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A Refined Hydrogeologic Framework Model for Gaines, Terry, and Yoakum Counties, Texas

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Abstract: Declining groundwater levels in Gaines, Yoakum, and Terry counties in the Southern High Plains have raised concerns about the amount of available groundwater and the potential for water-quality changes resulting from dewatering and increased vertical groundwater movement between adjacent water-bearing hydrogeologic units. More than 11,500 well records containing pertinent data were compiled, including data delineating the vertical extents of wells penetrating one or more of the units. Additional geophysical data were collected to improve the spatial coverage of available data across the study area and to reduce uncertainty regarding hydrogeologic unit extents. Across the study area, the average altitude of the base of the Ogallala Aquifer was approximately 1.7 feet lower compared to previous assessments of the altitude of the base of the aquifer, resulting in an increase in the saturated thickness by the same amount. Some of the largest increases in the altitude of the base of the Ogallala Aquifer were observed in central and east-central Gaines County where the units that compose the Edwards-Trinity Aquifer thin at approximately 136 feet and the largest decreases in altitudes are in Yoakum County at around 185 feet. Both the thickest and thinnest part of the Ogallala Aquifer is in Gaines County at just over 300 feet in west Gaines County and around 20 feet in northeast Gaines County.

Keywords: Ogallala, Edwards-Trinity, Fredericksburg, hydrogeologic, Gaines, Terry, Yoakum

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Terms used in paper

Acronyms	Descriptive name
°F	degrees Fahrenheit
ASTER	Advanced Space Borne Thermal Emission and Reflection Radiometer
ASTM	American Society of Testing and Materials
BRACS	Brackish Resources Aquifer Characterization System
DEM	digital elevation model
EM	Electromagnetic
ft	feet
Hz	hertz
LAS	Log American Standard
LEUWCD	Llano Estacado Underground Water Conservation District
m	meter
M	Measured apparent resistivity at the given time step
mi^2	square miles
mg/L	milligrams per liter
NAVD88	North American Vertical Datum of 1988
pdf	portable document format
PVC	polyvinyl chloride
RMSE	root mean square error
Rx	Receiver
SLUWCD	Sandy Land Underground Water Conservation District
SP	spontaneous potential
SPR	single-point resistance
SPUWCD	South Plains Underground Water Conservation District
TDEM	time-domain electromagnetic
TDS	dissolved solids
Tx	Transmitter
USGS	U.S. Geological Survey

INTRODUCTION

In 2014, the U.S. Geological Survey (USGS), in cooperation with Llano Estacado Underground Water Conservation District (LEUWCD), Sandy Land Underground Water Conservation District (SLUWCD), and South Plains Underground Water Conservation District (SPUWCD), (hereinafter referred to collectively as "the districts") began a multiphase study in and near Gaines, Terry, and Yoakum counties, Texas to develop a regional conceptual model of the hydrogeologic framework and geochemistry primarily for the Ogallala and Edwards-Trinity aquifers and to a lesser degree for the Dockum Group, the hydrogeologic unit that contains the Dockum Aquifer. The results of the first phase of the study were documented in Thomas et al. (2016) and included an assessment of the differences between early development (1930–1960) and recent (2005–2015) groundwater-level altitudes and selected water-quality constituents (dissolved-solids concentrations [TDS] and nitrate concentrations) for the Ogallala, Edwards-Trinity, and Dockum aquifers. This report documents the results of the second phase of the study designed to gain a refined understanding of the hydrogeologic framework in the study area. The term "hydrogeologic framework" as used in this report refers to the lateral and vertical extents of hydrogeologic units, bed orientation, unit thickness, and outcrop and subcrop locations in the study area. An accurate characterization of the hydrogeologic framework is important because small differences in the hydrogeologic framework can cause aquifer conditions (storage and flow gradients) to vary considerably within a relatively small area (Fleming and Rupp 2018).

As described in Thomas et al. (2016), the study area consists of the different areas managed by the districts in and near Gaines, Yoakum, and Terry counties, respectively, along the Texas-New Mexico State line (Figure 1). The districts share common groundwater resources—most notably, the Ogallala Aquifer. The Ogallala Aquifer is part of the High Plains aquifer system, a vast regional aquifer system that underlies about 174,000 square miles (mi^2) from South Dakota to Texas (Gutentag et al. 1984). The Ogallala Aquifer, contained within the Ogallala Group, is the shallowest aquifer in the study area and is the primary source of water for agriculture and municipal supply in the areas managed by the districts (Rettman and Leggat 1966). Groundwater withdrawals from deeper aquifers (primarily from the Edwards-Trinity Aquifer [TWDB 2018b], augmented to a lesser amount by withdrawals from the Dockum Aquifer), are additional water sources in the study area (Figure 1). Declining groundwater levels in the study area have raised concerns about the amount of available groundwater and the potential for water-quality changes resulting from dewatering and increased vertical groundwater movement between adjacent water-bearing units.

The amount and quality of water available in the study area from the Ogallala Aquifer varies locally depending on the saturated thickness of the Ogallala Group. The base of the Ogallala Group is a complex irregular erosional surface that was shaped by hydrogeologic processes such as the development of paleochannels and alluvial deposits during the Tertiary period. Prior to the deposition of the Ogallala Group, erosional processes thinned the Cretaceous-age units underlying the Ogallala Group in many areas. Thicker alluvial deposits of Ogallala Group rocks were generally deposited where erosion of the Cretaceous-age rocks was most extensive, resulting in a greater saturated thickness of the Ogallala Aquifer where erosion of the Cretaceous-age units was most extensive (Bradley and Kalaswad 2003).

Because the Ogallala Aquifer and underlying aquifers are hydraulically connected in some locations, water quality in adjacent aquifers may be affected by the mixing associated with water-level declines. In their report on the history of water-level changes in the Ogallala Aquifer from predevelopment to 1980, Dugan et al. (1994) reported water-level declines in the Ogallala Aquifer of as much as 150 feet (ft). During the past 50 to 60 years the rate of decline has slowed and water levels in the Ogallala Aquifer have risen in a few areas (McGuire 2017). Water-level declines can be accompanied by the increased upward movement of relatively saline groundwater; changes in water quality in the Ogallala Aquifer and in the underlying Edwards-Trinity Aquifer can result from the upward movement of deeper, relatively more saline groundwater (Bradley and Kalaswad 2003).

Purpose and scope

To help improve the understanding of the amount of available groundwater and the potential for water-quality changes resulting from dewatering and increased vertical groundwater movement between adjacent water-bearing hydrogeologic units, the USGS completed a study in cooperation with the districts to gain a refined understanding of the hydrogeologic framework in the study area. Existing data were primarily used in the analyses; additional geophysical data were collected to improve the spatial coverage across the study area and to reduce uncertainty regarding hydrogeologic unit extents. Of particular interest was the evaluation of data to improve the understanding of how the saturated thickness of the Ogallala Aquifer and total thickness of the hydrogeologic units that compose the Edwards-Trinity Aquifer vary laterally and vertically throughout the study area. The Dockum Group was evaluated as a single unit and the physical properties (storage, porosity, transmissivity), and neither the extent nor storage properties of Dockum Aquifer, a relatively minor source of water in the study area, were determined. All data that were compiled or collected for this assessment are available in Teeple et al. (2018).

Description of the study area

The study area (Figure 1) is bounded by the extents of the districts' management areas in Gaines, Terry, and Yoakum counties and a small part of Hockley County, Texas. The total study area covers about 3,225 mi^2, including 1,525 mi^2 in LEUWCD, 798 mi^2 in SLUWCD, and 902 mi^2 in SPUWCD (LEUWCD 2018b; SLUWCD 2018b; SPUWCD 2018a). The study area is in the Great Plains physiographic region and consists of an elevated and relatively undissected plain (Ryder 1996). As of July 1, 2017, the population of the study area was about 42,000 (USCB 2017). The combination of minimal topographic relief, availability of groundwater for irrigation, and excellent soils makes this an important agricultural region in Texas (Ryder 1996).

The climate of the study area is semiarid (Larkin and Bomar 1983). Precipitation averages 18.8 inches each year, mostly in the form of rain; the area receives about 5 inches of snow each year (NOAA 2015). The potential evapotranspiration is more than three times the annual precipitation (Larkin and Bomar 1983). The average temperature for the study area is about 60.5 degrees Fahrenheit (°F), with the warmest average monthly temperature in July (79.1 °F) and the coolest average monthly temperature in January (40.0 °F) (NOAA 2015).

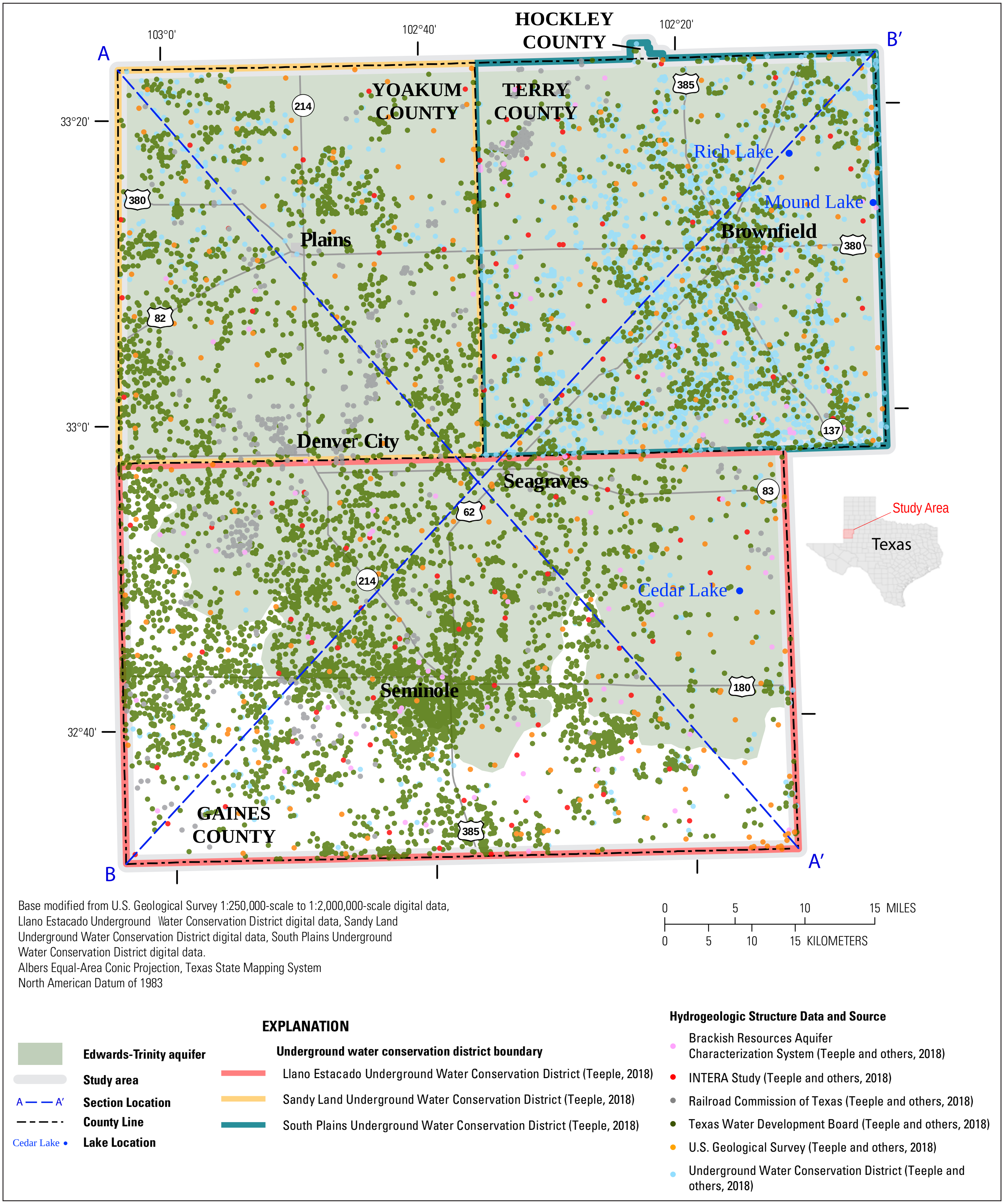

Figure 1. Map showing hydrogeologic data locations sources, and section locations in the study area, for Gaines, Terry, and Yoakum counties, Texas.

Table 1. Descriptions of the hydrogeologic units, their lithologic descriptions, and corresponding aquifers for Gaines, Terry, and Yoakum counties, Texas (modified from Bradley and Kalaswad 2003; Knowles et al. 1984; Thomas et al. 2016).

Era	Period	Series or group within the spatial extents of the Edwards-Trinity Aquifer	Series or group outside the spatial exents of the Edwards-Trininty Aquifer	Lithologic descriptions	Aquifers
Cenozoic	Tertiary	Ogallala Group	Ogallala Group	gravel, sand, silt, and clay	Ogallala Aquifer
Mesozoic	Cretaceous	Fredericksburg Group	Absent	clay, shale, and limestone	Edwards-Trinity Aquifer
		Trinity Group		sand and gravel	
	Truassis	Dockum Group	Dockum Group	sandstone, siltstone, mudstone, and shale	Dockum Aquifer

Hydrogeologic setting

The Ogallala Aquifer is composed primarily of poorly sorted gravel, sand, silt, and clay deposited during late Miocene and early Pliocene when the Ogallala Group formed. Multiple studies describe the general Ogallala Group structure with paleochannels eroded into the underlying hydrogeologic units that control groundwater flow and are filled with coarse gravel in the channel and often filled with sand and finer sediments in the interchannel areas (Cronin 1969; Seni 1980; Gustavson 1996). The highly variable distribution of coarse sediments influences the spatial distribution of porosity and permeability of the Ogallala Aquifer, which in turn influences water-storage capacity and water-availability characteristics (Seni 1980; TWDB 2018c).

TDS concentrations in the Ogallala typically are less than 1,000 milligrams per liter (mg/L) (the upper limit for what is generally considered freshwater [Winslow and Kister 1956]) but can vary from less than 600 to more than 6,000 mg/L within localized areas of the study area (LEUWCD 2018b; SLUWCD 2018a). In many areas, groundwater moves vertically between the Ogallala Group and the underlying Fredericksburg, Trinity, and Dockum groups (Table 1). Where the Fredericksburg and Trinity groups are absent, the Ogallala Group directly overlies the Dockum Group (Ashworth and Hopkins 1995) (Table 1).

The Cretaceous-age Edwards-Trinity Aquifer is a minor aquifer underlying the Ogallala Aquifer, except in the southern part of the study area where the Edwards-Trinity Aquifer is absent (George et al. 2011). Primary water-bearing units in the Edwards-Trinity Aquifer include sand and gravel layers of the Trinity Group and limestone layers of the overlying Fredericksburg Group (Bell and Morrison 1979). Groundwater flow in the Edwards-Trinity Aquifer is controlled by facies changes, structure orientation, local cementation, and paleochannels, that can produce local deviations in flow patterns (Fallin 1989). Groundwater from the Edwards-Trinity Aquifer is typically slightly saline (TDS concentrations range from 1,000 to 3,000 mg/L) (Winslow and Kister 1956; Fallin 1989) and contains more TDS than groundwater from the overlying Ogallala Aquifer (George et al. 2011) (Table 1).

The Dockum Aquifer is an additional minor aquifer in the study area (George et al. 2011) composed of the Triassic-age Dockum Group that underlies the Ogallala and Edwards-Trinity aquifers (Table 1) throughout much of the southern part of the High Plains physiographic region. The Dockum Group consists of sandstone, siltstone, mudstone, and shale originally deposited in fluvial and lacustrine environments (McGowen et al. 1979). Groundwater in the Dockum Aquifer is characterized by decreasing water quality with increasing depth, variable geochemistry, high concentrations of TDS and other constituents that exceed secondary drinking water standards (EPA 2016), and high concentrations of sodium that may negatively affect irrigated crops (Bradley and Kalaswad 2003).

Estimating saturated thickness

To help evaluate their water resources, each water conservation district uses base-of-aquifer and groundwater-level potentiometric maps to estimate the saturated thickness for the Ogallala and Edwards-Trinity aquifers within their respective jurisdictions. Saturated thickness, the difference between the altitude of the water table and the altitude of the base of the aquifer at a given location, is commonly used in conjunction with other aquifer conditions (lithology, porosity, and water quality) to estimate the volume of water in storage in the aquifer (McGuire et al. 2012). The districts collect groundwater-level altitude data and publish saturated thickness maps for the Ogallala Aquifer on a yearly basis. The Fredericksburg and Trinity groups that compose the Edwards-Trinity Aquifer are considered fully saturated (LEUWCD 2018a; SLUWCD 2018a; SPUWCD 2018b).

