higher priority. Moreover, while other user groups, including municipalities, compete for brackish water and effluent, there is little competition for reused or recycled produced water. Technological innovation unlocked shale resources and great economic returns, changing the global energy balance. That same adaptation of technological innovation can address the complex issues associated with production in water scarce regions. The policy framework in Texas could also be augmented to encourage more alternative water use, especially recycled and reused produced water.

ACKNOWLEDGMENTS

The authors would like to acknowledge John Tintera for his intellectual contributions to this work. The authors would also like to acknowledge the Texas Water Policy class taught by Karen Huber and the Lyndon B. Johnson School of Public Affairs. This work was funded by the National Science Foundation Integrative Graduate Education and Research Traineeship, the Cynthia and George Mitchell Foundation, and the U.S. Department of Energy.

REFERENCES

16 Texas Administrative Code § 3.46.

16 Texas Administrative Code § 3.9.

Adger P. 2014 June 13. College Station City Council votes unanimously for Apache Corp. treated water deal. KBTX [Internet]. Available from: http://www.kbtx.com/home/headlines/College-Station-city-council-votes-unanimously-for--262980441.html

Apache Corporation. 2014. Personal communication.

Buchele M. 2013 March 28. Fracking boom spurs a rush to harness brackish water. NPR State Impact [Internet]. Available from: http://stateimpact.npr.org/texas/2013/03/28/drilling-boom-spurs-a-rush-to-harness-brackish-water/

Combs S. 2014. The energy report 2008 [Internet]. Austin (Texas): Texas Comptroller of Public Accounts. Available from: http://www.window.state.tx.us/specialrpt/energy/

Cook M, Webber M. 2014. The influence of hydraulic fracturing on the water market in Texas. Shale Energy Engineering. 530-542 p.

Deeds N, Kelley V, Fryar D, Jones T, Whellan AJ, Dean KE. 2003. Groundwater availability model for the Southern Carrizo-Wilcox Aquifer. Report prepared for the Texas Water Development Board.

Doherty T, Smith R. 2012. Water transfers in the West 2012: projects, trends, and leading practices in voluntary water trading. Denver (Colorado): The Western Governors' Association. 133 p.

Dropkin A, Henry T. 2014. How the Denton fracking ban could work. NPR State Impact [Internet]. Available from: http://stateimpact.npr.org/texas/tag/denton/

Eagle Ford Shale. 2013. Alpha reclaim technology opening Eagle Ford water facility [IntPernet]. Available from: http://eaglefordshale.com/press-releases/alpha-reclaim-technology-opening-eagle-ford-water-facility/attachment/alpha-reclaim-tech-facility-karnes-city-tx/.

Eaton C. 2014 April 17. Texas heading for major water shortage with limited oil field recycling. Fuel Fix [Internet]. Available from: http://fuelfix.com/blog/2014/02/17/texas-heading-for-major-water-shortage-amid-limited-oil-field-recycling/

Folger P, Tiemann M. 2014. Human-induced earthquakes from deep-well injection: a brief overview [Internet]. Available from: http://www.fas.org/sgp/crs/misc/R43836.pdf

Fox G. 2014. Texas Oil & Gas Association applauds Railroad Commission's adoption of disposal well rule amendments related to induced seismicity [Internet]. Available from: http://txoga.org/assets/doc/TXOGA_News_Release_on_Final_Railroad_Commission_Rules_on_Seismicity.pdf

Freyman M. 2014. Hydraulic fracturing & water stress: water demand by the numbers [Internet]. Boston (Massachusetts): Ceres. Available from: http://www.ceres.org/resources/reports/hydraulic-fracturing-water-stress-water-demand-by-the-numbers/view

Galbraith K. 2013 March 8. In Texas, water use for fracking stirs concerns. The Texas Tribune [Internet]. Available from: http://www.texastribune.org/2013/03/08/texas-water-use-fracking-stirs-concerns/

Getches D. 2009. 4th edition. Water law in a nutshell. St. Paul (Minnesota): West Publishing Co. 492 p.

Godsey W. Fresh, brackish or saline water for hydraulic fracs: what are the options? [presentation, Internet]. Available from: http://www2.epa.gov/sites/production/files/documents/02_Godsey_-_Source_Options_508.pdf

Hiller J. 2013 March 9. Companies try selling effluent water in the Eagle Ford. The San Antonio Express-News [Internet]. Available from: http://www.mysanantonio.com/business/article/Companies-try-selling-effluent-water-in-the-Eagle-4342096.php

Holland S, Moore M. 2003.Cadillac Desert revisited: property rights, public policy and water-resource depletion. Journal of Environmental Economics and Management. 46:131-155,

IHS. 2014. Water management at forefront of exploration and production operators' considerations, says new IHS study. Available from: http://press.ihs.com/press-release/ep-water-use/water-management-forefront-exploration-and-production-operators-considera#sthash.NxpKoVxO.dpuf

Jester S, Bjornen K, Sharma R. 2013. Evaluation of produced water reuse for hydraulic fracturing in Eagle Ford [presentation, Internet]. Available from: http://www.slideshare.net/atlanticcouncil/produced-water-session-x-steve-jester

Kalaswad S, Christian B, Petrossian R. 2005. Brackish groundwater in Texas [Internet]. Available from: https://www.twdb.texas.gov/publications/reports/numbered_reports/doc/R363/B2.pdf

Lawler D. 2014 July 25. Direct potable reuse to provide cleaner drinking water. Houston Chronicle [Internet]. Available from: http://www.houstonchronicle.com/opinion/outlook/article/Direct-potable-reuse-to-provide-cleaner-drinking-5648285.php

Lee M. 2011 Oct. 6. Parched Texans impose water-use limits for fracking gas wells. FuelFix [Internet]. Available from: http://fuelfix.com/blog/2011/10/06/parched-texans-impose-water-use-limits-for-fracking-gas-wells/

Lewis T. 2014 Sept. 14. Guest view: why I am voting no to prop 1. Odessa American [Internet]. Available from: http://www.oaoa.com/editorial/columns/guest_columns/article5a5baae0-3b98-11e4-850a-001a4bcf6878.html

Lyons B. 2014. Produced water: asset or waste? [Internet]. Washington, D.C.: Atlantic Council. Available from: http://www.atlanticcouncil.org/publications/reports/produced-water-asset-or-waste

Lyons B, Tintera J. 2014. Sustainable water management in the Texas oil and gas industry [Internet]. Washington, D.C.: Atlantic Council. Available from: http://texasalliance.org/wp-content/uploads/2014/08/Texas-White-Paper-on-Sustainable-Water-Management-by-the-Oil-and-Gas-Industry-July-29-2014.pdf

Mittal A, Gaffigan M. 2009. Energy-water nexus: improvements to Federal water use data would increase understanding of trends in power plant water use [Internet]. Washington, D.C: U.S. Government Accountability Office. Report to the Chairman, Committee on Science and Technology, House of Representatives. GAO-10-23. Available from: http://www.gao.gov/assets/300/296960.pdf

National Drought Mitigation Center. 2013. Current U.S. drought monitor [Internet]. Available from: http://droughtmonitor.unl.edu/

Nicot JP, Reedy RC, Costley RA, Huang Y. 2012. Oil & gas water use in Texas: update to the 2011 mining water use report [Internet]. Austin (Texas): Texas Oil & Gas Association. Available from: http://www.beg.utexas.edu/water-energy/docs/Final_Report_O&GWaterUse-2012_8.pdf

Nicot JP, Scanlon BR. 2012. Water use for shale-gas production in Texas, U.S. Environmental Science & Technology. 46(6):3580-6.

Nicot JP, Scanlon BR, Reedy RC, Costley RA. 2014. Source and fate of hydraulic fracturing water in the Barnett Shale: a historical perspective. Environmental Science & Technology. 48(4):2464-71.

[NPR] National Public Radio. 2014. Deep injection wells: how drilling waste is disposed underground [Internet]. Available from: http://stateimpact.npr.org/pennsylvania/tag/deep-injection-well/

Pacsi P, Sanders KT, Webber ME, Allen DT. 2014. Spatial and temporal impacts on water consumption in Texas from shale gas development and use. ACS Sustainable Chemistry and Engineering. 2(8):2028-2035.

Paul C. 2014 July 22. City OK's Pioneer water deal. Odessa American [Internet]. Available from: http://www.oaoa.com/inthepipeline/article_a2a730fe-120c-11e4-8f17-0017a43b2370.html

Potter HG. 2004. History and evolution of the rule of capture. In: Mullican III WF, Schwartz S. editors. 100 years of rule of capture: from East to groundwater management. Symposium sponsored by the Texas Water Development Board, June 15, 2004. Austin, Texas. 1–9 p.

Ritter A, Fazio E. 2014. Interim report to the 84th Legislature [Internet]. Texas House Committee on Natural Resources. Texas House of Representatives. Available from: http://www.house.state.tx.us/_media/pdf/committees/reports/83interim/House-Committee-on-Natural-Resources-Interim-Report-2014.pdf

Ritter A, Fazio E. 2012. Interim report to the 83th Legislature [Internet]. Texas House Committee on Natural Resources. Texas House of Representatives. Available from: http://www.house.state.tx.us/_media/pdf/committees/reports/82interim/House-Committee-on-Natural-Resources-Interim-Report.pdf

[RRC] Railroad Commission of Texas. 2014a. Texas monthly oil & gas production [Internet]. Available from: http://www.rrc.state.tx.us/oil-gas/research-and-statistics/production-data/texas-monthly-oil-gas-production/

[RRC] Railroad Commission of Texas. 2014b. Saltwater disposal wells [Internet]. Available from: http://www.rrc.state.tx.us/about-us/resource-center/faqs/oil-gas-faqs/faq-saltwater-disposal-wells/

Scanlon BR, Reedy R C, Nicot JP. 2014a. Comparison of water use for hydraulic fracturing for unconventional oil and gas versus conventional oil. Environmental Science and Technology [Internet]. 12386-12393 p. Available from: http://pubs.acs.org/doi/abs/10.1021/es502506v

Scanlon BR, Reedy R C, Nicot JP. 2014b. Will water scarcity in semiarid regions limit hydraulic fracturing of shale plays? Environmental Research Letters. 9(124011). Available from: http://iopscience.iop.org/1748-9326/9/12/124011/pdf/1748-9326_9_12_124011.pdf

[TAGD] Texas Association of Groundwater Districts. 2014. Groundwater conservation district index [Internet]. Available from: http://www.texasgroundwater.org/gcdi-map.html

[TCEQ] Texas Commission on Environmental Quality. 2009. Rights to surface water in Texas [Internet]. (GI-228), Available from: http://www.tceq.state.tx.us/files/gi-228.pdf_4467322.pdf

[TCEQ] Texas Commission on Environmental Quality. 2014. Requirements for reclaimed water [Internet]. Available from: https://www.tceq.texas.gov/assistance/water/reclaimed_water.html

[TAC] Texas Administrative Code § 3.8.

Texas House Bill 3664, 83d Leg., R.S. 2013.

[NRC] Texas Natural Resource Code § 122.

The City of Lubbock, Texas v. Coyote Lake Ranch, LLC. Texas. 2014.

[TXDOT] Texas Department of Transportation. 2012. Task force on Texas' energy sector roadway needs [Internet]. Available from: http://ftp.dot.state.tx.us/pub/txdot-info/energy/final_report.pdf

U.S. Census Bureau. 2012. The 2012 statistical abstract [Internet]. Available from: http://www.census.gov/compendia/statab/cats/population.html

[US EIA] United States Energy Information Administration. 2011. Review of emerging resources: U.S. shale gas and shale oil plays [Internet]. Available from: http://www.eia.gov/analysis/studies/usshalegas

[US EIA] United States Energy Information Administration. 2014a. Annual energy outlook 2014 Early release overview [Internet]. Available from: http://www.eia.gov/forecasts/aeo/er/pdf/0383er%282014%29.pdf

[US EIA] United States Energy Information Administration. 2014b. Natural gas: number of producing wells [Internet]. Available from: http://www.eia.gov/dnav/ng/ng_prod_wells_s1_a.htm.

US EPA] United States Environmental Protection Agency. 2014a. Class II wells - oil and gas related injection wells (Class II) [Internet]. Available from: http://water.epa.gov/type/groundwater/uic/class2/

[US EPA] United States Environmental Protection Agency. 2014b. Classes of wells [Internet]. Available from: http://water.epa.gov/type/groundwater/uic/wells.cfm

[USGS] United States Geological Survey. 2014. Groundwater depletion [Internet]. Available from: https://water.usgs.gov/edu/gwdepletion.html

Vaughan EG, Crutcher JM, Labatt III TW, McMahan LH, Bradford BR, Cluck M. 2012. Water for Texas: 2012 State Water Plan.

Water Data for Texas. 2014. [Internet].Available from: http://www.waterdatafortexas.org/reservoirs/statewide

APPENDIX A. GROUNDWATER CONSERVATION DISTRICT POLICIES

The map shows total annual water production in groundwater conservation districts using English units. One acre-foot is approximately 3.25×10^5 gallons.

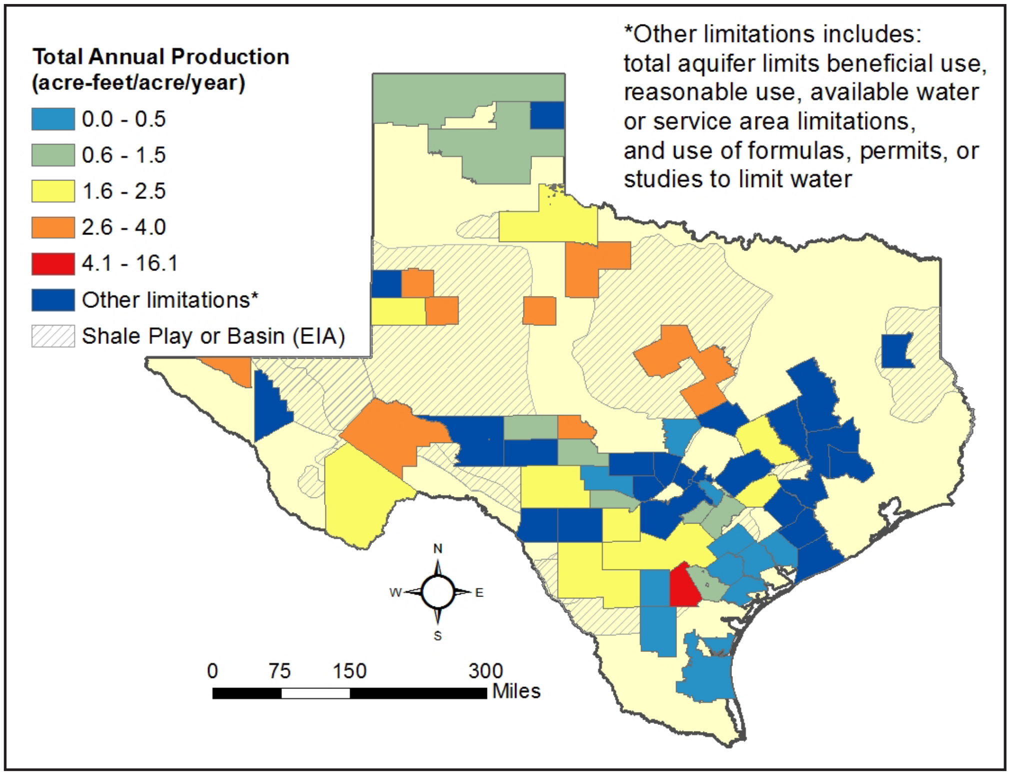


Figure 10. The map shows basic annual production limitations (acre-feet/acre/year) for non- exempt wells in Texas groundwater conservation districts. Some groundwater conservation districts with annual production limitations have other stipulations associated with these limits. Many groundwater conservation districts have non-numeric production limitations on all wells such as total aquifer limits, beneficial use, reasonable use, available water, or service area limitations. Some groundwater conservation districts limit production per well with use of formulas, permits, or studies. (Map created by the author based on data from TAGD 2014.)

Texas Water Resources Institute
Texas Water Journal
Volume 6, Number 1, Pages 64–66

Book review: Sharing the common pool: water rights in the everyday lives of Texans

Porter CR. 2014. Sharing the common pool: water rights in the everyday lives of Texans. College Station (Texas): Texas A&M University Press. ISBN 978-1-62349-137-6. 240 pp.

Reviewed by Robert E. Mace[1, 2, *]

[1]Texas Water Development Board

[2] This review does not necessarily reflect official Texas Water Development Board positions.

*Corresponding author: Robert.Mace@twdb.texas.gov

Citation: Mace RE. 2015. Sharing the common pool: water rights in the everyday lives of Texans. Texas Water Journal. 6(1):64-66. Available from: https://doi.org/10.21423/twj.v6i1.7024.

Capturing the backstories, complexities, and potential pitfalls of Texas water law in a single, readable book is a daunting task, but Charles R. Porter braves the challenge and, for the most part, succeeds in delivering a good overview in *Sharing the Common Pool: Water Rights in the Everyday Lives of Texans*. Written primarily for landowners and real estate agents, Porter, who is himself a real estate agent and broker, delivers a fairly comprehensive view of how water intersects with our lives and properties. As Porter notes, "Water is the ultimate zero sum game…", and it behooves landowners to be aware of water and their rights. However, there are some missed opportunities in the book, and given the complexity and nuances of the topic, there are plenty of details to quibble about. Nonetheless, despite its 240 pages, the book's conversational style goes down delightfully easy. (I was able to read it during an afternoon plane ride.) Porter appropriately hedges his writing by mentioning numerous times that one should consult a water attorney when getting down to the nitty-gritty of property and water.

A primary driver for the book is that as water becomes more important in our growing state, it becomes more important in our real estate transactions. In Porter's own words, "A major message of this book is that cities are desperate now and will be more desperate in the future for water resources; they are rightly and diligently trying to fulfill their duties to their citizens. Landowners should be aware that their individual interests in groundwater rights should no longer be taken for granted." Although with regard to water supply Porter leans toward the private property rights perspective, he provides a reasonably balanced view of water law and regulation in Texas and the policy issues entwined with those topics.

The book is organized into 5 parts: (1) an introduction to water and water rights, (2) ownership of water, (3) how we use water and who regulates that use, (4) water in real estate transactions, and (5) water policy. The outline works well, although topics unavoidably seep into each other. Porter includes an appendix where he provides detailed descriptions of key legal cases. The book also includes a reference list, endnotes, a glossary, and an index.

Where appropriate, Porter helpfully provides examples of broader concepts and thoughts. For instance, it would be mind-numbing to present rule summaries of the nearly 100 groundwater conservation districts in the state, but Porter includes details of how a specific district's rules might impact a landowner. Nonetheless, Porter misses several chances to amplify his points.

Porter notes how ownership of a water molecule can change depending on which "geologic bucket" that water molecule is in. It's private property when it's overland flow, public property when it reaches a state watercourse, private property when it seeps into the ground, and then public property again when it discharges to a state watercourse from a spring. Soon after, Porter refers to the Texas Supreme Court decision on *Edwards Aquifer Authority v. Day and McDaniel*. While he appropriately focuses on the takings implications of this decision, the brutally short summary of the case (Landowners apply for 700 acre-feet per year; Edwards Aquifer Authority gives them 14 acre-feet per year.) misses a fascinating intersection of groundwater and surface water law that serves as an important lesson for landowners. (Landowners apply for 700 acre-feet per year, and based on the reported irrigated acreage of 300 acres, Edwards Aquifer Authority staff initially recommend a permit for 600 acre-feet per year [2 acre-feet per year per acre]. After a site visit, Edwards Aquifer Authority staff note that groundwater discharging from the well is entering a state watercourse in an uncontrolled manner and collecting behind an on-channel dam from which it is then diverted for irrigation. Because well water becomes state water after it enters a state watercourse in an uncontrolled manner, authority staff changes its recommendation from 600 acre-feet per year to 0 acre-feet per year. Landowners challenge the recommendation and seek a contested case hearing. During the hearing, it is learned that 7 acres are irrigated directly from the well head with the rest irrigated from behind the dam, resulting in a permit recommendation from the administrative law judge of 14 acre-feet per year; Edwards Aquifer Authority gives the landowners 14 acre-feet per year.)

With the drought and the issues it has caused landowners and water managers, it would also have been helpful for Porter to include a discussion on lakefront property (the certainty of lake levels and littoral rights). A discussion of superior rights and how to value water would have also been useful inclusions.

Writing a non-fiction book requires a monumental effort. I know, because I've been failing at it for the past 10 years. Each minor and major topic is a potential black hole of side stories and fact checking, which is further complicated when you find out that the facts you are fact checking are not, in fact, facts. If your goal is to be 100% accurate, your goal is to not finish your book (Porter 2; Mace 0). We can't all be Robert Caro, dedicating 10 years of full attention to each book.

So inevitably, there are inaccuracies and misstatements in the book:

- All surface water rights have been granted. (This is perhaps true for some very senior run-of-river rights, but there are high-flow events available for permitting, not to mention temporary permits.)
- Landowners have a right to divert 200 acre-feet without a permit. (This is debatable among legal scholars.)
- The state has 23 minor aquifers. (There are 21.)
- The recharge zones of most of our major aquifers are environmentally protected. (Nope.)
- Rice farmers have a senior right but the Lower Colorado

River Authority has the right to curtail that right. (Nope.)

- The Texas Water Development Board should create a groundwater conservation district in Val Verde County. (The Board doesn't have the authority to do this.)

Descriptions of the desired future condition process and groundwater desalination at El Paso are hopelessly mangled.

Nonetheless, despite being a failed writer and a grumpy technocrat, I found a lot to like in the book. I loved reading Porter's take on the East case, Del Rio water issues, metering, opinions by the attorney general, and how people really need to pay attention to water when making property disclosures. This is also a good-looking book. Published by Texas A&M University Press, the book is a strongly bound softcover, in color, and beautifully formatted and copy-edited.

Water policy changes quickly, especially in this drouthy and post-Day and McDaniel world. Hopefully, a revised edition is planned for the future to include new developments and to address the concerns mentioned above. And always remember to make sure you talk to your favorite water attorney before you do anything with water and your property.

Texas Water Resources Institute
Texas Water Journal
Volume 6, Number 1, Pages 67–78

Groundwater use in the Eagle Ford Shale: some policy recommendations

Maxwell Steadman*, Benton Arnett, Kevin Healy, Zhongnan Jiang, David LeClere, Leslie McLaughlin, Joey Roberts[1]

Abstract: Advances in hydraulic fracturing (fracking) and horizontal drilling have allowed oil and gas companies to tap into Texas' previously inaccessible shale reserves. Fracking in the state has grown at an exponential rate and is not expected to decline until 2025. Fracking requires the consumption of vast amounts of groundwater, a resource that is already strained. This study quantifies the water consumption associated with fracking in the Eagle Ford Shale, evaluates the current regulatory framework, and proposes 3 policy recommendations. The data show that fracking has become the primary consumer of groundwater in the most active counties within the Eagle Ford. Our study proposes 3 policy solutions to ensure that groundwater is consumed in an economically efficient manner in these areas. These solutions are a more thorough system for reporting consumption, tax incentives for oil and gas companies to use substitutes for fresh groundwater, and an alternative property rights system to the current rule of capture system.

Keywords: Hydraulic fracturing, policy recommendations, groundwater, fracking incentives, groundwater bank accounts

[1]All authors are graduates of Texas A&M University's Bush School of Government and Public Service, Class of 2014

*Corresponding author: msteadman7@gmail.com

Citation: Steadman M, Arnett B, Healy K, Jiang Z, David LeClere, Leslie McLaughlin, Roberts J. 2015. Groundwater use in the Eagle Ford Shale: some policy recommendations. Texas Water Journal. 6(1):67-78. Available from: https://doi.org/10.21423/twj.v6i1.7023.

Terms used in paper

Short name or acronym	Descriptive name
DFC(s)	desired future condition(s)
GCD(s)	groundwater conservation district(s)
MAG(s)	modeled available groundwater(s)
RRC	Railroad Commission of Texas
TWDB	Texas Water Development Board
UWCD	underground water conservation district

INTRODUCTION

The proliferation of hydraulic fracturing (fracking) has allowed oil and gas companies to tap into the United States' vast and previously inaccessible shale resources. In just a few years, fracking for shale resources has transformed the energy landscape within the United States, placing the country on a path toward increased energy security. Nowhere has the growth been more profound than in the Eagle Ford Shale. As shown in Figure 1, the Eagle Ford Shale formation extends beneath 30 Texas counties, stretching from Brazos County (Bryan/College Station) to Webb County (Laredo).

According to the Railroad Commission of Texas (RRC), "the Eagle Ford Shale is considered one of the top-producing shale plays in North America, serving as the second largest tight oil play and ranking fifth in terms of shale gas production (RRC

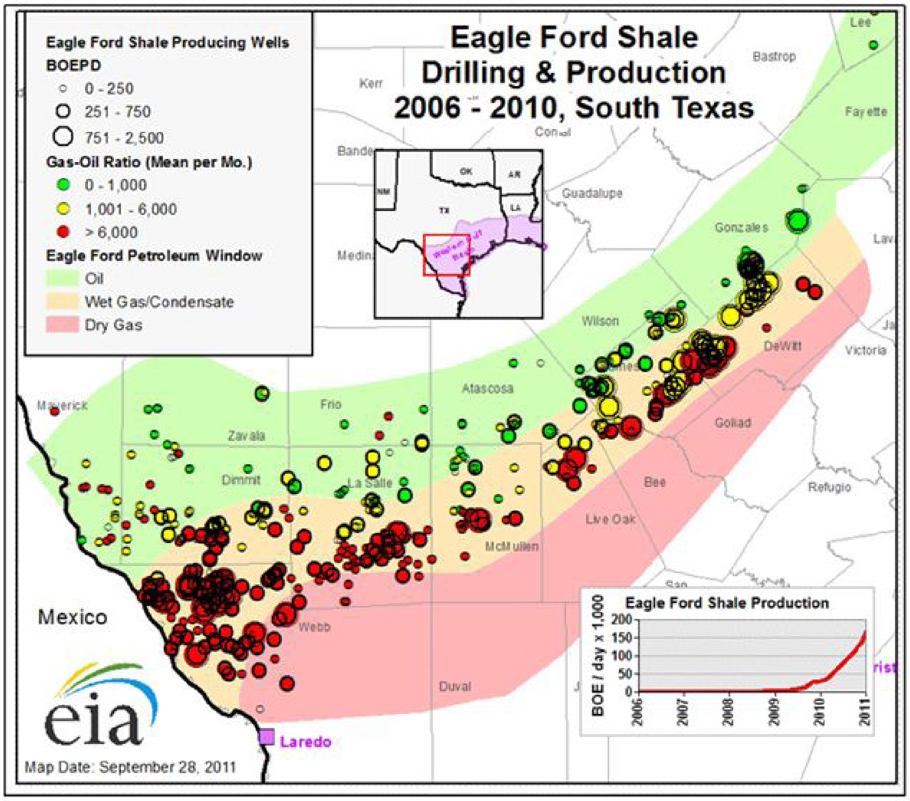


Figure 1. Map of the Eagle Ford Shale oil, gas and condensate play (EIA 2011).

2013).” What is perhaps most remarkable about oil and gas production in the Eagle Ford Shale is not only the phenomenal rate at which production continues to increase but also the short period of time in which the Eagle Ford has been under development. The area’s first well wasn’t drilled until 2008, but by 2012 there were 1,260 oil-producing wells and 875 gas-producing wells within the Eagle Ford (RRC 2013).

The large production growth seen in the Eagle Ford to date only represents a fraction of the potential production that could occur in the region. If gas prices rise and oil prices remain above $80 per barrel, then this rapid growth can be expected to continue. With January 2015 oil prices hovering near $50 per barrel, these lower prices will obviously slow the development of this area. Ultimately, prices are likely to rise again, meaning this development has simply been shifted forward into the future. A typical fracking well in the Eagle Ford is estimated to consume about 13 acre-feet of water for a standard 5,000-foot lateral (Arnett et al. 2014). Approximately 90% of water for fracking comes from fresh groundwater aquifers (Arnett et al. 2014).

At this point there has been no study to critically analyze the current state of water use for fracking operations versus other water uses within the Eagle Ford nor has there been any assessment of policy alternatives to the status quo. Using statistics and economics, this paper quantifies the relative importance of fresh groundwater use for fracking in the Eagle Ford counties and contrasts these with other uses. Next, we briefly describe the existing regulatory framework within which fresh groundwater is consumed. Finally, this paper concludes with 3 policy recommendations.

PIECING TOGETHER GROUNDWATER USE AND RECHARGE ESTIMATES

Through our research, we identified several potential issues with current groundwater trends in the Eagle Ford. The following sections show the relationship of water to recharge rates for the entire Eagle Ford and the groundwater usage in the 7 most active counties in terms of drilling activity in the play.

To determine water use by industry, we used water-use data from the Texas Water Development Board (TWDB) (TWDB 2015) for municipal, mining, irrigation, manufacturing, livestock, and power-generation sources. We combined power, manufacturing, and livestock into one category, which is listed as other, since these sources are typically minor in these counties. Under TWDB nomenclature, mining is essentially all oil and gas consumption. Unfortunately, its data for mining makes no attempt to measure water consumption for fracking. Thus, we replaced the TWDB mining estimate with oil and gas by relying on data reported to the RRC. After estimating the total water used for fracking in the Eagle Ford over the 4-year period, we assumed 90% of that water came from fresh groundwater, with the bulk coming from the Carrizo-Wilcox, Sparta, and Queen City aquifers (Industry interview 2014). Because of the semi-arid nature of the area, surface water supplies are quite limited, explaining the reliance on groundwater (Scanlon et al. 2014). The following 21 counties were used in this analysis: Atascosa, Bee, Brazos, Burleson, DeWitt, Dimmit, Fayette, Frio, Gonzales, Grimes, Karnes, La Salle, Lavaca, Lee, Live Oak, Madison, Maverick, McMullen, Webb, Wilson, and Zavala.

Each groundwater conservation district (GCD) publishes a water management plan, which includes annual recharge rates for each aquifer within the GCD. We totaled these rates to get the total annual recharge rate for the GCD and then aggregated across counties. This is represented in Figure 2 by the line labeled “recharge estimate.” It is important to realize that in confined aquifers, the recharge rate will be small, so usage will, often by necessity, exceed the recharge rate. Furthermore, much of the oil and gas activity in the Eagle Ford appears to be concentrated in the confined portion of the Carrizo-Wilcox Aquifer (Scanlon et al. 2014). The GCD management plans used in this paper came from Bee GCD (2012), Bluebonnet GCD (2013), Brazos Valley GCD (2010), Evergreen UWCD (2011), Fayette County GCD (2013), Gonzales County UWCD (2014), Lost Pines GCD (2012), McMullen County GCD (2008), Mid-East Texas GCD (2009), Pecan Valley GCD (2009), Post Oak Savannah GCD (2012), and Wintergarden GCD (2011). The most up-to-date management plans available at the time of this article were used.

More than 500,000 acre-feet per year of fresh groundwater are used annually within the study area (TWDB 2015). This was calculated by totaling the TWDB historical use estimates for counties in the Eagle Ford Shale region. This use level exceeds the estimated recharge rate for counties in the play by more than 300,000 acre-feet per year. The aquifers in this area are being drawn down at about 2.5 times their estimated average recharge rates. As shown in Figure 2, groundwater used for fracking operations has been increasing every year since 2010 and now makes up the third largest use of groundwater in the area (64,000 acre-feet per year or 12.5%). Despite the growth in this sector, irrigation still makes up more than half of all groundwater used in the study area, reflecting the rural nature of these counties. The amount of groundwater being used for irrigation alone exceeds the recharge rate by more than 50%.

The development of hydraulic fracturing activities within the Eagle Ford is still relatively recent, and further development is just a matter of time, price, and technology. If natural gas prices rise and oil prices return to 2014 levels, we can expect fracking operations to use an increasing amount of the

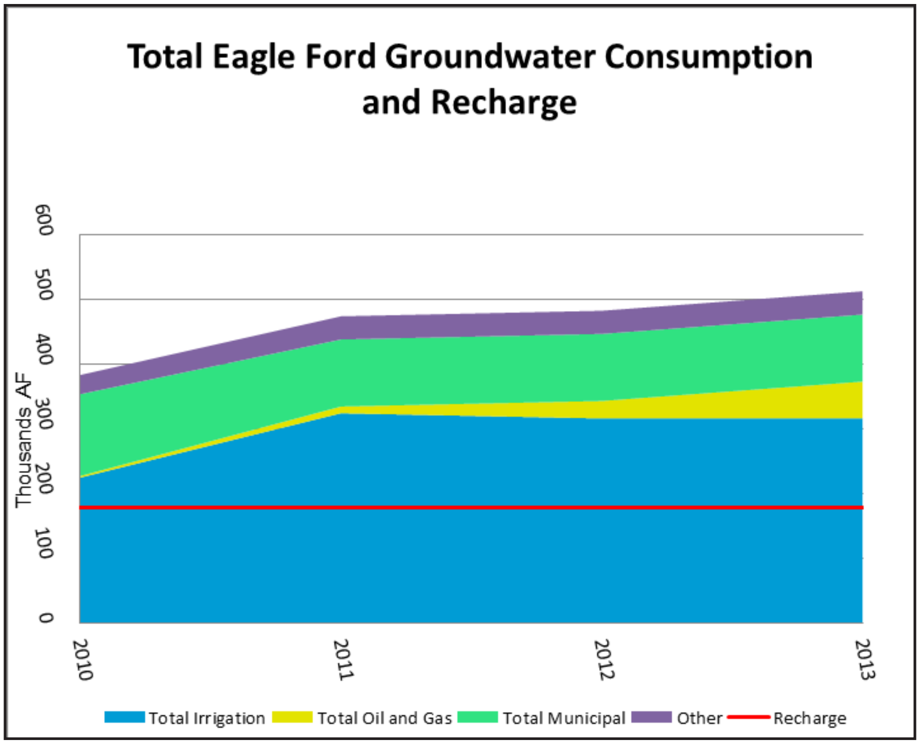


Figure 2. Total Eagle Ford groundwater use and recharge in acre-feet.

region's groundwater. To show how drilling could increase in the less-developed counties in the future, Figure 3 shows groundwater usage by sector for the top 7 counties in terms of drilling activity in the Eagle Ford: DeWitt, Dimmit, Gonzales, Karnes, La Salle, McMullen, and Webb. In 2013, these 7 counties accounted for 84.6% of the wells drilled in the Eagle Ford.