DEVELOPMENT OF A REFINED HYDROGEOLOGIC FRAMEWORK

The base of the Ogallala Group, as defined by the districts, provided both a starting point for the data compilation efforts and a dataset for use in developing a refined hydrogeologic framework. Data used for the High Plains Groundwater Availability Model (Deeds et al. 2015) and updated INTERA conceptual model (TWDB 2018a) were also included (Figure 2) in the initial data compilation and for comparison with the refined hydrogeologic framework.

Data compilation and collection

Hydrogeologic data and interpretative information pertaining to the hydrogeologic units in the study area were compiled from previous studies done by various local, state, and federal agencies. Compiled data and information were supplemented with surface and borehole geophysical data collected by the USGS. The resulting dataset was analyzed to identify the tops and bases of the selected hydrogeologic units along with their lateral extents and relation to overlying and underlying units in the study area (Table 1). The data were used to evaluate the hydrogeologic unit features, such as extent, bed orientation, thickness, and outcrop and subcrop locations.

More than 11,500 readily available digital data records for the study area consisting of geophysical, geologic, lithologic, and drilling and well-completion log data (recorded well reports of the hydrogeologic units penetrated by a borehole) were compiled to assess spatial variations of the Ogallala, Fredericksburg, Trinity, and Dockum groups in and adjacent to Gaines, Terry, and Yoakum counties (Figure 1). Digital data from over 900 wells within a 5-mi buffer area around the study area were also included in the compilation to extend the grids past the study area and minimize possible gridding errors near the extent of the data.

Because accuracy of reported altitude information varies between different methods used at a given well or time-domain electromagnetic (TDEM) location, and older well data typically have relatively poor vertical accuracy, land-surface altitudes were determined from a digital elevation model (DEM) to provide consistency and improve accuracy. DEM data were obtained from the Advanced Space Borne Thermal Emission and Reflection Radiometer (ASTER) Global DEM Version 2 (NASA 2015) to estimate land-surface altitudes across the study area.

Where possible, data available only in hard copy were digitized and combined with existing digital data before being entered into the database (Teeple et al. 2018). Geophysical logs typically are reliable sources for subsurface information; however, those determined to have inaccurate spatial data or missing information were not used in this assessment. To be used in this assessment, the geophysical log needed to provide correct, discernible location information, complete and correct header information, detailed well completion information, and valid, useable calibration data. Existing geophysical logs collected with appropriate methods and that contained sufficient spatial data were used to help identify the tops and bases of each hydrogeologic unit. Hydrogeologic and lithologic descriptions from Meyer et al. (2012) and Herald (1957) were used to help characterize the lithologic and geophysical properties of each hydrogeologic unit.

Depths to tops and bases of the hydrogeologic units were converted to altitudes by subtracting the depths from the ASTER Global DEM Version 2 (NASA 2015); depth data were referenced by altitude and spatial location for correlation among neighboring wells to create a regional network of data points.

Evaluating spatial coverage of compiled data

Compiled data were plotted, and maps for each hydrogeologic surface grid were used to evaluate the spatial data coverage and identify areas with higher uncertainty where the spatial distribution of data was relatively sparse. Generally, as the distance between data points becomes greater, correlation between points lessens, and uncertainty in areas between points increases (Isaaks and Srivastava 1989). Instead of only evaluating the distance between data points, variance maps were prepared by using a kriging process to evaluate the uncertainty in the

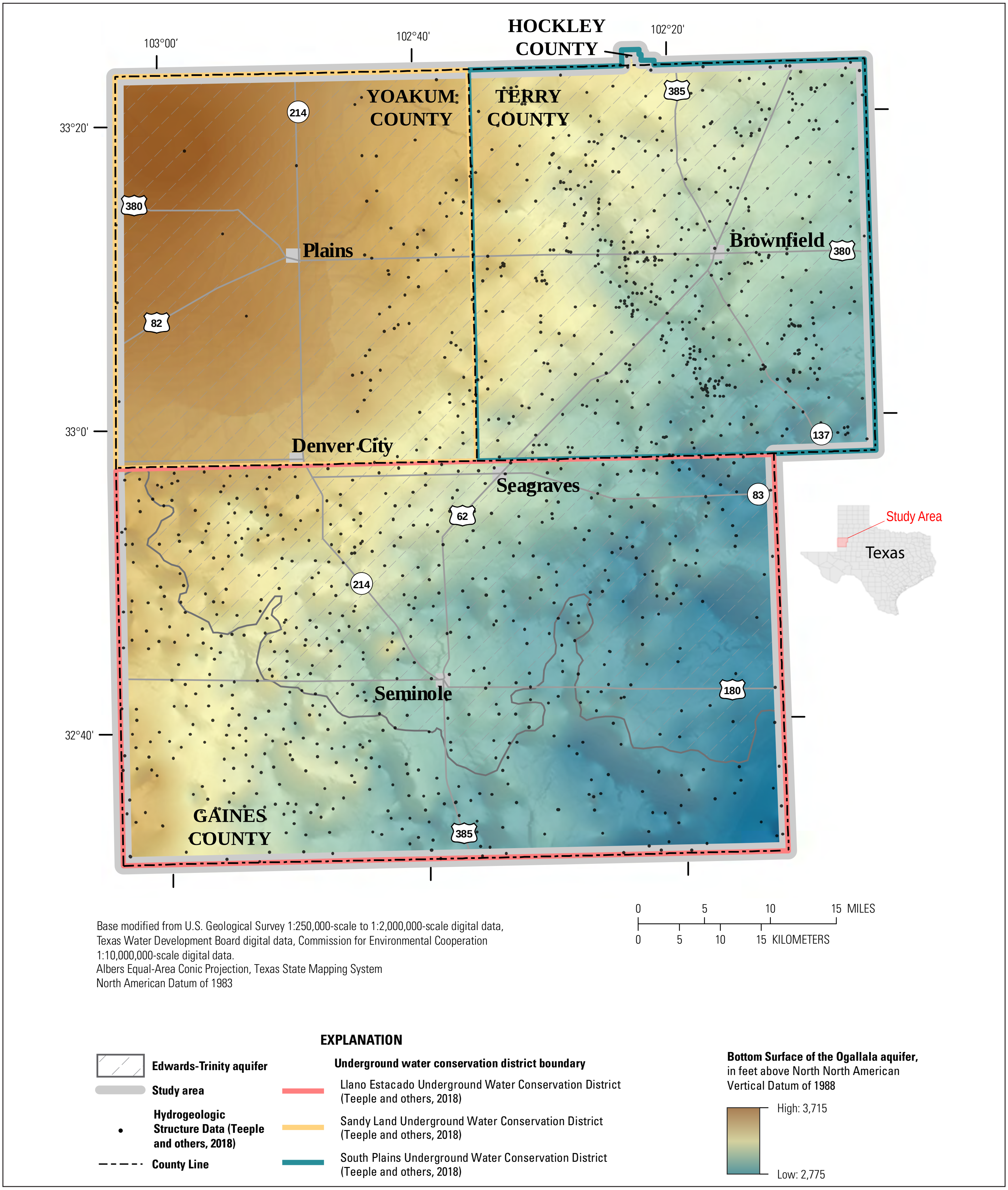

Figure 2. Existing mapped base of the Ogallala Aquifer and hydrogeologic data locations prior to this study.

gridded-surfaces for the entire study area (Isaaks and Srivastava 1989). These variance maps were used to identify areas with higher uncertainty and in the planning of additional data collection.

Collection of additional geophysical data

To improve the spatial coverage across the study area and to reduce uncertainty, the compiled dataset was supplemented by the collection of additional geophysical data (Figure 3). Borehole geophysical logs, including caliper, natural gamma, induction conductivity, normal resistivity, temperature, fluid resistivity, and surface time-domain electromagnetic soundings were collected to improve spatial coverage and reduce data gaps and gridding uncertainty.

Borehole geophysics

Conventional borehole geophysical logs were collected at 38 sites across the study area (Figure 3) where additional hydrogeologic information was needed (USGS 2018; Teeple et al. 2018). Additional information about the borehole geophysical methods used in this study are available in Teeple et al. (2018). All borehole geophysical data were collected by using a Century Geophysical, LLC system VI logging system or a Mount Sopris Instruments Matrix logging system. For this study, the Mount Sopris Instruments system was used to collect neutron logs; all other logs were collected using the Century Geophysical Corporation system. Explanations regarding the limitations of the logging systems, calibration procedures, and algorithms of the geophysical probes are available from the manufacturers (CGC 2018; MSI 2018). The additional geophysical logs were collected during 2012–2015 following American Society of Testing and Materials (ASTM) borehole geophysical standard procedures (ASTM 2004, 2007, and 2010). These geophysical logs were collected digitally in the proprietary format of the data acquisition equipment used to collect the logs. The geophysical logs data were converted to and stored as Log American Standard (LAS) Code for Information Interchange Standard for tabular data (CWLS 2018). All digital geophysical logs are available online on the Geolog Locator geophysical log archive (USGS 2018).

Surface geophysics

Surface geophysical resistivity methods, specifically TDEM soundings (Zohdy et al. 1974), were used to detect changes in the electrical properties of the subsurface across the study area (Figure 3). The electrical properties of soil and rock are determined by water content, porosity, clay content and mineralogy, and conductivity (reciprocal of electrical resistivity) of the pore water (Lucius et al. 2007). Additional information about the surface geophysical resistivity methods used in this study are available in Teeple et al. (2018). Comprehensive descriptions of the theory and application of surface geophysical resistivity methods, as well as tables of the electrical properties of earth materials, are presented in Keller and Frischknecht (1966) and Lucius et al. (2007). All surface geophysical data were collected in accordance with methods defined by the ASTM (1999).

Interpretation of hydrogeologic unit interfaces and hydrogeologic contacts

Hydrogeologic unit interfaces and hydrogeologic contacts between units were interpreted from the compiled and newly collected geophysical data that were combined to create the comprehensive database for the study area (Teeple et al. 2018). Hydrogeologic unit contact grids were created by using Oasis montaj (Geosoft 2015) and kriging techniques. Kriging is a geostatistical method that determines the most probable value at each grid node (200 meter [m] by 200 m [about 656 ft by 656 ft] for this study) based on a statistical analysis of the entire dataset (Isaaks and Srivastava 1989). Variance maps developed during the kriging process were used to evaluate the uncertainty in hydrogeologic unit surface grids in the planning of additional data-collection tasks. Generally, as the distance between data points became greater, correlation between points lessened, and uncertainty in areas between points increased (Isaaks and Srivastava 1989). Additional information on kriging is available in Isaaks and Srivastava (1989).

Preliminary hydrogeologic unit surface grids were periodically created as hydrogeologic contacts were interpreted and entered into a preliminary database, and used to help evaluate hydrogeologic features, extents, and data coverage. Gridded hydrogeologic unit surface grids were interactively compared to interpreted contact altitudes to evaluate outliers, grid accuracy, and clustered data. All outlier locations were evaluated through a correlation process to determine data-point uncertainty. The correlation process involved the comparison of hydrogeologic unit contacts at a given site to the hydrogeologic unit contacts at nearby sites and preliminary grids. Outliers were removed if review of the original data source indicated that data were questionable. Throughout the process, all hydrogeologic unit contacts were reviewed and revised as needed to provide the best possible final representation of each hydrogeologic unit (Teeple et al. 2018).

HYDROGEOLOGIC FRAMEWORK REFINEMENTS

Hydrogeologic unit contact interpretations were used to assess the vertical and lateral extents of hydrogeologic units, bed orientation, unit thickness, and outcrop and subcrop locations. In general, the Ogallala, Fredericksburg, Trinity, and

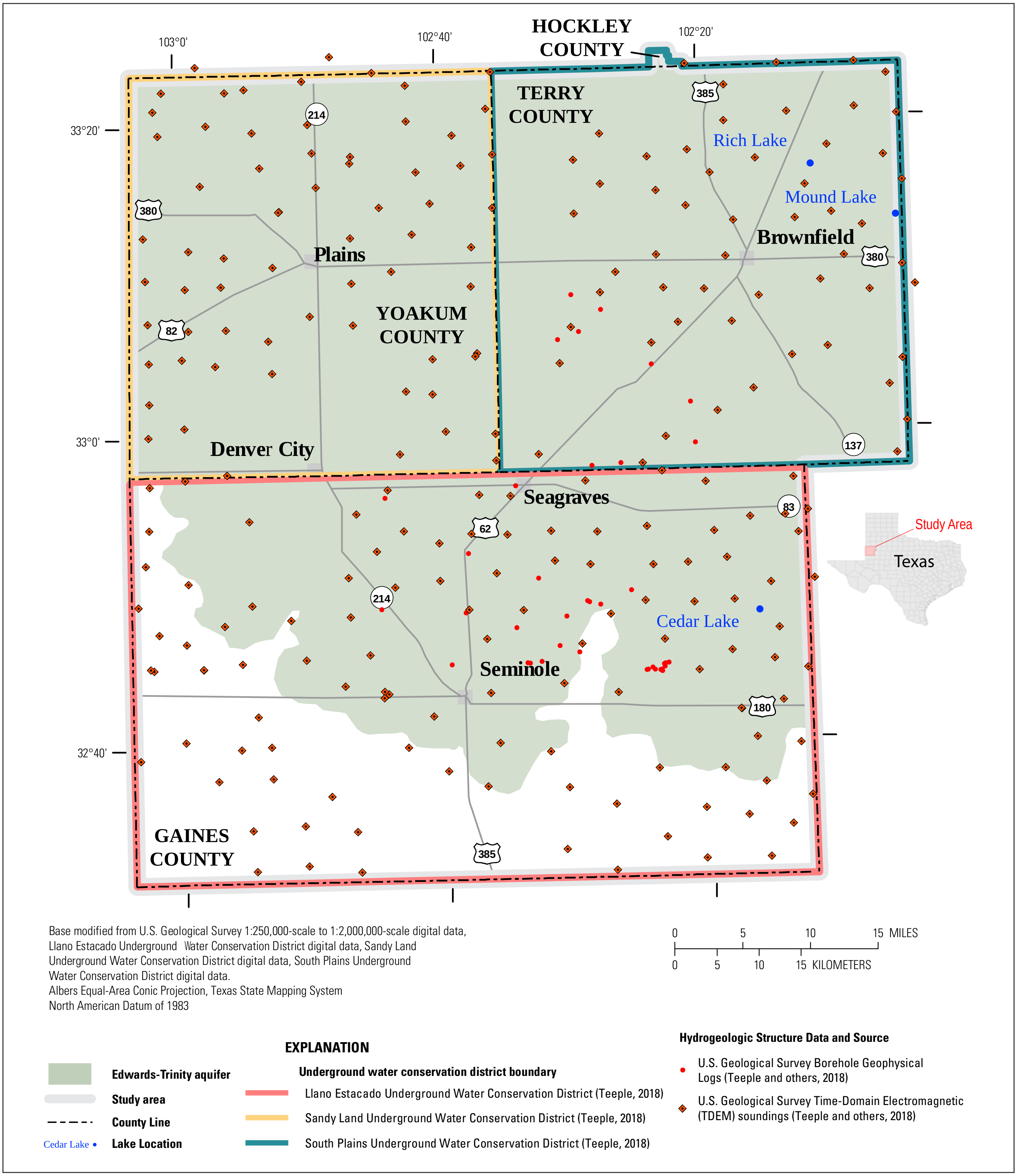

Figure 3. Map showing location of additional surface and borehole geophysical data across the study area, for Gaines, Terry, and Yoakum counties, Texas.

Table 2. Basic statistics for the primary hydrogeologic groups for each conservation district in the study area.

		LEUWCD	SLUWCD	SPUWCD	Study Area
Depth to base of Ogallala Group	min (ft)	21	65	30	21
	max (ft)	303	288	264	303
	mean (ft)	170	168	156	165
Thickness of Ogallala Group	min (ft)	21	65	30	21
	max (ft)	303	288	264	303
	mean (ft)	170	168	156	165
Change in base of Ogallala Group	min (ft)	-136	-84	-99	-136
	max (ft)	117	185	82	185
	mean (ft)	-14	27	4.3	1.7
Area of Ogallala Group	(mi^2)	1,525	798	902	3,225
Depth to Base of Fredericksburg Group	min (ft)	33	154	91	33
	max (ft)	335	406	431	431
	mean (ft)	192	272	266	244
Thickness of Fredericksburg Group	min (ft)	0	0	0	0
	max (ft)	102	228	237	237
	mean (ft)	35	106	111	86
Area of Fredericksburg Group	(mi^2)	840	795	890	2,526
Depth to Base of Trinity Group	min (ft)	35	193	152	35
	max (ft)	363	458	460	460
	mean (ft)	221	321	349	298
Thickness of Trinity Group	min (ft)	0	0	0	0
	max (ft)	147	164	157	164
	mean (ft)	30	49	83	55
Area of Trinity Group	(mi^2)	850	796	890	2,536

LEUWCD; Llano Estacado Underground Water Conservation District, SLUWCD; Sandy Land Underground Water Conservation District, SPUWCD; South Plains Underground Water Conservation District, min; minimum, max; maximum, ft; feet, mi^2 square miles

Dockum groups exhibit a slight regional dip to the southeast. Although the Ogallala and Dockum groups are present across the entire study area, the Fredericksburg and Trinity groups thin to the south and are absent in the southern part of the study area.