In Figure 3, the aggregation of counties shows the magnitude

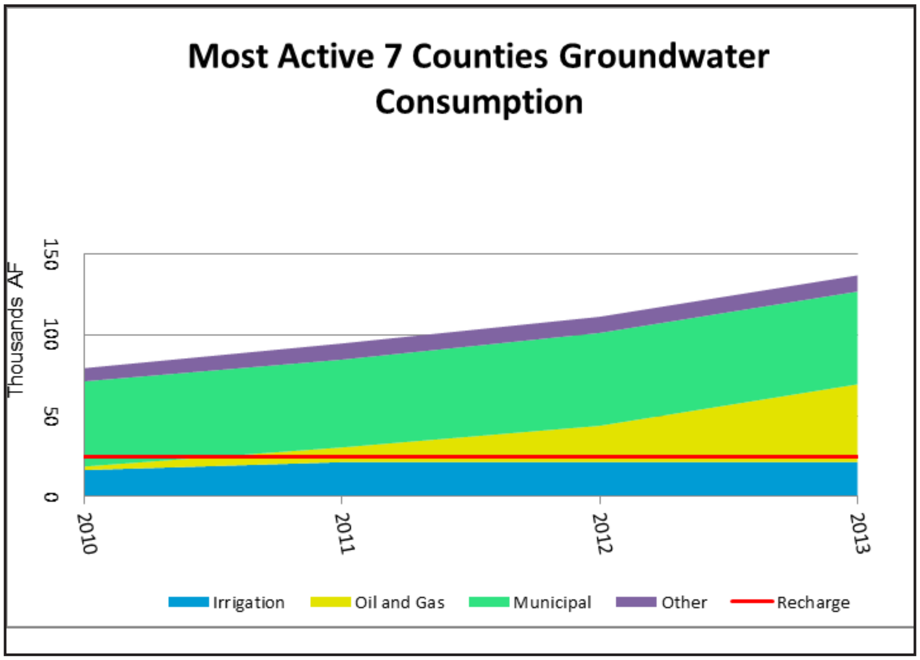


Figure 3. Groundwater use and recharge in acre-feet for the 7 most active counties in terms of drilling activity in the Eagle Ford Shale.

and speed at which fracking has grown in the area. In 2010, fracking was a minor user of groundwater. However, in just 4 years it has become the second highest user of fresh groundwater and currently makes up 30% of total consumption. By 2013, total consumption exceeded the average estimated recharge by 3.8 times. The rapid growth in drilling activity in these counties demonstrates the difficulty of predicting the growth of groundwater use for fracking operations and the potential to see rapid growth in other Eagle Ford counties under the right conditions.

As mentioned earlier, the Eagle Ford is still relatively young in its development despite the large growth already seen in the region. Table 1 shows the total freshwater used for fracking from 2010 to 2013 compared to the potential water needed to fully develop the estimated potential reserves of the Eagle Ford based on an estimated 13.6 billion barrels of oil and 119 trillion cubic feet of natural gas (ARI 2013).

Table 1 outlines the assumptions used to estimate future groundwater requirements assuming the status quo. These numbers should be used as a general reference and not an exact forecast due to the many factors that affect the Eagle Ford's development. These figures assume that oil and gas prices will eventually rise to a point where all of the proved reserve oil and gas in the Eagle Ford are economic to produce. These assumptions are made without a time frame restriction on drilling. We also assume that water consumption per well and the percentage of water from fresh groundwater will remain constant in the future. As explained later, unless there are policy changes, these assumptions appear to be realistic. Under these assumptions, past usage is only 6.7% of the total fresh groundwater that will be eventually needed, and future usage could require an additional 1.35 million acre-feet for fracking. But, is this realistic given the rapid technological changes in this industry?

Much of the analysis of water use for fracking within the Eagle Ford Shale, and across the state of Texas, has relied on data from the *Oil and Gas Water Use in Texas: Update to the 2011 Mining Water Use Report* (Nicot et al. 2012). This report indicates that over time technological improvements would allow the industry to drastically curtail its use of all water, including fresh groundwater for fracking operations. For some areas in Texas this may be true; however, our analysis concluded, at least in the Eagle Ford, this is not likely to be the case. In studying the rate of water use within the Eagle Ford over a 4-year period (2010–2013), it became apparent that, on a per-well basis, water use for fracking operations had indeed decreased, particularly in 2011 and 2012. However, by 2013 we did not observe any additional water-saving technological changes, suggesting that the technology had matured.

Arnett et al. (2014) concluded that the changes measured for water use in fracking operations are not the result of major discrete technological advances but of an industry learning to perfect its craft. The change in fracking water use seen from 2010 to 2011 and in 2012 and 2013 indicates there is a learn-

Table 1. Future fracking water potential consumption.

Assumptions	
Acre-feet/well	13.23
Fresh groundwater (%)	90%
Potential gas reserves (10^{12} cubic feet)	119
Reserves/well (10^9 cubic feet)	2
Total potential wells	59,500
Potential oil reserves (10^9 barrels)	13.6
Barrels/well	220,000
Total potential wells	61,818
Implied fresh groundwater use	
Potential acre-feet for gas wells	787,371
Potential acre-feet for oil wells	818,048
Total potential water (acre-feet) for oil and gas	1,605,420
Total potential groundwater (acre-feet) oil and gas	1,444,878
Previous consumption 2010–2013 (acre-feet)	97,157
Percent of total	6.72%
Potential future consumption (acre-feet)	1,347,721

ing curve present, thus there is little basis for assuming large water savings from technological improvements in the future. We hypothesize that without policy changes, fresh groundwater use for fracking within the Eagle Ford Shale will not decouple from drilling activity as was stated in the report by Nicot et al. (2012).

CURRENT REGULATORY APPARATUS: THE RULE OF CAPTURE AND GCDS

Groundwater use in Texas is primarily governed through the oversight of GCDs; however, that regulatory power has been significantly circumscribed by the rule of capture. For a detailed history, see Drummond et al. (2004). The rule of capture applies to groundwater and, prior to regulation by the RRC, to oil and natural gas. The principle behind the rule of capture is that, absent malice or willful waste, landowners have the right to take all the water they can capture under their land and do with it as they please, and they will not be liable to neighboring landowners even if they deprive their neighbors of the water use (Potter 2004). Absent strict regulatory limitations from GCDs, this creates a strong incentive for groundwater owners to pump as much as they can as quickly as they can, lest their neighbor captures the same groundwater.

In many key counties within the Eagle Ford Shale, there exists a real conflict between current and future fresh groundwater consumers, as well as between irrigation, municipal, and oil and gas users (Jervis 2014). Under the status quo, consumers of fresh groundwater place a scarcity value on fresh groundwater that is essentially zero. In this context, scarcity value is defined as the increased value of a resource as it is depleted. The primary cost of groundwater is the cost of drilling and pumping the water well. A water well used for fracking is assumed to cost an average of approximately $500,000 (Industry interview 2014). In oil and gas production, after fracking is completed, the water well becomes essentially free to the landowner, pursuant to the terms of the lease for oil or gas development. With no designated monetary value on the scarcity value of water, there is little incentive to use less today and save for future consumption. Whether for livestock, municipal, irrigation, or oil and gas, the average water producer consumes as much water as they like, only to the extent GCDs restrict their use. But this regulation is typically non-binding since GCDs set the ceiling for irrigation in excess of actual water usage. For oil and gas companies, Section 36.117b of the Texas Water Code exempts oil and gas companies use of water for drilling and exploration (Texas Water Code Ann. § 36.117). Some ambiguity arises about whether water for fracking is considered a part of drilling and exploration activity; nevertheless, GCDs have been reluctant to restrict permitting or water use, though they may limit groundwater pumped off the lease to other locations.

Thus, large-scale water users are competing for a diminishing aquifer resource with no market signals of increasing scarcity, which would otherwise moderate consumption. Huang et al. (2012) report drops of 100 feet to more than 300 feet in the Carrizo Aquifer in the southern portion of the Carrizo-Wilcox Aquifer—the primary aquifer for fresh groundwater in the Eagle Ford. Even if oil and gas drilling were not prevalent in this region, the Eagle Ford aquifers would still be drained by unrestrained use for other purposes. This reduction is because consumers of water resources are not slowed either by a price function or by the existing GCD regulatory structure in Texas. As a general matter, agricultural users usually have exemptions or an allotment, which is rarely exceeded. Statutorily, GCDs may not require a permit for a water well supplying water to a rig actively engaged in drilling or exploration, though the water well must conform to GCD rules on casing, piping, and fittings (Texas Water Code Ann. § 36.117). Even simple metering is not required or enforced for either agricultural or oil and gas users. Assigning blame to either category of user without adequately addressing the overall problem in Texas misses the crux of the water issue.

Other than wells used for oil and gas development, GCDs have the power to restrict drilling of wells and pumping of water, using a variety of approaches, including spacing rules and limiting proportionality of production to acreage stipulations (unless exempt, as with oil and gas). GCDs also develop periodically updated desired future conditions (DFCs), which are used in conjunction with modeled available groundwater (MAGs) and become the basis to permit, deny, or restrict groundwater use (Mace 2006). MAGs are quantitative descriptions of groundwater resources in a management area. GCDs preparing DFCs pursuant to recommendations for their groundwater management areas must identify aquifers, identify acceptable change to such aquifers over time, and produce a 50-year planning horizon in 10-year increments. In principle, the requirements to achieve the DFC within a groundwater management area should require GCDs to have rules with teeth. However, in practice GCDs can come back periodically and change to a more permissive DFC, thus avoiding regulations that significantly impact current uses.

As noted above, the ambiguous regulatory power of GCDs over wells drilled and groundwater pumped in connection with oil and gas exploration results in minimal enforcement. Furthermore, irrigation wells that fall under GCDs authority are assigned allotments of water that guarantee their maximum usage. Essentially, only physical waste is prohibited. Likewise, municipalities are allowed to pump their required allotments, which are based on their needs and not the drawdown of the aquifer. Although GCDs presumably have the power to reduce water use, it appears to be rarely done—at least in the Eagle Ford area.

Curiously, GCDs do restrict pumping in a peculiar, perverse manner. Typically, a landowner must receive GCD approval (an export permit) to sell groundwater to someone outside the boundary of the GCD. With a major city such as San Antonio nearby, rationality indicates that an irrigator growing corn for ethanol should instead be allowed to sell his water to San Antonio. Clearly, water for San Antonio has higher value than irrigated corn production. However, selling water outside the GCD is contingent; local control of GCDs results in electing board members who are likely to thwart water sales outside the GCD.

GCD power is further circumscribed by the rule of capture. The currently constituted powers of GCDs are in tension and potentially conflict with the rule of capture in light of recent case law. Regulatory overreach by GCDs may amount to a "taking" of property rights. Similarly, tighter regulation by GCDs may lead to courts narrowing GCD powers by declaring something close to a per se taking.

Eliminating the rule of capture doctrine in Texas may amount to a taking of property rights under the Fifth Amendment to the U.S. Constitution and Article I, section 17 of the Texas Constitution. The Takings Clauses of the U.S. and Texas constitutions are straightforward, though their application may not be. The Fifth Amendment states, "private property [shall not] be taken for public use, without just compensation." Article I, section 17 of the Texas Constitution guarantees,"No person's property shall be taken, damaged or destroyed for or applied to public use without adequate compensation being made." These Takings Clauses were "designed to bar Government from forcing some people alone to bear public burdens which, in all fairness and justice, should be borne by the public as a whole." (*Armstrong v. United States* 1960)

In 2012, *Edwards Aquifer Authority and Texas v. Day and McDaniel* held that, under Article I, section 17 of the Texas Constitution, regulators can limit water usage, but land ownership still includes an interest in groundwater in place, which cannot be taken for public use without compensation (*Edwards Aquifer Authority and Texas v. Day and McDaniel* 2012). Thus, tension exists between landowners' ownership of percolating water and Texas groundwater districts' statutory assertion of regulatory rights over such property. Under Chapter 36 of the Texas Water Code, GCDs have power to adopt minimum well spacing or tract size requirements, set water production shares according to acreage owned, and set production limits on specific wells.

Under the existing legal rulings and GCD structure, we appear headed for endless litigation, for which GCDs are ill-equipped. GCDs are funded by local tax sources and are likely unable to finance protracted litigation. The goal of our third proposal is to clearly define property rights of groundwater and thereby end the possibility of endless litigation.

In sum, the inherent problems in the Texas regulatory scheme for managing underground freshwater use cannot be solved by GCDs themselves. In addition to the political problems, GCDs are limited in power and resources. Some will argue that GCDs, through decades of tepid effectiveness, have contributed to the present magnitude of the problem. Even if GCDs were historically more effective, a new wave of takings cases asserting the primacy of the rule of capture and the Fifth Amendment could potentially bankrupt any GCD inclined to try to flex its regulatory muscle.

OVERVIEW OF POLICY RECOMMENDATIONS

Our 3 policy recommendations are organized in order of their ease of implementation. The first requires mandatory metering of groundwater use. This is a prerequisite to informed policy. Currently, the state relies on a mishmash of sources and estimates. Water has simply become too valuable to treat it as a free resource. Second, we propose a combination of incentives and public commendation to encourage oil and gas companies active in the Eagle Ford to avoid using fresh groundwater by substituting with brackish water, municipal treated wastewater, or recycled water. This proposal will allow the continued development of the Eagle Ford and have the advantage of removing the oil and gas industry from the future conflict over fresh groundwater. Our third recommendation is admittedly politically problematic and would face many hurdles. Nevertheless, its ambitious focus is on alleviating the perverse incentives of the rule of capture via a groundwater banking system.

Policy recommendation 1: mandatory reporting for all water uses

A prerequisite to any informed water policy is the need for accurate data on water consumption. Categorically, this means improving the transparency of data reporting by irrigation, municipal, oil and gas, and other use categories. Below is a summary of the status quo as it pertains to data reporting:

- ***Irrigation:*** The TWDB merely estimates the acre-feet of water consumption per observed crop and irrigation acreage by aerial and fence-line approximations.
- ***Livestock:*** Rural landowners' and ranchers' water consumption is formula-based in accordance with livestock and other miscellaneous factors. However, wells used solely for domestic and livestock purposes require no reporting of pumping or use.
- ***Municipal use:*** Municipalities and non-oil and gas-related industries have the most accurate data, as they measure production and use, including retail customer sales. However, the split between surface water uses versus fresh groundwater uses is not always clear.

- ***Industrial:*** Industrial and power plants that are not customers of local municipal utility companies may or may not have metering and accurate pumping data.
- ***Oil and gas:*** Beginning in February 2012, the RRC required a report for each well drilled that includes the number of barrels of water used for drilling and fracking purposes (1 16 TAC §3.29). However, the RRC reporting requirement does not require that the respondent provide either the type of water—surface water, fresh groundwater, brackish groundwater, or recycled water—nor the source—well depth and location.

If reported, these data are submitted either to the GCDs, the TWDB, or the RRC. There appears to be little coordination of data gathering and little ability to monitor the correctness of the data. For example, the water usage reported to the RRC had numerous errors where the respondent may have entered barrels instead of gallons. Out of 6,752 wells reported, our analysis indicated there were 3,002 wells either with implausible volumes of water used for fracking or missing data. To alleviate this lack of transparency, our policy recommendation will make all well depths and water consumption categories, including salinity of the water, reportable.

Our proposal is for groundwater consumption data to be reported online and subject to spot checks. Specifically, this proposal would cover the following groups:

- Irrigation users should be required to install metering equipment and report usage to the GCDs or equivalent county reporting agency.
- Rural homeowners with a water well would be exempt from metering but not from reporting estimated usage. In an applied system, we recommend the development of a formula to handle water consumption, estimating user consumption under a certain threshold. This information would be reported to the resident's GCD or equivalent county reporting agency.
- Other agricultural users, such as ranchers and poultry operations, would be required to meter groundwater usage. This information would be reported to the TWDB.
- Municipalities should be required to meter groundwater consumption and to distinguish between brackish and fresh groundwater. This includes requiring residential customers within the municipality's service areas who drill personal wells to meter and report to the utility. This information would be reported to the TWDB.
- Industrial users served by their own wells should be required to meter and report usage to the TWDB.
- Power plants with their own well should also be required to meter and report usage. This information would be reported to the TWDB.
- Oil and gas companies would be required to report not only total water uses (which they currently do) but the type of water—surface, fresh groundwater, brackish groundwater (with salinity content), or recycled water—in addition to water well location and depth. This information would be reported to the RRC.

Reliable consumption data is fundamental to informed policy and a necessary building block to reforming the current regulatory structure. Thus, our policy recommendation is a fundamental first step for which there should be little opposition.

Policy recommendation 2: incentivizing the substitution away from fresh groundwater

Our second policy recommendation is a 2-part plan to encourage oil and gas operators to use less fresh groundwater when possible. The options include using surface water, recycled water, brackish groundwater, or even municipal treated wastewater. The individual operators would be free to choose their preferred substitute for fresh groundwater. Based on the high cost of recycled water and limited supplies of municipal treated wastewater in the area, the least-cost choice for most operators will be brackish groundwater, which is available in abundant supply. First, operators would receive recognition from a proposed Green Star program through the RRC (and possibly the TCEQ) if they take the pledge to dramatically reduce their use of fresh groundwater. This program would consist of a bronze, silver, and gold tier, depending on the percentage of fresh groundwater used for fracking. Part 2 involves a severance tax reduction for wells drilled by Green Star operators that have qualified for at least bronze level status in the Green Star program. Together, these two components would provide operators a financial and social incentive to conserve fresh groundwater. As noted above, the pledge to dramatically reduce fresh groundwater use could, in principle, involve substituting recycled water (flowback and produced water). However, in most instances, this option is likely to be far more expensive than simply using brackish water (Slutz et al. 2012). For most areas of the Eagle Ford, brackish groundwater supplies are abundant and the least expensive option to fresh groundwater. Nevertheless, some companies might experiment with these other sources, which would be a good thing.

The Green Star program would recognize that it may not be reasonable to avoid using fresh groundwater in all instances because of inadequate supplies of surface water, brackish water, or recycled water. (Very slow flowback of produced water makes recycling prohibitively expensive.) At the very lowest level of participation in the Green Star program, an operator could use no more than 30% fresh groundwater for fracking. Given the current practice of using 90% fresh groundwater for fracking, this program would significantly reduce fresh groundwater consumption.

The incentive component of our proposal consists of granting Green Star operators a severance tax abatement of $50,000 per Eagle Ford well for using alternatives to fresh groundwater. This is not a large cost to the state, given that a typical well will pay many multiples of that in severance taxes. Arnett et al. (2014) compute that the fiscal impact on severance tax revenues would mean when oil prices are $100 per barrel, the severance tax collected would fall from 4.6% to about 4% in the first year of production and be unaffected thereafter. At $50 per barrel , the first year severance tax reduction would fall from 4.6% to about 3.4% just for the first year of production. In effect, this incentive would have a relatively minor effect on severance tax revenues and a substantial environmental benefit.

From the operators' perspective, this tax break would offset much of the cost of using brackish groundwater. Fresh groundwater typically sells for $0.50 per barrel in the Eagle Ford. Thus, a typical operator in the Eagle Ford would expect to spend $50,000 per 100,000 barrels of water on any well. A $50,000 severance tax savings would allow operators to double their investment in water, without taking a financial hit. Particularly for an operator drilling 8 to 10 wells on a lease, an incentive bundle of $400,000 to $500,000 should be sufficient to offset the added cost of drilling a deeper water well to tap into brackish water formations. Since most operators in an immediate area will be drilling multiple wells, 1 brackish groundwater well costing an additional $400,000 could provide water to a number of wells and would be justified on a cost basis.

The other essential component of this policy is to publically recognize Green Star operators as being environmentally responsible. By recognizing operators who pledge to use less fresh groundwater while abiding with other TCEQ and RRC environmental regulations, these companies could demonstrate that they are willing to do more than simply talk about being environmentally responsible.

In order to qualify for Green Star recognition at the bronze level, operators could only use fresh groundwater for 30% or less of their wells and be compliant with all other regulations. This would earn them bronze level status in the program and make them eligible for the aforementioned tax incentives. In order to qualify for the silver level, operators would have to lower this number to 20%. To qualify for the gold level, operators would use fresh groundwater for no more than 10% of their wells. While the silver and gold levels do not offer any additional tax benefits, they will show the public how much an operator is willing to conserve fresh groundwater.

The potential public relations benefits to Green Star operators are many. First, these operators will be drilling and producing oil and gas in the Eagle Ford for many decades to come. By curtailing the use of fresh groundwater for fracking, Green Star companies would no longer be competitors with irrigators and municipalities for increasingly scarce fresh groundwater supplies. Second, the Green Star designation would be something that the firms and the industry should welcome. Not only would it be a mechanism to improve the public image of individual companies, but, if widely adopted by the 200 plus operators in the Eagle Ford, it could vastly improve the industry's image. An additional benefit to the RRC is that this program would be evidence of the commission's forward-looking agenda and demonstrate its proactive efforts to solve both a quantitative and qualitative environmental problem.

The Eagle Ford Shale has provided the state budget with an enormous windfall. Using a small portion of this windfall to incentivize shifting away from using fresh groundwater is a wise long-term investment in Texas. For oil and gas operators, and the industry as a whole, these incentives should be adequate to tip the balance in favor of using brackish groundwater and greatly enhance their public image in the process. Farmers, ranchers, and municipalities in these counties would benefit from the reduced consumption of freshwater supplies. Finally, it demonstrates Texas' ability to solve its own problems and proactively address an important issue without interference from the Environmental Protection Agency.

A futuristic idea: groundwater bank accounts

As mentioned earlier in this paper, property rights for groundwater in Texas are defined primarily under the rule of capture. This legal precedent creates an incentive to consume water as quickly as possible and prices water close to the cost of extraction with little respect to its rising scarcity value. In a water-scarce region, such as the Eagle Ford, the result of this policy is artificially cheap water today and much more expensive water in the future once the cheap sources are depleted. In the past, when water use more closely matched aquifer recharge rates, the rule of capture as a means of defining property rights was sensible and administratively simple—water users were rarely pumping enough to impact their neighbor's water consumption. However, when consumption greatly exceeds the recharge rate, the rule of capture allows the landowner with the fastest pump to pull water from the surrounding area and use it as if it were a free resource. This incentive structure is similar to early difficulties with Texas oil and gas, where property owners had little power to control the resources they rightfully owned.

There is a variety of alternative ways to define property rights other than through the rule of capture. In many countries and most U.S. states, groundwater is the property of the state, so this eliminates competition between landowners. Regulators then face the dilemma of who can produce the water and how much. Yet another method of defining property rights is to allow private ownership but limit water consumption to a predetermined quantity each year. In researching these various means, it became apparent that few free market systems are in place throughout the nation; as a result, we began to think of how the market could solve the problem while still protecting private property rights. Below are several steps that would shift groundwater in the Eagle Ford toward a more open market structure that would both respect private property rights and provide for efficient consumption and pricing of water over time.

The idea is to create groundwater bank accounts that would work as follows:

- Determine the magnitude of the fresh groundwater geographically: Based on hydrological studies for a county or GCD, determine the acre-feet of fresh groundwater in major aquifers as defined on a per acre basis. The TWDB maintains detailed hydrological models of the various aquifers in the Eagle Ford area as well as in other areas of the state. These models provide, on a 1 square mile grid, the total estimated recoverable storage. These estimates, called total estimated recoverable storage, assume that between 25% and 75% of groundwater held in an aquifer can be recovered through pumping. Thus within a 1 square mile area, it is possible to compute an estimate of the acre-feet of groundwater underlying a landowner's property. The estimate of acre-feet of water per acre of surface area will vary across the county or GCD because these aquifers are not homogeneous.
- Define water as a resource similar to mineral rights: In doing this, landowners could now know with some certainty the quantity of water in place under their property and have the right to use, sell, or save that water as they see fit.
- Calculate year-to-year debits to each owner's groundwater bank: Each year, the landowner's quantity of water-in-place would be reduced by the number of acre-feet pumped by wells on his property. In principle, every 10 to 20 years, landowners could receive credits for recharge, based on new data. As a practical matter, this could be very difficult to measure with any precision. Recharge rates remain one of the most difficult numbers to quantify.
- Allow free trade of water rights: Landowners would be free to sell water either within or outside its GCD with no permit required.

The benefit of this policy recommendation is that it should greatly improve the inter-temporal consumption of groundwater. Clearly, the price of water will reflect the willingness to pay of the consumer and the opportunity costs of the supplier. This would ensure that water is allocated efficiently not only to the present generation but also to future generations. Landowners would have an incentive to include the potential for higher future demand and scarcity in their decisions to either use the water internally or sell it to other users who may choose to store or use the water. They would not have to fear that their water might be taken from them, as they do now under the rule of capture. As the price of water today increases as a result of resource scarcity, its price will rise gradually, forcing more conservation today. The transition to alternatives (i.e. desalination, importing water, and others) will become smoother with less drastic price jumps in the future.

Despite these obvious advantages, the transition to a system of groundwater bank accounts faces a number of roadblocks due to the existing regulatory landscape, administrative costs, underlying science, and legal obstacles. First, even though we found the GCDs in the Eagle Ford exercised little restraint on the rate of pumping, they potentially could exercise broad powers in the future. Turning the GCDs into metering and monitoring agencies would be opposed by users currently facing no effective restraints. Second, the groundwater bank accounts depend critically on our first proposal—mandatory metering of water use. Associated with this monitoring and reporting function would be significant administrative costs, which would be ideally handled at the GCD level. Third, the science of accurately measuring the groundwater under a given landowner's property is necessarily imprecise. While tremendous scientific progress has been made, these models are continually being refined and remain subject to error. As new information becomes available, it might become necessary to adjust the balances in the bank accounts. Fourth, just as the existing regulatory scheme has spawned a variety of lawsuits, this alternative would not be immune to challenges that the total estimated recoverable storage, which is based upon the TWDB's models, are in error. While the burden of proof would at least fall on the plaintiff, an end to legal challenges seems unlikely. Nevertheless, it should end the issue of takings since a landowner's property rights are protected.

CONCLUSION

A combination of the rule of capture, minimal regulation by GCDs, and the evolving law of takings has resulted in a dysfunctional regulatory apparatus. With the advent of substantial fresh groundwater use in the Eagle Ford Shale, the problem has only been exacerbated.

This paper proposes 3 policy recommendations to address this issue. First, it is necessary to better measure fresh groundwater pumping rates. Second, tax incentives plus recognition of environmentally responsible oil and gas companies, could lead to widespread substitution of fresh groundwater. Given large reserves of brackish groundwater, substituting brackish groundwater is the most obvious solution. Third, an entirely new approach to governing groundwater consumption, involving the creation of groundwater bank accounts, should be developed. We believe this change would fundamentally alter the incentives to conserve increasingly scarce groundwater resources.

ACKNOWLEDGMENTS

This paper is based on a capstone project at the Texas A&M Bush School of Government and Public Service under the direction of our faculty advisor, Professor James M. Griffin. The original report was to Commissioner Christi Craddick at the RCC. We wish to thank Professor Griffin as well as the 3 anonymous referees for numerous helpful comments.

REFERENCES

[1 16 TAC §3.29] Texas Administrative Code Title 16, Section 3.29

Armstrong v. United States, 364 U.S. 40 (1960)

Arnett B, Healy K, Jiang Z, LeClere D, McLaughlin L, Roberts J, Steadman M. 2014. Hydraulic fracturing in the Eagle Ford Shale. A report to Commissioner Christi Craddick, Texas Railroad Commission. College Station (Texas): Bush School, Texas A&M University.

[ARI] Advanced Resources International, Inc. 2013. EIA/ARI World Shale Gas and Shale Oil Resource Assessment [Internet]. Arlington (Virginia): Advanced Resources International, Inc.; [cited 2015 March 31]. Available from: http://www.adv-res.com/pdf/A_EIA_ARI_2013%20World%20Shale%20Gas%20and%20Shale%20Oil%20Resource%20Assessment.pdf

[Bee GCD] Bee Groundwater Conservation District. 2012. Bee Groundwater Conservation District management plan [Internet]. Beeville (Texas): Bee Groundwater Conservation District; [cited 2015 March 31]. Available from: http://www.beegcd.com/uploads/BeeDMPApproved_8_21_13_2_.pdf

[Bluebonnet GCD] Bluebonnet Groundwater Conservation District. 2013.Bluebonnet Groundwater Conservation District groundwater management plan [Internet]. Austin (Texas): Texas Water Development Board; [cited 2015 March 31]. Available from: http://www.twdb.texas.gov/groundwater/docs/GCD/bbgcd/bbgcd_mgmt_plan2013.pdf

[Brazos Valley GCD] Brazos Valley Groundwater Conservation District. 2010. Brazos Valley Groundwater Conservation District groundwater management plan [Internet]. Austin (Texas): Texas Water Development Board; [cited 2015 March 31]. Available from: http://www.twdb.texas.gov/groundwater/docs/GCD/bvgcd/bvgcd_mgmt_plan2010.pdf

Drummond D, Sherman LR, McCarthy E. 2004. Rule of capture in Texas – still so misunderstood after all these years. Texas Tech Law Review. 37(1):1-99.

Edwards Aquifer Authority v. Day and McDaniel, 55 Tex. Sup. Ct. J. 343, 369 S.W.3d 814 (Tex. 2012)

[Evergreen UWCD] Evergreen Underground Water Conservation District. 2011. Evergreen Underground Water Conservation District groundwater management plan [Internet]. Austin (Texas): Texas Water Development Board; [cited 2015 March 31]. Available from: https://www.twdb.texas.gov/groundwater/docs/GCD/euwcd/euwcd_mgmt_plan2011.pdf

[Fayette County GCD] Fayette County Groundwater Conservation District. 2013. Fayette County Groundwater Conservation District management plan [Internet]. Austin (Texas): Texas Water Development Board; [cited 2015 March 31]. Available from: http://www.twdb.texas.gov/groundwater/docs/GCD/fcgcd/fcgcd_mgmt_plan2013.pdf

[Gonzales County UWCD] Gonzales County Underground Water Conservation District. 2014. Gonzales County Underground Water Conservation District management plan [Internet]. Austin (Texas): Texas Water Development Board; [cited 2015 March 31]. Available from: https://www.twdb.texas.gov/groundwater/docs/GCD/gcuwcd/gcuwcd_mgmt_plan2014.pdf

Huang Y, Scanlon B, Nicot JP, Reedy RC, Dutton A, Van K, Deeds N. 2012. Sources of groundwater pumping in a layered aquifer system in the Upper Gulf Coast Plain USA. Hydrology Journal. 20:783-796.

[Industry Interview] Interview with Industry Experts. 2014.

Jervis R. 2014 January 15. Oil! New Texas boom spawns riches, headaches. USA Today.[cited 2015 March 31]. Available from: http://www.usatoday.com/story/news/nation/2014/01/15/texas-oil-boom-fracking/4481977/

[Lost Pines GCD] Lost Pines Groundwater Conservation District. 2012. Lost Pines Groundwater Conservation District management plan [Internet]. Austin (Texas): Texas Water Development Board; [cited 2015 March 31]. Available from: https://www.twdb.texas.gov/groundwater/docs/GCD/lpgcd/lpgcd_mgmt_plan2012.pdf

Mace RE, Petrossian R, Bradley R, Mullican WF. 2006. A streetcar named desired future conditions: the new groundwater availability for Texas. Austin (Texas): Texas Water Development Board.

[McMullen County GCD] McMullen County Groundwater Conservation District. 2008. McMullen County Groundwater Conservation District district management plan [Internet] McMullen Groundwater Conservation District; [cited 2015 March 31]. Available from: http://www.mcmullengcd.org/uploads/MGCDMPapproved_08_07_08.pdf

[Mid-East Texas GCD] Mid-East Texas Groundwater Conservation District. 2009. Management plan: Mid-East Texas

Groundwater Conservation District [Internet]. Mid-East Texas Groundwater Conservation District; [cited 2015 March 31]. Available from: http://www.mideasttexasgcd.com/Management%20Plan.pdf

Nicot JP, Reedy RC, Costley RA, Huang Y. 2012. Oil and gas water use in Texas: update to the 2011 mining water use report. Austin (Texas): The University of Texas at Austin.

[Pecan Valley GCD] Pecan Valley Groundwater Conservation District. 2009. Groundwater management plan: Pecan Valley Groundwater Conservation District [Internet]. Austin (Texas): Texas Water Development Board; [cited 2015 March 31]. Available from: http://www.twdb.texas.gov/groundwater/docs/GCD/pvgcd/pvgcd_mgmt_plan2014.pdf

[Post Oak Savannah GCD] Post Oak Savannah Groundwater Conservation District. 2012. Groundwater management plan [Internet]. Post Oak Savannah Groundwater Conservation District; [cited 2015 March 31]. Available from: http://www.posgcd.org/wp-content/uploads/2011/10/POSGCD-Mgt-Plan-Adopted-10-9-121.pdf

Potter HG. 2004. History and evolution of the rule of capture. In: Mullican III WF, Schwartz S. editors. 100 years of capture: from East to groundwater management [Internet]. Symposium sponsored by the Texas Water Development Board, June 15, 2004. Austin, Texas. Report 361. Available from: http://www.twdb.texas.gov/publications/reports/numbered_reports/doc/R361/Report361.asp

[RRC] Railroad Commission of Texas. 2013. Eagle Ford Shale task force report. [Internet]. Austin (Texas): Railroad Commission of Texas. Available from: http://www.rrc.state.tx.us/media/8051/eagle_ford_task_force_report-0313.pdf

Scanlon BR, Reedy RC, Nicot JP. 2014. Will water scarcity in semiarid regions limit hydraulic fracturing of shale plays?. Environmental Research Letters. 9(12): 124011.

Slutz J, Anderson J, Broderick R, Horner P. 2012. Key shale gas water management strategies: an economic assessment tool. International Conference on Health, Safety and Environment. Society of Petroleum Engineers.

[Texas Water Code Ann. § 36.117] Texas Water Code Chapter 36, Section 36.117.

[TWDB] Texas Water Development Board. 2015. Historical water use estimates, "County summary, 2000 and later" [Internet]. Texas Water Development Board. Available from: http://www.twdb.texas.gov/waterplanning/waterusesurvey/estimates/

[USEIA] U.S. Energy Information Administration. 2011 November 3. Eagle Ford Shale Drilling & Production, Trends in Eagle Ford drilling highlight the search for oil and natural gas liquids. Today in Energy [Figure, Internet]. Available from: http://www.eia.gov/todayinenergy/detail.cfm?id=3770

[Wintergarden GCD] Wintergarden Groundwater Conservation District. 2011. Wintergarden Groundwater Conservation District: Management Plan [Internet]. Wintergarden Groundwater Conservation District; [cited 2015 March 31]. Available from: http://wgcd.net/sites/wgcd.net/files/file/5/wgcdmanagementplan.pdf

Texas Water Resources Institute
Texas Water Journal
Volume 6, Number 1, Pages 79–85

Residential outdoor water use in one East Texas community

Timothy R. Pannkuk* and Lawrence A. Wolfskill

Abstract: Municipalities continue to implement efforts to encourage water conservation among residents. Landscape irrigation has been central to many of those conservation efforts. Reference evapotranspiration data is a tool that can be used in determining the appropriate amount of water to apply to amenity landscapes. Monthly water-use data for 3 years was examined in 1 neighborhood in Huntsville, Texas. The irrigated area for 1,229 residents was calculated and used to determine the depth of monthly irrigation for each residence. Replacement of 100% of local reference evapotranspiration data, minus rainfall, was used as a determinant of how much water to apply to the landscape each month for 3 years. Potential over-irrigation for each month was then compiled. Data expressed that over-irrigation was occurring among 99.51% of residents, of which 12% of these residents over-irrigated by at least 100,000 gallons in at least 1 month during the 36 month study. In 2011, the entire neighborhood of study over-irrigated by 21.2 million gallons. Outdoor water use accounted for 64% of the total water use by households. Average indoor water usage was 4,302 gallons per month. Based on the data overall, greater conservation efforts in landscape irrigation are crucial for Texas residents if water demands are to be met in the 21st century.

Keywords: evapotranspiration, outdoor water use, indoor water use, residential irrigation

Department of Agricultural Sciences and Engineering Technology, P.O. Box 2088, Sam Houston State University, Huntsville, Texas, 77340
* Corresponding author: pannkuk@shsu.edu

Citation: Pannkuk TR, Wolfskill LA. 2015. Residential outdoor water use in one East Texas community. Texas Water Journal. 6(1):79-85. Available from: https://doi.org/10.21423/twj.v6i1.7009.

INTRODUCTION

Potential estimated deficits between water use and water availability continues to be a topic of concern in Texas. On May 28, 2013, the Texas Governor signed House Bill 4, which presented Texas voters with the option of transferring $2 billion from the state's Economic Stabilization Fund, or Rainy Day Fund, to the existing $6 billion in the Texas Water Development Board's bond authority. These funds are dedicated to implementing capital projects in the state's 50-year water plan. On November 5, 2013, 73% of Texas voters approved Proposition 6, which enabled 2 funds that will help finance projects in the state water plan (TWDB 2013).

Municipal-urban water use in Texas has grown to be the second largest water use activity in Texas behind irrigated agriculture (TWDB 2012). Water use in irrigated agriculture has stabilized in recent years due to fewer irrigated acres and greater irrigation efficiency on farms. However, municipal-urban water use continues to increase primarily due to increases in population. The Texas Water Development Board (2012) forecasts that the Texas population will increase by 82% from 2010 to 2060, and water demand will increase by 22%. However, water supplies (surface water, groundwater, and re-use water) are predicted to decrease by about 10% over the same period of time. Information from the state water plan suggests that if Texas does not implement new water projects or plans of management, then farms, businesses, and homes are projected to need 8.3 million acre-feet of additional water supply by 2060 (TWDB 2012). In 2060, irrigation represents an estimated 45% of this total need, and municipal users account for 41% of needs (TWDB 2012). If these water needs are not met, it will result in economic losses and millions of lost jobs by 2060. Water conservation is one of a variety of methods that can be used to curb the projected increase in water demand in Texas. Other methods include demand-side management (e.g. time-of-day or day-of-week restrictions on outdoor water use and banning certain activities such as car-washing) and (sub)urban planning to design low water use into future municipality expansions.

In the municipal-urban water-use sector, where the number of users is continually increasing, conservation has become an integral part of the plan to supply enough water. Beyond human consumption, water has a variety of uses by the municipal user, including: recreation, cleaning, and irrigating the outdoor environment. Residential lawn irrigation has been suggested as a large user of municipal water supply; however that conjecture has not been well tested in the literature (Runfola et al. 2013). Regardless, outdoor irrigation is a highly visible practice and has been the target of many conservation efforts (Austin Water Utility 2014; Dallas Water Utilities 2014a; SAWS 2014). The U.S. Geological Survey (Kenny et al. 2009) found that about 349 billion gallons of freshwater are withdrawn each day in the nation by humans. Irrigation withdrawals accounted for 37% of all freshwater withdrawals and 62% of all freshwater withdrawals excluding withdrawals used for thermoelectric power production (Kenny et al. 2009).

In 2005 — the latest data available from the U.S. Geological Survey — residential water use totaled 29.4 billion gallons per day (Kenny et al. 2009). In 1999, mean residential outdoor water use accounted for 31.4% of total use in single-family homes (DOE 2011). Some estimates of outdoor water use are nearly 50% to 80% of the total residential use (Kjelgren 2000; Vickers 2001). The U.S. Environmental Protection Agency (2009) estimates that over half of this water is used for irrigating plants, including lawns.

To remain healthy and aesthetically pleasing, most plants in the home landscape typically have to be irrigated periodically to supplement insufficient rainfall. An irrigated landscape has a variety of benefits (Frank 2003). Landscape plants increase property value, benefit individuals psychologically, and reduce noise and pollution.

Water conservation methods, tools, and practices include: improved irrigation efficiency, time-of-day watering, odd-even address watering days, rain-off sensors on automatic systems, increased water rates, drought-tolerant plants, and irrigation based on soil moisture or climatological conditions. Many water purveyors and municipalities provide recommendations for conserving water in the landscape (e.g., City of Houston 2014; City of Lubbock 2014; Dallas Water Utilities 2014b; LCRA 2014; SAWS 2014). One effective method is to adjust landscape irrigation based on climatological conditions. This technique most often uses rainfall information to cancel watering whenever significant rainfall is detected. Including reference evapotranspiration from local weather station data can substantially increase the efficiency of irrigation measures (McCready et al. 2009). Reference evapotranspiration is calculated from local daily temperature, humidity, wind speed, and radiant energy (Allen et al. 1998). The reference evapotranspiration calculation can be used over multi-day periods to determine how much irrigation water to apply to a crop or a landscape (Pannkuk et al. 2010). Landscape irrigation based on the principles of reference evapotranspiration is an emerging area of water conservation.

Outdoor water use for irrigation varies geographically and seasonally (Kjelgren et al. 2000; Pannkuk et al. 2010; Cabrera et al. 2013). A recent study analyzed water consumption patterns in standard new homes and in high-efficiency new homes built after 2001 (DeOreo et al. 2011). In that study, only new standard homes had outdoor water use measured, and annual outdoor water use averaged 84,000 gallons. In another recent study, Hermitte and Mace (2012) analyzed metered water-use data from single-family residential connections from 2004 through 2011 from 259 municipalities across

Texas. In that study, outdoor water as a percentage of total water use varied from a low of 13% in Galena Park to a high of 64% in Gail. The weighted average across the entire state was 31% of the total water use. Average outdoor water usage in gallons was also calculated per household for urban areas. Houston had the low at 37 gallons per household per day, and the high was Tyler at 195 gallons per household per day. The Hermitte and Mace (2012) study concludes by recommending that a multi-year study of geographically diverse Texas cities involving individual surveys, billing data, and climatic data be conducted. This type of household-level exploration of single-family residential water consumption would provide more conclusive evidence of how we use our water.

The purpose of this study is to examine residential outdoor water use in one neighborhood in Huntsville, Texas. To accomplish this goal, we used the following: monthly residential water use by household for 3 years, the measured area receiving irrigation for each residential user, monthly local rainfall, and reference evapotranspiration data. These tools provided us with the ability to accurately measure landscape water use each month as well as calculate potential over-irrigation based on actual landscape water needs.

MATERIALS AND METHODS

The city of Huntsville, Texas provided monthly billed water usage data for 2009, 2010, and 2011. The data comprised 1,229 residential units (substantially all) in one neighborhood of the city. Before we received the data, the names and addresses were removed, and a unique identifier was applied to each residence. The city of Huntsville also allowed the researchers to use their ArcGIS© mapping platform and GIS data to measure the lot size, built area, and the irrigated area within each homeowner's lot.

To determine outdoor water usage, researchers measure or estimate indoor usage, and subtract that from total billed water usage. Thus, an accurate measure of indoor usage is critical to proper analysis. Romero and Dukes (2011) identified several methods that could be used to make the estimate. The most common method in the literature is to assume that winter usage includes a negligible amount of landscape watering, therefore the average monthly usage during the winter months must be subtracted from each month's metered consumption. While not exact, this method allows for reasonable estimates without requiring individual homes to be metered separately at each outdoor hose bib and is considered to be adequate for areas where a defined winter season exists.

Another method used in the literature involves estimating per capita consumption patterns and applying the rate to each household (DeOreo et al. 2011). Various rates have been proffered, including 0.57 cubic meters per person per day (Hanemann 1997) and 0.38 cubic meters, from the U.S. Environmental Protection Agency (2009). These 2 figures include both indoor and outdoor usage, and the U.S. Environmental Protection Agency estimates that approximately 30% of the total would be dedicated to outdoor use, while Haley et al. (2007) found in their study that 36% of the total water consumption was outdoors.

For this study, the indoor water usage was calculated for each residence from an average usage from November through February (Romero and Dukes 2011), a time when residents do not normally use outdoor irrigation. During this period, the city measures water usage to calculate sewer rates, so residents are encouraged through bill notices and advertising to limit outdoor water usage to minimize their sewer bill for the upcoming year. This average indoor usage for each residence was subtracted from the remaining months to estimate outdoor water usage. The outdoor water usage, in gallons, was converted to a depth of water, in inches, using the irrigated area information.

Local monthly reference evapotranspiration and monthly rainfall data were then used to determine net water loss in the landscape, which must be replaced using lawn irrigation to maintain a healthy landscape (Figure 1). The depth of monthly outdoor water usage was compared to that month's reference evapotranspiration minus rainfall depth. This calculation created an overwatering/underwatering figure. An example is presented in Table 1 for 1 customer over a 12-month period during 2009. For the customer in this example, overwatering in 2009 was by 12.56 inches, or 8,488 gallons of water. Underwatering figures were converted to zeros. Overwatering figures were calculated monthly and then compiled for each year by residence.

RESULTS

For the neighborhood under study, the 1,229 households had an average irrigation area of 9,300 square feet. Not every property had the full 3 years of monthly data available, and the average number of months of data were 34.5 of the 36 possible months. Eight of the lots (0.7%) had less than 1 year of data available, but we did not choose to discard these data although they could slightly affect the results. The majority of the properties (885, 72.0%) had 36 months of data.

Average monthly total water usage for all the properties was 11,878 gallons per month. Of this total, an average of 4,302 gallons (36.2%) was used indoors per household per month. For calculating the outdoor need, we used 100% replacement of monthly reference evapotranspiration values, minus rainfall, as the base amount of irrigation water that should be applied each month to the landscape. Based on this calculation, 277 residences (22.5%) overwatered by at least 50,000 gallons in

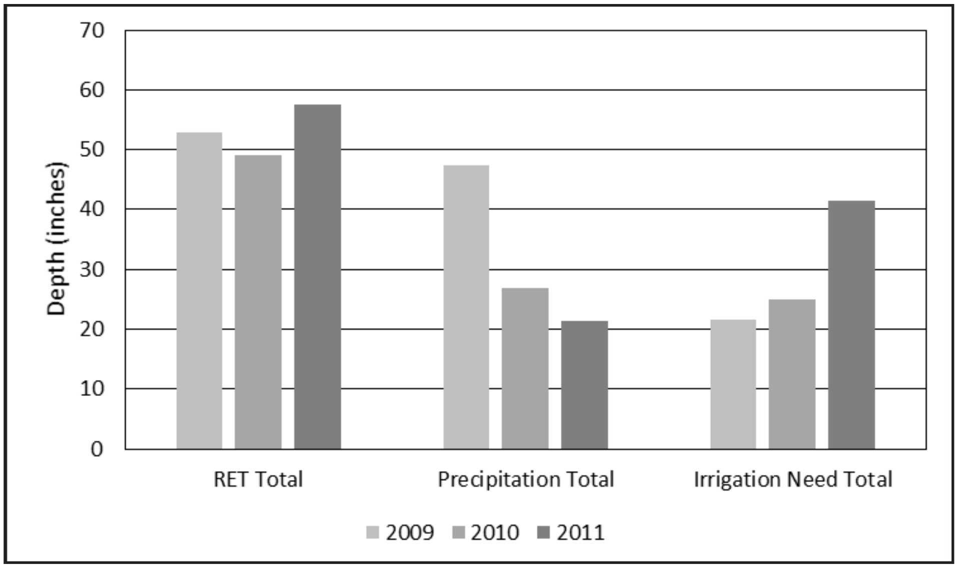


Figure 1. Total reference evapotranspiration (RET), precipitation, and irrigation depth need by year.

at least 1 of the years under study, and 148 residences (12%) overwatered by at least 100,000 gallons in at least 1 of those years (Figure 2).

The entire neighborhood overwatered by about 28.9 million gallons in both 2009 and 2010. In 2011, during a severe drought, the total amount of overwatering was 21.2 million gallons. Note that this is not the amount of water needed for irrigation each year but rather an extra amount of water that is above the rainfall plus reference evapotranspiration requirement. It could be considered "wasted water." Over the 3-year period of study, only 6 of 1,229 households (0.49%) did not have a net level of overwatering.

A common method in the industry for considering landscape watering relates to inches of irrigation, which is comparable from one site to another, irrespective of the actual square footage of each site. For the properties under study, the average overwatering per month was 0.62 inches, with a maximum of 33.55 inches (Figure 2). Of the studied households, 173 (14.1%) had a monthly average overwatering of at least 1 inch for all the months recorded for that property.

Table 1. Example of data organization and calculation from one household in 2009 with a Lot Area, Building Area, Pavement Area, and Irrigation Area of 12200, 3237, 633, and 8329 square feet, respectively.

Billing date	Total consumption (gallons)	Outdoor usage (gallons)	Depth of irrigation (inches)	Reference Evapotranspiration (inches)	Rainfall (inches)	Reference Evapotranspiration - Rainfall (inches)	Excess monthly water (inches)
20090210	12100	5660	1.10	2.66	1.06	1.6	0.00
20090310	11900	5460	1.06	3.50	1.9	1.6	0.00
20090408	21800	15360	2.97	3.97	4.85	0	2.97
20090511	9600	3160	0.61	4.87	7.84	0	0.61
20090611	31000	24560	4.76	5.66	2.68	2.98	1.78
20090714	45200	38760	7.51	7.36	0.25	7.11	0.40
20090811	41000	34560	6.69	7.47	3.51	3.96	2.73
20090914	30000	23560	4.56	6.71	2.70	4.01	0.55
20091013	13200	6760	1.31	3.86	5.56	0	1.31
20091112	5100	0	0.00	3.18	9.68	0	0.00
20091211	7400	960	0.19	2.17	1.87	0.3	0.00
20100112	5400	0	0.00	1.54	5.48	0	0.00

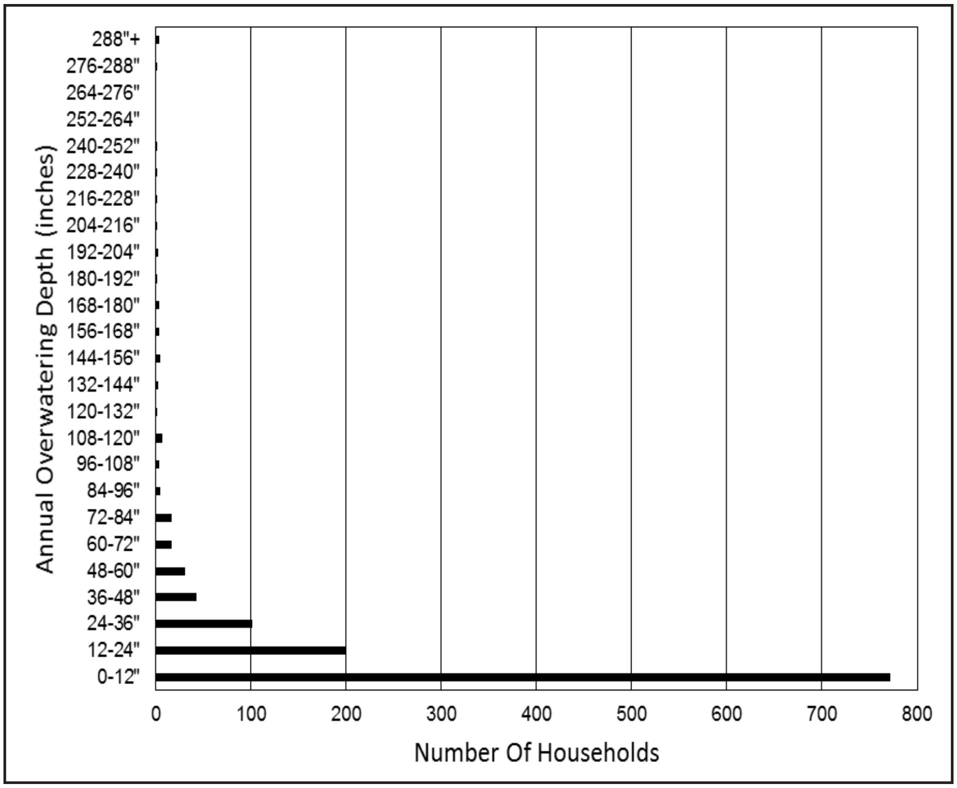


Figure 2. Number of households classified by total depth of overwatering, in inches.

We also performed correlation analysis on the variables being examined to further understand any trends in landscape water use. For this analysis, the PROC CORR procedure of SAS v9 was utilized (SAS 2002). There was no correlation between the size of the irrigated area and the amount of overwatering. This suggests that overwatering is occurring in all sizes of landscapes. There was also a lack of correlation between monthly indoor usage and the amount of overwatering. This is in contrast somewhat to a finding by Tinker and Woods (2000) that found a positive correlation between indoor water usage and outdoor water usage.

CONCLUSIONS AND IMPLICATIONS

This study took a systematic approach in measuring indoor and outdoor residential water usage in one community in Southeast Texas. Monthly water bills and irrigated area of each landscape were used in the calculations. Data provide conclusive evidence of how water was used over a 3-year period. Potential shortcomings of the study include the lack of analysis of water cost and the subsequent effects on water usage and the lack of inclusion of income data per household.

Water is being wasted in Texas residential landscapes during periods of both drought and plentiful rainfall. This wasted water increases demand for pumping, purchase, piping, and treatment of water by the water purveyor. If all the residents of this 1 neighborhood had watered based on reference evapotranspiration, then the yearly demand for the entire city of Huntsville, Texas would have decreased to the point whereby a new water well would not have been needed in 2012 (Reed 2011). The new well cost the city of Huntsville between $1.2 and $1.5 million (Brock 2011). This cost should be a powerful economic motive. In the long run, water users will not pay as much for their overall water bill if expensive water supply projects are delayed by 20 or more years due to conservation efforts.

If Texas is to meet its future water needs, then effective water conservation must be an integral input. Increased education and awareness of reference evapotranspiration principles for landscape watering as well as water purveyors focusing additional conservation information on individual homeowners who waste water, are proving to be viable solutions. One possibility for additional conservation information is providing homeowners a monthly “water budget” based on the size of their landscape. As the scarcity of water increases, evidence indicates that water costs will also rise (White 2012), and this too will further induce conservation.

REFERENCES

Allen RG, Pereira LS, Raes D, Smith M. 1998. Crop evapotranspiration – Guidelines for computing crop water requirements [Internet]. Rome (Italy): Food and Agriculture Organization of the United Nations; [cited 2014 January 10]. Chapter 2, FAO Penman-Monteith equation. Available from: http://www.fao.org/docrep/X0490E/x0490e06.htm

Austin Water Utilities. 2014. Watering your lawn [Internet]. Austin (Texas): City of Austin; [cited 2014 January 8]. Available from: http://www.austintexas.gov/department/watering-your-lawn

Brock T. 2011 July 23. City to drill first well since 1970. The Huntsville Item [Internet]. [cited 2014 July 22]. Available from: http://www.itemonline.com/news/local_news/article_7d47c59e-4c8d-5e8e-a91e-4819c2fccdfe.html

Cabrera RI, Wagner KL, Wherley B. 2013. An evaluation of urban landscape water use in Texas [Internet]. Texas Water Journal 4(2): 14-27. Available from: https://journals.tdl.org/twj/index.php/twj/article/view/6992

City of Houston. 2014. Understand your water use [Internet]. Houston (Texas): City of Houston; [cited 2014 January 9]. Available from: http://help.houstonwater.org/understand-high-water-use

City of Lubbock. 2014. Conservation tips [Internet]. Lubbock (Texas): City of Lubbock; [cited 2014 January 9]. Available from: http://www.ci.lubbock.tx.us/departmental-websites/departments/water-department/top-navigation-menu-items/conservation/tips

Dallas Water Utilities. 2014a. Saving water outdoors [Internet]. Dallas (Texas): Dallas Water Utilities; [cited 2014 January 8]. Available from: http://savedallaswater.com/how-to-save-water/saving-water-outdoors/

Dallas Water Utilities. 2014b. Seasonal watering [Internet]. Dallas (Texas): Dallas Water Utilities; [cited 2014 January 9]. Available from: http://savedallaswater.com/seasonal-watering/

DeOreo WB, Mayer PW, Martien L, Hayden M, Funk A, Kramer-Duffield M, Davis R, Henderson J, Raucher B, Gleick P, Heberger M. 2011. California single family water use efficiency study. Boulder (Colorado): Aquacraft Water Engineering and Management. 387 p. Prepared for the California Department of Water Resources.

[EPA] Environmental Protection Agency. 2009. WaterSense [Internet]. Washington (District of Columbia): U.S. Environmental Protection Agency; [cited 2014 January 8]. Available from: http://www.epa.gov/watersense/outdoor/index.html

Frank MS. 2003. The benefits of plants and landscaping [Internet]. Ukiah (California): Green Plants for Green Buildings; [cited 2014 January 9]. 7 p. Available from: http://greenplantsforgreenbuildings.org/wp-content/uploads/2014/01/BenefitofPlants.pdf

Haley MB, Dukes MD, Miller GL. 2007. Residential irrigation water use in Central Florida. Journal of Irrigation and Drainage Engineering 133(5):427–434. doi: 10.1061/(ASCE)0733-9437(2007)133:5(427)

Hanemann WM. 1997. Price rate and structures. In: Baumann DD, Boland JJ, Hanemann WM, editors. Urban water demand management and planning. New York: McGraw-Hill. p. 137-179.

Hermitte SM, Mace RE. 2012. The grass is always greener… Outdoor residential water use in Texas. Austin (Texas): Texas Water Development Board. 43 p. Technical Note 12-01.

Kenny JF, Barber NL, Hutson SS, Linsey KS, Lovelace JK, Maupin MA. 2009. Estimated use of water in the United States in 2005. Reston (Virginia): U.S. Geological Survey. 52 p. Circular 1344.

Kjelgren R, Rupp L, Kilgren D. 2000. Water conservation in urban landscapes. HortScience 35:1037-1040.

[LCRA] Lower Colorado River Authority. 2014. Save water [Internet]. Austin (Texas): Lower Colorado River Authority; [cited 2014 January 10]. Available from: http://www.lcra.org/water/save-water/watersmart/Pages/default.aspx/

McCready MS, Dukes MD, Miller GL. 2009. Water conservation potential of smart irrigation controllers on St. Augustine grass. Agricultural Water Management. 96(11):1623-1632.

Pannkuk TR, White RH, Steinke K, Aitkenhead-Peterson JA, Chalmers DR, Thomas JC. 2010. Landscape coefficients for single- and mixed-species landscapes. HortScience. 45(10):1529-1533.

Reed C. 2011. Personal interview. City of Huntsville Water Public Utilities Director.

Romero CC, Dukes MD. 2011. Are landscapes over-irrigated in southwest Florida? A spatial-temporal analysis of observed data. Irrigation Science. 29:391-401.

Runfola DM, Polshy C, Nicolson C, Giner NM, Pontius RG Jr, Krahe J, Decatur A. 2013. A growing concern? Examining the influence of lawn size on residential water use in suburban Boston, MA, USA. Landscape and Urban Planning 119:113-123.

[SAWS] San Antonio Water System. 2014. Watering efficiently [Internet]. San Antonio (Texas): San Antonio Water System; [cited 2014 January 8]. Available from: http://www.saws.org/conservation/outdoor/watering.cfm

SAS Institute Inc. 2002. The SAS system for Windows. Release 9.3. Cary (North Carolina): SAS Institute.

[TWDB] Texas Water Development Board. 2012. Water for Texas 2012 state water plan [Internet]. Austin (Texas):

Texas Water Development Board; [cited 2014 January 8]. Available from: http://www.twdb.texas.gov/waterplanning/swp/2012/

[TWDB] Texas Water Development Board. 2013. SWIFT fund [Internet]. Austin (Texas): Texas Water Development Board; [cited 2014 May 16]. Available from: http://www.twdb.texas.gov/financial/programs/SWIFT/index.asp

Tinker A, Woods, P. 2000. Development of a formula to determine outdoor residential water consumption in College Station, Texas. In: Associated Schools of Construction, Proceedings of the 36th Annual Conference. Purdue University, West Lafayette, Indiana. Windsor (Colorado): The Associated Schools of Construction. p. 147-154.

[DOE] U.S. Department of Energy. 2011. 2010 Buildings energy data book [Internet]. Washington (District of Columbia): U.S. Department of Energy; [cited 2015 March 16]. Available from: http://buildingsdatabook.eren.doe.gov/docs/DataBooks/2010_BEDB.pdf

Vickers A. 2001. Handbook of water use and conservation. Amherst (Massachusetts): WaterPlow Press. 464 p.

White C. 2012. Water scarcity pricing in urban centres. Global Water Forum [Internet]. [cited 2014 July 22]. Available from: http://www.globalwaterforum.org/2012/02/06/water-scarcity-pricing-in-urban-centres/

Texas Water Resources Institute
Texas Water Journal
Volume 6, Number 1, Pages 86–102

Implications of 3 alternative management policies on groundwater levels in the Texas High Plains

Jairo E. Hernández[1], Prasanna H. Gowda[2], Thomas H. Marek[3], Terry A. Howell[4], Wonsook Ha[5]

Abstract: Groundwater supply in the Ogallala Aquifer is diminishing at an unsustainable rate, which is affecting the crop and animal production in the region. The desired future condition adopted by the North Plains Groundwater Conservation District states that at least 40% of the volume of groundwater should remain in the Ogallala Aquifer after 50 years in Dallam, Sherman, Hartley, and Moore counties. The main objective of this study is to evaluate the effects of 3 proposed groundwater management policies on future groundwater levels using a calibrated MODFLOW model. The 3 groundwater management policies considered are permanent conversion of 10% of the total irrigated area to dryland production, temporary conversion of 10% of the total irrigated area to dryland production for the first 15 years, and adoption of advances in biotechnology that allow groundwater use reductions at a rate of 1% per year during the next 50 years. Results indicated that if future average groundwater pumping rates are kept at 2010 withdrawal rates, then 50% of groundwater in the Ogallala Aquifer would remain in 50 years, thus meeting the groundwater district's desired future condition in Dallam, Sherman, Hartley and Moore counties. The most favorable impact on diminishing depletion was obtained with the adoption of advances in biotechnology, which would leave 60% of groundwater remaining in 50 years in the study area. Similar results can be obtained if 1% of irrigated cropland is retired per year.

Keywords: groundwater modeling; irrigation; MODFLOW; Ogallala Aquifer; water management.

[1] Assistant Professor, Boise State University, Department of Civil Engineering, Boise, Idaho 83725-2060

[2] Research Agricultural Engineer, U.S. Department of Agriculture-Agricultural Research Service Conservation and Production Research Laboratory, Bushland, Texas, 79012-0010

[3] Senior Agricultural Engineer, Texas A&M AgriLife Research and Extension Center, Amarillo, Texas, 79106

[4] Retired (former Laboratory Director , U.S. Department of Agriculture-Agricultural Research Service, Conservation and Production Research Laboratory, Bushland, Texas) Lago Vista, Texas 78645

[5] Postdoctoral Scholar, School of Earth Sciences and Environmental Sustainability, Northern Arizona University, P.O. Box 4099, Flagstaff, Arizona 86011-4099

* Corresponding author: jairohernandez@boisestate.edu

Citation: Hernández JE, Gowda PH, Marek TH, Howell TA, Ha W. 2015. Implications of 3 alternative management policies on groundwater levels in the Texas High Plains. Texas Water Journal. 6(1):86-102. Available from: https://doi.org/10.21423/twj.v6i1.7005.

Terms used in paper

Short name of acronym	Descriptive name
LEPA	low energy precision application
GAMS	General Algebraic Modeling Systems

INTRODUCTION

In the Texas High Plains, groundwater from the Ogallala Aquifer is the main source of agricultural and public water supplies. The aquifer has sustained the economic development in the region for more than a century (Musick et al. 1990). Irrigated crop production consumes a majority of groundwater withdrawals from the Ogallala Aquifer (Marek et al. 2004 and 2009; Maupin and Barber 2005). Diminishing groundwater supplies in the Ogallala Aquifer would severely reduce agricultural production, particularly crop productivity, which, in turn, would negatively affect the regional economy (Marek et al. 2006). The North Plains Groundwater Conservation District is facing critical decisions regarding potential water conservation policies (NPGCD 2014) and is considering alternative strategies for extending the life of the aquifer within the area of its jurisdiction (Figure 1). The district is seeking to mitigate impacts on the regional economy due to the extensive future withdrawals of the limited groundwater resource through the application of potential strategies such as those described here.

The 3 water conservation policies selected for this evaluation study were identified from a survey performed by the Economics Group of the Ogallala Aquifer Program (Amosson et al. 2010). The survey's main purpose was to determine alternative water conservation policies for evaluating potential impacts on water savings, implementation costs, producer income, and regional economy of the Southern Ogallala. The survey did not consider policy feasibility in that assessment, but stakeholders explored potential alternatives to extend aquifer life.

The Ogallala Aquifer is one of the largest and most productive groundwater resources in the world and underlies an area of about 45 million hectares (111 million acres) in the central United States, covering parts of Texas, New Mexico, Oklahoma, Kansas, Colorado, Wyoming, Nebraska, and South Dakota. About 106,000 million cubic meter (86 million acre-feet) of groundwater is withdrawn per year from this aquifer to meet

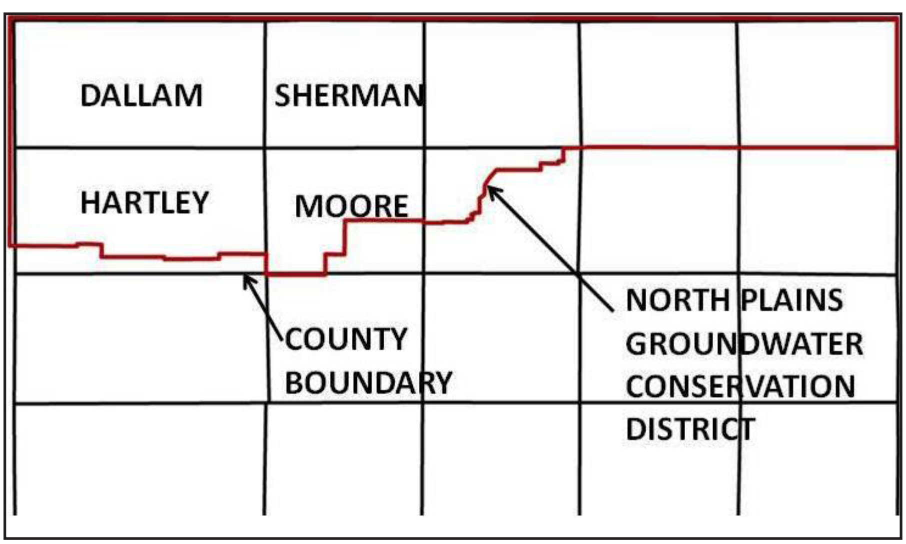


Figure 1. The Texas 4-county area of the Ogallala Aquifer region and the North Plains Groundwater Conservation District.

agricultural and urban water use demands (Maupin and Barber 2005). The Ogallala Aquifer sustains more than one quarter of the agricultural production in United States (Gurdak et al. 2009). The magnitude of agricultural water need makes water -use assessment critical in future planning efforts (Marek et al. 2009). The aquifer supports an approximately $20 billion dollar agricultural industry annually in the United States that includes 19% of the nation's wheat and cotton and 15% of the nation's corn (Qi and Scott 2010). The dominant land uses are rangeland (56%, includes grasslands and shrub lands) and agriculture (38%, includes cultivated crops, small grains, fallow, and pasture/hay) (McMahon et al. 2007). In 2005, approximately 6.3 million hectares (15.6 million acres), or about 14% of the Ogallala Aquifer region, was under irrigation (McGuire 2011).

The Ogallala Aquifer is a remnant of a vast plain formed by sediments deposited by streams flowing eastward from the ancestral Rocky Mountains (Reilly et al. 2008). The aquifer consists mainly of hydraulically connected geologic units of late Tertiary and Quaternary age deposits from a heterogeneous sequence of clays, silts, sands, and gravels (Gutentag et al. 1984). The depositional setting of the Ogallala Formation in Texas was described by Seni (1980) as a series of coalescing, humid-type alluvial fans. It is now known that the Ogallala Aquifer is an exhaustible and finite water resource (Osborn 1973; Wheeler et al. 2006).

Few regional aquifers have been studied as extensively as the Ogallala Aquifer has, and multiple computer models have been developed for water resource assessment. A comprehensive list can be found in Hernandez et al. (2013) and Dutton et al. (2001). The most recent modeling efforts for the Ogallala Aquifer in Texas have concentrated on assessing groundwater availability for the 50-year planning period, mostly conducted by the Texas Water Development Board (TWDB 2007). The main purpose of these planning studies is to ensure adequate groundwater management against user needs and to evaluate potential water management strategies. The Texas Water Development Board is currently funding a comprehensive overhaul of the existing regional groundwater availability model for the Ogallala Aquifer and underlying hydraulically connected formations, such as the Rita Blanca and Dockum aquifers. Recently, a groundwater model was developed for the 4-county area (Dallam, Sherman, Hartley, and Moore counties) in the Texas High Plains. The groundwater model is a MODFLOW model that was calibrated and validated for historically measured groundwater levels (Hernandez et al. 2013). Results from this study indicated that 2 zones in the eastern and northwest portions of Hartley County would become depleted in the future if current use continues at the current rate over the next 50 years.