Ogallala Aquifer

Compiled data were used in conjunction with geophysical data collected by the USGS to depict the base (bottom surface) of the Ogallala Aquifer (Figure 4). To help evaluate how the newly developed depiction of the base of the Ogallala Aquifer was refined from the existing depiction of the base of the Ogallala Aquifer (Figure 2), the surfaces were compared by subtracting the refined altitude surface obtained during this assessment from the previously mapped altitude surface (Figure 5). Most of the locations where the base of the Ogallala was shallower than previously depicted were in the southern part of the study area. Specifically, in areas where the Ogallala Aquifer overlies the southern extent of the Edwards-Trinity Aquifer, there were large areas where the Ogallala Aquifer was more than 100 ft shallower than previously mapped (Table 2; Figure 5). Along an erosional feature about 10 mi east of Seminole, Texas, where the Edwards-Trinity Aquifer is absent, the base of the Ogallala Aquifer was as much as 100 ft deeper than previously mapped. Across the northeast part of the study area there was relatively minimal change in the depiction of the base of the Ogallala Aquifer. The largest areas where the refined base of the Ogallala Aquifer was more than 50 ft deeper than the previous base were in western Yoakum County (Figure 5).

The altitudes of the top of the Ogallala Group range from about 2,950 ft to about 3,900 ft above North American Vertical Datum of 1988. The highest altitudes in the northwest corner of the study area, northwest of Plains, Texas, and the lowest altitudes in the southeast corner of the study area, southeast of Seminole.

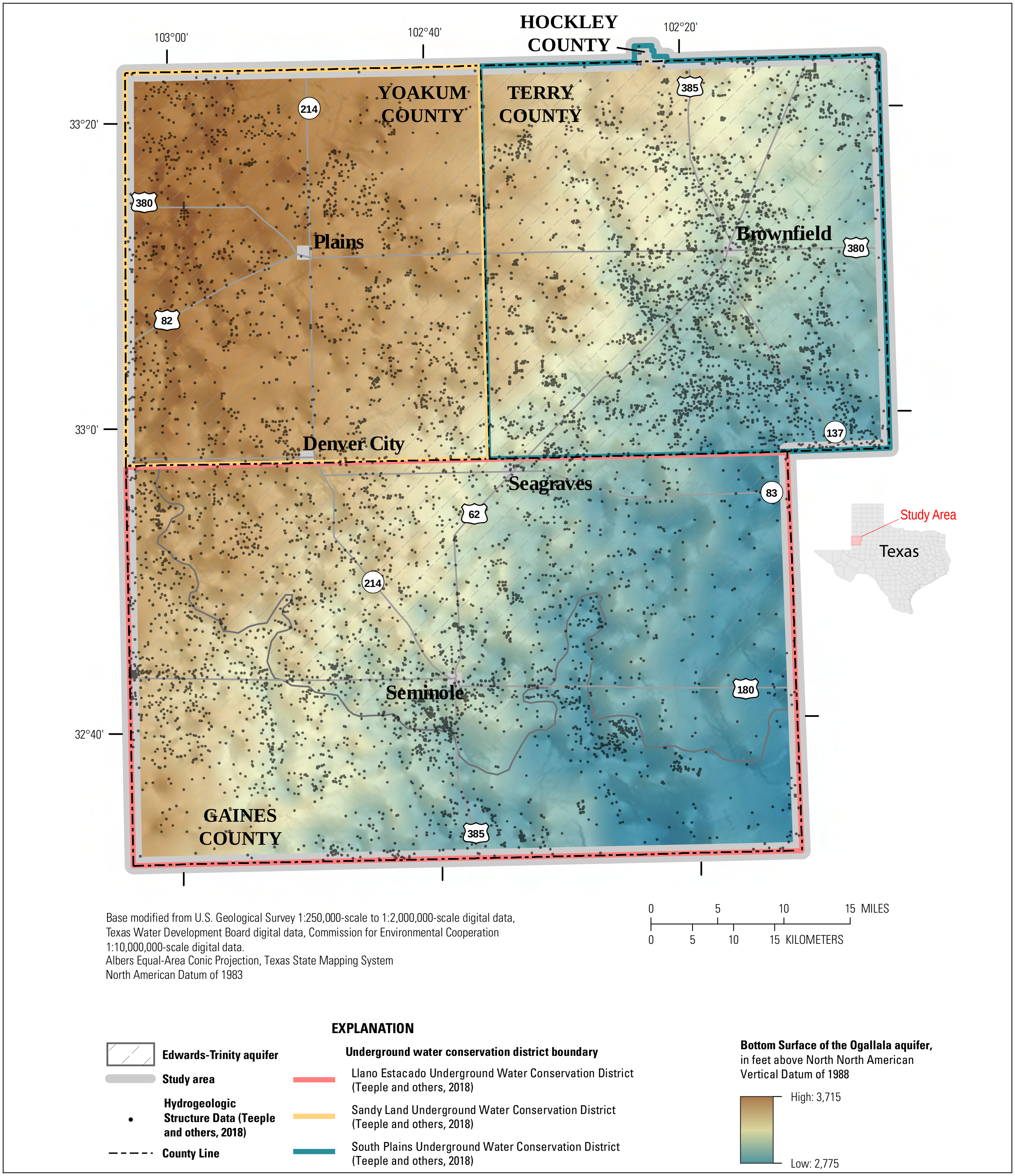

Figure 4. Revised (2018) base (bottom surface) of the Ogallala Aquifer and hydrogeologic data locations.

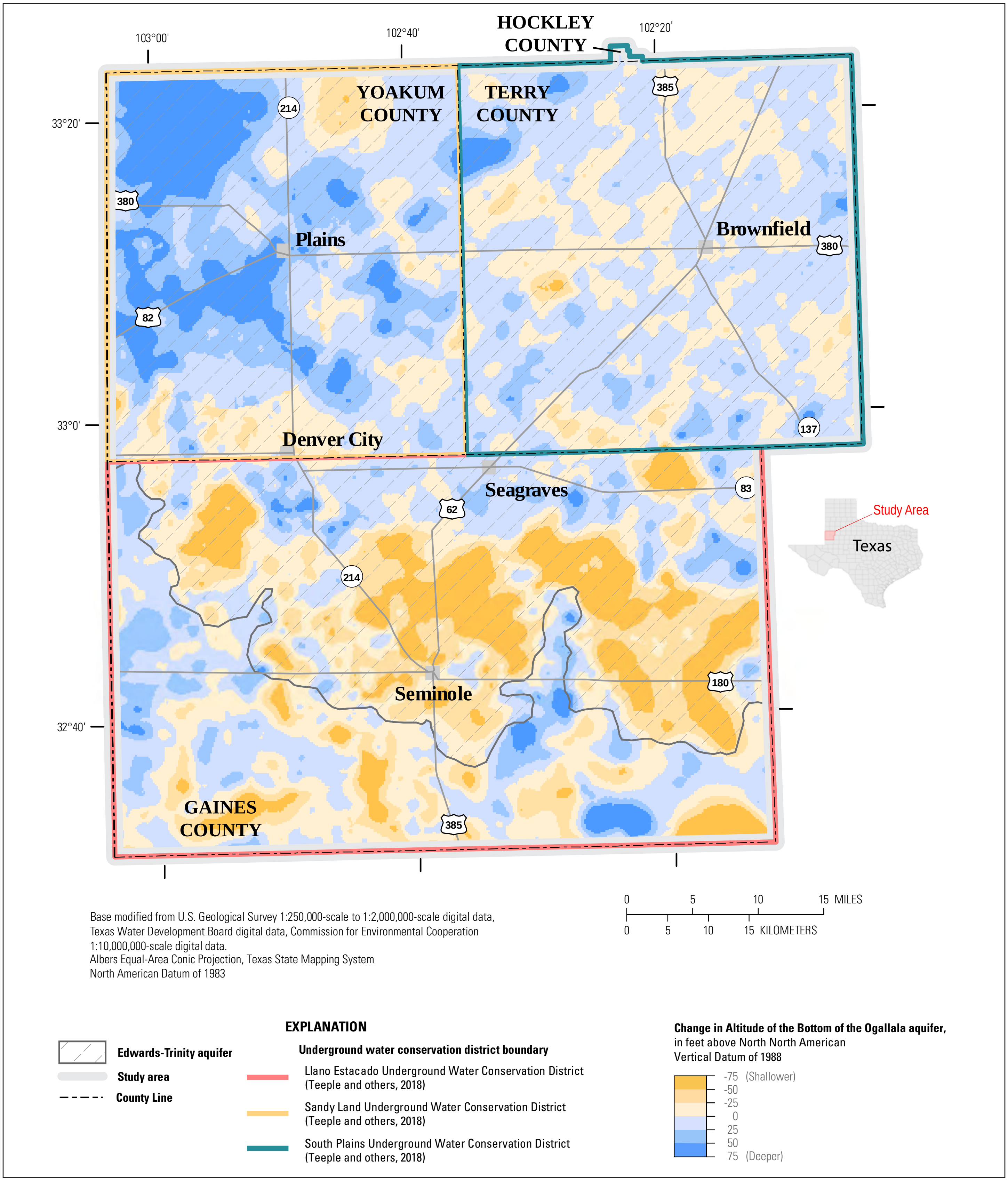

Figure 5. Change in altitude of the mapped base (bottom surface) of the Ogallala Aquifer between the existing depiction of the mapped base of the Ogallala Aquifer and the newly (2018) developed depiction of the base of the Ogallala Aquifer.

Three-dimensional representations of the hydrogeologic framework were prepared by using Oasis montaj (Geosoft 2015) to depict the unsaturated and saturated thickness of the Ogallala Group; the total unit thicknesses of the Fredericksburg, Trinity, and Dockum groups were also depicted (Figures 6-7). Across the study area, the total unit thickness of the Ogallala Group ranges from less than about 25 ft to more than 300 ft (Table 2), with a mean thickness of about 165 ft (Teeple et al. 2018). In general, the thickest parts of the Ogallala Group are in western Gaines County near Seminole (Teeple et al. 2018) and the northwest corners of Yoakum and Terry counties (Table 2); the thinnest parts are in the eastern part of the study area. Localized areas where the Ogallala Group is relatively thin occur in some low-lying areas (for example, near Cedar Lake, Mound Lake, and Rich Lake [Table 1]). To quantify the saturated thickness of the Ogallala Aquifer, a potentiometric surface of the Ogallala Aquifer developed by Thomas et al. (2016) was used in conjunction with the altitude of the base of the Ogallala Aquifer. This potentiometric surface was developed by using Ogallala Aquifer water-level measurements collected during each dormant part of the growing season (November through April) from 2005 through 2015 when groundwater withdrawals were typically lower compared to the rest of year. A detailed description of the data and methods used to develop the potentiometric surface of the Ogallala Aquifer during the dormant season is provided by Thomas et al. (2016). Two-dimensional and three-dimensional representations of different hydrogeologic cross sections (cross sections A–A' and B–B') of the study area were prepared (Figures 8-9).

The saturated thickness of the Ogallala Aquifer can vary substantially in a relatively small area in response to changes to the base (bottom surface) of the Ogallala Group. For example, there is evidence of erosional paleochannels, such as elongated areas of increased saturated thickness, in the updated base (bottom surface) of the Ogallala Group (Figure 4) and in a three-dimensional representation of the hydrogeologic framework (Figures 6-7). To help evaluate paleochannels across the study area, generalized derivative grids were developed (Figure 7) that calculate curvature of the potential field response and is an attribute that is helpful in enhancing smaller features obscured by larger gradients (Geosoft 2018). Smaller paleochannels in the base of the Ogallala Aquifer vary in orientation whereas the larger paleochannels typically trend from the northwest to the southeast in orientation and deepen and widen downgradient (Figures 4 and 6) to the south and east. The saturated thickness of the Ogallala Aquifer ranges from less than 10 ft in the far southern extent of the study area to more than 150 ft southeast of Seminole and northwest of Brownfield, Texas. Although the saturated thickness varies locally, a regionally thinner section of the Ogallala Aquifer extends from central Terry County to the southwest and a regionally thicker section extends from northeast Yoakum County to the southeast corner of Gaines County. The volume of water stored within the saturated thickness depends on many factors including the lithology, specific yield, and porosity of the hydrogeologic unit (Gutentag et al. 1984).

Fredericksburg and Trinity groups of Edwards-Trinity Aquifer

In general, the Fredericksburg and Trinity groups thin to the south and are not present in the southern part of Gaines County (Figures 6-9). Although the Fredericksburg and Trinity groups are present throughout most of the northern parts of the study area, there are localized areas where one or both groups thin or are absent (Figure 6; Table 2). The frequency of thinning or absence of the Fredericksburg and Trinity groups increases at the southern extent of the aquifer, particularly in the Fredericksburg Group (Figure 6).

Similar to the Ogallala Group, the thickness of the Fredericksburg and Trinity groups varies locally depending on the presence of erosional features such as paleochannels (Figure 7). Although the orientations of erosional features in the Ogallala Group are typically toward the southeast or south, erosional features in the Fredericksburg and Trinity groups are generally oriented toward the east (Figure 7). The mean unit thicknesses of the Fredericksburg and Trinity groups are 86 ft and 55 ft, respectively (Table 2). Throughout the study area, the thickness of the Fredericksburg Group is more variable than the thickness of the Trinity Group (Figure 6; Table 2). The Fredericksburg Group is thickest in the north-central part of the study area (about 237 ft thick), whereas the Trinity Group is thickest in northeast Yoakum County (about 164 ft thick). Among the three counties that compose most of the study area (Gaines, Terry and Yoakum counties), the average thickness of the Trinity Group is the greatest in Terry County (about 83 ft thick). The Trinity Group increases in thickness to the east along an erosional feature starting near the Yoakum-Gaines County line, south of Plains, where it is about 50 ft thick, and increases to the east, where it is more than 150 ft thick, near Brownfield (Figure 6).

Dockum Group

The water-bearing units of the Dockum Group were not evaluated for this study, and the extent of the Dockum Aquifer was not determined. Relative to the other geologic units assessed for this study (the Ogallala, Fredericksburg, and Trinity groups), the Dockum Group was found to have a much larger mean thickness (approximately 1,795 ft). The Dockum Group is mostly composed of siltstone and shale, with only a small amount of sandstone that could serve as a productive aquifer (Bradley and Kalaswad 2003). Natural gamma and resistivity geophysical data were the primary data used to identify the signature of the various units. This signature of the base

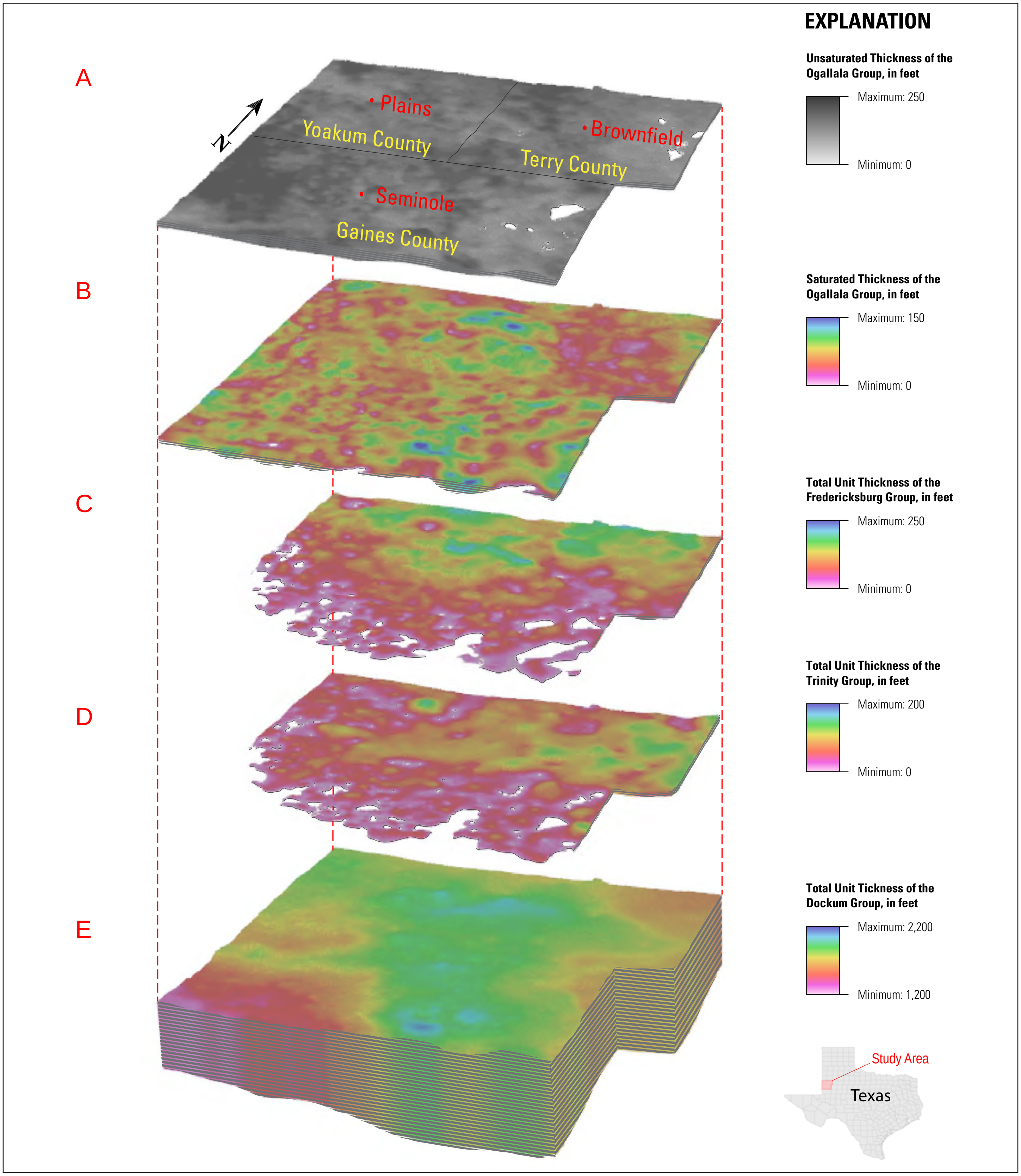

Figure 6. Three-dimensional representation of the hydrogeologic framework for Gaines, Terry, and Yoakum counties, Texas, including (A) unsaturated thickness of the Ogallala Group; (B) saturated thickness of the Ogallala Aquifer; (C) the total unit thickness of the Fredericksburg Group; (D) the total unit thickness of the Trinity Group; and (E) the total unit thickness of the Dockum Group.

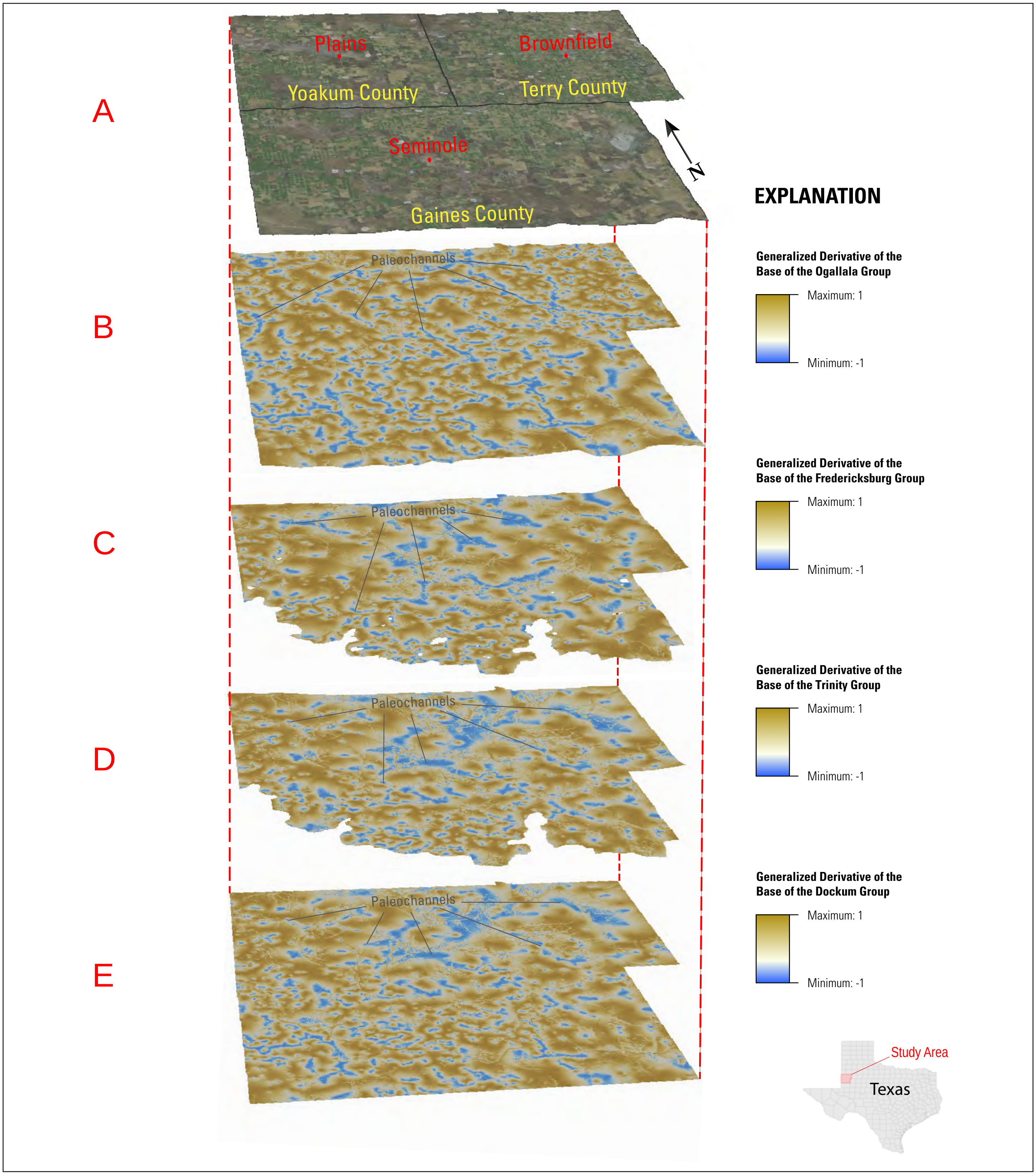

Figure 7. Three-dimensional representation showing paleochannel locations in the base surfaces of the hydrogeologic framework for Gaines, Terry, and Yoakum counties, Texas, including (A) satellite imagery of the study area; (B) generalized derivative map of the base of the Ogallala Group (C) generalized derivative map of the base of the Fredericksburg Group; (D) generalized derivative map of the base of the Trinity Group; and (E) generalized derivative map of the base of the Dockum Group.

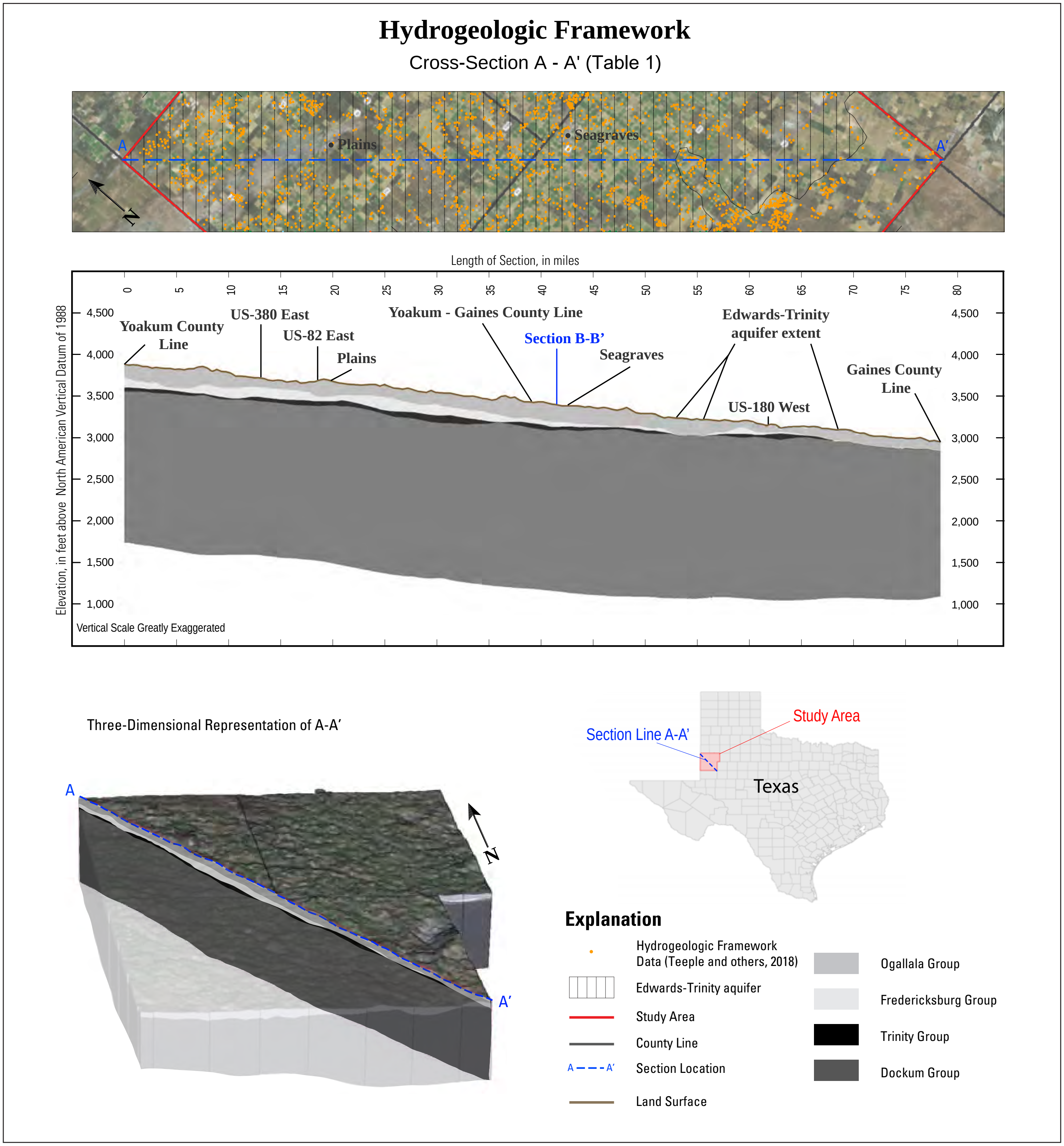

Figure 8. Two-dimensional and three-dimensional representations of the hydrogeologic framework from A to A' for Gaines, Terry, and Yoakum counties, Texas, of the Ogallala Group, Fredericksburg Group, Trinity Group, and the Dockum Group.

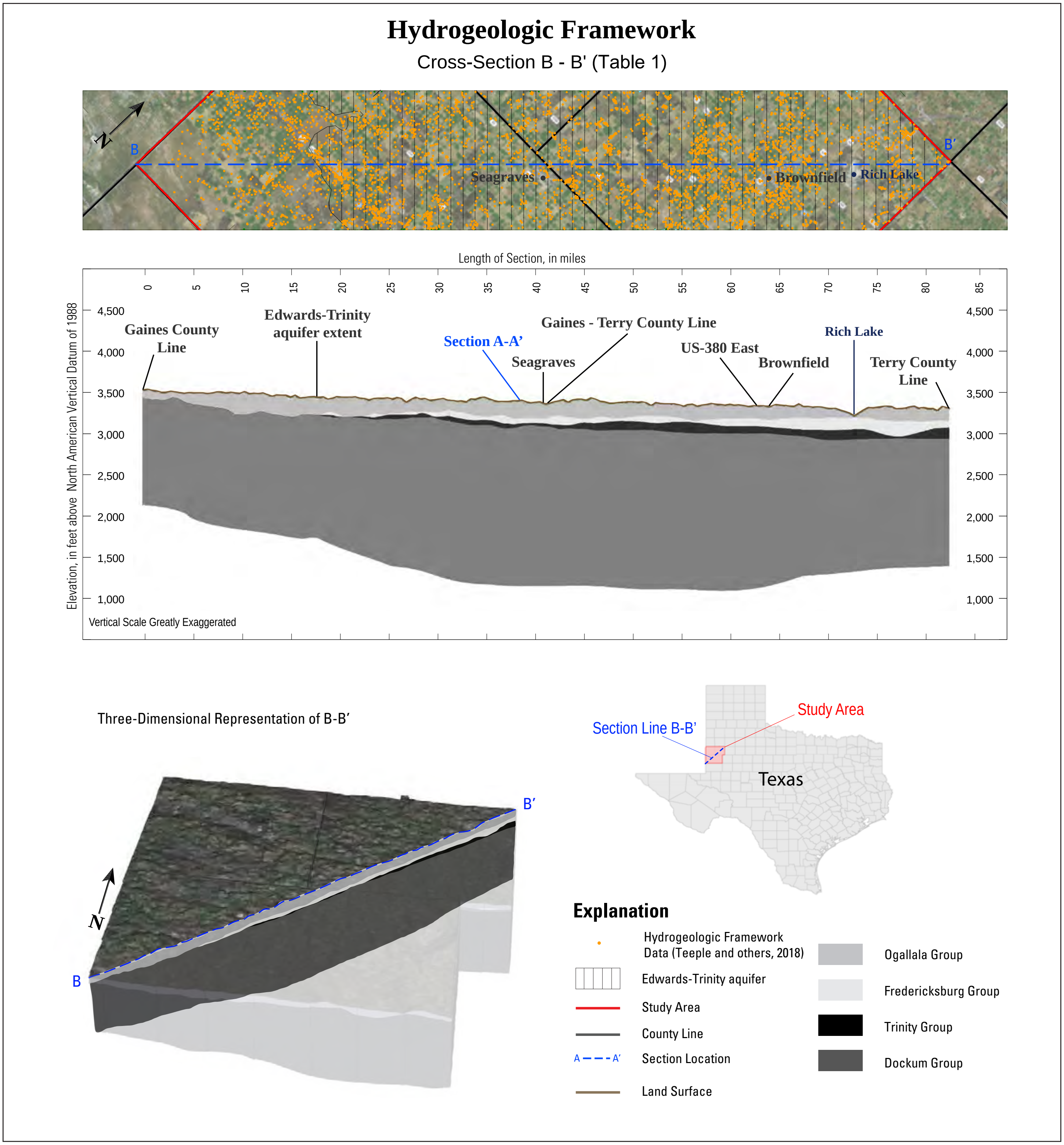

Figure 9. Two-dimensional and three-dimensional representations of the hydrogeologic framework from B to B' for Gaines, Terry, and Yoakum counties, Texas, of the Ogallala Group, Fredericksburg Group, Trinity Group, and the Dockum Group.

of the Dockum Group varied some across the study area but in general the top of the Dockum was determined as the top of the red beds (high natural gamma/low resistivity) and the base of the Dockum Group was determined as the top of the Dewey Lake Formation. Key words in compiled drillers' logs were also reviewed to identify the base of the Dockum Group. The top of the Dockum Group is deepest to the north, where the overlying Fredericksburg and Trinity groups are present and shallowest to the south where the Dockum Group directly underlies the Ogallala Group (Figures 7-9). The thickness of the Dockum Group is mostly consistent across the study area, except in the northeast and southwest where it thins (Figures 6-9). The thickness of the Dockum Group ranges from approximately 1,260 ft in the southwest corner of Gaines County to more than 2,145 ft in the south-central part of the study area, southeast of Seminole (Figures 6, 9). A relatively small amount of data were collected as part of this assessment pertaining to the Dockum Group; to better quantify the water content of the Dockum Group, additional data are needed to better define various layers of the Dockum Group and the viability of the unit as a water-supply resource for the area.

REFINEMENT AND IMPROVED RESOLUTION OF THE HYDROGEOLOGIC-UNIT INTERFACES

The refinement and improved resolution of the hydrogeologic-unit interfaces provides water resource managers a tool to better understand the groundwater system, and the surfaces can be used with potentiometric water-level surfaces to calculate Ogallala Aquifer saturated thicknesses, help estimate the volume of water in storage, and assess aquifer changes over time. Refinements to the saturated thickness of the Ogallala Aquifer can be indirectly assessed by evaluating changes to the base of the Ogallala Group, and therefore the Ogallala Aquifer. Compared to previous datasets, the altitude of the refined base of the Ogallala Aquifer is on average 14.7 ft higher in 25% of the study area; in an additional 25% of the study area, the altitude is 18.9 ft lower (Figure 5). Across the entire study area, the average altitude of the base of the Ogallala Aquifer is approximately 1.7 ft lower compared to the previous assessments of the altitude of the base of the aquifer (Table 2), resulting in a subsequent increase in the saturated thickness by the same amount. Some of the largest areas where the altitude of the base of the Ogallala Aquifer are higher are in central and east-central Gaines County where the Edwards-Trinity Aquifer thins (Figure 5). The large differences between the previously identified base altitude and the revised base altitude may have implications for availability of stored water. Local water resource managers and stakeholders can use this revised understanding of the base of the Ogallala Aquifer, along with aquifer hydraulic properties, to refine water management strategies.