The main data sources for this modeling effort were the United States Geological Survey (Harbaugh et al. 2000; Maupin and Barber 2005; McGuire 2007; McMahon et al. 2007; Reilly et al. 2008; USGS 2008; Gurdak et al. 2009; Qi and Scott 2010), the United States Department of Agriculture (Musick et al. 1990; National Agricultural Statistics Service 2008; Hernandez et al. 2013), the Texas Water Development Board (Christian 1989; Dutton et al. 2001; TWDB 2007 and 2014; George et al. 2011), and the North Plains Groundwater Conservation District (NPGCD 2008a; 2008b; 2013; Hallmark 2008 and 2013).

Water management policy has been proposed for slowing the rate of groundwater pumping for more than 25 years and for facilitating orderly community adjustment (Supalla et al. 1986). An economic implication study (Wheeler et al. 2006) suggested that there is a high cost to conserving groundwater in low water use counties and that efficient conservation policies should focus on heavily irrigated counties to optimize benefits. This study included a 5-year average of planted acreage of cotton, corn, grain sorghum, wheat and peanuts under conventional furrow, low energy precision application (LEPA), and dryland on the Southern sub-region of the Great Plains. Tewari and others (2014) performed an economic analysis for future planning and management of groundwater resources for the same counties of this study using General Algebraic Modeling Systems (GAMS). They found that there was a greater reduction in net present value per acre with increasing rates of restrictive scenarios when compared to the baseline in all 4 counties. Numerous alternative water management policies are currently being studied and debated by researchers and groundwater conservation district personnel in the Central and Southern High Plains of the Ogallala Aquifer region.

The desired future condition adopted by the North Plains Groundwater Conservation District in 2009 (NPGCD 2008a) stated that at least 40% of the volume of the Ogallala Aquifer (and the underlying Rita Blanca Aquifer) should be remaining in 50 years (year 2058) for the area of Dallam, Sherman, Hartley and Moore counties. Recently, the North Plains Groundwater Conservation District adopted a management plan (NPGCD 2013) for the period of 2013–2023. The plan addresses several management goals, which updated the desired future condition values among others. A major desired future condition update corresponded to combining the Rita Blanca Aquifer (Figure 2) with the Ogallala Aquifer to retain 40% of the remaining volume for 50 years (year 2060) in both aquifer storage areas. Before implementing any new policy or modifying current policies, it is recommended to evaluate the policies for their impact on groundwater levels and related regional economics.

The objective of this study is to develop a methodology for simulating groundwater pumping rates with different ground-

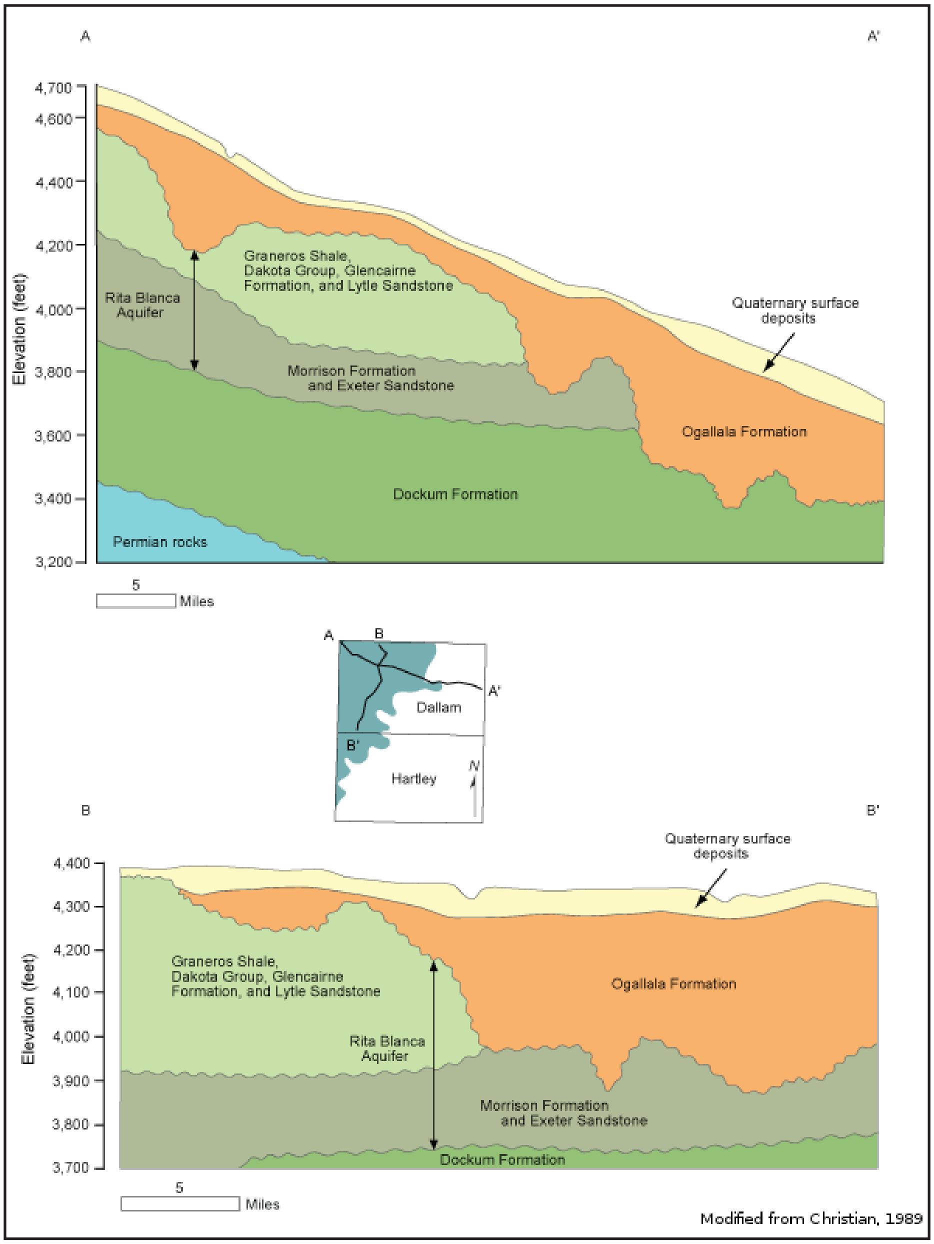


Figure 2. Geologic cross sections across the Rita Blanca Aquifer in the 4-country area (modified from Christian 1989; George et al. 2011).

water management policies and to evaluate policy implications on future groundwater levels. It is expected that this methodology can be applied to identify and clarify constraints for policy-makers. It is also expected that model results can be used for projecting financial impact in the study area to facilitate decision-making processes. The methodology was applied to 3 different water conservation policies to evaluate their impacts on groundwater levels in the Ogallala Aquifer in the study area. The general rationale of the groundwater study was to develop advanced tools to evaluate aquifer level impacts on groundwater policies. This study is part of a comprehensive regional analysis of the Ogallala Aquifer depletion study with the purpose of understanding short- and long-term effects of existing and alternative land-use scenarios on groundwater levels. It is important to note that the model does not include current and future land-use change assessment nor an economic assessment of implications.

STUDY AREA

The study area consists of the intensively irrigated area in the Texas High Plains that includes Dallam, Sherman, Hartley, and Moore counties (Figure 1). The study area shares state borderlines with the Oklahoma Panhandle to the north and

New Mexico to the west, and it occupies an area of 12,158 square kilometers (1.2 million hectares or 3 million acres). There are no major reservoirs in the study area, and all waterways are non-perennial streams. Consequently, the vast majority of the area's water supply is extracted primarily from the Ogallala Aquifer.

Climate

The study area has an arid to semi-arid climate. Surface water availability is limited to the late summer season. Average annual precipitation increases from 381 millimeters per year (15 inches per year) in the northwest to 483 millimeters per year (19 inches per year) in the southeast end of the study area. Potential evaporation rates from free water surface ranges from 2,200 to 2,400 millimeters per year (87 to 94 inches per year), which significantly exceeds the amount of precipitation and leaves little amount of water to recharge to the groundwater system. Average temperature ranges from 4 °C (39 °F) in January to 27 °C (81 °F) in July (NOAA 2009).

Geology

The Ogallala Aquifer is an unconfined aquifer (Gutentag et al. 1984). The Ogallala formation overlies Permian, Triassic, and Cretaceous strata and consists primarily of heterogeneous sequences of coarse-grained sand and gravel in the lower part of the formation, grading upward into fine clay, silt, and sand. The sands are generally tan, yellow, or reddish brown, medium- to coarse-grained, moderate to well sorted, and poorly consolidated to unconsolidated, although local cementation exists by calcium carbonate and silica (NPGCD 2008b). The gravel is usually associated with sand and silt. Clay is present and occasionally cemented. No fractured rock zones and faults were identified within the study area, and some hydraulic continuity occurs between the Ogallala formation and the 2 underlying local aquifers, Rita Blanca and Dockum aquifers (NPGCD 2008b).

The Rita Blanca Aquifer (Figure 2) is a minor aquifer that underlies the Ogallala Aquifer in Dallam and Hartley counties over an area of 2,400 square kilometers (593,000 acres) (TWDB 2007) in the north-west vicinity of these counties. In some places, the Rita Blanca is also hydraulically connected to the underlying Dockum Aquifer. The Dockum Aquifer extends to 46 counties in Texas (TWDB 2007) with a subsurface area of 57,000 square kilometers (14 million acres). The water quality does not meet drinking water standards in some locations because of salinity, hardness, and radioactivity, but it is potentially useful for irrigation, oil field operation, and municipal water supplies in some locations (TWDB 2007). However, there were no water quality data available to extend this assessment to the study area. The Ogallala Aquifer underlies Dallam and Hartley counties, about 25% of Moore County, and about 10% of Sherman County (Figures 1 and 2). Cross-formational flow between these local aquifers was not accounted for in the model. A previous study (Hernandez et al. 2013) indicated that flows between Rita Blanca, Dockum, and Ogallala aquifers have not been quantified, and no studies were found for defining this cross-formational flow in the study area. There is consensus in the region that multiple wells might be screened in more than one aquifer (Hernandez et al. 2013). Hence, the Ogallala Aquifer, as referred to in this paper, should be interpreted as the Ogallala Aquifer, including unknown interaction with Rita Blanca and Dockum aquifers, due to a lack of information that could prove that data used in this study is exclusively of the Ogallala Aquifer.

Hydraulic conductivity and specific yield are highly variable within the study area, and they do not follow any particular spatial tendency due to the dependency on sediment type, which widely varies horizontally and vertically (Gutentag et al. 1984). Estimated hydraulic conductivity values are between 8 and 120 meters per day (26 and 394 feet per day) and specific yield ranges from 2.5 to 27.5% (USGS 2008). The Ogallala Aquifer in the study area (Hallmark 2013) has an estimated saturated thickness that ranges from 3 to 140 meters (9.8 to 460 feet), with an average of 44 meters (144 feet). Depth to groundwater ranges from the land surface to in excess of 152 meters (500 feet). Aquifer base varies in elevation from approximately 900 meters (2,953 feet) above mean sea level on the eastern edge of the study area in Sherman and Moore counties, to approximately 1,400 meters (4,593 feet) above mean sea level in the north-west corner of Dallam County.

Agriculture

Grain, fiber, forage, and silage production in the study area demands 89% of groundwater withdrawals for irrigation (Marek et al. 2004), and the regional economy is heavily dependent on the use of water from the Ogallala Aquifer. Major crops are corn, cotton, hay, sorghum, potatoes, and wheat. Minor crops are peanuts, sunflower, and soybeans. According to a 2012 survey for the 4-county area, it was estimated that 5.4 million cubic meters (or 5.4 gigaliters or 4,400 acre-feet) of groundwater was withdrawn per day and from that 5.2 million cubic meters (or 5.2 gigaliters or 4,200 acre-feet) corresponded to irrigation uses, increasing irrigation needs from 89% in 2004 to 97% in 2012 (TWDB 2014). The remaining portions of groundwater withdrawals (3%) are used for livestock, municipal uses, manufacturing, mining, and power generation.

Even though the total number of farms that reported harvesting crops has decreased between 1987 and 2007 by 26%, according to agricultural censuses (National Agricultural Statistics Service 2008), harvested cropland area has increased appreciably (64%) during the same period. Total cropland area was estimated at 635,310 hectares (1.6 million acres) in 2007 in the 4-county area. Approximately 42% of total cropland (269,240 hectares or 665,000 acres) in the study area was under irrigation and about 80% of that was for irrigated corn production. The 4-county area produced approximately 30% of the total corn production (2073 gigagrams or 82 million bushels) in Texas (National Agricultural Statistics Service 2008), and this region has one of the greatest measured mean countywide yields (13.2 megagram per hectare or 210 bushel per acre), due primarily to the corn being irrigated with practically no dryland corn production.

METHODOLOGY

Management policy includes crop selection, amount of irrigation water, and location and timing of pumping. This model represents management policy on the amount of irrigation water and location and timing of pumping. This model does not represent crop selection explicitly, but the effect on the amount of water that is required by crops. Therefore, amount of water and location and timing of pumping were parameters selected for translating management policy into input to the groundwater model. This model does not represent the change in crop location, either. This method was selected because land area and crop selection would generate additional uncertainty due to multiplicity of choices on selecting geographical distribution of land and crops. The pumping schedule was changed through time for the whole area of study as a mechanism to generalize effects of management policy. Each selected management policy was translated into input to the groundwater model as explained below.

The hydrologic simulations for this study were done using MODFLOW-2000 (Harbaugh et al. 2000), a computer program that solves the 3-dimensional groundwater flow equation through porous media using a finite-difference method. A Visual MODFLOW Pro 4.3[1] (Schlumberger Water Services 2008) interface was used to facilitate data input and results analysis for this study. This simulation was performed using the calibrated MODFLOW model for the study area (Hernandez et al. 2013) for the period of 2010–2060. The aquifer model was calibrated and validated for a steady-state condition to represent a pre-development period (before 1950) and as a transient model for the period 1950–2007. It uses a grid of 800 meter x 800 meter (0.5 mile x 0.5 mile) size and is divided into 5 layers. The model boundaries were defined to maximize the length of natural boundaries to represent the model more realistically, in spite of increasing computing time.

Alternative management policies

The 3 management policies desirable to implement correspond to several that were proposed by stakeholders, which include water districts, senators and representatives, commodity organizations, water planning groups and agencies, state authorities and the Ogallala Aquifer Program leadership team. The 3 management policies are: (1) permanent conversion of 10% of the total irrigated area to dryland production, (2) temporary conversion of 10% of the total irrigated area to dryland production for the first 15 years, and (3) adoption of advances in biotechnology that allow groundwater use reductions at a rate of 1% per year during the next 50 years, assuming that advances in biotechnology are realized and adopted by users.

Evaluated policies were contrasted with a baseline, which represents the current groundwater pumping rates and maintains the status quo for simulating future aquifer development. The baseline assumed that no changes to additional water policy would be implemented for the 4-county area during the projection period, and consequently, current groundwater withdrawal rates would remain constant during the projection period. Year 2010 was chosen as a nominal reference year for implementing alternative policies, and year 2060 was chosen as the target year. A statistical analysis was performed to quantify differences among the studied policies. Future groundwater withdrawals were scheduled (Figure 3) to be applied during the period 2010–2060 using the 2008 average groundwater withdrawals for irrigation for each county in the study area (Dutton et al. 2001). Groundwater extraction was spatially distributed using the location of registered wells in 2008. Model dry-wetting condition was set to keep a minimum saturated thickness of 5 meters for the aquifer's bottom layer for areas in Union County (New Mexico), due to computation instability, thus reducing local pumping when cells run dry (Hernandez et al. 2013). The model did not consider specific spatial distribution for converting 10% of irrigated areas to dryland production. A 10% reduction of pumping rate at pumping cells was taken as subrogate to represent the location of land conversion instead. This is equivalent to retiring 10% of the area of each irrigated land to dryland production instead of retiring complete farms to dryland up to 10% of the study area. It was also assumed that the number of wells for establishing the baseline would remain constant. No other modification was applied to the model. Each policy was transformed into future groundwater pumping schedules based on the corresponding reduction of the baseline withdrawal rate.

To perform the aforementioned statistical analysis, groundwater levels for every cell in the MODFLOW modeling grid

[1]The use of trade, firm, or corporation names in this article is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the United States Department of Agriculture or the Agricultural Research Service of any product or service to the exclusion of others that may be suitable.

Figure 3. Future groundwater withdrawal for the baseline and proposed policies.

were exported to a text file to perform cell-to-cell computations. The groundwater depletion was computed based on the groundwater level for the reference year of 2010 and subtracting the corresponding cell for the end of the modeled period of 2060. It is noteworthy to mention that output data from MODFLOW was used for computing cell-to-cell subtraction, and the classification was applied to the value obtained from the subtraction with the purpose of interpreting and exploring new ways of presenting of results. The advantage of the applied methodology is that the groundwater level at every cell obtained from the MODFLOW is presented as processed by the authors and was not interpolated or post-processed using software programs.

The computation of remaining groundwater storage was consolidated at the county level as follows: the Ogallala Aquifer area in each county was computed by overlaying an Ogallala Aquifer boundary over the 4-county political boundaries. Similarly, the average specific yield per county was computed by overlaying U.S. Geological Survey-specific yield data (Gutentag et al. 1984) over the 4-county political boundaries and computing the specific yield average per county area. Groundwater levels for year 2010 were not available to estimate the average groundwater storage values for this study. Therefore, data for year 2007 were used as reference points to assess groundwater storage for year 2060. Estimated average saturated thickness in 2007 for each county was obtained from the Hydrology and Water Resources 2008 Report (Hallmark 2008). The average groundwater storage per county for 2007 was computed as the product of the Ogallala Aquifer county area, times the 2007 average saturated thickness and then times the average county-specific yield. The projected remaining storage for each policy by 2060 was computed as the difference between the average groundwater storage per county for 2007 for the 4-county area and the projected percentage of the volume of the groundwater drawdown.

The spatial distribution of groundwater drawdown in the 4-county area was analyzed and compared to the percentage of the area affected using multiples of 5 meters of groundwater drawdown (Figure 4). The simulated groundwater drawdown in each model cell from the aforementioned text file was sorted from the largest value to the smallest value, involving a total number of cells for the study area. Then, cell values were classified using 5 meters class mark (i.e. a class mark of 25 meters represents a number of cell values in the range between 22.5 meters and 27.5 meters). The purpose was to illustrate groundwater drawdown for every 5 meters of drawdown and class marks were selected coincident to multiples of 5 meters. Hence, the total study area would experience groundwater drawdown greater than the minimum value obtained from cell value. Similarly, no area would experience groundwater drawdown greater than the maximum computed value from the model output. The remainder values were computed for each class mark. For example, the area with modeled groundwater level declines greater than 80 meters was zero; the area with modeled level declines of 75 meters (meaning between 72.5 meters and 77.5 meters) was 1%, Therefore the cumulated area that would experience drawdown greater than 75 meters becomes 1%, and the accumulation process continues in a similar way. Computed areas for each range represented the area in the 4 counties that had the selected class mark value as groundwater drawdown for the nominal period of 2010–2060 (Figure 4).

Policy #1: Permanent conversion of 10% of the total irrigated area to dryland production

The permanent conversion to dryland production policy would be a voluntary incentive-based program that compensates landowners to permanently convert irrigated cropland to

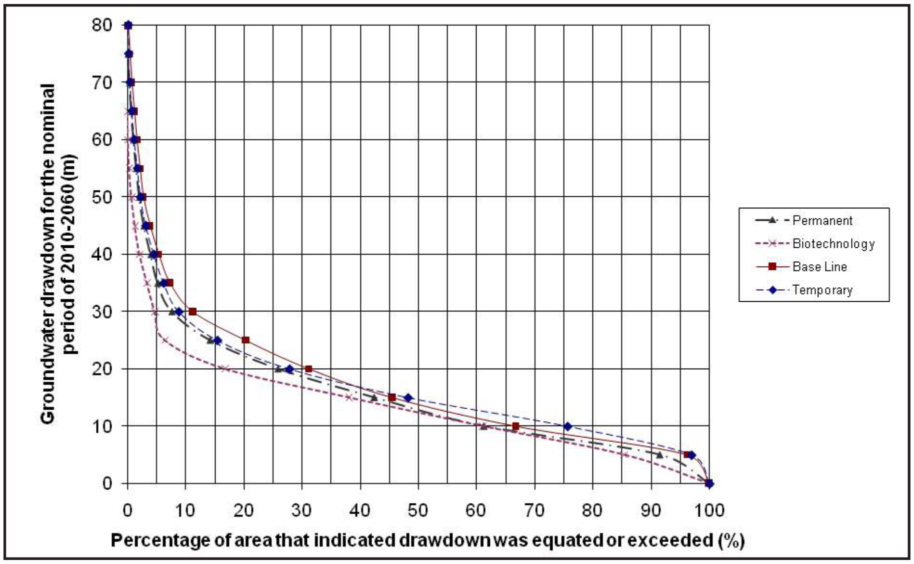


Figure 4. Percentage of the 4-county area that would experience groundwater level decline for the period of 2010–2060.

dryland (Amosson et al. 2010). The objective of this policy is to achieve an absolute long-term reduction in agricultural water use by purchasing and permanently retiring irrigation water rights from participating landowners. The duration of the program is scheduled for 15 years; the maximum allowed program-enrolled area is 10% of the total irrigated area within the study region, and 2% of the area is expected to be registered in the conversion program for each of the first 5 years. The enrolled area subsequently either resumes non-irrigated production or remains in pasture after the 15-year enrollment (Figure 3). The current exploitation rate was decreased 2% per year relative to the current aquifer use during the first 5 years of projection until completing a 10% reduction after the fifth year. Afterwards, groundwater exploitation was assumed as remaining constant at 90% of the baseline rate for the rest of the simulation period.

Policy #2: Temporary conversion of 10% of the total irrigated area to dryland production for the first 15 years

The temporary conversion of 10% of the total irrigated area to dryland production policy is a voluntarily incentive-based program that would compensate landowners by temporarily converting irrigated cropland to dryland (Amosson et al. 2010). The purpose of this policy is to achieve a short-term reduction in agricultural groundwater use by leasing and retiring irrigation water rights obtained from participating landowners during the temporary conversion period. The duration of the conversion program is 15 years, and the maximum enrolled area in the program is 10% of the total irrigated area within the study region. The policy would be implemented by requiring that 2% of the irrigated area be registered for the program in each of the first 5 years of the simulation period. Producers would be allowed to resume irrigated crop production at the termination of the 15-year program period. As a result, the current water-pumping rate was decreased by 2% per year relative to the current aquifer use during the first 5 years of projection until completing the 10% reduction after the fifth year. The groundwater pumping rates were kept constant at the 10% reduction rate for 10 years to complete the 15-year program period. Afterwards, as for year 16, the groundwater pumping rates were increased back to the baseline pumping rate and remained at that rate for the rest of the simulation period as shown in Figure 3. The difference relative to the permanent conversion is that for the temporary conversion, the groundwater pumping rate remains constant at the full baseline rate for the rest of the 50-year simulation period, while the permanent conversion groundwater pumping rate remains constant at 90% of the baseline rate.

Policy #3: Adoption of advances in biotechnology

The biotechnology water conservation policy is an incentive-based policy that encourages landowners to voluntarily adopt more water-efficient crop varieties (Amosson et al. 2010). To implement this option, further advances in drought-tolerant varieties of crops must first come to market. Biotechnology adoption for this study only refers to the adoption of drought-tolerant varieties that increase production per unit of water. Therefore, this policy does not include yield increase by adoption of virus-, insect-, and/or herbicide-resistant crops.

Drought-resistant crops could allow producers to achieve higher crop yield levels than current yields with decreasing water use and therefore enhance future availability of this resource. The model does not assess yield improvement for evaluating future scenarios. An incentive-based policy would encourage adoption of more water-efficient technologies if drought-resistant varieties of crops are developed and made available to producers, and regulatory policies established and enforced to either decrease or maintain groundwater use at current groundwater withdrawal rates. Consequently, groundwater use was assumed to be reduced at the rate of 1% per year for applying a biotechnology water conservation policy throughout the full simulation period of 50 years. Overall, groundwater withdrawals would be reduced by 50% from the baseline water use by the end of the simulation period, as shown in Figure 3.

Each policy was evaluated by performing independent simulations. Quality assurance was performed by checking that groundwater levels for the year 2010 were coincident for each policy. The yearly groundwater levels obtained from model performance were compared for subsequent years, assessing that the trend corresponded to policy definition. Groundwater levels were exported as contour lines from MODFLOW to a Geographic Information System environment for visual comparison. The analysis of a contour line overlay was done to detect anomalous results such as increasing groundwater levels where decreasing levels were expected and vice versa.

RESULTS AND DISCUSSION

The average groundwater storage in year 2007 was 27,100 million cubic meters in Dallam County, 20,900 million cubic meters in Sherman County, 28,600 million cubic meters in Hartley County, and 17,800 million cubic meters in Moore County as shown in Table 1. The baseline projection of groundwater levels by year 2060 is presented in Figure 5. Two areas in Hartley County could experience groundwater level declines with magnitudes up to 75 meters in the eastern area and up to 80 meters in the northwestern corner (Figure 6).

From the baseline scenario, about 11% of the 4-county region is expected to experience groundwater level declines greater than 30 meters if the current pumping rate continues with no change until the year 2060 (Figure 4). In other words, 89% of the area would experience groundwater level declines less than 30 meters if current pumping rates continue with no change until year 2060. Additional analysis indicated that 5% of the area would expect groundwater level declines greater than 40 meters by 2060 (Figure 4) and 95% of the 4-county area would expect groundwater level declines greater than 6 meters for the case of the baseline scenario. In comparing half of the 4-county area from the baseline, 50% of the area would expect groundwater level declines greater than 14 meters by 2060. It is important to mention that results for remaining groundwater storage by 2060 (Table 2) show that 50% of storage would be remaining by year 2060. These results suggest that keeping future groundwater pumping rates at the 2010 rates would satisfy the desired future condition of keeping 40% storage in 50 years.

Policy #1: Permanent conversion of 10% of the total irrigated area to dryland production

Simulated aquifer groundwater levels for year 2060 are depicted by contour lines in case of the permanent conversion policy compared to the baseline (Figure 7). This figure indicates groundwater level recovery by a downward (rightward most of the time and represented as dotted lines) contour shifted for the permanent conversion policy with respect to the baseline. Results from the application of this policy indicate that approximately 62% of the area would experience drawdown greater than 10 meters (Figure 4). Additionally, 10% of the area would expect groundwater level declines greater than 28 meters by 2060. The 2 zones identified in Hartley County as future depleted zones (Figure 8) are expected to experience maximum groundwater level declines of 70 meters and 60 meters by year 2060 for the eastern and northwestern zones, respectively.

With this policy, about 7% of the area would experience groundwater level declines greater than 30 meters, which is 4% less area compared to the baseline scenario area. Groundwater

Table 1. Average groundwater storage per county for 2007.

Counties	Ogallala Aquifer area (square kilometer)	2007 average saturated thickness (meter)	Specific yield (%)	Storage (million cubic meter or gigaliter)
Dallam	3,899	45	16	27,100
Sherman	2,391	53	17	21,000
Hartley	3,766	44	17	28,600
Moore	2,102	60	14	17,800
Total	12,158	50	16	94,400

level declines greater than 20 meters would affect 26% of the 4-county area and this is 5% less area than the baseline. The computed storage available by 2060 is approximately 50,500 million cubic meters or gigaliters, and it corresponds to 55% of the storage of year 2010 (Table 2). The result indicated that this policy would achieve the goal of having more than 40% of

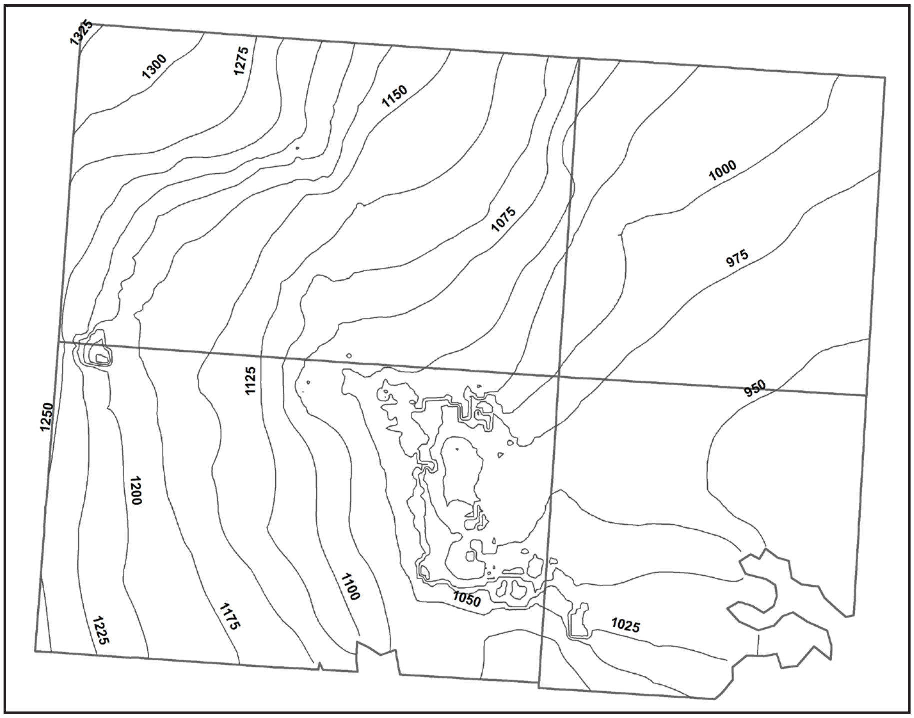


Figure 5. Predicted groundwater levels for the baseline by year 2060 (meters above mean sea level).

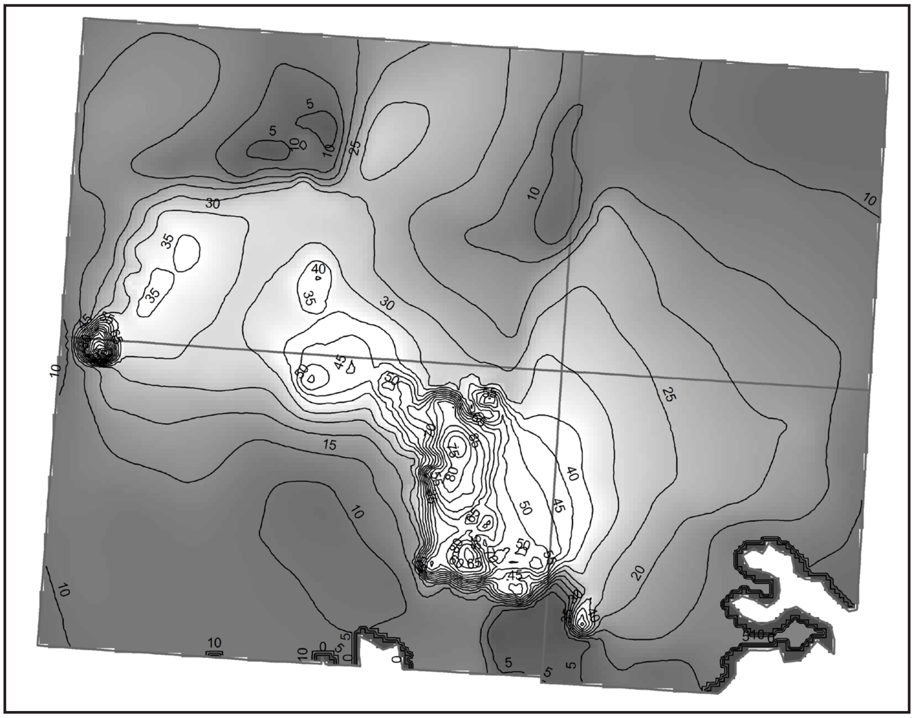


Figure 6. Grid image and contour lines for predicted groundwater drawdown (meters) for the baseline by year 2060.

Table 2. Remaining groundwater storage by nominal year 2060.

Policies	4-county average drawdown	Drawdown volume	Remaining storage by 2060	
	(meter)	(million cubic meter or gigaliter)	(million cubic meter or gigaliter)	%
Baseline	20	45,600	46,300	50
Permanent Conversion	18	41,400	50,500	55
Temporary Conversion	20	45,100	46,800	51
Biotechnology	16	36,800	55,100	60

groundwater in the Ogallala Aquifer remaining in storage after 50 years in the area of Dallam, Sherman, Hartley, and Moore counties.

Policy #2: Temporary conversion of 10% of the total irrigated area to dryland production for the first 15 years

In general, the effect of adopting a temporary conversion of irrigated cropland to dryland production seems similar to the long-term effect on groundwater level declines predicted for the permanent conversion to dryland. This was observed by comparing predicted groundwater levels for Policy 2 (Figure 9) with Policy 1 (Figure 7). However, a comparison of predicted groundwater drawdown for both policies (Figures 8 and 10) changes the perspective. Results from the application of this policy showed that approximately 28% of the 4-county area is predicted to experience groundwater level declines greater than 20 meters (Figure 4) for temporary conversion of irrigated land to dryland, which represents 3% less of the area than the baseline. The minimum groundwater level decline that is predicted for 25% of the 4-county area during the 50-year period is 21 meters, and the baseline scenario would experience decline greater than 23 meters for similar areas. Groundwater level declines greater than 10 meters is expected by year 2060 for 76% of the area, and approximately 10% of the area is predicted to experience groundwater level declines greater than 28 meters, which consists of 1% less area than the baseline, showing that this policy results in some water savings in respect to baseline. Simulated groundwater levels for 2060 are depicted by contour lines for the temporary conversion policy compared to the case of a baseline scenario (Figure 9) showing less decline by a downward (eastward most of the time) contour shifted for the temporary conversion policy with respect to the baseline. On the contrary, a contour line that is shifted upward (to the west mostly) indicates that groundwater levels have declined relative to the baseline. This trend can be observed in south-central Hartley County and in the northeastern corner of Sherman County, but not for the other policies. These areas would experience up to 3 meters of additional groundwater drawdown compared to the baseline. The magnitude of this drawdown does not impact regionally, but it is an interesting consideration that could be taken into account for interpreting model results and defining future policies. A policy that would benefit the whole area could generate results that are not completely beneficial for localized areas. In addition, eastern and northwestern Hartley County are 2 areas that have simulated maximum groundwater pumping by the end of the simulation period that produced drawdown up to 75 meters and 65 meters (Figure 10).

The computed storage available by 2060 is approximately 46,800 million cubic meters or gigaliters, corresponding to 51% of the year 2010 storage (Table 2). It is worth mentioning that computed average drawdown for this policy is 20 meters, which is similar to the corresponding magnitude for baseline (Table 2), and consequently its impact is not notorious. This policy would achieve the goal of having more than 40% of the Ogallala Aquifer remaining in storage for 50 years in the area of Dallam, Sherman, Hartley, and Moore counties.

Policy #3: Adoption of advances in biotechnology

Predicted groundwater levels for year 2060 are represented by contour lines for the adoption of advances in biotechnology policy compared to baseline levels (Figure 11) showing groundwater level recovery by a downward (rightward most of the time) contour shift. If advances in biotechnology policy were to occur and adopted during the next 50 years, 15% of the 4-county area would experience less than a 5 meter of groundwater drawdown by year 2060 (Figure 4). Groundwater level declines greater than 10 meters would be expected for approximately 62% of the study area, similar to results obtained from the permanent conversion by the end of the simulation period. The maximum groundwater drawdown that would occur in

Hartley County by the end of the study period could be up to 60 meters and 40 meters for the eastern and northwestern parts of the study area (Figure 12), respectively.

With the biotechnology-based policy, approximately 5% of the area would experience drawdown greater than 30 meters, which is 6% less area than that for the baseline condition

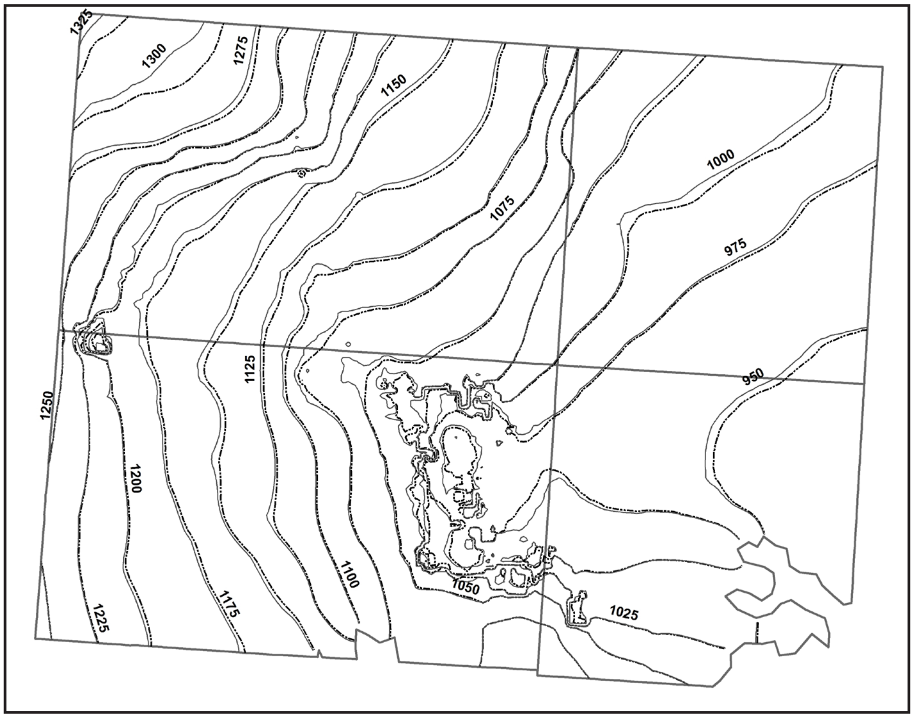


Figure 7. Comparison of predicted groundwater levels for baseline (solid lines) and Policy #1: Permanent conversion to dryland (dotted lines) by year 2060 (meters above sea level).

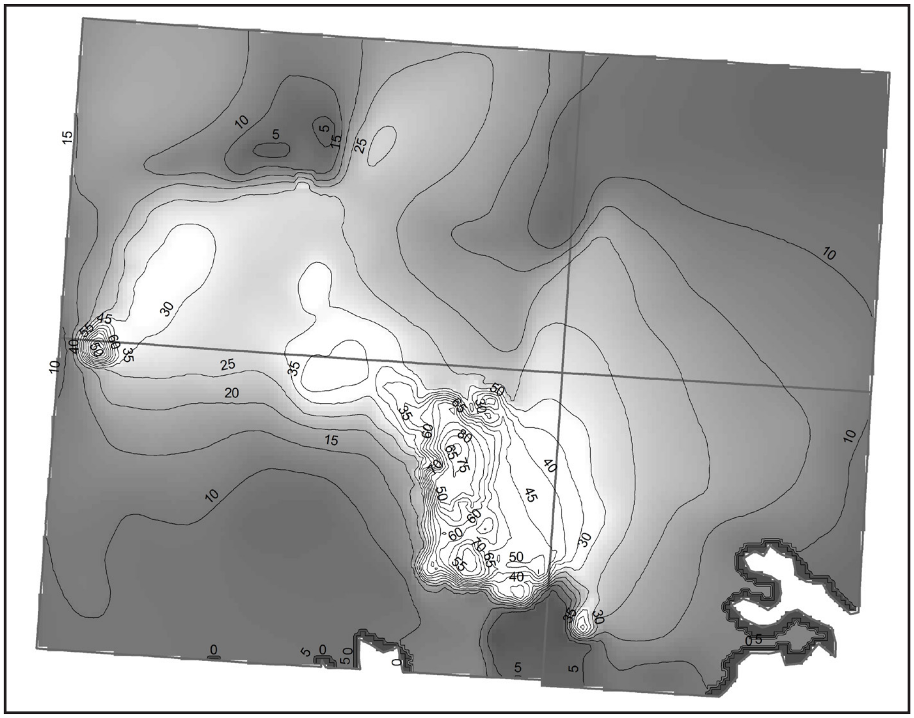


Figure 8. Grid image and contour lines for predicted groundwater drawdown (meters) for Policy #1: Permanent conversion by year 2060.

(Figure 4). Drawdown of groundwater level greater than 20 meters would affect approximately 17% of the 4-county area, and this is about 14% less area than the baseline scenario. The predicted water storage available by 2060 is 55,100 million cubic meters or gigaliters, corresponding to 60% of the year 2010 storage (Table 2). These results show that the biotechnol-

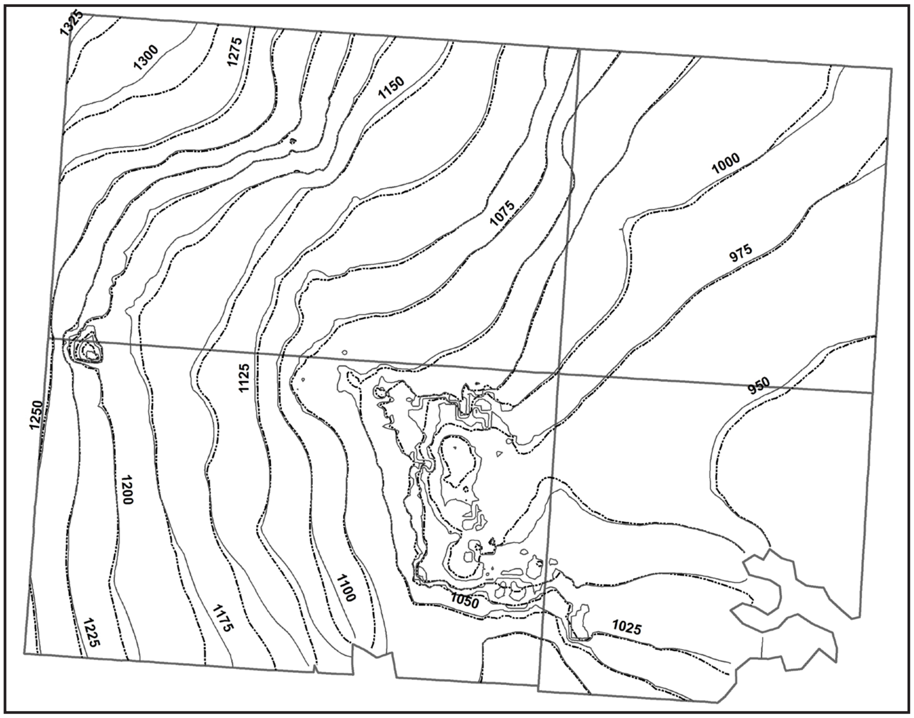


Figure 9. Comparison of predicted groundwater levels for baseline (solid lines) and Policy #2: Temporary conversion (dotted lines) by year 2060 (meters above sea level).

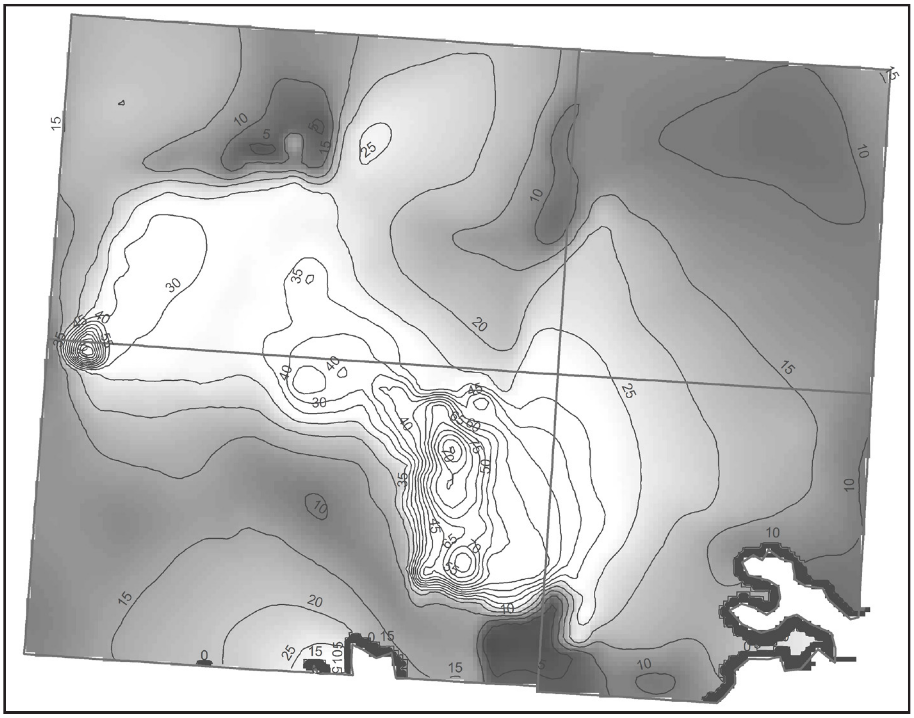


Figure 10. Grid image and contour lines for predicted groundwater drawdown (meters) for Policy #2: Temporary conversion by year 2060.

ogy-based policy would achieve the goal of having more than 40% of the Ogallala Aquifer remaining in 50 years. However, this policy definition is very sensitive to time, and even perhaps ambitious.

By comparing results from the policies simulated above, it is evident that of the studied policies the application of advances

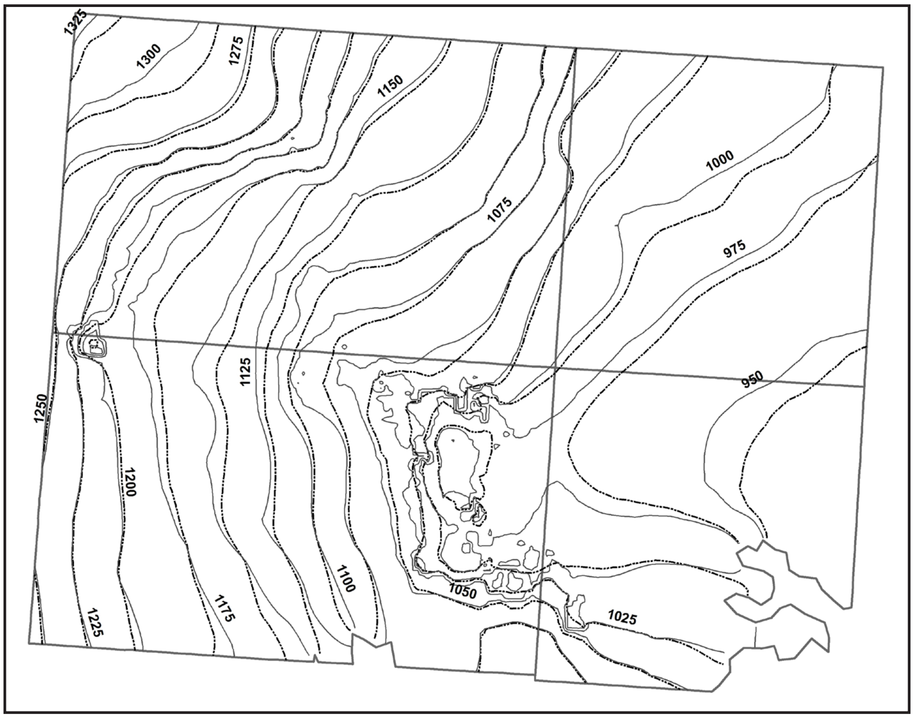


Figure 11. Comparison of predicted groundwater levels for baseline (solid lines) and Policy #3: Biotechnology (dotted lines) by year 2060 (meters above sea level).

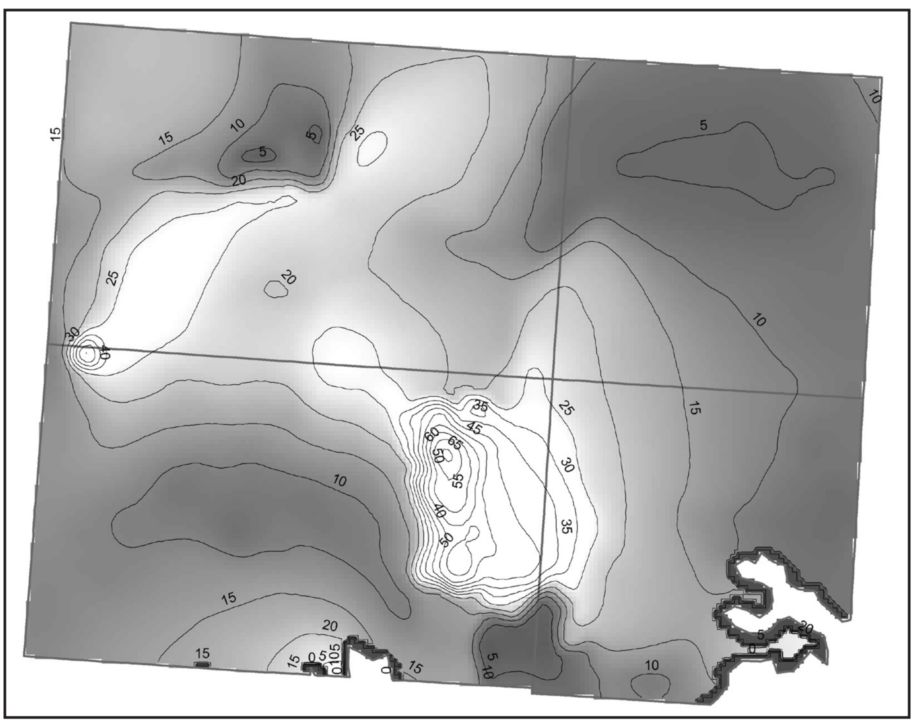


Figure 12. Grid image and contour lines for predicted groundwater drawdown (meters) for Policy #3: Biotechnology by year 2060.

in biotechnology would offer the most mitigation of drawdown in the 4-county area. This can be observed by comparing the shift in contour lines for the 3 policies with respect to the baseline (Figures 7, 9, and 11); whereas groundwater level recovery is shown by the most notable downward contour shift (Figure 11) for the adoption of advances in biotechnology policy. The contrast is highlighted by comparing the percentages of the 4-county area that would experience groundwater level declines greater than 20 meters by the year of 2060, which is approximately 17% for the biotechnology policy (Figure 4), 26% for the permanent conversion policy, 27% for the temporary conversion policy, and 31% for the baseline. Similarly, approximately 5% of the area would experience groundwater level declines greater than 30 meters by year 2060, whereas percentages for the permanent conversion policy, the temporary conversion policy, and the baseline are 7%, 9%, and 11%, respectively (Figure 4).

In addition, the comparison of the remaining storage by 2060 for the 3 policies showed that the adoption of advances in biotechnology policy allows the largest quantity of groundwater storage after the simulated period. This policy showed that 60% of the groundwater in the Ogallala Aquifer in the 4-counties would remain by year 2060, if this policy were to be implemented (Table 2). The percentages for the other policies are 55% for the permanent conversion of 10% of the irrigated land to dryland production policy and 55% for the temporary conversion of 10% of the irrigated area to dryland production. The percentage of the aquifer remaining in 50 years in the 4-county area for the baseline scenario would be 50% according to this study. The impact of the temporary conversion policy to the amount of groundwater remaining in storage and relative to the baseline is not significantly different, showing a 1% increase in storage. In contrast, the difference in the aquifer storage remaining in the 4-county area, for the case of the advances in biotechnology policy relative to the baseline, would be 10%. Finally, the average groundwater level decline for the 4-county area would be 16 meters if the advances in biotechnology policy were fully realized and adopted (Table 2), which is lower than the 18 meters for the permanent conversion, and 20 meters for the temporary conversion policy.

SUMMARY AND CONCLUSION

Using a MODFLOW simulation package, 3 alternative policies were evaluated for their potential impact on future groundwater levels in the Ogallala Aquifer beneath 4 heavily irrigated counties (Dallam, Sherman, Hartley, and Moore) located in the northwestern corner of the Texas High Plains. The 3 groundwater management policies were: (1) permanent conversion of 10% of the total irrigated area to dryland production, (2) temporary conversion of 10% of the irrigated area to dryland production for the first 15 years, and (3) adoption of advances in biotechnology that allow groundwater use reductions at a rate of 1% per year during the next 50 years. Groundwater pumping rates for these water conservation policies were used in simulations conducted with a MODFLOW model. Simulations were conducted for the 2010–2060 period. Results indicated that the adoption of advances in biotechnology policy would produce the least amount of drawdown compared to those with the permanent or the temporary conversion to dryland policy. However, advances in biotechnology are independent of water conservation policies that may be enforced or adopted in particular groundwater districts over the entire irrigated area. In addition, it is worthwhile to mention that the way the advances in biotechnology policy was implemented in the model is equivalent to any prescribed regulation or financial incentive that would represent reduction of water use in an amount of 1% per year. The results from this study indicate that it is advised to support effort on developing biotechnologies, prescribe regulation and/or provide financial incentive as ways to achieve conservation goals. Similarly, the first two policies combined with policies that could be equivalent to the advances in biotechnology policy may provide additional confidence in being able to achieve the policy goals of the groundwater conservation district as expressed in the desired future conditions statement.

The greatest reductions in drawdown in the Ogallala Aquifer in the 4-county area are projected by employing advances in biotechnology, assuming that water use reductions are realized. The biotechnology-based policy would allow a 10% increase in the remaining groundwater storage by 2060 with respect to the baseline. The permanent conversion of 10% of the irrigated land to dryland production would increase the remaining storage volume by 5%.

There were 2 zones in the eastern and northwestern parts of Hartley County where groundwater levels would decline more than other areas by simulation year 2060, and this was predicted with all 3 policies. Projected drawdown in these zones would be reduced if the biotechnology policy is adopted, reducing groundwater drawdown from 75 to 60 meters for the eastern location and from 80 to 40 meters for the northwestern location. The reason that these 3 policies resulted in impacting similar geographical areas is because the model assumed that pumping station locations did not change during simulation time, but the pumping rates changed.

Approximately 50% of the groundwater volume in the aquifer would remain in storage after 50 years in the 4-county area. This indicates that the desired future condition of having 40% of the year 2010 aquifer storage remaining after 50 years could be accomplished with continuation of existing pumping rates assumed for this study. However, any additional conservation effort would extend the availability of the groundwater resource. Additional research is also recommended regarding potential new technologies for increasing groundwater recharge in an effort to extend the availability of groundwater in the future.

ACKNOWLEDGMENTS

This research was supported in part by the Ogallala Aquifer Program, a consortium between U.S. Department of Agriculture-Agricultural Research Service, Kansas State University, Texas A&M AgriLife Research, Texas A&M AgriLife Extension Service, Texas Tech University, and West Texas A&M University. Partial support also provided by the National Science Foundation award number IIA- 1301792 from the National Science Foundation-Idaho Experimental Program to Stimulate Competitive Research Program and by the National Science Foundation. The authors highly appreciate constructive comments from anonymous peer-reviewers that increased manuscript's quality.

REFERENCES

Amosson S, Almas L, Golden B, Guerrero B, Johnson J, Taylor R, Wheeler-Cook E. 2010. Economic impacts of selected water conservation policies in the Ogallala Aquifer. 50 p. Report to Ogallala Aquifer Program.

Christian P. 1989. Evaluation of ground-water resources in Dallam County, Texas, Austin (Texas): Texas Water Development Board. 27 p. Report 315.

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. Panhandle Regional Planning Commission. Austin (Texas): The University of Texas at Austin, Bureau of Economic Geology. Contract number UTA01-462. Final report sponsored by the Panhandle Water Planning Group of the Panhandle Regional Planning Commission.

George PG, Mace RE, Petrossian R. 2011. Aquifers of Texas. Austin (Texas): Texas Water Development Board. 182 p. Report 380.

Gurdak JJ, McMahon PB, Dennehy KF, Qi SL. 2009. Water quality in the High Plains Aquifer, Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming, 1999–2004. Alexandria (Virginia): U.S. Geological Survey. 63 p. Circular 1337.

Gutentag ED, Heimes FJ, Krothe NC, Luckey RR, Weeks JB. 1984. Geohydrology of the High Plains Aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas and Wyoming. Alexandria (Virginia): U.S. Geological Survey. 68 p. Professional Paper 1400-B.

Hallmark D. 2013. Hydrology and water resources 2012–2013. Dumas (Texas): North Plains Groundwater Conservation District. 45 p. Technical report.

Hallmark D. 2008. Hydrology and water resources 2008. Dumas (Texas): North Plains Groundwater Conservation District. 48 p. Technical report.

Harbaugh AW, Banta ER, Hill MC, McDonald MG. 2000. MODFLOW-2000, the United States Geological Survey modular ground-water model – User guide to modularization concepts and the ground-water flow process. Reston (Virginia): U.S. Geological Survey. 121 p. Open-file report 00-92.

Hernandez JE, Gowda PH, Marek TH, Howell TA, Ha W. 2013. Groundwater levels in the Northern Texas High Plains: baseline for existing agricultural management practices. Texas Water Journal. 4(1): 22-34.

Marek T, Amosson S, Bretz F, Guerrero B, Kotara R. 2009. 2011 Panhandle regional water plan – Task 2 report: agricultural water demand projections. Amarillo (Texas): Freese and Nichols, Inc. Texas A&M University System, AgriLife Research and Extension Center. A water planning report.

Marek T, Gaskins D, Bretz F, Guerrero B, Jones D. 2006. Water management strategies to conserve groundwater in Texas Region A. Conference Proceedings Universities Council on Water Resources, Southern Illinois University Carbondale, 19 July 2006.

Marek T, Amosson S, New L, Bretz F, Almas L, Guerrero B. 2004. Senate Bill 2 - Region A Task 2 Report agricultural (Irrigation and Livestock) water demand projections. Amarillo (Texas): Freese and Nichols, Inc. Revised November 2, 2004. Texas A&M University Agricultural Research and Extension Center. Technical report.

Maupin MA, Barber NL. 2005. Estimated withdrawals from principal aquifers in the United States, 2000. Reston (Virginia): U.S. Geological Survey. 46 p. Circular 1279.

McGuire VL. 2011. Water-level changes in the High Plains aquifer, predevelopment to 2009, 2007–08, and 2008–09, and change in water in storage, predevelopment to 2009 [Internet]. Reston (Virginia): U.S. Geological Survey. 13 p. Scientific Investigations Report 2011–5089; [cited 2013 February 13]. Available from: http://pubs.usgs.gov/sir/2011/5089/

McMahon PB, Dennehy KF, Bruce BW, Gurdak JJ, Qi SL. 2007. Water-quality assessment of the High Plains Aquifer, 1999–2004. Reston (Virginia): U.S. Geological Survey. Professional Paper 1749.

Musick JT, Pringle FB, Harman WL, Stewart BA. 1990. Long-term irrigation trends – Texas High Plains. Applied Engineering in Agriculture. 6(6): 717-724.

National Agricultural Statistics Service. 2008. 2008 Agricultural Statistics by County [Internet]. United States Department of Agriculture-National Agricultural Statistics Service. Available from: http://www.nass.usda.gov/Statistics_by_State/Texas/index.asp#.html

[NOAA] National Oceanic and Atmospheric Administration. 2009. Climate data products [Internet]. [cited 2009 October 16]. Available from: http://www.climate.noaa.gov/

[NPGCD] North Plains Groundwater Conservation District. 2008a. Proposed desired future conditions for the Ogallala Aquifer. Dumas (Texas): North Plains Groundwater Conservation District. 15 p. Internal report.

[NPGCD] North Plains Groundwater Conservation District. 2008b. Ogallala Aquifer, general geology, stratigraphy, and hydrology [Internet]. Dumas (Texas): North Plains Groundwater Conservation District; [cited 2013 February 15]. Available from: http://www.northplainsgcd.org/science-a-technology/ogallala-aquifer.html

[NPGCD] North Plains Groundwater Conservation District. 2013. Management plan 2013–2023 [Internet]. Dumas (Texas): North Plains Groundwater Conservation District; [cited 2014 May 28]. Available from: http://www.northplainsgcd.org/downloads/category/5-district-documents.html?download=98%3A2013-revised-management-plan

[NPGCD] North Plains Groundwater Conservation District. 2014. Evaluation of changing land use and potential water conservation strategies: North Plains Groundwater Conservation District. Amosson S, Guerrero B, Mitchell D, Johnson J, Johnson P, editors. Dumas (Texas): North Plains Groundwater Conservation District. 25 p.

Osborn JE. 1973. Economic effects of an exhaustible irrigation water supply: Texas High Plains. Southern Journal of Agricultural Economics. 1973(7): 134-139.

Qi SL, Scott C. 2010. Assessing groundwater availability in the High Plains Aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming. Reston (Virginia): U.S. Geological Survey. Fact Sheet FS-2010-3008.

Reilly TE, Dennehy KF, Alley WM, Cunningham WL. 2008. Ground-water availability in the United States [Internet]. Reston (Virginia): U.S. Geological Survey; [cited 2013 February 13] 70 p. Circular 1323. Available from: http://pubs.usgs.gov/circ/1323/

Seni SJ. 1980. Sand-body geometry and depositional systems, Ogallala formation, Texas. Austin (Texas): The University of Texas at Austin, Bureau of Economic Geology. 36 p. Report of Investigations No. 105.

Supalla R, Lamphear FC, Schaible GD. 1986. Economic implications of diminishing groundwater supplies in the High Plains region. Journal of Regional Analysis and Policy. 16(1): 86-99.

Tewari R, Almas L, Johnson J, Golden B, Amosson S, Guerrero B. 2014. Multi-year water allocation: an economic approach towards future planning and management of declining groundwater resources in the Texas Panhandle. Texas Water Journal. 5(1): 1-11.

Schlumberger Water Services. 2008. Visual MODFLOW Pro Ver. 4.3 user's manual. Waterloo (Ontario) Canada: Schlumberger Water Services. 680p.

[TWDB] Texas Water Development Board. 2007. Water for Texas 2007. Austin (Texas): Texas Water Development Board. Document No. GP-8-1.

[TWDB] Texas Water Development Board. 2014. 2012 Water use survey summary estimates by county [Internet]. Austin (Texas): Texas Water Development Board; [cited 2014 May 30]. Available from: http://www2.twdb.texas.gov/ReportServerExt/Pages/ReportViewer.aspx?%2fWU%2fSumFinal_CountyReport&rs:Command=Render

[USGS] U.S. Geological Survey. 2008. Geographical information system data for the High Plains regional groundwater study [Internet]. Reston (Virginia): United States Geological Survey; [cited 2011 June 27]. Available from: http://co.water.usgs.gov/nawqa/hpgw/html/GIS.html.

Wheeler EA, Segarra E, Johnson P, Willis DB, Johnson J. 2006. Aquifer depletion and the cost of water conservation: The southern High Plains of Texas case. 26th International Conference of Agricultural Economists, August 12-18, 2006, Queensland, Australia.

Texas Water Resources Institute
Texas Water Journal
Volume 6, Number 1, Pages 103–120

Commentary: 84th Texas State Legislature: summaries of water-related legislative action

Editor-in-Chief's Note: September 1 of every odd-numbered year is the date when new legislation from the most recent session of the Texas Legislature typically goes into effect. With this in mind, the Texas Water Journal invited 4 organizations that work closely with the Texas Legislature to provide their take on the changes to Texas water policy and law that were made during the 2015 session. The opinions expressed in these summaries are the opinions of the individual organizations and not the opinions of the Texas Water Journal or the Texas Water Resources Institute.

Organizations:

- Texas Water Conservation Association
- Sierra Club, Lone Star Chapter
- Texas Alliance of Groundwater Districts
- Texas Water Infrastructure Network

Citation: Robbins D, Steinbach SA, Kramer K, Schlessinger SR, Fowler PL. 2015. 84th Texas State Legislature: summaries of water-related legislative action. Texas Water Journal. 6(1):103-120. Available from: https://doi.org/10.21423/twj.v6i1.7030.

Terms used in paper

Short name or acronym	Descriptive name
ASR	aquifer storage and recovery
CMAR	construction manager-at-risk
DFC(s)	desired future condition(s)
ERCOT	Electric Reliability Council of Texas
GCD(s)	groundwater conservation district(s)
HB	House Bill
PUC	Public Utility Commission of Texas
SB	Senate Bill
SOAH	State Office of Administrative Hearings
SWIFT	State Water Implementation Fund for Texas
TAGD	Texas Alliance of Groundwater Districts
TCEQ	Texas Commission on Environmental Quality
TDLR	Texas Department of Licensing and Regulation
TDS	total dissolved solids
TWCA	Texas Water Conservation Association
TWDB	Texas Water Development Board
TxWIN	Texas Water Infrastructure Network

84TH LEGISLATIVE SESSION WRAP-UP

By Dean Robbins, Stacey Allison Steinbach, Texas Water Conservation Association

The "Groundwater Session"

Like the 83rd session, it was no surprise when the 84th Legislature was inundated with water bills. This time, however, the main focus was on groundwater management rather than state water plan funding. With the latter issue largely addressed through legislative action and voter approval in 2013, legislators turned their attention to some long-standing groundwater policy issues this year. From the perspective of the Texas Water Conservation Association (TWCA), those groundwater bills and the river authority sunset bill comprised the bulk of high-priority tracked legislation that made it to the Governor's desk.

Session statistics

In the House, the Natural Resources Committee continued to hear most of the bills affecting TWCA members. Though the committee had a number of familiar faces, both the Chair, Representative Jim Keffer, and Vice-Chair, Representative Trent Ashby, were new to that committee's leadership this session and provided a great opportunity for collaboration and new perspectives. Other committee members included Representatives Dennis Bonnen, DeWayne Burns, James Frank, Kyle Kacal, Tracy King, Lyle Larson, Eddie Lucio III, Poncho Nevárez, and Paul Workman.

Similarly, freshman Senator Charles Perry led the newly created Agriculture, Water, and Rural Affairs Committee that addressed the bulk of the water bills considered this session. Senator Judith Zaffirini served as Vice-Chair of the 7-member committee that also included Senators Brandon Creighton, Bob Hall, Juan "Chuy" Hinojosa, Lois Kolkhorst, and José Rodríguez.

All told, legislators filed 6,276 House and Senate bills this session, up more than 400 bills from the session before. Of those, just over 20% passed, compared to a 24% passage rate during the 83rd. TWCA tracked over 350 bills this session, including 142 priority bills, numbers that are nearly identical to our tracked bill counts in 2013. Thirty-four high-priority bills made it to the Governor this year, and we have outlined 23 here in this article. For more information about TWCA and legislation that we tracked this session, visit TWCA's website at www.twca.org.

TWCA Groundwater Committee

On the groundwater front, the beginning of the 84th felt like something of a "do over" from previous sessions, with the refiling of numerous bills that failed to pass in the 83rd or before. But the end of the 84th looked a lot different from the end of the 83rd: legislators passed more than 20 separate pieces of groundwater legislation this year but sent just 2 groundwater bills to the Governor's desk in 2013.

One significant difference between the 2 sessions was the stakeholder work that occurred before the 2015 session. Shortly after the close of the 83rd Legislature, TWCA established a "Groundwater Committee" to address issues that were left on the table at sine die. More than 60 TWCA members, representing numerous stakeholder groups, joined the committee and began the arduous process of tackling controversial groundwater issues such as aquifer storage and recovery (ASR), brackish groundwater management, long-term groundwater permitting, appeals of desired future conditions (DFCs), contested case hearings on groundwater permits, apprentice programs for well drillers and pump installers, the State Auditor's Office review of groundwater conservation districts (GCDs), and cleaning up a very fractured Chapter 36 of the Water Code.

The committee formed multiple subcommittees and drafting groups, and met frequently throughout 2013 and 2014, ultimately achieving consensus on 7 pieces of draft groundwater legislation. To reach consensus, 90% of the voting members had to support the draft—a noteworthy accomplishment considering the diversity of stakeholders on the committee. The committee and TWCA staff worked closely with House and Senate leadership in an effort to move these bills through the legislative process, and 6 of them made it to the Governor's desk. Summaries of those bills are included in the next section, with summaries of TWCA's other high priority bills in the following section.

TWCA Groundwater Committee bills

House Bill (HB) 655: Aquifer Storage and Recovery (Larson/Perry)

Chapters 11 and 27, Water Code, are amended to streamline permitting requirements for aquifer storage and recovery (ASR) projects, making it easier and more cost efficient to initiate an ASR project. The bill gives the Texas Commission on Environmental Quality (TCEQ) exclusive jurisdiction over ASR projects so long as the water produced by the project does not exceed the amount authorized for withdrawal by the TCEQ. Withdrawals above the amount authorized by the agency will be subject to a GCD's spacing, production, and permitting rules and fees, as applicable. All wells will continue to be subject to GCD registration requirements.