CONCLUSION

Declining groundwater levels have raised concerns about the amount of available groundwater in the study area and the potential for water-quality changes resulting from dewatering and increased vertical groundwater movement between adjacent water-bearing units. Hydrogeologic data and interpretative information from previous studies done by various local, state, and federal agencies were compiled and supplemented with surface and borehole geophysical data collected by the USGS. The resulting dataset was analyzed to identify the tops and bases of the selected hydrogeologic units along with the lateral extent and relation to overlying and underlying units in the study area.

Most of the locations where the altitude of the base (bottom surface) of the Ogallala Aquifer was higher (shallower) than previously depicted were in the southern part of the study area. Specifically, in areas where the Ogallala Aquifer overlies the southern extent of the Edwards-Trinity Aquifer, there were large areas where the base of the Ogallala Aquifer was more than 100 ft higher than previously mapped. Along an erosional feature about 10 mi east of Seminole, where the Edwards-Trinity Aquifer is absent, the base of the Ogallala Aquifer was as much as 100 ft lower (deeper) than previously mapped. Across the entire study area, the average altitude of the base of the Ogallala Aquifer was approximately 1.7 ft lower compared to the previous assessments of the altitude of the base of the aquifer, resulting in a subsequent increase in the saturated thickness by the same amount. Localized areas where the Ogallala Group is relatively thin are found in some low-lying areas such as lakes (for example, Cedar Lake, Mound Lake, and Rich Lake). The saturated thickness of the Ogallala Aquifer ranges from less than 10 ft in the far southern extent of the study area, to more than 150 ft southeast of Seminole and northwest of Brownfield.

Although the Fredericksburg and Trinity groups are present throughout most of the northern parts of the study area, there are localized areas where one or both groups thin or are absent. The mean unit thicknesses of the Fredericksburg and Trinity groups are 86 ft and 55 ft, respectively. Throughout the study area, the thickness of the Fredericksburg Group is more variable than the thickness of the Trinity Group. The Fredericksburg Group is thickest in the north-central part of the study area (about 237 ft thick), whereas the Trinity Group is thickest in northeast Yoakum County (about 164 ft thick). The Trinity Group increases in thickness to the east along an erosional feature starting near the Yoakum-Gaines County line, south of

Plains, where it is about 50 ft thick, and increases to the east, where it is more than 150 ft thick, near Brownfield.

Relative to the other geologic units assessed for this study, the Dockum Group has a much larger mean unit thickness of approximately 1,795 ft, much of which is composed of siltstone and shale, with only a small amount of sandstone that could serve as a productive aquifer. The top of the Dockum Group is deepest to the north, where the overlying Edwards-Trinity Aquifer is present and shallowest to the south where it directly underlies the Ogallala Aquifer.

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Commentary:
Water Fuels Our Future

Charles Perry[1]

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.

[1] Senator, Texas Senate; Chairman, Senate Committee on Water and Rural Affairs.

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It is the beginning of the 86th Legislative Session, and state officials have begun laying out priorities ranging from school finance, property tax reform, school security, healthcare, and Hurricane Harvey assistance, just to name a few. This session will be narrow in scope but large in dollars needed.

One of the biggest events to change the landscape of the state in the interim was the landfall of Hurricane Harvey and its aftermath. Estimates for damage hover around $125 billion, and 68 Texans lost their lives directly from the hurricane.[1]

At some time every county in Texas has had some form of flash flooding or flood event.[2] Chances are everyone in our state could be directly or indirectly affected by flooding in their lifetime. In Senate District 28, Sonora, Texas experienced a flooding event that destroyed or damaged 250 homes in September 2018.[3] The following month, Junction, Texas and the Llano River experienced two catastrophic floods. The first flood struck a campground causing Texans to be rescued from trees and the loss of three lives.[4] The second produced a wall of water that traveled through the Llano watershed into the Highland Lakes creating the first official boil water notice for the City of Austin.[5]

Flooding, whether from Hurricane Harvey or other events, only reminded Texans that there is a lot of work to do in order to be prepared for the next event. During the interim I met and shared ideas with federal, state, and local partners. Learning best practices from those who have worked in disaster management helped establish the framework for the best solution going forward. I have filed SB 396, which outlines a State Flood Plan developed under the Texas Water Development Board. Texans rightfully expect and assume that Texas has adequate flood prevention and recovery planning in place in order to protect property and lives. SB 396 is a strong step in the right direction.

The State Flood Plan is a comprehensive look at the state through mapping and cooperative planning between watersheds. Without planning and properly pulling all projects under one umbrella, Texas is left with a patchwork solution to a problem that requires cooperation from all. The most important item for the state is to openly discuss solutions and not limit projects to one watershed without talking to the neighboring watershed. A bottom-up approach to flood planning incorporates local input while supporting the collaboration between watersheds.

Proper flood management planning should include water supply development when possible. Texas peaked at almost 90% of the state experiencing a level of drought conditions in 2012. In May 2017, almost half of the state was experiencing drought conditions. Currently, Texas has under 10% of the state under drought conditions.[6] Texas is a large and diverse geographical region with significant variances in weather patterns. It is the state's responsibility to research, plan, incentivize, and implement strategies that deal with both flooding and water supply needs, remembering these strategies should not be mutually exclusive.

In the State Flood Plan framework, a ranking system is created including: federal matching opportunities, an emergency need, and the creation of a new or enhanced water supply source. A reservoir does not just have to prevent a flood; it can catch and store water or be used in aquifer storage and recovery.

Knowing how much water is available is crucial to supplying our state with its most vital resource. Because of this, I will refile Water Availability Model (WAM) legislation. Sound science will guide the state going forward to make the best decision. Both flooding and drought has changed the look and capacity of the river basins in the state. The WAMs will map several basins so that water permitting is completed with a thorough view of water availability.

The balance between private property rights and water development will continue to be a focus in the 86th Legislature. I plan to refile legislation related to groundwater and surface water permitting as well.

There will be an abundance of legislation this session that will address flooding, groundwater, surface water, mapping, and water science. It is important to receive input from all stakeholders to make the best decisions for Texans. As Chairman, I strive to protect private property rights, insist on a coordinated effort to tackle the flood challenges and continue to be the "canary in the coal mine" when it comes to water supply development. Texas is the greatest state in the union and has the resources to meet the needs of all future Texans. The only question is, "Will we?"

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An Internet for Water: Connecting Texas Water Data

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Foreword by Editor Robert E. Mace: As a hydrogeologist in Texas, I have been spoiled. At my fingertips, for as long as I can remember, was the Texas Water Development Board's (Board) groundwater database. At first, I had to visit the Board in person to access its data via a terminal. Then the data was available through the internet. As a researcher, the database allowed me to quickly access information to efficiently advance my understanding of our state's aquifers. The database also allowed others to quickly assess meeting their groundwater needs, understanding the implications of contamination events, and determining long-term groundwater availability trends. Most states do not have such a treasure trove of data. Phil Nordstrom, Janie Hopkins, and Bryan Anderson—keepers of this data for the past 30 plus years—are true heroes of data availability and accessibility.

Unfortunately, unlike the Board's groundwater database, all water data isn't FAIR: Findable, Accessible, Interoperable, and Reusable (and even here, the Board's groundwater database could use enhancements in interoperability). Today's world moves fast; accordingly, it demands fast answers. And fast answers require accessible data. This paper by Rosen and others presents the outcomes from a workshop on creating a Texas water hub where digital water data is freely available and easily accessible. Attendees agreed that there's a need for a Texas water hub and many reasons to have one—for example, see the massive data needs for the emergency response to Hurricane Harvey.

Fortunately, work on developing a Texas water hub will continue. The Meadows Center for Water and the Environment, with support from the Mitchell Foundation, is working with stakeholders to address the recommendations of this workshop included in this paper. As Director Kathleen Jackson of the Texas Water Development Board, a keynote speaker at the workshop, astutely noted: "The better the data, the better the science. And the better the science, the better the policy."

It's time for all of us to get on board—and get our data online.

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Abstract: The Connecting Texas Water Data Workshop brought together experts representative of Texas' water sectors to engage in the identification of critical water data needs and to discuss the design of a data system that facilitates access to and the use of public water data in Texas. Workshop participants identified "use cases" that list data gaps, needs, and uses for water data and answered questions on who needs data, what data do they need, in what form do they need the data, and what decisions need to be made about water in Texas. They described desires for future water data management and access practices and articulated key attributes of a comprehensive, open access, public water data information system. Next, steps were described to include a subset of workshop participants meeting regularly to further define the goals of a Texas public water data hub, develop a strawman of the hub's structure, characterize several use cases, and facilitate development of pilot projects that demonstrate the value of connected public water data for improved decision making.

Keywords: public water data, Texas water, internet of water, water management, water data management

Terms used in paper

Acronyms	Descriptive name
GAM	groundwater availability model
WAM	water availability model
TACC	Texas Advanced Computing Center
TWDB	Texas Water Development Board

INTRODUCTION

In many areas of Texas where the human population is growing rapidly, major water-related concerns are growing as well. Water availability and use are affected by frequent droughts in some areas, flooding in others, and multiple human-caused events such as the introduction of pollutants. The consequences of these events can limit overall economic growth, business development, agricultural productivity, ecosystem health, and the stability of communities. Pressure is placed on public officials to protect against adverse consequences and on water managers to limit the pollution of our waterways and ensure continued access to dependable supplies of safe water. While several public agencies collect vast amounts of data to support decision-making around our water resources, too often that data is either inaccessible or unusable. This leaves Texas' decision-makers, industries, landowners, and communities with significant amounts of data of limited use to support real-time decision-making, development of opportunities for water security, or for modeling an accurate picture of Texas' water future. Making better decisions about water will require more data, better data, better access to data, and data that can be universally used (interoperable) through open and transparent public data systems, where data are presented in ways that are relevant to the needs of decision-makers and the public.

Texas water experts explored building an "internet" for Texas water data at the Connecting Texas Water Data Workshop held on April 17, 2018, at the Texas Advanced Computing Center (TACC) located at the University of Texas in Austin. While most states have one or more public agencies known for collecting and supplying water data, advancement of an internet of water acknowledges a need to gain open access to much larger amounts of water data currently inaccessible or in non-interoperable formats held by all public sources. What is meant by this term, "internet of water," is a water-information focused interconnected network and network of networks linking and providing access to devices holding water data by an array of electronic and wireless technologies. The workshop brought together almost 90 invited experts representative of Texas' government and water agencies, utilities, academia, businesses, industries, research institutes, water associations, and advocacy organizations. A comprehensive report of the workshop details the proceedings (Rosen and Roberts 2018). This program review presents a summary of the key findings.

METHODS

Workshop participants received background information about recent efforts on the internet of water (Patterson et al. 2017; Cantor et al. 2018) and Texas water data security (Rosen et al. 2017) in advance of the workshop. In addition to receiving advanced information, a portion of workshop participants met on the day immediately preceding the Connecting Texas Water Data Workshop in a roundtable discussion on the topic of "advancing the internet of water" in Texas. The roundtable was held by the Aspen Institute Dialogue Series on Sharing and Integrating Water Data for Sustainability.

On the following day all participants in the Connecting Texas Water Data Workshop met together and heard a series of plenary presentations on data access in Texas. They also worked in small groups in six concurrently held facilitated sessions and participated in plenary discussions. They worked together to address four predetermined objectives:

1. Identify specific "use cases" that list data gaps, needs, and uses for water data, and answer questions on (a) who needs data, (b) what data do they need, (c) what form do they need the data in, and (d) what decisions need to be made about water in Texas.
2. Describe desires for future water data management and access practices.
3. Articulate key attributes of a comprehensive, open access, public water data information system.
4. Inform next steps to further define, design, and build a public water data system for Texas.

A post-workshop survey allowed participants to enhance and add to information provided during the workshop.

Figure 1. Responses to the question "Who needs data?". Size of each word indicates the frequency of mention in the reporting of the workgroups.

RESULTS

Who needs what water data, in what form, to inform decisions

Participants provided over 60 different responses to the question, "who needs water data?". Answers ranged from "everyone" to specific water decision-makers, such as the "National Weather Service." The relative frequency of listing of who needs water data is described using a word cloud (Figure 1), where the size of words indicates the frequency of mention in the reporting by participant workgroups.

To help draw meaningful connections, we diagrammed how many workgroups mentioned users associated with major categories of use, such as for "agriculture," and also added specific user groups, such as "engineers" and "first responders" that workshop participants associated with those categories (Figure 2). The connection between all water users is indicated by the center circle, with different terms listed in the circle used by the six workgroups that point to "everyone." Note that the general technical professions, "resource managers, engineers, planners, and consultants," were mentioned as "who needs water data" in virtually every category of use.

Participants listed over 60 different "kinds of water data needed," with some kinds of data being subcategories of others (Figure 3). Several categories of needed data were mentioned repeatedly by the workgroups including "soil moisture, stream flow, water rights, water use, and water quality."

The next question to participants focused on the form of data needed. While there were over 50 descriptions of the form of data needed, two stood out. These were "raw data and metadata." The terms were mentioned most frequently, with many other terms used to describe various degrees of open data, accessible data, usable data, free data, and standardized data (Figure 4).

Figure 2. Responses to the question "Who needs data?" aggregated by users associated with each major use category. (Large circle noted by six workgroups, medium by three to four, and small by one to two workgroups.)

Participants were then asked to describe the purposes for which data are most needed. There were about 50 different responses with very little overlap. A wide diversity of interests of participants is not surprising given the wide variety of purposes for which data are needed and the situational, geographic, and temporal variability of water-related decisions. Responses ranged from general purposes, such as understanding how much water a person uses or how clean one's water is, to highly technical purposes, such as making flood risk determinations and updating water availability models. All recommendations are available for review in the workshop detailed summary (Rosen and Roberts 2018).

Narrowing the questions still further, participants in the workgroups were asked to describe gaps in water data that need to be filled. Not all workgroups listed gaps, but the data gaps that were noted provide insight into where more data are needed both now and for the future. Data gaps described can be grouped into (1) access to and integration of data, (2) availability due to insufficient amounts of data or lack of any data at all, and (3) specific kinds of data. These categories are listed in Figure 5.

Use cases

Participants were asked to identify potential "use cases" that may serve as ready models to inform development of open data systems. A use case is a short summary organizing, in a concise and consistent format, the data gaps, needs, uses, users, regulatory requirements, and workflow for a particular objective (BerkeleyLaw 2017; See Appendix VIII, Rosen and Roberts 2018). Use cases serve as a tool for organizing and assessing stakeholder data needs and for communicating those needs to decision-makers.

Participants identified 35 potential use cases (Rosen and Roberts 2018). Several major categories of suggested use cases emerged. Major categories were (1) groundwater, (2) water rights, and (3) event planning, which included two subcategories: (a) drought planning and (b) flood planning (Figure 6).

Five of the six workgroups arrived at consensus on a single use case each to recommend for potential future development. All five of these use cases focus heavily on data needs for water use and management, including environmental management. Those use cases involve technical water database management

Figure 3. Responses to the question "What kind of data are needed?".

as well as socio-economic and policy challenges. Those five use cases are:

1. water utility reporting to the Texas Water Development Board (TWDB);
2. environmental flow transactions;
3. flood water management in ephemeral streams;
4. integration and updating of the Texas water availability models (WAM) and groundwater availability models (GAM); and
5. risk management of the probability of reservoir water supplies falling below target criteria at three, six, nine, and 12 months.

CONCLUSIONS AND RECOMMENDATIONS

The ideal data system

The ideal public water data system was described by participants as a series of integrated data hubs or nodes—with more added over time—specialized by water sector and application (i.e., ranging from expert to general water stakeholders), with incentives for adding data into the hubs. Participants concluded that the most critical data to be included in an open data system are (1) raw data or data as close to raw data as possible, and (2) metadata. Such data may also be among the most difficult to access in general without an open system due to the likelihood of such data being proprietary or difficulties in readily accessing the data due to matters of interoperability or quantity.

Data needed by the full diversity of users must be easily accessible and interoperable to serve a wide variety of user needs. This includes needs for data at various geographic, spatial, and temporal scales, and in formats that conform to standards generally employed by the various users of data. Participants also identified qualities of data essential to ensuring data usefulness, such as data being findable, accessible, universally usable, and reusable. They suggested these qualities must exist in the ideal water data system.