The bill also clarifies that a surface water right amendment is not needed to store appropriated surface water in an ASR project prior to beneficial use, an important amendment as the prior language was a significant hindrance to ASR projects. Finally, the bill outlines water quality and quantity considerations that must be made by the TCEQ, as well as reporting and monitoring requirements that must be followed by project developers.

HB 930: TDLR Bill (Miller/Perry)

Chapters 1901 and 1902, Occupations Code, are amended to authorize the Texas Department of Licensing and Regulation (TDLR) to reinstate apprentice programs for water well drillers and pump installers. TDLR abandoned earlier versions of these programs in 2012 after it determined the agency lacked the requisite statutory authority to implement them.

HB 1221: Sellers' Disclosure Bill (Lucio III/Estes)

Chapter 5, Property Code, is amended to require a seller of residential property to disclose whether any portion of the property is located in a GCD or a subsidence district.

HB 2179: Contested Case Hearings Bill (Lucio III/Perry)

Chapter 36, Water Code, is amended to streamline and clarify permit hearings processes before GCDs.

HB 2767: Chapter 36 Clean Up Bill (Keffer/Perry)

Chapter 36, Water Code, is amended throughout to make corrective changes and clarifications necessitated by the many amendments made to the chapter over the past decade.

Senate Bill (SB) 854: Permitting Bill (Zaffirini/Lucio III)

Chapter 36, Water Code, is amended to require a GCD to automatically renew a production permit provided that prescribed conditions are met and no conditions have changed. If the holder of a permit requests a change that requires an amendment, the existing permit remains in effect until the amendment process is completed. A GCD may initiate an amendment to a permit in accordance with the GCD's rules.

Other bills of interest

HB 30: Brackish Groundwater (Larson/Perry)

Chapter 16, Water Code, is amended to require the Texas Water Development Board (TWDB) to further study the development of brackish groundwater, including the identification and designation of brackish groundwater production zones that can be used to significantly reduce the use of fresh groundwater. The TWDB must determine amounts of brackish groundwater that may be produced in a zone over a 30- and 50-year period. Certain areas are excluded from study. Studies must be completed by 2022. Regional planning groups must identify opportunities for and the benefits of developing large-scale desalination facilities for seawater or brackish groundwater in designated zones.

HB 200: Appeal of Desired Future Conditions (Keffer/Perry)

Chapter 36, Water Code, is amended to define "best available science;" to add "in order to protect property rights, balance the development and conservation of groundwater to meet the needs of this state, and use the best available science in the development of groundwater" to the purposes of the chapter; to limit a district's recovery of attorneys fees to those issues on which the district prevails; to establish a contested case hearing process for the appeal of a DFC via a hearing at the State Office of Administrative Hearings (SOAH); and to repeal the process for appeal of a DFC to the TWDB.

HB 1232: Texas Water Development Board Mapping (Lucio III/Estes)

The TWDB, not later than December 31, 2016, must conduct a study of the hydrology and geology of confined and unconfined aquifers in Texas to determine quality and quantity, whether those aquifers are tributary or non-tributary, their contributions to surface water, and their contributions to other aquifers.

HB 1378: Financial Reporting of Debt Information (Flynn/Bettencourt)

Chapter 140, Local Government Code, is amended to require political subdivisions to annually compile and report certain comprehensive financial information. The information must either be posted on the political subdivision's website or provided to the Comptroller for posting. Alternatives are provided for a municipality with a population of less than 15,000 or a county with a population of less than 35,000. A district as defined by Section 49.001, Water Code, satisfies the requirements if the district complies with the requirements in Chapter 49, Subchapter G, relating to audit reports, affidavits of financial dormancy, and annual financial reports, and submits the financial documents to the Comptroller.

HB 1665: Notice to Property Owners along Impoundments (Bonnen/Kolkhorst)

Chapter 5, Property Code, is amended to require notice of water level fluctuations to purchasers of residential or commercial property adjoining an impoundment with a capacity of at least 5,000 acre feet.

HB 1902: Graywater Regulation (Howard/Zaffirini)

The Health and Safety Code and the Water Code are amended to add a definition of "alternative on-site water" and to expand TCEQ's authority to adopt and implement minimum standards for the indoor and outdoor use and reuse of treated graywater and alternative on-site water.

HB 1919: Invasive Species (Phillips/Estes)

Chapter 66, Parks and Wildlife Code, is amended to exempt certain water transfers by a political subdivision from prohibitions and permitting requirements associated with the transfer of invasive species into water of this state.

HB 2031: Marine Seawater Desalination (Lucio III/Hinojosa)

The bill amends Chapter 11, Water Code, to exempt the diversion and use of marine seawater with total dissolved solids (TDS) of more than 10,000 milligrams/liter from permitting requirements. The TCEQ is directed to permit by rule bed and banks authorizations for the movement of marine seawater. Chapter 16, Water Code, is amended to further encourage marine seawater desalination projects. A new Chapter 18, Water Code, is added to provide authorization to political subdivisions for marine seawater projects, to further define the jurisdiction of state agencies over these projects, and to require streamlined permitting processes for them. The Health and Safety Code is amended to streamline TCEQ approvals of desalination projects providing potable water.

HB 3357: Notice of Political Subdivision Meetings (Lucio III/Eltife)

The Government Code is amended to authorize a political subdivision to post notice of a meeting on its website as an alternative to the requirement to provide notice to the county clerk.

HB 4097: Seawater Desalination Projects (Hunter/Kolkhorst)

The Health and Safety Code is amended to require the TCEQ to adopt rules for the use of desalinated seawater for non-potable uses. The Utilities Code is amended to require a study of infrastructure needs for the transmission of desalinated seawater and the demand response potential of seawater desalination projects. Chapter 11, Water Code, is amended to authorize diversions of water from the Gulf of Mexico for industrial purposes without notice or an opportunity for a contested case hearing. Water availability requirements are also waived, and the TCEQ may include environmental flows provisions. Chapter 26, Water Code, is amended to establish procedures for the issuance of permits to dispose of brine into the Gulf of Mexico from the desalination of seawater as part of an industrial process. Chapter 27, Water Code, is amended to authorize a general permit for an injection well for the disposal of brine produced by the desalination of seawater.

SB 523: Sunset Review of River Authorities (Birdwell/Keffer)

Chapter 325, Government Code, is amended to subject 18 entities listed in the legislation to a limited review under the Texas Sunset Act. The entities may not be abolished. Each entity must pay the cost incurred by the Sunset Commission in performing a review. A political subdivision reviewed by the commission under this bill may not be required to conduct a management audit by the TCEQ. Conforming amendments are made to various chapters of the Special District Local Laws Code and a schedule for review is established.

SB 695: Coastal Barrier System Study (Taylor/Faircloth)

A joint interim committee is established to study the feasibility and desirability of creating and maintaining a coastal barrier system to prevent storm surge damage.

SB 709: Environmental Permitting Procedures (Fraser/Morrison)

Chapter 2003, Government Code, is amended for certain TCEQ-contested cases referred to SOAH, the bill limits issues that may be considered and establishes timelines for completion of the proceeding. It also establishes that the applicant's filing, the Executive Director's preliminary decision, and any other supporting documentation establish a prima facie demonstration that the draft permit meets all state and federal requirements and issuance of the permit, if consistent with the draft, would protect human health and safety, the environment, and physical property. Criteria for rebutting such a demonstration are provided. The legislation applies to applications under Chapters 26 & 27, Water Code, and to Chapter 361, Health and Safety Code. Related changes are made to Chapter 5, Water Code.

SB 912: Wastewater Spill Reporting Exemption (Eltife/Crownover)

Chapter 26, Water Code, is amended to exempt from reporting by local governments certain accidental spills of wastewater that have a volume of 1,000 gallons or less.

SB 1148: Economic Regulation of Water and Sewer Service (Watson/Geren)

Numerous changes are made to Chapter 13, Water Code, relating to the water and wastewater rate jurisdiction of the Public Utility Commission (PUC). Changes relate to disclosure by a municipally owned utility, required notices, time lines for rate cases, and procedures for emergency orders.

SB 1267: Administrative Procedure Act (Estes/Clardy)

This bill makes comprehensive changes to procedures for contested case hearings at SOAH.

SB 1812: Eminent Domain Database (Kolkhorst/Geren)

Chapter 2206, Government Code, is amended to require the comptroller to create and make accessible on an Internet website an eminent domain database for public and private entities authorized to exercise the power of eminent domain. The database must be updated at least annually. Not later than February 1 of each year, these entities must provide prescribed information to the comptroller. Penalties are established for non-compliance.

SIERRA CLUB: EVOLUTION, NOT REVOLUTION, IN WATER POLICY

By Ken Kramer, Water Resources Chair, Lone Star Chapter, Sierra Club

Long-time observers of the Texas Legislature have noted that when state legislators tackle a major public policy issue in 1 legislative session, they rarely put that issue back on the front burner in the next regular session. Such was the case with water in the 84th Texas Legislature. After proposing major new state funding for water projects in 2013, approved by the voters as a state constitutional amendment, the Legislature in 2015 did not make water resources a priority topic. Important water bills were enacted, but they represented an evolution, not a revolution, in state water policy.

Furthermore, while Texas is making progress on water conservation and efficiency—and some new bills add to that progress, water development continues to be the major impetus for water legislation, and water suppliers and economic interests seeking to gain from new water projects continue to play a prime role in the politics of water. Nevertheless, these development interests were not totally successful in 2015. An informal alliance among rural interests, East Texas legislators, "Tea Party" conservatives, and environmental groups, for example, stopped the infamous water "gridzilla" proposal for turning Texas into a statewide plumbing system.

Groundwater and aquifer storage and recovery (ASR)

In the 2015 session the water topic that generated the most attention and largest number of water bills passed was groundwater management. A number of bills addressed issues left unresolved at the end of the 2013 session, including major subjects such as brackish groundwater development, aquifer storage and recovery (ASR), and groundwater district operations and processes.

There is an ongoing tension between the statutory declaration made several years ago that "groundwater districts are the preferred means of groundwater management" and the unwillingness of many legislators to give districts the powers, financial resources, and freedom to carry out their mission effectively. Certainly there are legitimate questions about whether single-county districts that only manage parts of an aquifer (the largest number of districts in the state) are the best way to oversee these vital water sources. However, the Legislature took reasonable steps a decade ago to establish a balance between a heavy reliance on single-county districts and the need for aquifer-wide management by creating the joint planning process for districts overlying the same aquifer.

Debate over that process aside, the fact is that groundwater districts have had to fight hard to maintain existing authority in recent legislative sessions from a disparate group of interests, including groundwater marketers, some urban water utilities, oil and gas companies, and some landowners asserting absolute rights of groundwater ownership. That continued to be the case in 2015, although some conflict was ameliorated by a negotiating process conducted under the auspices of the Texas Water Conservation Association (TWCA) during the interim following the 2013 session. That process produced a number of draft groundwater bills that were enacted into law in 2015, along with some other legislation that, with some exceptions, reflected compromises among the interests.

Several groundwater bills dealt primarily with groundwater conservation district (GCD) operations and processes. These included:

- House Bill (HB) 200 made changes to the process by which groundwater districts determine desired future conditions (DFCs) for aquifers under their management and set out detailed procedures for challenges to those DFCs
- HB 2179 set out in more detail the process for contested case hearings on applications for permits issued by groundwater districts and the specific manner in which the administrative law judge conducting a hearing and the district board interacts
- HB 2767 made a number of updates and minor changes to Chapter 36 of the Texas Water Code (which governs most groundwater districts) but also established detailed procedures for an "affected person" to challenge failure of a groundwater district to take a number of actions to protect the groundwater sources for which it is responsible, including failure to adopt or update DFCs
- Senate Bill (SB) 854 established a requirement that operating permits issued by a groundwater district be automatically renewed, subject to certain conditions, but allowed a district to initiate amendments to such operating permits

These bills taken together seem to indicate a desire by legislative leaders to be more "directive" in determining how GCDs should operate. On the one hand, this limits the flexibility of the districts. On the other hand, the additional specifics may lessen some controversies over groundwater district actions (or in some cases inaction) because certain procedures and powers have been clarified. However, continued pressure for groundwater development likely means that fights over groundwater use will continue or intensify.

That situation was evident in the legislative fight over whether and how to bring certain portions of the Trinity Aquifer (primarily in Hays County) under management by a groundwater district. The threat of development of a here-to-fore unregulated part of the Trinity eventually resulted—after last-minute legislative drama—in the Barton Springs-Edwards Aquifer Conservation District in southern Travis and Hays counties being given (through HB 3405) jurisdiction over the part of the Trinity Aquifer within its territory.

Another fight over groundwater management manifested itself in HB 2647—legislation that, although compromised during the process, sought to restrict the ability of groundwater districts to limit groundwater production used for power generation or mining. In a somewhat surprising move, the Governor vetoed that legislation on the grounds that allowing the state to give priority to 1 class of groundwater users might abridge the rights of other groundwater users and that any such decisions should be made at the local level based on sound science and public input.

Although there were other groundwater bills, probably the 2 most important bills related to this water resource enacted in 2015 were HB 30 and HB 655. The bills focus respectively on 2 water supply options: brackish groundwater development and ASR.

Texas has abundant brackish groundwater sources, according to Texas Water Development Board (TWDB) estimates. However, it is not always clear how and where those brackish groundwater sources may be developed and used without, for example, affecting freshwater sources or having other impacts. HB 30 will move the state forward in being able to make those determinations. The legislation, among other things, requires the TWDB, working together with groundwater districts and stakeholders, to identify and designate brackish groundwater "production zones" in certain parts of the state that are most appropriate for development of that resource. Specific areas of focus for research to make those initial determinations, as noted in HB 30, are the portion of the Carrizo-Wilcox Aquifer between the Colorado River and the Rio Grande, the Gulf Coast Aquifer, the Blaine Aquifer, and the Rustler Aquifer. One of the most positive things about the passage of HB 30 was the fact that an appropriation of $2 million to the TWDB for brackish groundwater studies became effective with the enactment of this new law. In a testament to the remaining political strength of groundwater districts at the Capitol, initial provisions of HB 30 that would have limited the authority of groundwater districts to manage brackish groundwater were dropped before passage of the bill.

The power of groundwater districts was diminished somewhat, however, by the passage of HB 655—the "ASR bill." ASR, where either surface water or groundwater is injected into an aquifer for storage and withdrawal later when needed, is getting increased attention as a water supply option, spurred by a successful ASR project undertaken by the San Antonio Water System. ASR, where feasible, has major advantages over storage of water in surface water reservoirs in Texas, where high evaporation rates and eventual sedimentation result in major water loss. The thrust of HB 655 was to streamline the process for review and approval of ASR projects, including the elimination of outmoded requirements in the permitting process at the Texas Commission on Environmental Quality (TCEQ).

A potential complication with HB 655 is that it eliminated any authority for groundwater districts to govern injection or withdrawal of water from aquifer formations under their jurisdiction with the exception of limited circumstances in which the amount of water withdrawn from an aquifer exceeds the volume of water injected. Approval of injection of water will be within TCEQ's jurisdiction, although a groundwater district might provide input to that permitting process. Implementation of HB 655 will need to be monitored to see that ASR projects are properly vetted.

Seawater desalination

While brackish groundwater development and ASR have been getting a lot of "buzz," perhaps the holy grail of water developers is the prospect of an "unlimited supply" of seawater off the Texas coast. Many people see seawater desalination as "drought-proof" (as long as one ignores the water requirements for electric power generation for the desalination). But a clear framework for permitting seawater desalination has not been in place. Moreover, concerns about the power requirements of energy-intensive desalination and the impacts of disposal of the concentrates left after desalination and related cost issues have tempered enthusiasm for seawater desalination.

Two bills that passed the Legislature in 2015 seek to facilitate seawater desalination. One bill, HB 4097, dealt primarily with desalination of seawater for industrial water use. Some of its provisions, however, call for the Public Utility Commission (PUC) in cooperation with the Electric Reliability Council of Texas (ERCOT) to conduct studies on electrical power issues affecting seawater desalination in general. One study is to evaluate whether "existing [electric power] transmission and distribution planning processes are sufficient to provide adequate infrastructure for seawater desalination projects." A second study is to determine "the potential for seawater desalination projects to participate in the existing demand response opportunities in the ERCOT market."

With regard to authorizing seawater desalination projects for industrial water use, HB 4097 makes changes to Chapter 11 of the Texas Water Code that differentiate requirements for such projects depending upon the location of the diversion of seawater to be desalinated. If the point of diversion of seawater is less than 3 miles seaward of the Texas coast or the seawater diverted contains a total dissolved solids (TDS) concentration of less than 20,000 milligrams per liter, then the project must obtain a permit from the TCEQ for the diversion. That permit application is subject to most of the general provisions of Chapter 11, including the opportunity for a contested case hearing on the permit. If the point of diversion is 3 or more miles seaward of the coast or the seawater diverted has a TDS of less than 20,000 milligrams per liter, then the seawater desalination project is not required to obtain a permit for diversion from the TCEQ.

HB 4097 also authorizes the TCEQ to require either individual or general permits for the discharge into the Gulf of Mexico (within the territorial waters of the state) of brine and other concentrates from a seawater desalination facility that produces water for industrial use. The bill also authorizes the TCEQ to allow disposal of concentrate from seawater desalination into an injection well.

HB 2031 takes a somewhat different approach on seawater desalination (termed "marine seawater"). This legislation creates a new Chapter 18 of the Water Code that outlines alternative processes that a seawater desalination project may use instead of the usual processes in Chapter 11 and Chapter 26 respectively for obtaining TCEQ authorization for diversion of water and discharge of concentrate. Chapter 18 specifically prohibits diversion or discharge into a bay or estuary and requires the TCEQ to prescribe by rule reasonable measures to minimize impingement and entrainment of marine species during the diversion of seawater. The new Chapter 18 has the same "bright lines" as in HB 4097, however, for determining whether a seawater desalination project must obtain a permit from the TCEQ for a diversion—the not-less-than 3 miles seaward or a TDS concentration of less than 20,000 milligrams per liter. Only within those parameters is a permit required.

An interesting aspect of HB 2031 is the requirement that the Texas Parks and Wildlife Department and the General Land Office jointly "conduct a study to identify zones in the Gulf of Mexico that are appropriate for the diversion of marine seawater, taking into account the need to protect marine organisms." This joint study is to be completed and a report submitted to the TCEQ by September 1, 2018. The report is to include recommended diversion zones, and the TCEQ is tasked, based on that report, to designate by rule appropriate diversion zones by September 1, 2020. Seawater desalination projects authorized after that time, whether by permit or not, must locate their diversions within those designated zones. Prior to that time, a seawater desalination project developer is required to consult with the Texas Parks and Wildlife Department and the General Land Office on appropriate diversion points. HB 2031 provides parallel requirements for the location of discharges of concentrates, and discharge zones may be the same as or overlap diversion zones.

Whether this new legislation actually jump starts seawater desalination projects remains to be seen. Many municipal water suppliers are wary of pursuing such projects because of the costs, although the Guadalupe-Blanco River Authority has now obtained funding from the TWDB for a feasibility study of a proposed project. Some observers believe that seawater desalination for industrial water use, especially in the Corpus Christi area, is more likely in the near term than municipal projects. The bottom line is that the Legislature has established a clearer road map for the authorization of such projects, but it is not clear how many people are going to start down that road.

Water conservation and reuse

Water conservation and reuse were not major topics in the 2015 legislative session. Two positive but relatively minor pieces of legislation related to water were enacted:

- SB 551 specifically authorizes the state Water Conservation Advisory Council to make recommendations for legislation to advance water conservation (there had been disagreement about whether or not the Council had such authority)
- SB 1356 establishes a sales tax "holiday" for the purchase of water-conserving products. Similar to the annual sales tax holiday for energy efficient products, any water-conserving products, as defined in the bill, purchased during the 3-day Memorial Day weekend are exempt from payment of sales tax

Water conservation did receive some attention in HB 1—the appropriations bill—although not all of the attention was positive. Approximately $3.5 million was appropriated to the TWDB for "Water Conservation Education and Assistance" for FY 2016, and $2.5 million was appropriated to the agency for that purpose for FY 2017. Rider 26 to the TWDB appropriations specifies that $1.125 million each year out of those amounts shall be used to meet the municipal water conservation goals of the 2012 state water plan. The rider further notes that these funds are to be used by the agency "to develop and manage a provider contract to deliver the most cost effective and accurate process by which to measure water conservation statewide." This appropriation has not been made in the past.

One water conservation item in the FY 2016/FY 2017 appropriations bill did not make it past the Governor. Rider 20 to the TWDB appropriations directed $1 million out of the line item for Water Conservation Education and Assistance for FY 2016 to be earmarked for "Water Conservation Education Grants," a competitive grant program for water conservation education groups that was first funded in the 2014-2015 biennium. Governor Abbott vetoed that rider, saying that activities supported by this funding were duplicative of other water conservation education (an argument panned by water conservation advocates). At this time the validity of the Governor's veto of this and other riders has been called into question by the Legislative Budget Board executive director, and the fate of these grants is unclear.

What is clear, however, is that there is legislative interest in encouraging and expanding the use of graywater and "alternative on-site water," forms of water "reuse." Graywater has been defined in the Texas Water Code as "wastewater from clothes-washing machines, showers, bathtubs, hand-washing lavatories, and sinks that are not used for disposal of hazardous or toxic ingredients." Graywater use has been slowly increasing but primarily for lawn, garden, and golf course irrigation.

A bill enacted into law in the 2015 session—HB 1902—expands the potential use of graywater by requiring the TCEQ to adopt by new standards for both indoor and outdoor use of this source, including for toilet and urinal flushing. The legislation further requires the TCEQ to adopt new standards for "alternate on-site water"—defined as "rainwater, air-conditioner condensate, foundation drain water, storm water, cooling tower blowdown, swimming pool backwash and drain water, reverse osmosis reject water, or any other source of water considered appropriate by" the TCEQ. This legislation could prove to be significant in the long term depending upon what standards are adopted and how strongly the use of graywater and alternate on-site water is encouraged.

The Water "Gridzilla"

Perhaps the most controversial water legislation of the session was the proposed state water grid—a massive system to move water around Texas (with the possible importation of water into Texas from other states). The Sierra Club labeled this monstrous water concept a water "gridzilla."

The proposal came in the form of 2 companion bills introduced in the House and the Senate: HB 3298 and SB 1907. As introduced, the legislation would have directed the TWDB to do the following:

- Conduct a study of "the establishment of a water grid, including an integrated network of pipelines, pumping stations, reservoirs, and other works for the conveyance of water between river basins, water sources, and areas of water use in the state;"
- Connect the establishment, construction, operation and management of the water grid to the state water planning process;
- Evaluate alternative methods for ownership, construction, operation, maintenance, control, and financing of the water grid;
- Identify and evaluate methods to fund the establishment of a water grid; and
- Evaluate methods of incorporating existing water conveyance infrastructure into a grid.

It is important to note that the legislation did not propose a study of *whether* a water grid was needed or even a good idea; the proposal was to study *how* to create, fund, and operate it.

There was a foregone conclusion on the part of the proposal backers, which included energy interests seeking to benefit from the production and sale of power to move large volumes of water around the state, that a water grid should be pursued.

The water "gridzilla," however, was opposed by environmentalists, many rural and East Texas interests, private property rights advocates, and many fiscal conservatives for a variety of reasons:

- Texas already has an extensive water planning process, costing millions of dollars, which looks at local or regional water transfers where they are needed and make sense; a state water grid is unnecessary to consider with these more targeted and reasonable water transactions.
- The TWDB is already working expeditiously to implement the new State Water Implementation Fund for Texas (SWIFT) to provide financial assistance for water projects in the regional and state water plans; requiring the agency to focus on a state water grid (including yet another revolving fund to finance it) would only distract it from implementing SWIFT.
- If the TWDB is to be directed to do a water study, what Texas really needs is a study of how much more the state might gain from expanding water efficiency and water conservation measures to minimize the need for additional water infrastructure and all the financial, environmental, and social costs that accompany some of that infrastructure.
- The current situation in California, which has had a system of massive water movements for decades, shows the folly of depending on a water grid in times of drought and also demonstrates the negative impacts of such large-scale water transfers on areas where the water comes from.
- Private property rights are likely to be trampled by a massive water grid that would take private lands for the building of surface water reservoirs and would potentially deplete aquifers that rural areas depend on for their economic vitality.
- The proposed water grid makes no accommodation to the need to maintain river flows and freshwater inflows to the state's highly productive bays and estuaries, which are important not only environmentally but also economically to millions of Texans.

HB 3298 did actually pass the House, with a somewhat surprising large vote in favor, perhaps aided by the assertion that "it's only a study." For environmentalists, it was disconcerting to see that despite the controversy over this proposal, there was little discussion of it on the House floor, and many usually reliable pro-environmental legislators in the House voted for the state water gridzilla. The main opposition to HB 3298 came from Tea Party conservatives and East Texas legislators. In part the outcome on the House floor may have reflected the fact that the bill came to the floor fairly late in the session as House members were trying to move as many of their bills to the Senate as possible. Some observers expected the bill to die in the Senate anyway.

Indeed, HB 3298 was pretty much dead on arrival in the Senate; the bill never even got out of committee despite being carried by the committee chair. The Senate version of water gridzilla, SB 1907, had earlier been voted out of committee but never had enough votes to be brought up on the Senate floor—thanks to opposition from both liberal Democrats and conservative Republicans. A later attempt to add water gridzilla language to another Senate bill on the House floor eventually faltered, and the monster was finally declared dead for the session.

As anyone who follows horror movies knows, however, monsters do not always stay dead. A state water gridzilla proposal is likely to be resurrected—a testimony to the tenacity of water development interests with grandiose ideas going all the way back to at least the 1968 Texas Water Plan. That plan proposed bringing water from the Mississippi River to pipe it around our state for the manifest destiny of Texas. The proposal was defeated at the polls by a coalition of environmentalists and fiscal conservatives.

Almost 50 years later, some things in Texas water politics have not changed. The struggle continues between those whose primary focus, for economic or other reasons, is to develop massive "new" water supplies and those who take a more comprehensive view that emphasizes water efficiency and management and meeting the water needs of both people and the environment.

Stay tuned for the next episode of "Texas Water Politics" in the 85th Texas Legislature.

TEXAS ALLIANCE OF GROUNDWATER DISTRICTS LEGISLATIVE SUMMARY 84th TEXAS LEGISLATURE, REGULAR SESSION

By Sarah Rountree Schlessinger, Executive Director, Texas Alliance of Groundwater Districts

The 84th Texas Legislature, Regular Session saw the introduction of more than 6,000 House and Senate bills, of which 1,323 were passed into law and 41 were vetoed by Governor Greg Abbott. Of these, the Texas Alliance of Groundwater Districts (TAGD) monitored over 300 bills by way of bimonthly tracking reports to its membership, and of which over 120 were identified as high priority groundwater bills. Regular TAGD Legislative Committee meetings were held throughout session to vote on and discuss those bills and to determine TAGD's position on them.

Statistically, both the House and Senate saw an increase in the number of bills filed this year. As such, it was an accurately predicted busy but overall positive groundwater session. TAGD's Legislative Committee showed active engagement throughout, providing expert testimony when necessary and working collaboratively with other stakeholder groups such as the Texas Water Conservation Association (TWCA) Groundwater Consensus Committee.

TAGD's membership at large carried well this session's particular interest in and focus on groundwater conservation districts (GCDs) and can expect a number of signed bills to directly affect daily operations, permitting processes, and regional planning efforts. The 84th Legislative Session also saw a number of local GCD bills, with the creation of 2 new GCDs, the annexation of the Barton Springs-Edwards Aquifer Conservation District as well as local election and fee setting bills.

GCD administration and operations

A number of positive operational housekeeping bills were passed this session. Two of these provide for the use of GCD websites as being in reasonable compliance with requests under the Public Information Act (HB 685) as well as public meeting posting requirements (HB 3357). Estes' Senate Bill (SB) 1267 similarly addresses the Administrative Procedure Act, defining the requirements for posting notice of a hearing in a contested case. Keffer's House Bill (HB) 2767 achieved TAGD and TWCA consensus support, serving as a Chapter 36 clean-up bill and providing clarification of terminology.

Permitting

From a groundwater permitting perspective, the passage of 3 bills in particular should be noted. HB 2179 cleans up the existing permit-hearing process in Chapter 36 of the Water Code, further defining the boundaries of board action as it relates to contested case hearings and preliminary hearings. SB 854 positively streamlines GCD operations by allowing for the automatic renewal of an operating permit without a hearing, provided certain requirements are met.

The passage of HB 655 provides definition of an aquifer storage and recovery (ASR) project and clarification on its permitting process. The bill states that while ASR wells are required to be registered with a GCD and subject to regular well registration fees, the Texas Commission on Environmental Quality (TCEQ) holds exclusive jurisdiction over its permitting. HB 655 requires the TCEQ to limit the recoverable amount of water from the project to the total amount injected, requiring further limitation if it finds unrecoverable losses will occur. The bill further defines that should the project produce more water than the amount authorized for withdrawal by the TCEQ, a GCD's spacing production, permitting rules and fees will apply to the withdrawals above the amount authorized.

Regional planning

Much attention was given to the subject of interstate cooperation and the perception of heterogeneous groundwater management. On a state level, HB 163 addresses interstate cooperation and regional water issues by amending Chapter 8 of the Water Code, laying out the conditions for the water commission created to advise the Governor and the Legislature and renaming it the Southwestern States Water Commission. HB 30 similarly addresses regional water planning by requiring the inclusion of large-scale desalination facilities in regional water plans and expanding the definition of desalination to include both seawater and brackish groundwater.

Perhaps the most significant in regional planning, however, is the passage of HB 200, which revises the desired future conditions (DFCs) appeals process. As part of its revision, HB 200 adds a contested case hearing process for the appeal of a DFC via a State Office of Administrative Hearings (SOAH) hearing and allows a petitioner to appeal a district's final decision to a local district court.

GCD boards

Responding to the increasing pressure placed on district board members, the passage of HB 3163 will positively affect GCD boards and their decision-making process. HB 3163 states that a district board member acting in their individual capacity is immune from suit and liability for actions taken on behalf of the board. Further, HB 3163 determines the attempt to bring suit against a board member for those actions as constituting coercion of a public official.

Local elections

The 84th Legislative Session also saw the passage of a number of local election bills (i.e. HB 1819, SB 363, and SB 2030). Benefiting further housekeeping and financial savings for GCDs, Fraser's SB 733 extends the deadline for a political subdivision to change its election date to the uniform election date to December 31, 2016.

New GCDs

HB 2407 Filed Without Signature: Effective Immediately

Relating to the creation of the Comal Trinity Groundwater Conservation District.

HB 3405 Filed Without Signature: Effective Immediately

Relating to the territory and authority of the Barton Springs/Edwards Aquifer Conservation District to regulate certain wells for the production of groundwater.

HB 4207 Filed Without Signature: Effective 9/1/15

Relating to the creation of the Aransas County Groundwater Conservation District.

Drillers, real estate, and research

Beyond bills directly affecting GCD operations, a number of significant groundwater bills saw success this session. HB 930 amends the Occupations Code by authorizing the Texas Department of Licensing and Registration (TDLR) to reinstate the apprentice driller and apprentice pump installer program. The passage of this bill and restoration of TDLR's programs will help protect Texas aquifers and compliment GCD efforts by ensuring that water well drillers and pump installers receive proper guidance.

Similarly, HB 1221's amendment of the Texas Property Code will compliment GCD involvement in local management by requiring sellers of residential real property to include GCD information as a disclosure form provided to potential buyers. At the state level, the passage of HB 1232 will benefit groundwater management by requiring the TWDB to conduct a study to define the quality and quantity of groundwater and to produce a map showing the area and water quality of aquifer by December 31, 2016.

Vetoed Bills

HB 2647: Vetoed

Relating to a limitation on the authority to curtail groundwater production from wells used for power generation or mining.

Governor Abbott's objections to HB 2647 are expressed in his June 20, 2015 Proclamation, in which he states that HB 2647 "eliminates local discretion by mandating the preferential treatment of certain types of groundwater use over other important uses." Governor Abbott's veto is significant in its protection of GCDs' pursuits to implement management strategies that treat all users equitably and its recognition of the benefit of local groundwater management that responds to local needs and concerns.

Looking ahead

Looking ahead, we expect to see substantial change in Texas water policy leadership. Shortly after the session closed, long-time water policy champions Senator Fraser and Representative Keffer announced that they would not be seeking reelection, followed closely by an announcement of retirement from the Texas Water Development Board (TWDB) Chairman Rubenstein. TAGD intends to participate in the inheritance of their institutional knowledge that has carried the development of Texas water legislation.

With the adjournment of the 84th Texas Legislature on Monday, June 1, 2015, TAGD provided its membership with a final tracking report of a total of 40 bills. Governor Abbott had until Sunday, June 21, 2015 to sign or veto bills. Of those 40, the following bills were passed:

Passed Bills

HB 23 Signed: Effective 9/1/2015

Relating to disclosure of certain relationships with local government officers and vendors.

HB 30 Signed: Effective 6/19/2015

Relating to the development of brackish groundwater.

HB 40 Signed: Effective immediately

Relating to the express preemption of regulation of oil and gas operations and the exclusive jurisdiction of those operations by the state.

HB 163 Signed: Effective 9/1/2015

Relating to interstate cooperation to address regional water issues.

HB 200 Signed: Effective 9/1/15

Relating to the regulation of groundwater.

HB 280 Signed: Effective 9/1/2015

Relating to the information required to be posted by the TWDB on the board's Internet website regarding the use of the State Water Implementation Fund for Texas.

HB 655 Signed: Effective immediately

Relating to the storage and recovery of water in aquifers.

HB 685 Signed: Effective 9/1/2015

Relating to the production of public information available on the website of a political subdivision of this state.

HB 930 Signed: Effective 9/1/2015

Relating to water well drillers and pump installers.

HB 1221 Signed: Effective 1/1/16

Relating to seller's disclosures in connection with residential real property subject to groundwater regulation.

HB 1232 Signed: Effective immediately

Relating to a study by the TWDB regarding the mapping of groundwater in confined and unconfined aquifers.

HB 1378 Signed: Effective 1/1/16

Relating to annual financial reporting of debt information.