Following the workshop, participants were asked to refine their recommendations for open public data hubs by responding to a survey question asking them to describe the ideal hosting option for such hubs. Respondents were almost evenly split in recommending as host (1) a Texas state agency, (2) a consortium of Texas state agencies and universities, and (3) a consortium of Texas state agencies, universities, and the private sector.

Imagine the future

Participants described a vision for the ideal public water data system for Texas as one with open access that includes an ability to obtain available water data, including raw data, metadata, and legacy data, in a digitized form. The data system should be user-friendly and robust, and provide real-time information using web services with source information and built-in visualization tools that allow experts and non-experts alike to use the system. Data and information should be free, and should be created and kept in consistent reporting formats so that data can "talk to each other" as users search and gain access. The ideal form of public data system is envisioned as consisting of several integrated data hubs specialized by water sector, with incentives for people to add new data and share existing data through the hubs. There should be adequate funding to sustain the data system over time.

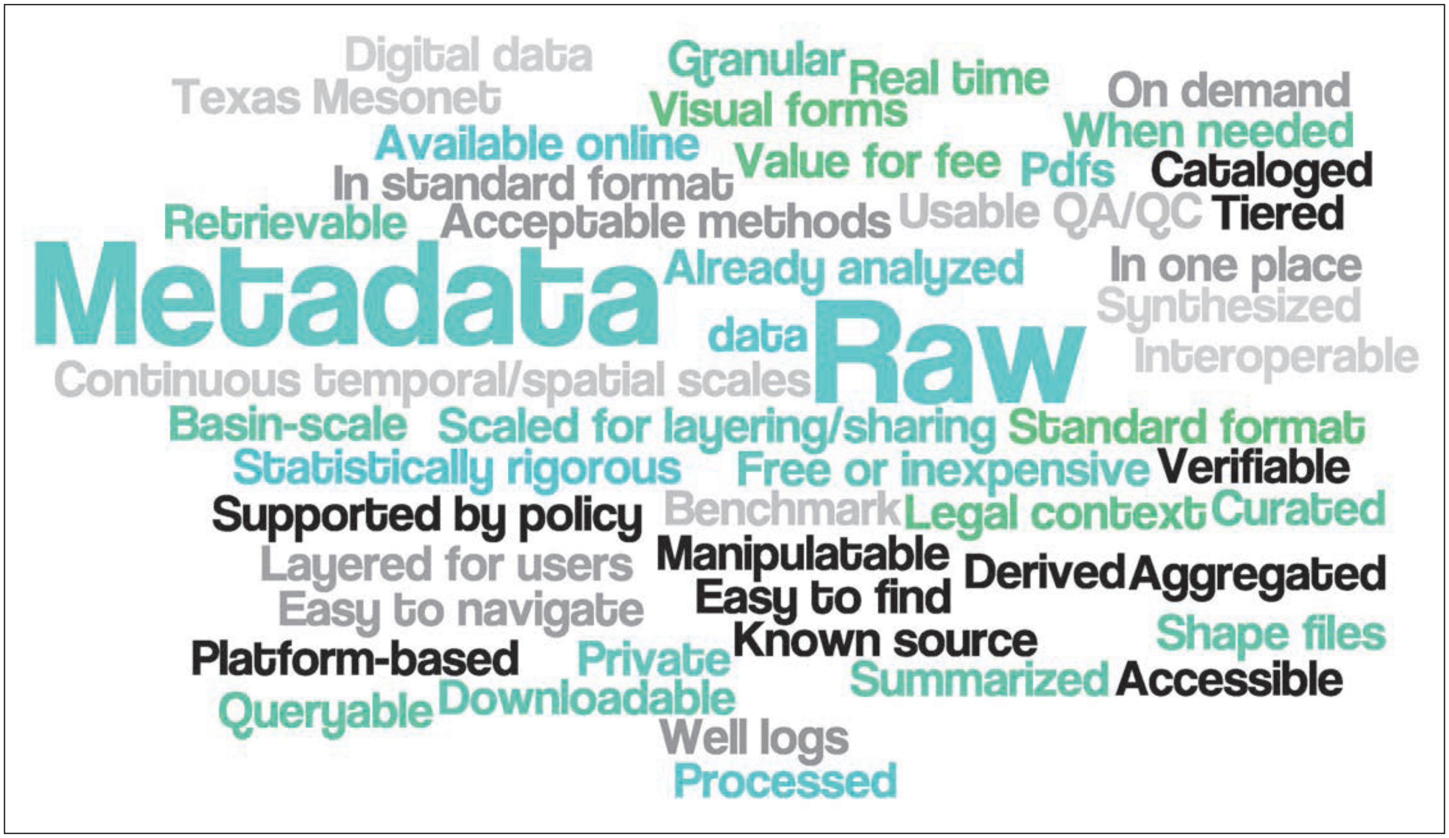

Figure 4. Responses to the question "What form of data is most needed?".

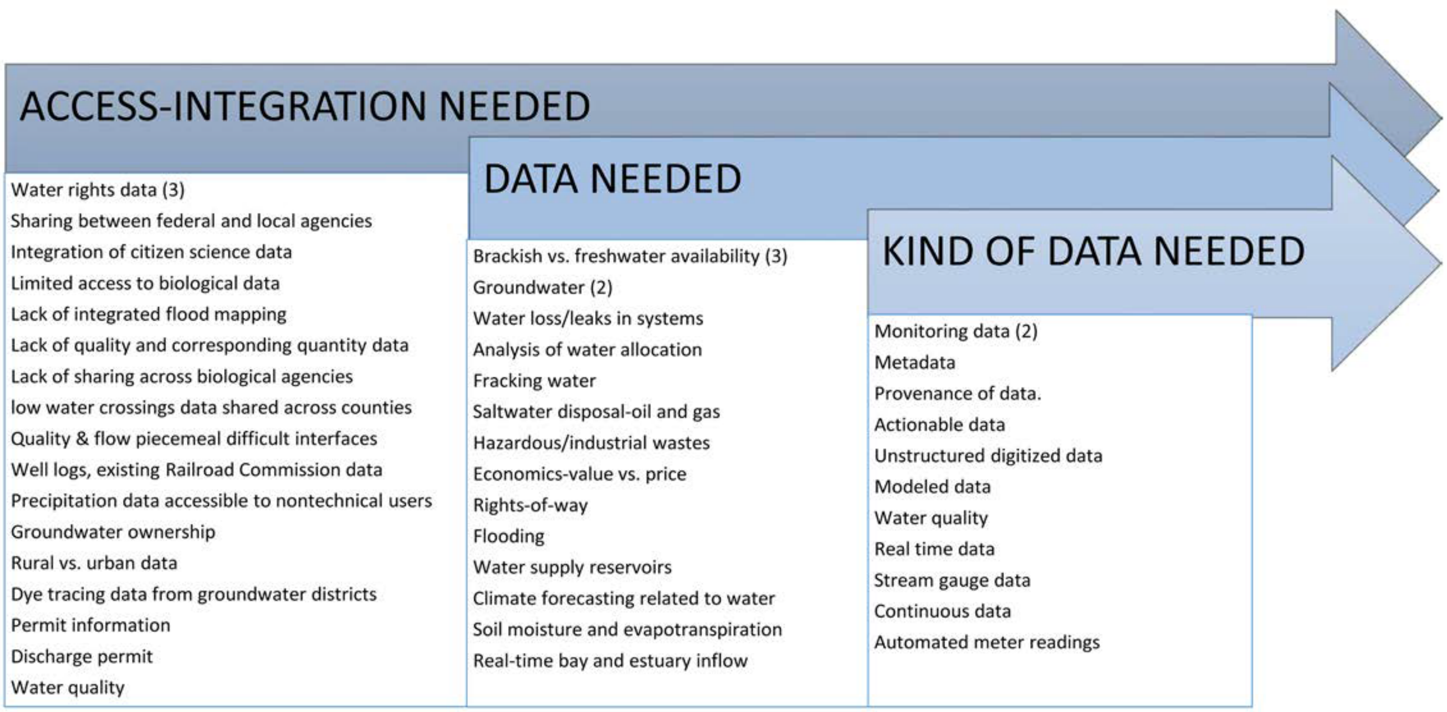

Figure 5. Data gaps arranged by category.

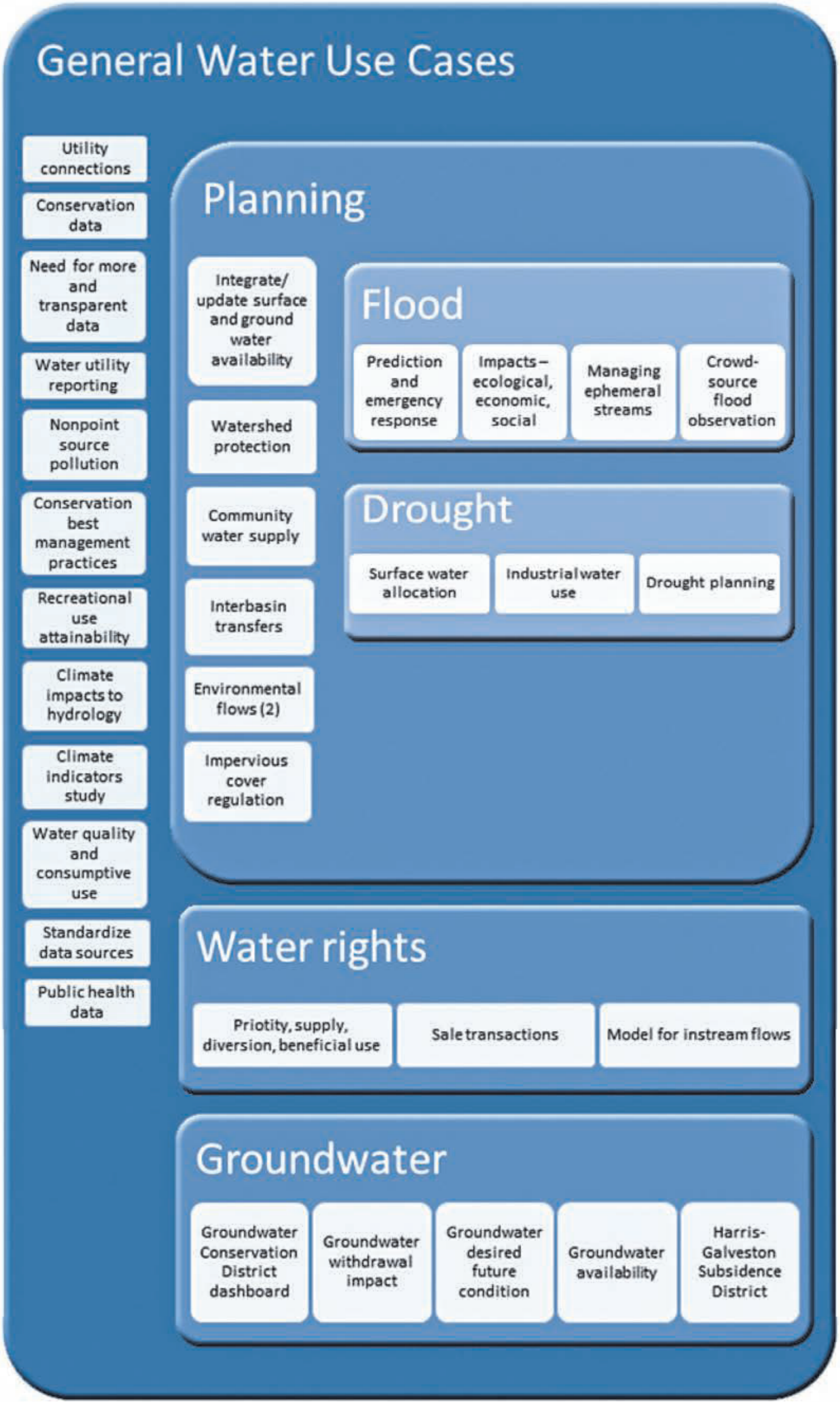

Figure 6. Use cases by categories and subcategories.

Next steps

Participants provided a list of next steps for connecting Texas data. There was considerable excitement among participants when developing this final—and perhaps most direct action-focused—part of the workshop. Key takeaways included strong support for and consensus around the need for and value of a Texas public water data hub to exist; deep commitment to the belief that Texas public water data should be FAIR: F – Findable, A – Accessible, I – Interoperable, and R – Reusable, and; continued engagement with water stakeholders in the development of a Texas public water data hub is needed.

Following from these conclusions, the group recommended that a subset of workshop participants meet regularly to further define the goals of a Texas public water data hub, develop a strawman of the hub's structure, characterize several use cases of primary interest to decision-makers and the public, and facilitate the development of pilot projects that demonstrate the value of connected water data for improved decision-making.

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Floating Solar: An Emerging Opportunity at the Energy-Water Nexus

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Abstract: Texas is experiencing tremendous growth, which puts pressure on resources including water and electricity supplies. Texas leads the nation in renewable energy production and is experiencing tremendous growth in the solar energy sector, with the Solar Energy Industries Association reporting that Texas is on track to become the fastest growing utility-scale solar market in the United States within the next five years. In this market, a new photovoltaic (PV) technology, floating solar, is gaining attention. Floating solar PV systems use the same types of PV panels as land-based systems, but the panels are either floating in the water (tethered to the land or substrate) or are suspended over a water body. Floating solar panels typically produce more energy than similarly-sized terrestrial systems (because of the cooling effect and reflectivity of the water). The shading provided by the solar panels can also significantly reduce evaporation and can improve water quality by inhibiting the growth of some types of algae and inhibiting bromide converting to bromate. In a climate where much of the state is arid or semi-arid and the entire state is subject to drought, a technology such as floating solar can be part of the solution. Texas reservoirs, water and wastewater treatment facilities, power plant cooling ponds, and irrigation ponds all have the opportunity to realize multiple benefits from floating solar that could not be achieved with a standard ground-mounted PV installation.

Keywords: floating solar, energy-water nexus, renewable energy, emerging energy technologies

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Terms used in paper

Acronyms	Descriptive name
AMTA	American Membrane Technology Association
AWEA	American Wind Energy Association
CHP	combined heat and power
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
Gal/kWh	gallons per kilowatt hour
GTM	generative topographic mapping
GW	gigawatts
LAPW	Los Angeles Department of Water and Power
MGD	million gallons per day
MW	megawatt
NREL	National Renewable Energy Laboratory
PV	photovoltaics
SAWS	San Antonio Water System
SEIA	Solar Energy Industries Association
TDA	Texas Desalination Association
TWDB	Texas Water Development Board
WEF	water-energy-food
USCB	U.S. Census Bureau

INTRODUCTION

Texas is experiencing tremendous growth. According to the U.S. Census Bureau, Texas has five of the 11 fastest-growing cities and five of the eight cities that added the most people (USCB 2016). This growth will place additional pressure on many of the state's electric supply and water systems. This paper describes the challenges that Texas is facing at the energy-water nexus, explains how renewable energy can be a part of the solution, and provides details on one innovative use of solar PV technology, called floating solar, which can have a wide variety of applications and benefits for both power production and water quality and quantity.

ENERGY-WATER NEXUS

The phrase "energy-water nexus" refers to the fact that it takes energy to treat, store, and move water, and it takes water to produce energy. This is particularly noteworthy in Texas, which has the highest production and energy use of the 50 states, both because of its size and because of the prevalence of energy intensive industries. This is an active area of research in Texas, including the University of Texas at Austin's Webber Energy Group's research[3], University of Texas San Antonio[4] Energy-Water Nexus Research Group, the Texas A&M Water-Energy-Food (WEF) research group[5], several non-profit organizations, and others. The approaches to these issues are complex and wide ranging, from improving efficiency, to identifying new supply, and changing policy.

Water use related to power production in Texas

In 2008, the Texas Water Development Board (TWDB) published the report "Water Demand Projections for Power Generation in Texas" (King and Duncan 2008). The report noted that in 2006, "The typical water consumption rate in gallons per kilowatt hour (gal/kWh) for the Texas power generation fleet is 0.2-0.7 for coal and natural gas using steam turbines,

[3] For more information see: http://www.webberenergygroup.com/research/energy-water-nexus-research/

[4] For more information see: http://texasenergy.utsa.edu/research/energy-water-nexus/

[5] For more information see: http://wefnexus.tamu.edu/

0.6 for nuclear, 0.23 for natural gas combined cycle units using cooling towers, and 0.0 for wind turbines. The water consumption rates are a factor of both the type of power generation unit and the cooling system employed." Technologies like wind (as cited in the TWDB report) or floating solar do not require water withdrawals, and thus there is no water consumed for floating solar-based power generation.

Energy use related to water supply in Texas

Drinking water and wastewater systems account for approximately 1% of the total energy use in the United States (Pabi et al. 2013). The U.S. Environmental Protection Agency (EPA) has noted that for many municipalities, drinking water and wastewater plants are the largest energy consumers, often 30-40% of the total energy consumed by the municipality (EPA 2016). As growth increases and demand for water supply increases, desalination will likely play an increasing role in meeting Texas' water supply needs. Desalination is significantly more energy intensive, and thus more costly, than more traditional fresh water supply. In 2012, TWDB found the average cost to produce 1 acre-foot (about 326,000 gallons) of desalinated water from brackish groundwater ranged from approximately $357 to $782, or $1.25 to $2.60 for 1,000 gallons, including capital, operational, and maintenance costs. One specific example is the El Paso Water Utilities, which says the cost to produce its desalinated water is 210% more than the cost for fresh groundwater and 70% more than surface water. Up to half of the cost is tied to the energy required for treatment.[6]

About 95% of the desalination plants in Texas use a reverse osmosis for desalination, where the brackish water is pushed at high pressure through a semi-permeable membrane, causing freshwater to diffuse through the membrane and leaving behind the more saline water. This is a highly energy-intensive process, although progress is being made to improve the energy intensity and cost efficacy (Wythe 2014).

Other notable facts about desalination in Texas:

- Nearly 100 inland desalination facilities across Texas produce 138 million gallons per day (MGD) of water from the 2.7 billion acre-feet of brackish water from aquifers (TDA 2014).
- The Kay Bailey Hutchison Desalination Plant in El Paso is the world's largest inland desalination plant, with a capacity of 27.5 MGD (El Paso Water 2014).
- The Southmost Regional Water Authority Brackish Groundwater Treatment Facility in Brownsville has a capacity of 10 MGD (Brownsville Public Utilities Board 2015).
- The San Antonio Water System (SAWS) operates a 12 MGD facility. Plans are already under way to expand the capacity to 30 MGD by 2026 (San Antonio Water System 2017).

Aside from the three major plants, most of the others are small and used intermittently. However, in the long term, brackish water from local aquifers and the Gulf of Mexico will likely be necessary to meet the growing water needs in Texas.

RENEWABLE ENERGY IN TEXAS

As energy efficiency programs are spreading, and water-saving methods are being implemented at power generation facilities, challenges remain. One of the ways that Texas is approaching the challenges of the energy-water nexus is to integrate renewable energy technologies. As evident from the TWDB report, renewable energy technologies such as wind and solar are less water-intensive methods of producing electricity. Both wind and solar technologies have been deployed in Texas in the last 20 years with different intensities and results.

It was in 1999 when Governor George W. Bush signed legislation that deregulated the electric utilities across much of Texas, which is credited with spurring Texas' leadership in renewable energy. Before deregulation, utilities typically controlled the generation, transmission, and retail sales of electricity. Since deregulation, generated electricity is sold on the wholesale market to regulated transmission and distribution utilities, and customers can choose retail electric providers. This initial legislation also included a requirement to have at least 2,000 megawatts (MW) of renewable generating capacity by 2009. That goal was exceeded in 2005. The goal was then raised to 10,000 MW by 2025. That goal was exceeded in 2011. By April 2016, Texas had over 19,000 MW of renewable energy generating capacity, most of that from wind turbines. Texas leads the nation in production of electricity using wind turbines (Spindle and Smith 2016). For the 12-month period ending in July 2016, 12.14% of the energy production in Texas was from wind turbines (AWEA 2019). On the other hand, solar production is a significantly smaller percentage but is growing rapidly in the state.

There remains a perception that producing electricity using photovoltaics (PV) is a relatively new and untested technology. However, Albert Einstein first published a paper on the PV effect in 1905 (DOE 2001). In 1953, scientists at Bell Laboratories made PV cells from silicon (Perlin 2016), greatly increasing their efficiency, and this is the technology used in the majority of PV panels in use globally. By 1959, PV cells were commercially available. In the 1970s the price of PV panels dropped from $100 per watt to $20 per watt and began being used in remote locations where it was challenging to connect to the grid.

[6] Early desalination plants required 7.0 to 9.0 kilowatt-hours per cubic meter of water. Newer technologies are reporting 2.5 to 3.5 kilowatt-hours per cubic meter of water (AMTA 2016).

In 2016, PV panels can be purchased for less than $1.00 per watt, and panel prices continue to drop.[7] Generative Topographic Mapping (GTM) Research and the Solar Energy Industries Association (SEIA) report, "U.S. Solar Market Insight, Q2 2016" noted that Texas is on track to become the fastest-growing utility-scale solar market in the United States within the next five years (SEIA 2016). The report also notes that:

- In 2015, over $375 million was invested in solar in Texas, a 48% increase over 2014.
- Texas is currently 10th in the nation in solar installations and is expected to rise to second in just five years.
- Installed prices have dropped 66% from 2010.

FLOATING SOLAR

The concept of floating solar is simple: PV panels (like those used for traditional terrestrial systems) that float on water bodies. Solar PV plants use the same technologies as traditional ground-mounted PV plants. But floating solar is creating new opportunities to scale up solar energy around the world, particularly in countries with high population density, competing uses for available land, or where natural or artificial water bodies are available for different reasons or uses. The deployment of PV panels on surface water bodies has grown considerably in the last four years, going from a worldwide installed capacity of 10 MW at the end of 2014 to 1.1 gigawatts (GW) by September 2018, according to the market report presented by the World Bank Group and the Solar Energy Research Institute of Singapore. According to this study, the most conservative estimate of floating solar's overall global potential based on available man-made water surfaces exceeds 400 GW, which is equal to the 2017 cumulative installed PV capacity globally (World Bank Group; ESMAP; SERIS 2018).

Floating solar is a relatively new application of PV technologies, with markets growing in Asia, Australia, and Europe. Over 250 floating solar plants have been documented around the world from 5 kW (Ciel & Terre 2019) to 40 MW (Daley 2017). The market in the United States is expected to grow along with the global market at still undetermined rates. In general and according to the Solar Energy Industries Association (SEIA 2018) PV capacity installed in the United States is expected to more than double over the next five years, and by 2023, over 14 GW of PV capacity will be installed annually. According to a recent paper published by the National Renewable Energy Laboratory (NREL), a total of 24,419 man-made water bodies were identified as being suitable for floating PV generation in the United States. Floating PV systems covering just 27% of the identified suitable water bodies could produce almost 10% of current national generation. Many of these eligible bodies of water are in water-stressed areas with high land acquisition costs and high electricity prices, suggesting multiple benefits of floating PV technologies (Spencer et al. 2019).

Given the tremendous population growth that Texas is experiencing, innovative approaches to water and energy are needed. Wind and PV require significantly less water to generate electricity when compared to more traditional methods of electricity generation (IEA 2012). Texas has shown leadership in renewable energy technologies and is expected to experience rapid growth in the PV market. Floating solar is currently a niche PV application, but it offers a number of water and energy benefits for many different applications in Texas.

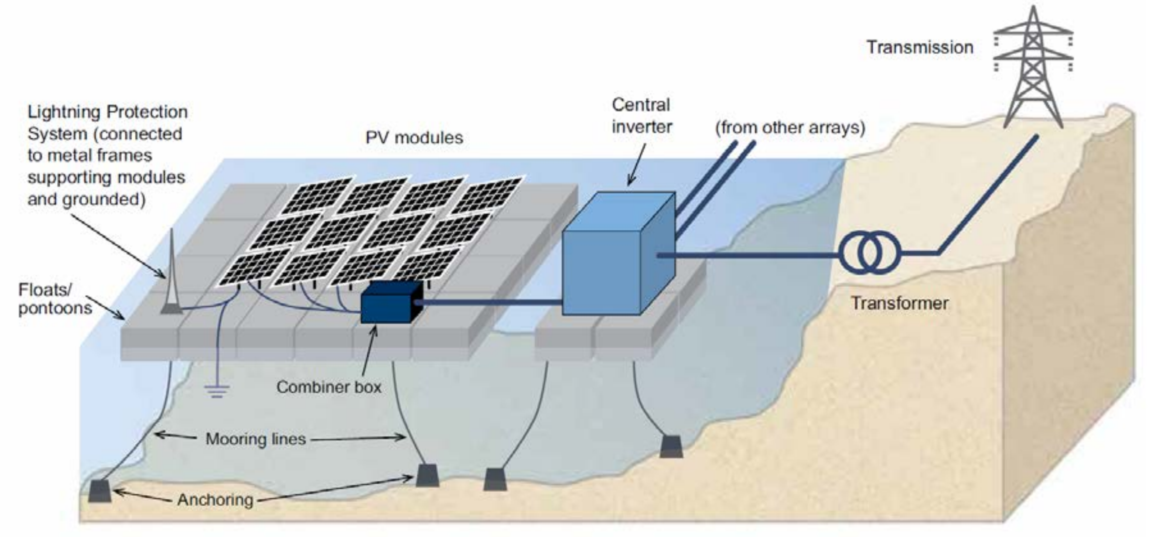
State-of-the-art of floating solar

Although floating solar is not a new topic in research journal and conferences, the number of publications is limited. For instance, 53 documents appear in Scopus searching by the words *floating* and *solar* as of July 2018. Only 16 of these papers are based on floating solar power plants. Six of these papers have been published in 2018, four in 2017, three in 2016, two in 2014, and one in 2011.

The most-cited paper is a review defining the state-of-the-art of floating PV technology, in which technology status and various design options are presented with potential applications, pros, and cons (Sahu et al. 2016). Other papers discuss pilot projects or study the application of floating solar in countries including Bosnia and Herzegovina (Pasalic et al. 2018), the United Kingdom and Japan (Patel 2014), India (Patel 2014; Mittal et al. 2017a; Mittal et al. 2017b), Bangladesh (Rahman et al. 2017), the United Arab Emirates (Safarini et al. 2017), Portugal (Proctor and Patel 2017), and Indonesia (Handara et al. 2016). Regarding applications, just one paper describes a use other than power generation, which is water desalination (Ni et al. 2018).

Regarding technology, most of the papers are focused on PV but two papers study the use of concentrated solar (Diendorfer et al. 2014; Ni et al. 2016). Ni et al. studied in 2016 the feasibility of an innovative, low-cost, scalable, floating solar receiver able to generate 100 °C steam under ambient air conditions without optical concentration, while Diendorfer et al. studied in 2013 the applications of different floating concentrated solar technologies under the geospatial conditions of the Mediterranean Sea. The feasibility of developing floating structures made of varying materials such as coconuts (Fauzan et al. 2017) or plastics like and high-density polyethylene (Sahu and Sudhakar 2017) are discussed in the existing literature too.

[7] Note: these prices are for the PV panels, not PV installation nor permitting. For estimates on installed rooftop PV costs in Texas, see, for example: https://solarpowerrocks.com/texas/



Source: Solar Energy Research Institute of Singapore (SERIS) at the National University of Singapore (NUS).

Figure 1. Floating solar scheme (World Bank, ESMAP; SERIS 2018).

While the solar industry currently has ongoing research attention, research is needed on the unique aspects of floating solar, such as floating structures and adapted technology development addressing different installation, maintenance, operation, and ownership challenges in different locations and under different conditions. For instance, it is expected that traditional business models applied to solar energy will be applicable to floating solar, but more research is required on this new approach.

System design

As mentioned before, floating solar consists of regular PV panels that are installed over a body of water. Typical systems are designed to float on water and can adjust to variations in water levels (Pickerel 2015). Other installations are designed in a fixed position over a water body but are still sometimes referred to as floating solar (e.g. an installation in Gujarat, India where the panels are on a racking system over a canal (Jenna 2015)).

Because of the challenges of wave action in open-water, floating solar is more common in inland applications. These can include lakes, reservoirs, retention ponds, water treatment ponds, or canals. The systems have anchoring systems in place, tethering the racking systems to land or the bed of the body of water, as shown in Figure 1. The structural design of the racking and tethering systems needs to be tailored to the specific location of the proposed installation, making the structural engineering slightly more complicated than typical ground mount or rooftop systems.

Other than the components that float, are anchored to the bed of the water body, or are suspended over the water body, a floating system is similar to typical land-based systems. Like traditional PV, floating solar can be designed with a fixed tilt or the PV can be installed on tracking systems that change the angle of the panels to follow the sun throughout the day. The systems are typically modular, so that once the system is designed it is easily deployed and scalable.

Estimated costs

The cost of floating solar has not yet been analyzed intensely in the technical literature. Some papers have proposed and studied cost structure for floating energy plants (Castro-Santos et al. 2016), including wave energy and wind energy, but not floating solar. Some internet sources provide cost references for the Asian market comparing traditional and floating solar, which go from almost equal to a 25% more expensive in the case of floating solar, but more research on this topic for the American market is required. Only the World Bank Group's floating solar market report provide references for costs and installed capacity in different countries in the world. This report defines total capital expenditures for turnkey floating PV installations in 2018 between \$0.8–\$1.2 per installed Watt depending on the location of the project, the depth of the water body, and variations in that depth for facilities in the 0.2 to 150 MW range. For instance, in 2018 a 150 MW floating solar plant built on top of an abandoned coal mine located in Anhui, China has come online with a budget around \$148 million dollars. But the costs of smaller systems in different regions could vary significantly (World Bank Group; ESMAP; SERIS 2018).

In the United States, the University of Arizona evaluated the feasibility of using floating solar to produce power and reduce evaporation in Arizona. The study found that a utility-scale floating solar project would have similar costs to a land-based

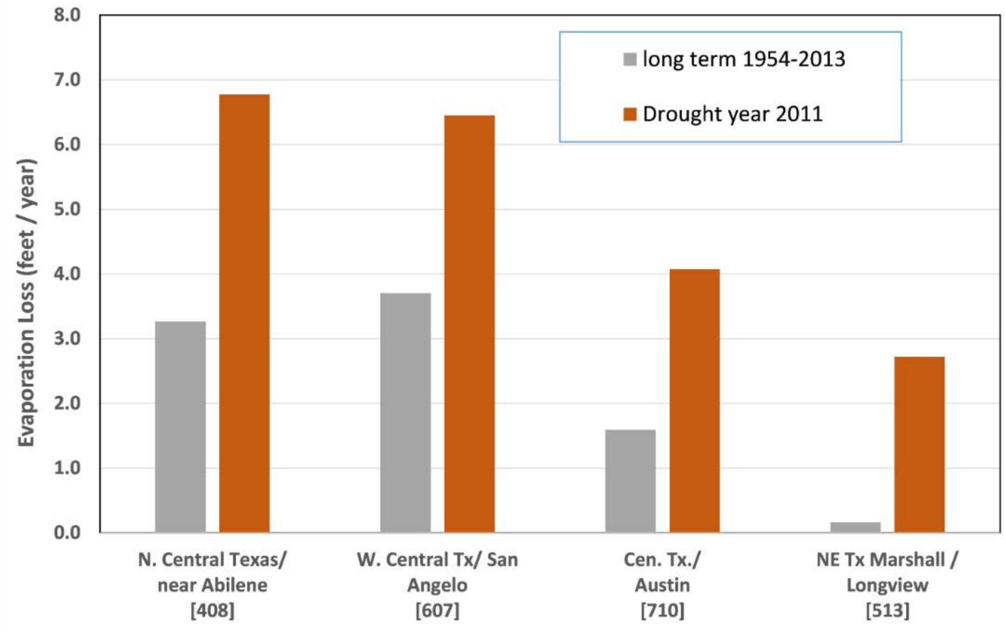


Figure 2. Evaporation loss (Johns 2014).

PV installation in the United States, and power production would be higher for the floating system than for a land-based system due to the lower temperatures that the panels reach. Based on the results of the review of the technology and applications, the researcher recommended a pilot-scale study to confirm the results of the research. The proposed pilot study would be located on the Lake Pleasant Reservoir, part of the Central Arizona Project. The researcher modeled production and costs and noted that while the lifetime costs per unit energy were higher than the current Central Arizona Project rates, the estimated costs did not include projected electricity price increases, savings from water conservation, or other benefits (Hartzell 2016). In addition, The U.S. Bureau of Reclamation completed a study in October 2015, "Fundamental Considerations Associated with Placing Solar Generation Structures at Central Arizona Project Canal," and concluded that placing panels over the canal would be approximately 24% more expensive than traditional land-mounted systems (U.S. Department of Interior 2015). The report further recommended additional research for "improved structural cost estimates, improved operating and maintenance cost estimates, improved impacts to operating and maintenance, impacts to the canal and canal lining, evaporation studies including evaporation with shading, viability of solar power over small canals (Pickerel 2016), and a robust design for solar panels to be installed in remote locations," (U.S. Department of Interior 2015).