HB 1421 Signed: Effective immediately

Relating to fees charged by the Coastal Plains Groundwater Conservation District.

HB 1819 Filed Without Signature: Effective immediately

Relating to the date for the election of directors of the Hill Country Underground Water Conservation District.

HB 2031 Signed: Effective immediately

Relating to the development and production of marine seawater desalination, integrated marine seawater desalination, and facilities for the storage, conveyance, and delivery of desalinated marine seawater.

HB 2154 Signed: See remarks for effective date

Relating to the functions and operation of the State Office of Administrative Hearings.

HB 2179 Signed: Effective immediately

Relating to hearings that concern the issuance of permits by a groundwater conservation district.

HB 2230 Signed: Effective 9/1/15

Relating to the authority of the TCEQ to authorize an injection well used for oil and gas waste disposal to be used for the disposal of nonhazardous brine.

HB 2407 Filed Without Signature: Effective immediately

Relating to the creation of the Comal Trinity Groundwater Conservation District.

HB 2767 Signed: Effective immediately

Relating to the powers, duties, and administration of groundwater conservation districts.

HB 3163 Signed: Effective immediately

Relating to filing suit against board members of groundwater conservation districts.

HB 3357 Signed: Effective 9/1/15

Relating to permitted methods for certain political subdivisions to post notice of a meeting.

HB 3405 Filed without signature: Effective immediately

Relating to the territory and authority of the Barton Springs/Edwards Aquifer Conservation District to regulate certain wells for the production of groundwater.

HB 3858 Signed: Effective immediately

Relating to fees charged by the Coastal Bend Groundwater Conservation District.

HB 4097 Signed: Effective immediately

Relating to seawater desalination projects.

HB 4112 Signed: Effective immediately

Relating to the rights of an owner of groundwater.

HB 4207 Filed without signature: Effective 9/1/15

Relating to the creation of the Aransas County Groundwater Conservation District.

SB 363 Signed: Effective 9/1/15

Relating to election dates for directors of the Bandera County River Authority and Groundwater District.

SB 374 Signed: Effective 9/1/15

Relating to requiring state agencies to participate in the federal electronic verification of employment authorization program, or Everify.

SB 551 Signed: Effective 9/1/15

Relating to the duty of the Water Conservation Advisory

Council to submit a report and recommendations regarding water conservation in this state.

SB 733 Signed: Effective immediately

Relating to the authority of certain political subdivisions to change the date of their general elections.

SB 854 Signed: Effective 9/1/15

Relating to the renewal or amendment of certain permits issued by groundwater conservation districts .

SB 991 Signed: Effective immediately

Relating to a requirement that the General Land Office and the TWDB conduct a study regarding the use of wind and solar power to develop and desalinate brackish groundwater.

SB 1101 Signed: Effective 9/1/15

Relating to the authority to determine the supply of groundwater in certain regional water plans.

SB 1267 Signed: Effective 9/1/15

Relating to contested cases conducted under the Administrative Procedure Act.

SB 1336 Signed: Effective 9/1/15

Relating to the construction of laws and election dates of certain groundwater conservation districts.

SB 1812 Signed: Effective immediately

Relating to transparency in the reporting of eminent domain authority and the creation of an eminent domain database.

SB 2030 Signed: Effective 9/1/15

Relating to the election date of the North Plains Groundwater Conservation District.

SB 2049 Signed: Effective 9/1/15

Relating to qualifications of members of the board of directors of the Lone Star Groundwater Conservation District.

TEXAS WATER INFRASTRUCTURE NETWORK SUMMARY OF LEGISLATION IMPACTING THE TEXAS WATER INFRASTRUCTURE MARKET IN THE 84th TEXAS STATE LEGISLATURE

By Perry L. Fowler, Executive Director, Texas Water Infrastructure Network

The Texas Water Infrastructure Network (TxWIN) is a 501 C6 non-profit trade association founded in September, 2013 to represent the interests of general contractors, subcontractors, service suppliers, and equipment and materials suppliers and manufacturers involved in the planning and construction of water infrastructure projects. TxWIN is the only statewide association specifically focused on construction issues and advocacy in the Texas water infrastructure market. TxWIN's primary focus is to provide our advocacy and resources for our membership in active partnership with owners, legislators, regulatory bodies and other industry organizations to ensure a healthy and competitive construction market place that promotes value for public dollars invested in water infrastructure projects.

TxWIN entered the 2015 Texas Legislative Session with a narrow focus on promoting specific contracting reforms and supporting a broader legislative agenda to promote fair and ethical contracting, reduced regulatory burdens, and responsible policy in the promotion of Texas water infrastructure projects. TxWIN tracked over 350 bills throughout the course of the session, and the following legislation is of particular interest for governmental entities and others involved in the finance, construction, and design of water infrastructure projects.

While there are still many issues in the contracting realm that need to be addressed, overall this was a very positive session for the promotion of the TxWIN legislative agenda, which, in turn, should benefit all facets of the broader market including owners and the public.

TxWIN looks forward in the 2017 session to working closely with the owner and design professional community in addition to legislators and regulators to address a number of contracting and procurement issues in the promotion of a healthy and competitive Texas construction market.

TxWIN-supported legislation that passed

House Bill (HB) 23 (Davis/Nelson)

Relating to disclosure of certain relationships with local government officers and vendors.

TxWIN supported this local ethics and contracting legislation, which increases disclosure and reporting requirements for local government officials and employees who may influence in the contract selection process, and also includes disclosure requirements for vendors and other entities seeking to enter contracts with political subdivisions. HB 23 expands definitions of what constitutes "conflicts of interest" providing criminal penalties for failure to disclose gifts including travel and meals. This may be 1 of the most important bills to pass this session to ensure that there is transparency on the local level regarding those who seek to influence local contracting processes.

HB 2475 (Geren/Eltife)

Relating to the establishment of the Center for Alternative Finance and Procurement within the Texas Facilities Commission and to public and private partnerships.

TxWIN supported legislation that clarifies rules and procedures and promotes transparency for public-private partnerships including application of Government Code 2269 for alternative project delivery contracting and procurement process.

HB 2634 (Kuempel/Zaffirini)

Relating to the construction manager-at-risk used by a governmental entity.

TxWIN supported this contracting reform legislation that reforms the construction manager-at-risk (CMAR) project delivery method and contracting process. Current public works contracting law for CMAR in Gov. Code 2269.251 calls for separate contracts for design and construction but failed to expressly ensure that said contracts were awarded to separate entities per industry best practices, allowing qualifications to be established which favored related "construction" entities of design firms thus undermining the competitive process. HB 2634 amends the law by prohibiting related entities from serving as designer and construction manager-at-risk. For example, an integrated engineering firm may not serve as both the designer and construction manager, or general contractor. This change in the law eliminates potential conflicts of interest and misuse of the CMAR method as de-facto design-build without appropriate safeguards where qualifications might be crafted which undermine the competitive process for procuring the CMAR contractor. HB 2634 not only ensures the integrity of the competitive process but also ensures the appropriate use of the CMAR procurement and project delivery method, eliminating potential conflicts of interest that undermine protections for public owners. This may be the most significant contracting legislation of the session with respect to the design and construction of water infrastructure projects.

HCR 96 (Hunter)

Requesting the Speaker of the House of Representatives and the Lieutenant Governor to create a joint interim committee to study the issue of advertising public notices.

Several bills were introduced this session with the goal of reducing costs, making public notices more accessible to the public, and providing additional flexibility to political subdivisions through the use of electronic means. This concurrent resolution assures the issue will be discussed and evaluated in the interim.

Senate Bill (SB) 20 (Nelson/Price)

Relating to state agency contracting.

Omnibus state contracting reform bill. Although this legislation will not affect financial assistance from the TWDB or locally administered funds, TxWIN will monitor the implementation of this legislation, which is intended to promote fair and ethical contracting reforms for direct state contracting and purchasing including additional review authority for large contracts and training for state agency purchasing personnel.

SB 709 (Fraser/Morrison)

Relating to environmental permitting procedures for applications filed with the Texas Commission on Environmental Quality.

This legislation expedites and streamlines TCEQ permitting process.

Other legislation of interest that passed

SB 1081

Relating to the disclosure of certain information under a consolidated insurance program.

HB 2049

Indemnification and duties of engineers and architects under certain governmental contracts.

This legislation removes from the obligations of architects and engineers to defend local governments and limits their obligation to repay local governments for liability from negligence or fault. The bill also allows local governments to be insured on the architect's or engineer's general liability policy and establishes a standard of care for architects and engineers to perform services.

Other significant contracting and related legislation that did not pass

HB 1007

Relating to the purchase of iron, steel, and manufactured goods made in the United States for certain state, state-aided, and governmental entity construction projects.

This legislation would have applied U.S. iron, steel and manufactured good requirements to all state and local public construction contracts adding increased costs, regulatory burdens and unnecessary liability for contractors. These types of policies diminish local control and fail to recognize the global supply chain that is particularly important with regard to highly complex technologies used in water and wastewater treatment plants.

SB 1337

Relating to the authority of the TWDB to provide financial assistance to political subdivisions for water supply projects.

This legislation would have expanded TWDB flexibility for financial assistance programs. Unfortunately, an amendment expanding "Buy American" requirements was added to the legislation on the floor of the house that would have expanded application of requirements for U.S. iron, steel materials and manufactured goods to SWIFT funded projects thus increasing costs, regulatory burdens and constraining choices of financial assistance recipients.

HB 3687

Relating to design-build procedures for civil works projects.

This legislation would have added 1-step design-build authority for civil works construction projects, creating a subjective procurement process without cost considerations that would have seriously impacted the ability to determine project costs and conduct competitive procurements. The bill also sought to remove all current population and project limits. Without additional safeguards to ensure fair competition in the evaluation of design-build qualifications and additional procurement safeguards TxWIN will not support expansion of current design-build authority.

HB 3688

Relating to the process for the selection of construction managers-at-risk used by governmental entities.

This legislation would have completely gutted the CMAR process allowing it to be used as de facto design build without any appropriate safeguards or rules.

HB 3939

Relating to the requirements for construction projects for certain public works projects.

This retainage reform legislation would have required retainage to be placed in an interest-bearing account for public works construction projects, and prohibited retainage in excess of 5% without consent of the prime contractor. HB 3939 also would have eliminated the practice of "hidden retainage" by prohibiting withholding of payments on additional items in the schedule of values or contract general conditions. The legislation also prohibited the practice of withholding retainage for non-allocated project funds and withholding of retainage during the warranty period. The legislation also established a trigger for release of retainage once facilities were capable of being used for their intended purpose.

TxWIN looks forward to working with the owner community in the interim to address retainage issues in the hope of reaching consensus on reforms that will bring more fairness to the process.

Texas Water Resources Institute
Texas Water Journal
Volume 6, Number 1, Pages 121–135

Texas water policy appendix: the weather

Carlos Rubinstein[1,2]

Abstract: The climate of Texas makes our state particularly susceptible to droughts, floods, and hurricanes. Weather events over the past 150 years have resulted in policy changes at the state and federal level that have helped us prepare for, respond to, and prevent weather disasters. Many of these efforts have been successful; however, continuous planning and improvement will be necessary to meet the needs of our growing population. Recent droughts and floods have demonstrated that traditional infrastructure must work in tandem with early forecasting and warning systems, which will require effective policies at both the state and federal level to support them along with citizen engagement.

Keywords: Drought, flood, weather, disaster, planning

[1]Former Chairman and Board member of the Texas Water Development Board (TWDB), and former Commissioner, Deputy Executive Director, and Rio Grande Watermaster of the Texas Commission on Environmental Quality.

[2]The author wishes to extend special thanks to TWDB staff for their assistance with the article: Kathleen B. Ligon, Senior Policy Analyst; Todd Chenoweth, Senior Advisor; and Dr. Robert Mace, Deputy Executive Administrator.

Corresponding author: kathleen.ligon@twdb.texas.gov

Citation: Rubinstein C. 2015. Texas water policy appendix: the weather. Texas Water Journal. 6(1):121-135. Available from: https://doi.org/10.21423/twj.v6i1.7015.

Term used in paper

Short name of acronym	Descriptive name
TWDB	Texas Water Development Board

INTRODUCTION

In 1892, Mark Twain published the novel the *American Claimant*, at the beginning of which he announced: "No weather will be found in this book." It was reportedly the first work of fiction without mention of the weather; all weather was contained in an appendix at the back of the book, which the reader was encouraged to consult from time to time.

Fittingly, the book was published near the beginning of the modern era of weather recordkeeping. As Mark Twain concedes, despite being relegated to an appendix, "…weather is necessary to a narrative of human experience." This observation holds true for the weather in Texas, which has not only informed how we manage our water and our other natural resources, but has also helped shape the course of our history. Knowledge of these events is essential to a thorough understanding of Texas water policy.

In addition to the advent of scientific recordkeeping, a considerable amount of change has occurred since the late 1800s in not just how we manage our water resources but how we live our daily lives. Before 1900, most Texans got their water from private wells, springs, rainfall, or running streams. Plumbing was rare, and there were no sewage treatment plants, little to no treatment of drinking water, and no significant flood control or water supply infrastructure (Freese and Sizemore 1994). Texas saw tremendous population growth in the last 50 years of the 19th century, growing from just over 200,000 to 3 million (Figure 1). This growth set the stage for steady and significant progress in water management during the entire 1900s, and our weather undoubtedly played a role in that progress.

Climate of Texas

The climate of Texas is marked by extremes in temperature, precipitation rates, and the variation and extent of severe weather, making our state particularly susceptible to droughts, floods, and hurricanes (TWDB 1966). Since 1980, Texas has suffered the greatest number of billion-dollar weather and

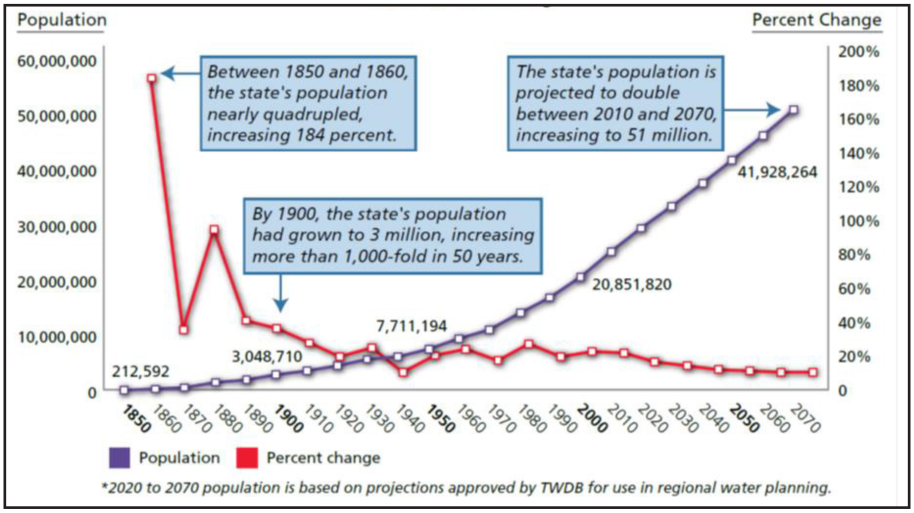


Figure 1. Texas historical and projected population growth* and percent change.

climate disasters of any U.S. state, with 58 such disasters (NOAA 2015a).

Droughts have influenced Texas history since the very beginning of European settlement and before. Though droughts develop slowly, they can ultimately have socio-economic consequences as catastrophic as other weather disasters. Droughts have devastated Texas agriculture, caused hardship in all economic sectors, and early in our history, left communities vulnerable to fire and famine. Modern droughts still cause economic hardship but have helped foster a growing appreciation of water as a scarce resource that should be conserved—even in times of plenty.

As we have witnessed in recent events in 2015, floods can take an especially dramatic toll on our collective conscious, since their sudden force can result in a swift and ruthless taking of human life. Prior to the construction of much of our flood control infrastructure and use of early warning systems, major floods could take hundreds of lives in a single event, often disproportionally affecting economically disadvantaged settlements in low-lying areas. Prior to the construction of dams on the Colorado River, our state capital was bifurcated by major floods on multiple occasions.

Central Texas—often called "Flash Flood Alley"—has a greater risk of deadly flash flooding than most regions of the United States because of its steep terrain, shallow soils, and unusually high rainfall rates. Heavy rains can quickly transform rivers and streams into walls of fast-moving water that can evade even our contemporary warning systems (LCRA 2015a).

The construction of dams not only made much of the state far safer from catastrophic floods but also put people to work during the Depression of the 1930s. These dams provided electricity to the rural Texas Hill Country, which lagged considerably behind most of the country in electrification. Construction of multipurpose reservoirs in the 20th century also provided reliable water supplies in an otherwise arid landscape.

It is difficult to compare droughts because of the variables in measuring them, and floods are just as challenging to compare. Droughts are generally ranked by intensity, duration, and areal extent. Floods are evaluated by comparison of peak flow with known averages, intensity and duration of rainfall rates, and areal extent of flooding. Rain can fall in tremendous amounts and flood relatively small geographic areas, such as the 2015 Memorial Day weekend floods in Blanco and Hays counties. Floods can also occur when considerable amounts of rain fall over a large area of the state, such as the 1957 floods that affected most of the major river basins of Texas. Floods can occur at the beginning, end, or even during a major drought event. Some floods are most notable for the catastrophes that they *did not* cause, because of infrastructure that tempered their effects.

Weather and public policy

It is axiomatic to say that weather drives state water policy. Both droughts and floods have led to the creation of many of our water management entities, such as river authorities, state agencies, and hundreds of local water districts. Weather events have informed how we administer surface water rights, regulate groundwater, and plan for future water supplies and flood mitigation.

The "appendix" that follows provides a brief summary of many of Texas' major weather events in the past 150 years, the state's population at the time, and policy changes at the state and federal level that resulted from these events. As can be seen in the timeline, some weather events unmistakably precipitated specific policy changes, such as the droughts of the 1880s that made fence cutting a felony and the 1950s drought that brought about mechanisms to both fund water projects and plan for future droughts. Other weather events likely had indirect or cumulative effect on public policy over time.

This timeline is not comprehensive due to time and space constraints: droughts and floods have occurred in Texas in every single decade of the last 100 years. Several other excellent histories and timelines are available, without which this piece would not have been possible. Most notably, these include:

- Texas Water Law Timeline (LRL 2015)
- Timeline of Droughts in Texas (TWRI 2011)
- National Water Summary 1988–89, Hydrologic Events and Floods and Droughts (USGS 1991)
- A Century in the Works, Freese and Nichols Consulting Engineers, 1894–1994 (Freese and Sizemore 1994)
- A Chronology of Major Events Affecting the National Flood Insurance Program (American Institutes for Research 2005)

The primary purpose of this article is to not only provide context to the evolution of state and federal policy related to droughts and floods but to prompt the reader's consideration[1] of our successes, failures, and challenges to come, such as:

- Are our current policies and planning processes sustainable?
- How reliable is our current infrastructure?
- How effective are our early warning systems?
- How viable are our current plans?

[1] Consideration of the vast scope of these issues will not be attempted in this article, but it is hoped that they will be explored further in other venues.

TIMELINE

Prior to 1900

1850 Population: 212,592

1860 Population: 604,215

1870 Population: 818,579

1880 Population: 1,591,749

1890 Population: 2,235,527

Flood of 1869: *After 64 hours of continuous rains in July—and prior to any significant damming of the river—the Colorado River crested at 51 feet in Austin and inundated both Bastrop and La Grange. The flood still stands as the worst on record for the Colorado River (LCRA 2015b).*

1875 Indianola Hurricane: *At the peak of Indianola's prosperity, the storm nearly wiped out the low-lying city and caused considerable loss of life (Malsch 2015).*

Droughts of mid-1800s: *Predating official weather records, the droughts devastated farmers new to the dry climate of Texas, with some suffering up to complete crop losses (TSHA 2002). The drought was a landmark in the history of West Texas, with many old settlers referring to events as taking place, "before the drought" or "after the drought" (TSHA 1928).*

1886 Indianola Hurricane: *After rebuilding from the previous decade's storm, the hurricane and accompanying fire permanently destroyed Indianola.*

Flood of 1899: *In June, average rainfall of almost 9 inches fell over 60,000 square miles, causing the Brazos River to overflow and inundate an estimated 12,000 square miles (Bishop 2010).*

Texas and the American West saw a great deal of change in the later decades of the 19th century. Pioneers from the eastern states that came to Texas to farm were unaccustomed to and unprepared for the harsh and variable weather, particularly droughts. The drought in the mid-1880s led to policy discussions at both the state and federal level. The "fence cutting wars"—a series of disputes in Texas and the American West—were exacerbated by the drought that made it more difficult for those without land of their own to find grass and water necessary for grazing herds of cattle. By the fall of 1883, the conflict between landless cattlemen and those who fenced land with barbed wire, first patented in 1874, had resulted in millions of dollars in damages, discouraged farming, and scared away prospective settlers. Governor John Ireland called a special session of the Texas Legislature to meet January 1884; after heated debates, the Legislature made fence cutting a felony punishable with prison time (Gard 2015). Though this action did not affect water policy per se, it effectively linked Texans' access to water with private property rights.

The drought of the 1880s also resulted in the creation of a state geological survey[2]—to study artesian wells and to propose a state program to build reservoirs—and the introduction of a prior appropriation system of "first in time, first in right" for managing surface water. Inspired by the plight of the farmer and rebelling against the interests of cattlemen, Governor Lawrence Sullivan "Sul" Ross advocated for prior appropriation in Texas. The Legislature passed the First Irrigation Act in 1889, establishing the doctrine of prior appropriation in the arid portion of the state; all unappropriated water was declared to be the state's property but could be acquired through a "certified fining." In 1895, the Second Irrigation Act applied the prior appropriation system statewide (LRL 2015).

At the national level, the drought of the mid-1880s set off a policy debate on how the federal government should respond to disasters. In response to efforts by John Brown, an Albany, Texas minister, and those of Clara Barton, founder of the American Red Cross, Congress passed the Texas Seed Bill of 1887. The bill appropriated $10,000 for the purchase of seed grain for distribution to farmers in Texas counties that had suffered from the drought. The legislation was vetoed by President Grover Cleveland, but the Texas Legislature appropriated $100,000 for drought relief, providing a little over $3 to each needy person. The Red Cross and other donors also sent clothing, household goods, tools, and seed to drought-stricken areas (TSHA 2002).

Despite a number of major floods around the country, no far-reaching state or federal policy actions relating to floods emerged until the beginning of the 20th century, with the exception of the initiation of the U.S. Geological Survey Stream Gaging Network in 1889. The purpose of the initial network was to determine the potential for irrigation development in 8 river basins in the arid West, a vital concern for the economic development of the region. Now known as the National Streamflow Information Program, the network is a cooperative effort between federal, state, and local agencies. Data produced by the program is used for forecasting and operational decisions as well as long-term resource planning, infrastructure design, and flood hazard mitigation (USGS 1998).

1900s

1900 Population: 3,048,710

Galveston Hurricane of 1900: *Although more violent and costlier storms have struck coastal areas of the United States in the years since, the September hurricane is still widely known as the*

[2] A drought in 1856 led to the creation of a first geologic survey to make scientific recommendations on soil utilization and water resources to assist drought-stricken farmers, but the survey was suspended after the start of the Civil War.

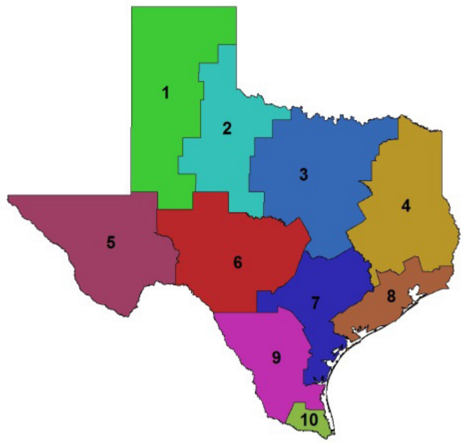
deadliest natural disaster in our country's history. The Category 4 storm submerged the entire island and took an estimated 6,000 to 12,000 lives (NOAA 2015b).

Flood of 1900: *In April, flooding destroyed a 500-foot section of the original Austin Dam, reported at the time to be the largest dam in the world spanning a major river. Shortly after it was reconstructed, the dam suffered damage in 1915 and again in 1935 (Freese and Sizemore 1994). Remains of the old structures can still be seen just downstream of Tom Miller Dam, dedicated in 1940 as the "Third and Final Austin Dam."*

Drought of 1896 to 1902: *Though much of Texas escaped the worst of the turn-of-the-century drought, it was one of the state's longest and most intense, particularly for northeast Texas and the lower Rio Grande Valley (Table 1).*

Flood of 1908: *In May, a 10-inch rainfall in the upper Trinity*

Table 1. Ranking of Palmer Drought Severity Indices based on drought duration and intensity for climate divisions of Texas.



Climate Division	Duration Ranking 1	Duration Ranking 2	Duration Ranking 3	Peak Intensity Ranking 1	Peak Intensity Ranking 2	Peak Intensity Ranking 3
1: High Plains	1950 to 1957	2010 to 2014	1961 to 1965	2010 to 2014	1950 to 1957	1932 to 1936
2: Low Rolling Plains	1951 to 1957	2010 to 2014	1962 to 1966	2010 to 2014	1951 to 1957	1915 to 1918
3: Cross Timbers	1950 to 1957	1908 to 2013	2010 to 2014	1950 to 1957	1924 to 1925	1915 to 1918
4: Piney Woods	1908 to 2013	1896 to 1899 & 1962 to 1965		2010 to 2013	1915 to 1918	1924 to 1925
5: Trans-Pecos	1949 to 1957	1998 to 2003	1961 to 1966	2010 to 2014	1949 to 1957	1915 to 1918
6: Edwards Plateau	1949 to 1957	2010 to 2014	1908 to 1912	2010 to 2014	1949 to 1957	1915 to 1918
7: Post Oak Savanna	1949 to 1957	2010 to 2014	1915 to 1918 & 1896 to 1899	1949 to 1957	2007 to 2009	2010 to 2014
8: Gulf Coastal Plains	1961 to 1965	2010 to 2014	1937 to 1940 & 1953 to 1957	1915 to 1918	1953 to 1957	2010 to 2014
9: South Texas Plains	1949 to 1957	1906 to 1911	2010 to 2014	2010 to 2014	1949 to 1957	2008 to 2009
10: Lower Rio Grande Valley	1896 to 1902	1906 to 1911	1949 to 1954	1896 to 1902	2010 to 2014	2004 to 2006
Entire State	**1950 to 1957**	**2010 to 2014**	**1961 to 1965**	**2010 to 2014**	**1950 to 1957**	**1915 to 1918**

*Drought duration is defined as the number of months from when the Palmer Drought Severity Index went negative to when it returned to a positive (or zero) value; drought "intensity" is defined as the lowest (peak) value of the Palmer Drought Severity Index during the drought period.

River Basin caused flooding in Dallas, killing 11 people (TRA 2015). It was immediately followed by the most serious drought and water supply crisis of the city's history (Freese and Sizemore 1994).

Shortly after its first drought, the 20th century was marked with a momentous state water policy shift when the Texas Supreme Court in 1904 adopted the "rule of capture" doctrine in *Houston & T.C. Railway Co. v. East*. Though Texas had historically followed the English common law rule that landowners have the right to remove all of the water that can be captured from beneath their land, the *East* case and later court rulings established that landowners, with few exceptions, may pump as much water as they choose without liability.

That same year also marked the beginning of a new era of water development efforts, with Texas voters approving a constitutional amendment allowing local issues of bonds and lending of credit for irrigation, navigation, flood control, drainage, and other public purposes (TLC 2014).

1910s

1910 Population: 3,896,542

Drought of 1908 to 1913: *The drought was second in duration only to the drought of the 1950s in a large portion of the state, impacting the heart of Texas from the Oklahoma border to the lower Rio Grande Valley. At the worst of the Dallas drought, water mains were used only for fire protection and tank wagons were provided for domestic supply (Freese and Sizemore 1994).*

Flood of 1913 (Figure 2): *In December, the Guadalupe and Trinity rivers left their banks and the Colorado and Brazos rivers were joined by floodwaters below Columbus, resulting in a lake 65 miles wide covering over half a million acres (LCRA 2015b). The flood killed 177 people and caused the Brazos River to change course and enter the Gulf of Mexico at Freeport (USGS 1991).*

Drought of 1915 to 1918: *One of the most significant droughts in Texas history, the drought of the mid-1910s severely impacted the state's economy.*

As bad as the flood of 1913 was in Texas, it was eclipsed by events on the Mississippi and Ohio rivers. A flood the same year in the Ohio River valley killed over 400 people, caused extensive property losses, and spurred great public interest in flood control (American Institutes for Research 2005). In response, Congress approved the Flood Control Act of 1917, the first federal act aimed exclusively at controlling floods. Though the $45 million program was targeted solely at the lower Mississippi and Sacramento rivers, the action set a precedent with the federal government accepting responsibility for flood control (American Institutes for Research 2005).

The decade's weather events also led to policy developments at the state level. As a result of the drought, the 1913 Burges-Glasscock Act created the Texas Board of Water Engineers to regulate appropriations of water and to centralize claims for water rights. After the epic flooding, the Brazos River and Valley Improvement Association was formed with the goal of harnessing the Brazos River, but the association's efforts were hindered by a lack of financing (BRA 2015). The Legislature responded by passing the Conservation Amendment of 1917, enabling the creation of "conservation and reclamation districts" to develop water resources. The conservation amendment was significant because it declared water resources to be public rights and duties. The Legislature used this authorization over the next several decades to create a number of new special purpose districts, later dubbed river authorities, to build and operate public works such as dams and water delivery systems.

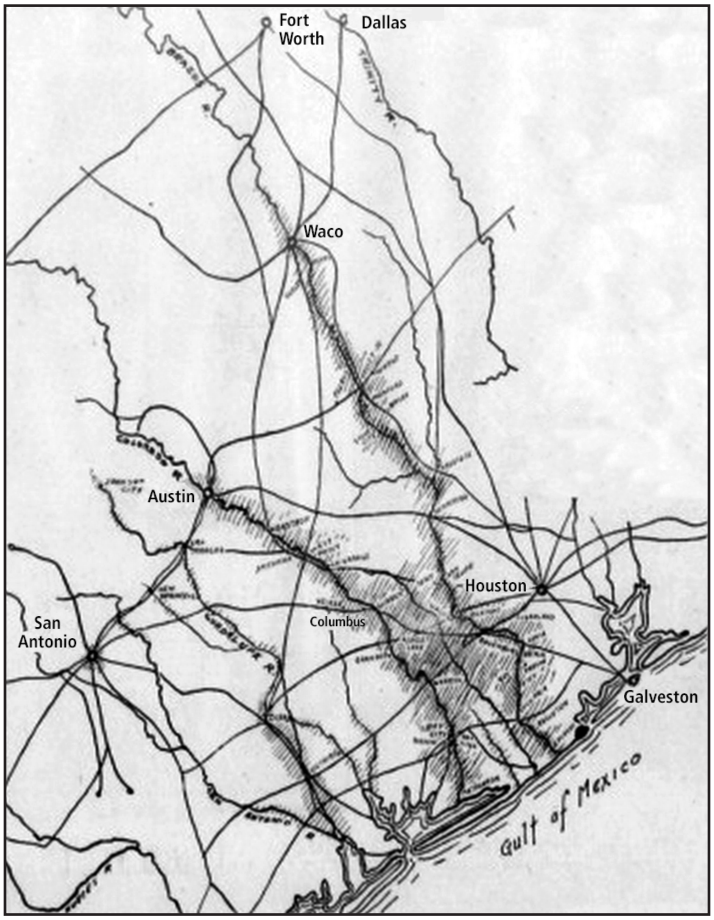


Figure 2. 1913 flood on the Brazos and Colorado Rivers (San Antonio Express News 1913). The Colorado and Brazos rivers were joined by floodwaters below Columbus, resulting in a lake that covered over half a million acres just southwest of Houston.

1920s

1920 Population: 4,663,228

Flood of September 1921: *A tropical storm produced widespread flooding in Central Texas that caused a 12-foot flood wave to rush through downtown San Antonio. Statewide, 215 deaths were reported and rainfall totals at Thrall—over 38 inches in 24 hours—set a Hill Country record (USGS 1991).*

Flood of 1922: *A cloudburst in April inundated low-lying sections of Fort Worth, drowning 16 people and driving hundreds from their homes. The flood shut down the city's water system and washed out rail lines and nearly a mile of the city's levee system (Freese and Sizemore 1994).*

After the extensive damage to the San Antonio business district from the 1921 flood, the next year San Antonio began construction of Olmos Dam, the first Texas dam specifically for flood control (TWC 1964).

Despite its local impacts, the 1922 Fort Worth flood proved to have ripple effects far beyond the city. Local groups quickly began to investigate how to prevent such a disaster from happening again, culminating in the creation of the Tarrant County Water Improvement District in 1924. It soon became clear though that Texas law was inadequate to allow the district to effectively and economically address the city's dual problems of water supply and flood control. After local interests proposed legislation, the Texas Legislature passed the Water Control and Improvement District Act of 1925. The first such district in Texas, Tarrant County Water Control and Improvement District Number One, was approved in 1926. The next year Tarrant County voters approved the construction of Bridgeport and Eagle Mountain reservoirs, the first large reservoirs in the country to provide separate capacities for flood control and water supply (Freese and Sizemore 1994).

In 1923, the Legislature appropriated funds for a survey of all rivers in the state and an analysis of flood and water problems (BRA 2015). The study clearly established the need for a state agency with sufficient powers to tame the Brazos River (BRA 2015). In 1929, 12 years after the passage of the Conservation Amendment, the Legislature authorized the creation of the first river authority—the Brazos River Conservation and Reclamation District[3]. A milestone event in the history of water management, the law was the first in the country to assign the management of a river and its watershed to a single public entity (Freese and Sizemore 1994).

[3]The name of the district was officially changed to the Brazos River Authority in 1955.

1930s

1930 Population: 5,824,715

"The Dust Bowl" of 1930s: *Caused by drought, high temperatures, strong winds, and a failure to prevent wind erosion, the Dust Bowl affected millions of acres across the Great Plains. The worst year for storms was 1935, when 1 complete blackout lasted for 11 hours in Amarillo (Worster 2015).*

Floods of 1930s: *Heavy rainfall in West Texas in 1935, 1936, and 1938 resulted in massive downstream flooding on the Colorado, making the river impassable and splitting the city of Austin in two (LCRA 2015b). San Angelo was hit the worst with rains exceeding 30 inches over a large part of the Concho River Basin during September 1936 (Slade 2003).*

The 1930s were eventful for water policy at both the state and federal level. It began with the passage of the state Wagstaff Act of 1931, which provided protection to upstream municipal water suppliers from downstream senior appropriations for hydroelectric and irrigation purposes. The act declared that it was the public policy of the state that in the allotment and appropriation of water and issuance of permits after the date of the act, preference and priority were to be given to uses in the order listed in statute. Domestic and municipal were first priority, followed by agricultural and industrial uses, followed by mining, hydropower, and other beneficial uses. The Wagstaff Act also recognized the prior appropriation doctrine but further provided that new appropriations of water would be granted subject to the right of municipalities to make additional appropriations without the necessity of condemnation or paying for that water[4].

Like the floods of 1913, those of the mid-1930s were not unique to Texas: disastrous events on a number of the nation's rivers galvanized Congress behind the cause of flood control (Arnold 1988). The resulting Flood Control Act of 1936 represented an initial step toward the development of a national flood control program by providing for studies, surveys, and the construction of around 250 projects using work relief funds (American Institutes for Research 2005).

After the Legislature created the Lower Colorado River Authority in 1934, the state's third river authority[5] received a $20 million federal allotment to complete the Highland Lake dams and reservoirs above Austin; the federal appropriation was third only to federal funds provided for Hoover and Grand Coulee dams (Freese and Sizemore 1994). Combining flood control, water supply, and power, the Highland Lakes

[4]This provision was controversial but never used and therefore never tested in court. It was finally repealed in 1997.

[5]The Guadalupe-Blanco River Authority, created in 1933, was the state's second river authority.

were one of the most important national river developments of the decade. Federal New Deal programs also funded the Red Bluff Dam on the Pecos River and a number of smaller water projects around the state.

The Dust Bowl of the 1930s prompted a considerable amount of debate regarding groundwater management. In 1936, President Roosevelt created the Great Plains Committee, which noted that the Great Plains states, with the exception of New Mexico, had inadequate or non-existent groundwater statutes. State legislation to regulate groundwater failed in 1937, but the following year the Texas Board of Water Engineers called for state ownership of groundwater, echoing previous recommendations.

In 1935, Texas Governor James Allred created the Texas Planning Board to seek federal emergency Depression relief funds and to make recommendations for a number of other issues, including development of the state's natural resources (Freese and Sizemore 1994). In 1938, the Board published, *Development of Texas Rivers, A Water Plan for Texas* (Figure 3). Effectively the first comprehensive state water plan, it acknowledged that flood protection, hydroelectric power, and water supply development should not be treated separately from one another (TPB 1938a). The plan inventoried water problems in each major Texas river basin and included recommendations for each basin that addressed an impressive range of issues: salt water intrusion, waste disposal, water supplies, malaria control, flood control, drainage, hydroelectric power, navigation, land use and conservation, streamflow measurement, groundwater surveys, topographic mapping, and climate data. Notably, the plan included a prioritized list of projects for each basin, a concept not truly utilized again in Texas water planning until the Legislature and voters approved creation of the State Water Implementation Fund for Texas in 2013.

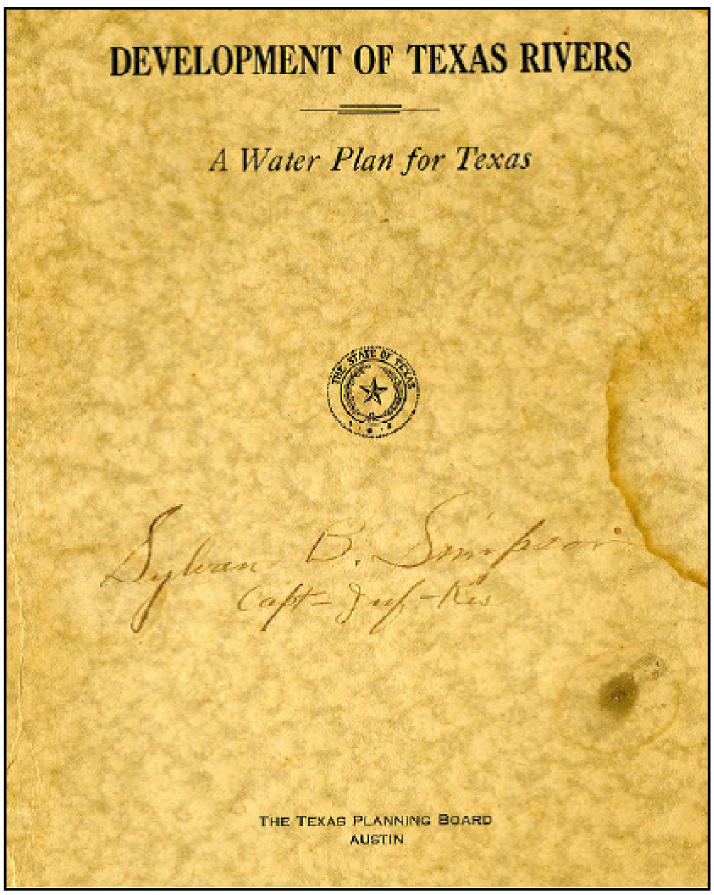


Figure 3. The Texas Planning Board's 1938 water plan. Effectively Texas' first comprehensive state water plan, the plan advocated that flood protection, hydroelectric power, and water supply development should not be treated as separate issues.

The Texas Planning Board also weighed in on the groundwater debate. The Board sent a second report to Governor Allred in 1938 calling for "administrative control of ground water," in the form of legislation consistent with existing surface water law (TPB 1938b).

1940s

1940 Population: 6,414,824

Veritably the calm before the storm, Texas experienced only a few notable floods during the decade of the 1940s and no significant droughts, with the exception of the beginnings of the drought of the 1950s that got an early start in the western and south central portions of the state (Table 1).

Continuing the groundwater debate from the previous decade, state legislation to regulate groundwater failed again in 1941. In 1946, both Lubbock and Big Spring passed resolutions calling for the regulation of groundwater, but irrigation interests from the High Plains formed a group called the High Plains Water Conservation and Users Association to fight legislation to regulate groundwater.

Groundwater legislation died once more in 1947, and concern over water level declines continued to grow with more calls for regulation by industry and municipal groups. Finally in 1949, the Texas Legislature authorized the creation of groundwater conservation districts for the local management of groundwater. The weather of the 1940s may have been uneventful, but the Texas Groundwater Act represented a landmark event in the evolution of Texas water policy. The first district created was the Martin County Underground Water Control District Number 1 in September 1951[6], followed by 5 more in the Texas Panhandle in the 1950s.

[6]Martin County Underground Water Control District No. 1 was later reorganized with Howard County to form the Permian Basin Underground Water Control District in 1985.

1950s

1950 Population: 7,711,194

Drought of the 1950s (Figures 4a, 4b, and 4c): *For most of Texas, the drought of the 1950s is still the longest drought in recorded history. In 1953, 28 municipalities were forced to use emergency sources of water supply, 77 were rationing water, and 8 resorted to hauling in water from neighboring towns or rural wells (TBWE 1959). In 1956, President Dwight Eisenhower declared most of Texas' counties as drought disasters.*

Flood of 1952: *In the middle of the state's worst drought on record, September rains caused Lake Travis to rise 57 feet in about 14 hours (LCRA 2015b). It was later estimated that without the capacity of Lake Travis to store floodwaters, peak flow would have been over 803,000 cubic feet per second at the Colorado River at Austin, instead of 3,720 cubic feet per second as recorded (USGS 1991).*

1954 Hurricane Alice: *In June, the storm moved directly up the Rio Grande Valley and stalled between the Devils and Pecos river drainages, flooding much of Eagle Pass and Laredo. Falcon Dam, just completed in October 1953, captured the floodwaters and in doing so went from nearly empty to close to conservation storage in only 3 days (Slade 2003).*

Floods of 1957: *Ending the historic drought, May rains flooded much of the state, recharging groundwater and sending many reservoirs over their spillways (Freese and Sizemore 1994).*

The entire 1950s proved to be a watershed year in Texas, with some activity also at the federal level. Proving opportune and timely for Texas later in the decade, Congress passed the Disaster Relief Act of 1950 to assist states and local governments in responding to major disasters without the need for congressional action. State governments had to formally request the president declare a major disaster, and if granted, the federal government could then provide disaster assistance to supplement state and local resources (American Institutes for Research 2005).

Following massive flooding in Kansas and Missouri in 1951, President Harry Truman recommended the creation of a national system of flood disaster insurance; however, no law providing a federal source of flood insurance was enacted until the Federal Flood Insurance Act of 1956. Despite extensive discussions among various federal agencies, state and local governments, and the insurance industry, no program was ultimately developed to implement the act, and Congress refused to grant appropriations.

After World War II, Texas and the nation saw a great spike in water consumption due to increased use per person, rapid population growth, urbanization, and industrialization. These factors, combined with an unprecedented drought, made for a busy water policy decade. While cities did what they could to survive the drought, many interests continued to persist for a comprehensive, long-term solution to the state's water problems (Freese and Sizemore 1994). In 1953, the Legislature created the Texas Water Resources Committee to make a detailed inventory of both surface water and groundwater in the state and to develop a long-range water policy and conservation program. By 1957, the committee had drafted 16 bills, including 1 that would authorize state support of local water development projects (Freese and Sizemore 1994).

Following the May 1957 rains, the Legislature passed a resolution in August that authorized $200 million in bonds to help construct water supply projects and created the Texas Water Development Board (TWDB) to administer the funds from the bond sale. In November, voters approved the constitutional amendment—by a greater than 2 to 1 margin—authorizing the TWDB to administer the $200 million water development fund. Then in December of that year, the Legislature passed the Water Planning Act of 1957 during a special session called by Governor Price Daniel. The act created the Water Resources Planning Division of the already existing Board of Water Engineers, which was assigned the responsibility of water resources planning on a statewide basis[7].

In addition to new planning and financing mechanisms, the historic drought brought about other significant changes in Texas water law. In the 1950s, Texas still recognized stream-side landowner or "riparian" water rights based on English common law, along with the western prior appropriation system. This dichotomy continued to lead to conflicts, especially in the lower Rio Grande Valley where some water right holders claimed rights under Spanish law as well. These conflicts were particularly fierce during the drought, leading to the *State vs. Hidalgo County Water Control and Improvement District no. 18*, also known as the "*Valley Water*" case[8], which effectively settled the various claims for water from Falcon Reservoir to the mouth of the Rio Grande. To govern all water rights in the Rio Grande from Amistad Reservoir and below, the case established a priority of use system—with municipal, domestic, and industrial use first, reservoir system operations second, and agriculture last—with a "watermaster" appointed to administer the court's decision.

---

[7]In 1962, the Texas Board of Water Engineers became the Texas Water Commission, with additional responsibilities for water conservation and pollution control.

[8]The *Valley Water* case involved roughly 3,000 parties, cost an estimated $10 million in court costs and attorney's fees, and took more than 30 years to decide (Jarvis 2014).

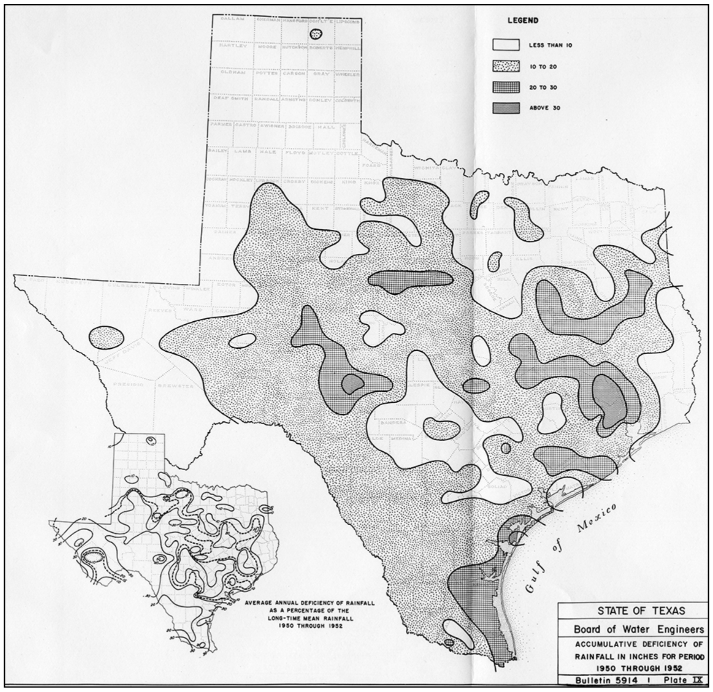


Figure 4a. Accumulative deficiency of rainfall in inches for period 1950 through 1952 (TBWE 1959). The early years of the 1950s drought were particularly severe, with some parts of the state more than 30 inches deficient in rainfall.

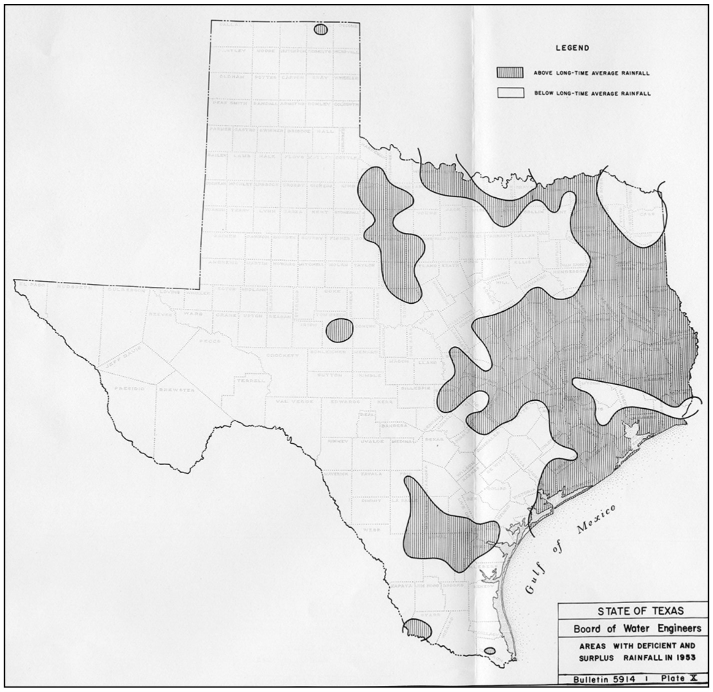


Figure 4b. Areas with deficient and surplus rainfall in 1953 (TBWE 1959). Despite 1953 being one of the worst years of the state's drought of record—with many communities forced to haul in water—some areas received above average annual rainfall.

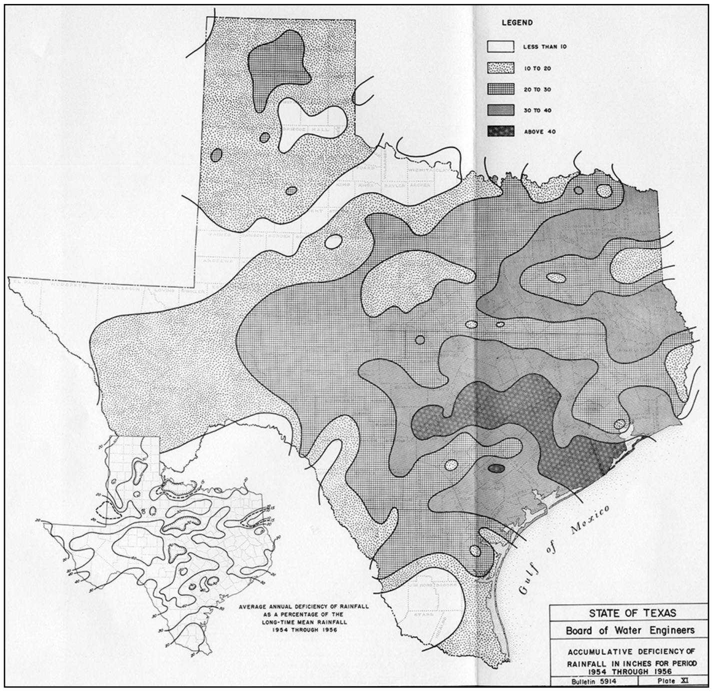


Figure 4c. Accumulative deficiency of rainfall in inches for period 1954 through 1956 (TBWE 1959). By 1956, most of the state had faced years of devastating drought.

1960s

1960 Population: 9,579,677

Three deadly hurricanes struck Texas during the 1960s: Cindy, Carla, and Beulah.

Drought of 1961 to 1966: *Though not one of the most intense droughts, the duration of the 1960s drought ranks third for Texas as a whole (Table 1).*

In response to severe flooding following a series of hurricanes in the 1960s, Congress established the National Flood Insurance Program. Despite the failure of the 1956 Federal Flood Insurance Act, the federal government had continued to study insurance and other financial assistance programs to aid victims of floods and related disasters. Finally in 1968, Congress passed the National Flood Insurance Act, which created the National Flood Insurance Program with 3 key objectives: to reduce the nation's flood risk through floodplain management, to improve flood hazard data and risk assessment by mapping the nation's floodplains, and to make affordable flood insurance widely available in communities that adopt and enforce flood control measures.

Water planning efforts that were kicked off by the drought of the 1950s continued through the 1960s, with the Texas Board of Water Engineers developing a state water plan in 1961, and the TWDB releasing a subsequent plan in 1968[9]. The 1968 plan included an ambitious proposal of 67 dams and reservoirs, redistribution of surplus East Texas water, and importation of water from an out-of-state source such as the Mississippi River (Freese and Sizemore 1994). The next year, Texas voters refused to adopt constitutional changes to enable implementation of the 1968 State Water Plan, including a $3.5 billion water bond authorization and authorization for the TWDB to enter into contracts with other states, the federal government, and other parties for acquisition and development of water resources and facilities (TLC 2014).

After the initiation of the *Valley Water* case during the drought of the 1950s, it was clear that Texas would need a state-administered adjudication process to organize and sort out competing water rights claims. This realization led to the Legislature passing the Water Rights Adjudication Act of 1967 to consolidate all surface water rights into a unified system, transforming previously held Spanish and Mexican grants, riparian rights, and other claims into "certificates of adjudication" (LRL 2015). It took the state a full 40 years to adjudicate all water rights claims, with the final adjudication of the Upper Rio Grande segment above Fort Quitman in 2007 (Jarvis 2014).

[9]In 1965, the Texas Water Commission became the Texas Water Rights Commission, a precursor agency to the Texas Commission on Environmental Quality; functions not related to water rights were transferred to the Texas Water Development Board.

The *Valley Water* case also demonstrated that a system of watermasters would be necessary where water was especially in short supply relative to the number and amounts of water rights recognized. Today the Texas Commission on Environmental Quality administers the Rio Grande, South Texas, Concho, and Brazos river watermaster programs.

1970s to 1990s

1970 Population: 11,196,730
1980 Population: 14,229,191
1990 Population: 16,986,510

Despite a relative lull in hurricane activity, Texas was struck by a series of tropical storms in the 1970s, 1980s, and 1990s. In July 1979, Tropical Storm Claudette deluged Alvin with 43 inches of rain in 24 hours, setting the all-time greatest 24-hour precipitation record for the United States (NOAA 2015c).

Shoal Creek Flood of 1981: *Ten inches of rain fell in a span of 4 hours in central Austin, damming Shoal Creek with more than 500 cars from local dealerships and killing 13 people (LCRA 2015b; Slade 2003).*

Christmas Flood of 1991: *Lake Travis rose to an all-time high of 710 feet above mean sea level, just shy of the Mansfield Dam spillway (LCRA 2015b).*

Drought of 1996: *A short drought in the middle of the decade caused Texas agricultural losses estimated at $2.1 billion.*

Flood of 1998: *Canyon Reservoir filled to capacity and water rushed over the spillway for the first time ever, carving a new gorge in its path.*

Flooding experienced at the national level in the 1970s led to the National Weather Service's development of the first early warning systems designed to reduce loss of life, property damage, and disruption of commerce and human activities from flash floods.

While Texas remained relatively drought free for most of the 1970, 1980s, and 1990s, water supply planning efforts initiated at the end of the state's drought of record continued[10]. And despite defeat of the constitutional amendment to implement the 1968 water plan, studies on transporting water from the Mississippi River continued, but costs were found to be largely prohibitive.

The brief drought of 1996 again galvanized state leadership and led to the passage of Senate Bill 1 the next year, which

[10]TWDB failed to adopt a revised state water plan that was anticipated in 1977 (TWDB 1976) but adopted subsequent state-level plans in 1984, 1990, 1992, and 1997.

provided for a new regional water planning process[11], a state Drought Preparedness Council, and water conservation and drought contingency plans. Senate Bill 1 explicitly reiterated that groundwater districts were the state's preferred method for managing groundwater resources and brought enhanced scrutiny of interbasin transfers in an attempt to balance the interests of the basin of origin and the receiving basin. Senate Bill 1 also repealed the provision of the 1931 Wagstaff Act that could make water available for municipal use on a watercourse that is otherwise fully appropriated. And to address municipal shortages in times of drought, the bill amended emergency authorizations for water rights.

The 1996 drought was not isolated to Texas: at its peak in May, portions of California, Nevada, Utah, Oklahoma, Kansas, Arkansas, and Louisiana were experiencing severe drought, and most of Arizona and New Mexico were experiencing extreme drought conditions. In response, the Western Governors' Association set an aggressive goal to change the way our nation prepares for and responds to droughts, which ultimately led to the National Drought Policy Act of 1998 and the National Integrated Drought Information System Act of 2006 (Western Governors' Association 2004). These acts began new efforts to implement drought monitoring and forecasting at federal, state, and local levels, including development of early warning systems.

2000s to Present

2000 Population: 20,851,820
2010 Population: 25,388,505

Drought of 1999 to 2002: *During an intense drought in the Lower Rio Grande Valley, low flows—combined with sedimentation and more than 10 years of lack of compliance by Mexico with the 1944 treaty[12]—caused the Rio Grande to cease flowing into the Gulf of Mexico for several months during 2001 (MWH 2003).*

Flood of 2007: *In June, a 19-inch "rain bomb" near Marble Falls resulted in massive runoff into Lake Travis that was contained by Mansfield Dam, minimizing flooding downstream (LCRA 2015b).*

Drought of 2010 to 2014: *2011 was the worst 1-year drought since statewide weather records began. It resulted in record agricultural losses of $7.6 billion (Texas AgriLife Extension Service 2012) and loss of several million urban trees, and contributed to thousands of wildfires across the state, including the Bastrop County Complex fire, the most destructive wildfire in Texas history. Despite its severity, only 1 community had to haul in water during the 4-year drought[13].*

Memorial Day Weekend Floods of 2015: *A brutal storm system ravaged communities in Central Texas and Houston over the Memorial Day weekend, leaving dozens of people dead, missing, injured, or displaced. The Blanco River at Wimberley rose from 5 to near 41 feet in only 4 hours, surpassing the 500-year floodplain and washing away federal stream gages (NWS 2015).*

Only barely through the first 2 decades of the new century, Texas has already experienced the most intense 1-year drought in Texas' recorded history, along with historic flooding on an otherwise tranquil river. The drought, which began suddenly in 2010, again led to significant changes in not only water supply planning but in the financing of water development projects. In 2013, the 83rd Texas Legislature passed legislation providing for the creation of the State Water Implementation Fund for Texas (SWIFT) and the State Water Implementation Revenue Fund for Texas. In addition, it authorized a 1-time, $2 billion supplemental appropriation from the state's Economic Stabilization Fund (also known as the Rainy Day Fund) to SWIFT, contingent on voter approval. Proposition 6 passed on November 5, 2013, with more than 70% in favor. The investment in the SWIFT is designed to support billions of dollars in state financial assistance for water supply projects over the next 50 years. As part of the planning effort, regional water planning groups and the TWDB were directed by the Legislature to prioritize projects based a number of criteria.

The historic flood on the Blanco River in 2015 exposed weaknesses in both local and federal early warning systems, beginning a dialogue that may continue into the next legislative session. The discussion may well include the need for greater support of the National Streamflow Information Network, which has steadily lost both state and federal funding since 2000 (Table 2).

CONCLUSION

Both floods and droughts have had a significant impact on generations of Texans. Lessons have been learned after every event, and the timeline is largely a story of our successful efforts to prepare for, respond to, and prevent disasters. Our flood control infrastructure has time and again prevented the types of catastrophes that predated modern flood control, more than repaying the cost of the original investment. Despite the severity of our most recent drought, only 1 community had to haul

[11]Three state water plans have been developed though the regional water planning process: 2002, 2007, and 2011.

[12]Since the early 1990s, Mexico has repeatedly failed to meet its obligations to a treaty signed in 1944 that allocates waters in the lower reach of the Rio Grande.

[13]The community of Spicewood Beach on Lake Travis had to haul in water for over 2 years beginning in January 2012.

Table 2. Streamgage joint state-federal funding agreement.

Fiscal Year	TWDB	USGS	Total Contract	Percent of Cost TWDB	Percent of Cost USGS	Lake Gages	Stream Gages
2000	$773,795	$618,502	$1,392,297	55.6%	44.4%	58	105
2001	$873,282	$616,046	$1,489,328	58.6%	41.4%	58	104
2002	$1,021,161	$643,726	$1,664,887	61.3%	38.7%	58	104
2003	$1,022,000	$643,800	$1,665,800	61.4%	38.6%	60	120
2004	$1,027,746	$643,800	$1,671,546	61.5%	38.5%	57	110
2005	$1,085,980	$669,860	$1,755,840	61.8%	38.2%	57	109
2006	$977,315	$669,860	$1,647,175	59.3%	40.7%	57	109
2007	$963,421	$721,205	$1,684,626	57.2%	42.8%	56	104
2008	$971,120	$785,580	$1,756,700	55.3%	44.7%	57	108
2009	$965,717	$739,500	$1,705,217	56.6%	43.4%	57	101
2010	$917,085	$608,910	$1,525,995	60.1%	39.9%	57	92
2011	$926,565	$601,800	$1,528,365	60.6%	39.4%	57	86
2012	$709,250	$456,095	$1,165,345	60.9%	39.1%	43	59
2013	$687,495	$400,600	$1,088,095	63.2%	36.8%	43	56
2014	$690,545	$372,200	$1,062,745	65.0%	35.0%	40	56
2015	$635,261	$372,200	$1,007,461	63.1%	36.9%	35	53

in water, a testament to our water supply planning efforts.

However, no plans are perfect. The timeline also reinforces the need for continuous planning and improvement. Drought and floods will visit Texas again, and our projected population growth will, if we do not plan accordingly, place more Texans in harm's way. Recent droughts and floods have demonstrated that traditional infrastructure is not the only solution: infrastructure must now work in tandem with early forecasting and warning systems for both floods and droughts. These systems need effective policies at both the state and federal level to support them, and more than ever before, engagement by all citizens. Texans need to know where their water comes from, how they can do their part to mitigate water challenges, and what their responsibilities are when severe weather hits. Only then will our future plans be truly viable.

REFERENCES

American Institutes for Research, The Pacific Institute for Research and Evaluation, Deloitte & Touche LLP. 2005. A chronology of major events affecting the National Flood Insurance Program. Completed for the Federal Emergency Management Agency. Washington D.C. Contract Number 282-98-0029. Available from: http://www.fema.gov/media-library-data/20130726-1602-20490-7283/nfip_eval_chronology.pdf

Arnold JL. 1988. The evolution of the 1936 Flood Control Act. Fort Belvoir (Virginia): United States Army Corps of Engineers. Available from: http://www.publications.usace.army.mil/Portals/76/Publications/EngineerPamphlets/EP_870-1-29.pdf

Bishop C. 2010. Brazos flood of 1899. Handbook of Texas Online. Austin (Texas): Texas State Historical Association. Available from: https://tshaonline.org/handbook/online/articles/ydb01

[BRA] Brazos River Authority. 2015. Timeline of the Brazos River Basin. Waco (Texas): Brazos River Authority. Available from: https://www.brazos.org/About-Us/About-the-BRA/About-the-Brazos-River/Basin-History

Freese SW, Sizemore DL. 1994. A century in the works, Freese and Nichols Consulting Engineers, 1894–1994. First edition. College Station (Texas): Texas A&M University Press. 435 p.

Gard W. 2015. Fence cutting. Handbook of Texas Online. Austin (Texas): Texas State Historical Association. Available from: https://tshaonline.org/handbook/online/articles/auf01

Jarvis G. 2014. Historical development of Texas surface water law: background of the appropriation and permitting system and management of surface water resources McAllen (Texas). Available from: http://glennjarvis.com/water-rights-adjudication/3_Hist_Devlpmnt_TX_Surf_Wtr_Law.pdf

[LRL] Legislative Reference Library. 2015. Texas water law timeline. Austin (Texas): Legislative Reference Library. Available from: http://www.lrl.state.tx.us/legis/waterTimeLine.cfm

[LCRA] Lower Colorado River Authority. 2015a. Managing floods in Flash Flood Alley. Austin (Texas): Lower Colorado River Authority. Available from: http://www.lcra.org/water/floods/pages/default.aspx

[LCRA] Lower Colorado River Authority. 2015b. Major floods on the Colorado River. Austin (Texas): Lower Colorado River Authority. Available from: http://www.lcra.org/water/floods/Documents/Major-Floods-on-the-Colorado-River.pdf

Malsch B. 2015. Indianola, Texas. Handbook of Texas Online. Austin (Texas): Texas State Historical Association. Available from: https://tshaonline.org/handbook/online/articles/hvi11

[MWH] Montgomery Watson Harza. 2003. Rio Grande mouth closure study. Prepared for International Boundary and Water Commission, United States Section. El Paso (Texas). Contract number IBM02D0001 Task Order Number IBM02T0002.

[NOAA] National Oceanic and Atmospheric Administration. 2015a. Billion-dollar weather and climate disasters: mapping. Available from: https://www.ncdc.noaa.gov/billions/mapping

[NOAA] National Oceanic and Atmospheric Administration. 2015b. The Galveston Hurricane of 1900. Available from: http://oceanservice.noaa.gov/news/features/sep13/galveston.html

[NOAA] National Oceanic and Atmospheric Administration. 2015c. State Climate Extremes Committee. Available from: http://www.ncdc.noaa.gov/extremes/scec/records

[NWS] National Weather Service. 2015. Memorial Weekend flooding–May 2015. Austin/San Antonio (Texas): National Weather Service Forecast Office. Available from: http://www.srh.noaa.gov/ewx/?n=memorial_weekend_floods_2015

San Antonio Express News. 1913 December 11. Flood waters of Texas rivers take costly toll in life and property in sweep over wide area. Vol. 48, No. 345, Ed. 1. Available from: http://texashistory.unt.edu/ark:/67531/metapth432670/m1/8/?q=%22colorado

Slade RM, Patton J. 2003. Major and catastrophic storms and floods in Texas. United States Geological Survey Open-File Report 03-193. Available from: http://pubs.usgs.gov/of/2003/ofr03-193/cd_files/USGS_Storms/patton.htm

Texas AgriLife Extension Service. 2012. Updated 2011 Texas agricultural drought losses total $7.62 billion. AgriLife TODAY. College Station (Texas). Available from: http://today.agrilife.org/2012/03/21/updated-2011-texas-agricultural-drought-losses-total-7-62-billion/

[TBWE] Texas Board of Water Engineers. 1959. A study of droughts in Texas. Bulletin 5914. Austin (Texas): Texas Board of Water Engineers. Available from: http://www.twdb.texas.gov/publications/reports/bulletins/doc/Bull.htm/B5914.asp

[TLC] Texas Legislative Council. 2014. Amendments to the Texas Constitution since 1876. Austin (Texas): Texas Legislative Council. Available from: http://www.tlc.state.tx.us/pubsconamend/Constamend1876.pdf

[TPB] Texas Planning Board. 1938a. Development of Texas rivers, a water plan for Texas. Austin (Texas): The Texas Planning Board. Available from: http://www.twdb.texas.gov/publications/reports/other_reports/doc/1938WaterPlanforTexas.pdf

[TPB] Texas Planning Board. 1938b. The need for administrative control of ground water. Austin (Texas): The Texas Planning Board.

[TRA] Trinity River Authority. Our History. Dallas (Texas): Trinity River Authority. Available from: http://www.trinityra.org/ourhistory

[TSHA] Texas State Historical Association. 1928. West Texas drouths. The Southwestern Historical Quarterly. 32(2).

[TSHA] Texas State Historical Association. 2002. "God help them all and so must we:" Clara Barton, Reverend John Brown, and drought relief efforts, 1886–1887. The Southwestern Historical Quarterly. 106(4).

[TWC] Texas Water Commission. 1964. Fifty years of water development in Texas. Bulletin 6403. Austin (Texas): Texas Water Commission. Available from: https://www.twdb.texas.gov/publications/reports/bulletins/doc/B6403.pdf

[TWDB] Texas Water Development Board. 1966. Technical papers on selected aspects of the preliminary Texas Water Plan, Report 31. Austin (Texas): Texas Water Development Board. Available from: https://www.twdb.texas.gov/publications/reports/numbered_reports/doc/R31/R31.pdf

[TWDB] Texas Water Development Board. 1976. An assessment of surface water supplies of Arkansas with computations of surplus supplies and a conceptual plan for import to Texas. Austin (Texas): Texas Water Development Board. Available from: https://www.twdb.texas.gov/publications/reports/historic_groundwater_reports/doc/SurfaceWaterSupplies_Arkansas.pdf

[TWRI] Texas Water Resources Institute. 2011. Texas drought: now and then. txH2O. College Station (Texas): Texas Water Resources Institute. Available from: http://twri.tamu.edu/publications/txh2o/fall-2011/

[USGS] United States Geological Survey. 1991. National water summary 1988–89—hydrologic events and floods and droughts. USGS Water-Supply Paper 2375. Denver (Colorado): United States United State Geological Survey. Available from: http://pubs.usgs.gov/wsp/2375/report.pdf

[USGS] United States Geological Survey.1998. A new evaluation of the USGS Streamgaging Network. Washington D.C.: U.S. Geological Survey. Available from: http://water.usgs.gov/streamgaging/report.pdf

Western Governors' Association. 2004. Creating a drought early warning system for the 21st century. Denver (Colorado): Western Governors' Association. Available from: https://www.drought.gov/media/pgfiles/nidis.pdf

Worster D. 2012. Dust Bowl. Handbook of Texas Online. Austin (Texas): Texas State Historical Association. Available from: https://tshaonline.org/handbook/online/articles/ydd01