Benefits and applications of floating solar

PV has benefits compared to other methods of electricity generation, and floating PV has several benefits over traditional terrestrial PV. Both PV systems are silent and do not consume water for the power generation process, a boon to the energy-water nexus. PV can also be easily deployed as a local power system, especially in locations where:

- the costs of extending transmission lines might be prohibitive;
- power quality is not good, or an additional layer of security is required for the power supply (i.e., extra resilience);
- current electricity prices are high; and
- there is a desire to minimize or offset emissions associated with power consumption.

Obstacles are easier to avoid in medium and large water bodies, thus floating solar has the potential added benefits of suffering fewer shading issues than traditional PV systems, while reducing water evaporation. Water quality can be improved too. Algae formation in the water bodies can be reduced by floating solar as the amount of sunlight in the water would decrease, reducing the photosynthesis process to produce less algae in water (Sharma et al. 2015).

Most of the annual rainfall in Texas occurs during rain storms, when a large amount of precipitation falls over a short period of time. Except for the subtropical humid climate of the eastern quarter of the state, evaporation exceeds precipitation—yielding a semiarid or steppe climate that becomes arid in far west Texas (TWDB 2012). Figure 2 presents evaporation losses for different areas in Texas. In most of these regions evaporation during a drought year might be twice the evaporation during a regular year.

The shading provided by floating solar panels can reduce evaporation in lakes, reservoirs, canals, and other surface water bodies, helping to increase the efficiency of water supply systems. Also, the proximity of the water has an evaporative cooling effect on the panels that increases their efficiency, resulting in a higher electricity production per panel. For example, a project in South Australia at a wastewater treatment basin is currently underway. In that hot, dry climate, the project developer is estimating that a floating PV system would be 50% more efficient than a land-based system and would reduce evaporation in the covered area by 90% (Doran 2014). That estimation seems high to these authors since typical power losses due to high temperature are around 16%, so saying a 50% efficiency increase might mean reducing temperature-based power losses by half. However, while this is the anticipated result, there is a need to conduct additional research to quantify the real-world effects on evaporation from this and other projects. This South Australian project may provide valuable data to evaluate whether this technology could benefit the regions of Texas that have a similar climate.

Like traditional PV, floating solar can provide electricity to where it is needed in remote areas. It may be integrated with equipment such as pumps, data loggers, sensors, and analyzers. For example, the City of Houston's Lake Houston SolarBee project uses solar-powered water circulators to improve water quality. The City of Houston uses the 11,000-acre water body as one of three sources of drinking water. Although the water quality is generally good, seasonal blue-green algae blooms and depleted oxygen levels at depth were resulting in odor and taste issues. Installed as a pilot program in 2006, the solar-powered circulators help oxygenate the lake, helping maintain a healthy ecosystem and reducing the need for chemical treatment. The three-year pilot program was successful and continues today (City of Houston; Green Houston Texas 2006; Bleth 2007; C40 Cities 2011).

Shading can also provide water quality benefits. When sunlight reacts with naturally-occurring bromide in the water, it creates bromate, which is a carcinogenic compound. The sunlight also promotes algae growth. Because floating solar also provides shading, it has the potential to offer similar benefits while concurrently producing power. Bacterial issues have been detected on some projects that tried to minimize water evaporation through shading, so more research on the materials to be used as standing structures for floating solar in water reservoirs for drinking water is needed (De Graaf 2015).

Floating solar projects can also provide shelter for fish from feeding birds, especially in water bodies used for aquaculture. Although these are consistent advantages, when developed in natural ecosystems such as natural lakes or the sea, the environmental impact of floating solar plants must be carefully studied in advanced.

Since floating solar is best suited to inland applications such as lakes, reservoirs, retention ponds, water treatment ponds, and canals, the ideal location has power needs suited to the size of the system and would benefit from reduced evaporation and shading. Therefore, wastewater treatment plants and surface water supply and transport systems, particularly those in hot, dry climates, can be well suited to the application of floating solar technology. Irrigation ponds, such as those used for agriculture, may also benefit. The authors provide examples of floating solar installations in the United States below.

Potential in Texas

Texas is well-positioned to take advantage of the benefits of floating solar. According to the Texas Water Development Board (2012), "Except for the wetter, eastern portion of the state, evaporation exceeds precipitation for most of Texas, yielding a semiarid climate that becomes arid in far west Texas. The El Niño Southern Oscillation affects Pacific moisture patterns and is responsible for long-term impacts on Texas precipitation, often leading to periods of moderate to severe drought." Because floating solar systems can prevent water evaporation, this helps to conserve water.

Texas has approximately 191,000 miles of streams and 196 major reservoirs, with a combined reservoir capacity of over 30 million acre-feet (TWDB 2016). These reservoirs along with wastewater treatment plants, power plant cooling water ponds, and irrigation ponds may all potentially benefit from not only the power production provided by floating solar but also the reduction in evaporation resulting from the shading. Irrigation ponds with floating solar can use the power to operate irrigation pumps, making it easier to maintain ponds that require aeration pumps in remote locations. Or, if the user prefers to irrigate at night when the sun is not shining, solar pumps could be used to pump the water into an elevated tank that could then be used to irrigate when the sun is not shining, or the energy could be stored in batteries and used at night.

Floating solar can also help places in Texas with persistent blue-green algae. Blue-green algae can cause taste and odor problems and produce toxins that are poisonous to fish and wildlife. According to the Texas Parks and Wildlife Department, "Fish kills have occurred in private stock ponds as a result of blue-green algal blooms and there have been a few reports of livestock dying from drinking water contaminated with blue-green toxins" (TPWD 2016). Blue-green algae can also compromise human health through both external exposure and ingestion (UNL 2019). Solar-powered floating mixing systems such as those used on Lake Houston might be helpful for these water bodies with persistent blue-green algae, blocking the sunlight that hits the water and the reducing the photosynthesis process to produce less algae (Sharma et al. 2015).

Figure 3. Ground-mounted and floating solar plants in Far Niente Winery, Oakville, California. Source: Google maps.

EXISTING FLOATING SOLAR EXAMPLES IN THE UNITED STATES

So far, no energy agency or government-related entity has published a database of the existing floating solar plants in the world. In January 2018, a list of the 70 top floating solar plants was published by the website Solarplaza (Mesbahi and Minamino 2018). Although it is not clear which is the criteria used to consider a plant as "top," the list presents some of the facts of the floating solar market, such as:

- Asia is the continent with the highest number of facilities deployed: Japan is probably the country in the world with the highest number of plants while China is the country with the biggest plants (by capacity).
- Floating solar plants have already been developed in almost every climatic area of the world where water bodies exist.
- Sizes range from less than 2 MW for commercial and small industrial facilities, to hundreds of MW for larger power plants.
- Owners and developers vary from commercial or industrial clients to public entities such as municipalities, water authorities, or electric companies.

There is no information about the business models adopted by these 70 plants in the cited website. Most of these 70 plants began operating from 2014 to 2016, reflecting how the global market has grown rapidly over the last five years, based on technological advances that enabled the deployment of PV technologies and the other components of floating platforms.

The foundations of the present floating solar technologies were established in the early 2000s, beginning in 2007, the year in which the annual number of patents on floating solar began ramping up. In February 2008, a winery in Oakville, California installed what was perhaps is the first commercial-scale floating solar plant in the United States: Far Niente Winery (Business Wire 2008). Other facilities have followed in the United States in different sectors, developed with different drivers and goals by different entities.

Far Niente Winery, Oakville, California

In 2008, Far Niente Winery installed a 175-kW floating solar plant in their irrigation pond. After looking at several configurations for the expansion of their existing solar array, all the alternatives involved taking out a significant amount of its vineyard. The idea of installing the panels in its irrigation pond came up during a meeting and the winery found a company with the right technology to develop the project. The floating array's positioning on the pond saved 3/4 of an acre of valuable Cabernet vines that would have been ripped out for a total land-mounted system, as seen in Figure 3. This is equivalent to about $150,000 dollars' worth of bottled Far Niente Cabernet annually. This expansion of the existing solar arrays helps the company with its goals to be annual net zero (to sell more electricity back into the grid than the energy purchased from the grid) and to reduce its electricity bills considerably (cost savings).

Figure 4. Panels at the Bordentown Avenue Water Treatment Facility. Source: www.wateronline.com.

Bordentown Avenue Water Treatment Plant Reservoir, Sayreville, New Jersey

Another large project that began construction in 2016 is the 4.1 MW floating solar array in Sayreville, New Jersey. The $12 million project is located on a reservoir for the Bordentown Avenue Water Treatment Plant. The array, shown in Figure 4, produces all the electricity required to operate the plant over the course of a year. While the plant is connected to the electrical grid, the expectation is that the plant will result in net zero annual energy consumption from the grid (Pickerel 2016).

Olivenhain Reservoir, San Diego County Water Authority, San Diego, California

San Diego County Water Authority is installing floating solar panels on a portion of the 200-acre Olivenhain Reservoir according to the layout presented in Figure 5, producing around 6 MW of peak capacity. Exploiting the additional potential of these facilities to generate power and to minimize water evaporation are some of the drivers of this project.

Figure 5. Olivenhain Reservoir and Dam in San Diego, California and floating solar plant layout in initial design. Source: Google Maps and San Diego County Water Authority.

Figure 6. Installation process of the Walden, Colorado Plant. Source: NREL.

Walden Municipality, Walden, Colorado

In 2018, the Colorado Energy Office supported the development of a 75-kW floating solar array in the town of Walden, as a part of an energy performance contract with the company Johnson Controls. NREL documented the installation process (Figure 6). The project is expected to generate approximately $10,000 in annual savings and to offset part of the municipal environmental emissions (Runyon 2018).

Salad Cosmo, Dixon, California

In Dixon, California, Salad Cosmo, a family-owned bean sprout producer, installed a 600-kW floating solar system as part of its environmental commitment. Placing a traditional solar system on its farm land would have harmed productivity. Floating solar enabled this company to utilize the surface area of the pond, as seen in Figure 7, saving money and reducing environmental emissions (Ciel & Terre 2018).

CONSIDERATIONS

Floating solar systems are finding new opportunities in the U.S. market. Depending mostly on geospatial factors such as location, size (economies of scale), and other factors such as how easy or complex the access to the body water is, floating solar may range from equal to more expensive per watt installation costs than ground-mounted systems. Among these factors, the extra engineering and design for the racking and tethering systems must be included, since floating solar is not yet as stan-

Figure 7. Aerial view of Salad Cosmo's pond and floating solar plant. Source: Google maps and Ciel & Terre.

dardized as ground-mounted PV. But these costs may be offset because the reflectivity of the water surface and the slight cooling effects on the panels can result in higher power production.

Additional research and case studies on existing installations will help quantify these potential benefits in different climate areas of the United States, such as the paper recently published by the company Solener and the University at Albany (Perez et al. 2018). In this paper, they analyze the potential of floating solar in the United States with some interesting findings such as:

- Deploying floating PV on the 128 largest U.S. reservoirs could supply firm, 24/7 electricity equivalent to 100% of U.S. electrical demand. Deployed on all the lakes considered for their study, floating PV would produce 10 times that amount.
- Floating solar requires a smaller footprint than a hydroelectric facility to produce an equivalent amount of energy. Perez et al. affirm that covering 1.2% of their surface with PV would generate as much electrical energy as hydropower currently generates. Although the value of the percentage might fluctuate a little, the idea can be easily validated. In 2006, out of a database of 245 hydro plants in operation in the world with at least 30 MW of installed capacity, the average power density was 2.95 W/m2 (UNFCCC 2006). On the other hand, in 2019, power density for solar panels in the market is around 180 W/m2. According to these numbers, a floating solar plant with a 180 W/m2 power density would require just 1.6% of the area required by a hydropower plant to generate the same power.
- Floating PV panels can generate water savings not only reducing evaporation in the water bodies they float on, but also replacing other water-intensive power generation technologies.
- While PV deployment may have a vast potential on reservoirs and lakes, it is far from the only deployment option for this technology.

These authors also mention among their conclusions that hydroelectric production via turbines could be reduced or eliminated as a reservoir management objective, especially at the end of the life cycle of the most critical technological components. An alternative would be to deploy floating PV on a small fraction of reservoir area, focusing the management on other goals, such as flood control and water supply.

The combination of both technologies (floating solar and hydro power) is an opportunity worth exploring since hydro power plants have all the components of a power plant already installed onsite. But this statement might not be correct, considering that sometimes these turbines do not only generate power but also provide regulation services for the bulk power system. Providing this kind of service with a renewable (non-dispatchable) energy source such as solar is more challenging from a technical and economic standpoint. In that regard, energy storage technologies are gaining traction in power system regulation markets and could be a practical alternative for that scenario to occur (floating solar plus battery storage providing regulation services for the power grid).

Additional factors to consider are the potential infrastructure savings (if in remote locations), the durability of the systems (e.g., from biofouling and corrosion), operation and maintenance costs, access, the value of surrounding land, and the economic impact the structure may have on the body of water. For example, if the structure would interfere with sport fishing, and/or recreation, it may have negative economic consequences. In addition, for non-grid connected systems, power production and demand loads should be evaluated and the costs of storage, if necessary, should be included. Finally, non-economic factors should be considered as well. For example, if a project is proposed on a reservoir, the design should take into consideration the potential effect on aquatic life from both the structure itself and the shading that will occur from the panels.

CONCLUSION

Texas is experiencing tremendous growth, which brings challenges at the energy-water nexus. Texas has been a leader in renewable energy and the PV sector is predicted to grow rapidly in the next five years. In a climate where much of the state is arid or semi-arid and the entire state is subject to drought, floating solar may be part of the solution. Texas reservoirs, water and wastewater treatment facilities, power plant cooling ponds, and irrigation ponds all have the opportunity to realize benefits from floating solar that could not be achieved with standard land-mounted PV installations. Additional data on economics, evaporative effects, and environmental effects would help support planners and designers in evaluating the potential for this technology in the Texas market. The types of contributions that would be most valuable at the current life stage of this technology include: demonstration projects, laboratory studies, case studies, economic studies, and modeling of the energy, water quantity, and water quality benefits of floating solar.

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A Tool for Rapid Assessment of Hydrological Connectivity Patterns in Texas Coastal Wetlands: Linkages between Tidal Creeks and Coastal Ponds

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Abstract: Coastal salt marshes are heterogeneous, spatially complex ecosystems. The degree of hydrological connectivity in these systems can be a significant driver in the flux of energy, organisms, and nutrients across the marsh landscape. In tidally driven systems, the frequency and magnitude of hydrological connection events results in the creation of a matrix of intermittently connected coastal wetland habitats, some of which may be hydrologically isolated or partially drained at any given time. Previous approaches to understanding landscape-level hydrologic connectivity patterns have required either intensive long-term monitoring or spatially explicit modeling. In this paper, we first describe a 13-month field study in the Guadalupe Estuary of the Texas Gulf Coast that linked hydrological connectivity patterns between a saltwater pond to water levels in an adjacent tidal creek and nearby San Antonio Bay. We next describe the integration of these field data with high-resolution digital elevation models and environmental parameters to develop a spatially explicit model that is a Simulation of Landscape-level Oscillations in Salt Marsh Hydroperiod (SLOSH). We evaluated the ability of SLOSH to simulate trends in landscape-level patterns of hydrological connectivity between a tidal creek and an inland marsh pond. Magnitude and periodicity of simulated and observed water-level fluctuations in the pond were similar. Highest creek water levels, resulting in high frequency and duration of hydrological connectivity with the pond, corresponded with the highest bay water levels, which occurred during September and October. Lowest creek water levels, resulting in low frequency and duration of hydrological connectivity, corresponded with the lowest bay water levels, which occurred during December through February. By simulating the pulsing structure of salt marsh hydrology, SLOSH creates the foundation on which to assess how additional drivers (precipitation, wind, freshwater inflows, etc.) can influence coastal marsh hydrology and overall ecology.

Keywords: Aransas National Wildlife Refuge, freshwater inflows, hydroperiod, saltwater ponds, water level, whooping crane (*Grus americana*)

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Terms used in paper

Acronyms	Descriptive name
ANWR	Aransas National Wildlife Refuge
BR_t	mean daily tidal creek water levels
BR	Boat Ramp
cm	centimeters
DEM	Digital Elevation Models
ET	evapotranspiration
ft	feet
GIW	Gulf Intracoastal Waterway
GIS	geographic information system
ha	hectares
in	inches
km^3	cubic kilometers
lidar	Light Detection and Ranging
$MaxT_t$	daily maximum temperatures
m	meters
mm	millimeters
$MinT_t$	daily minimum temperatures
NAVD88	North American Vertical Datum of 1988
Ra	mean daily solar radiation (MJ $m^{-2}day^{-2}$)
Sd_t	mean daily water levels at the Seadrift gage in San Antonio Bay
SLOSH	Simulation of Landscape-level Oscillations in Salt Marsh Hydroperiod

INTRODUCTION

Coastal salt marshes are heterogeneous, spatially complex landscapes comprised of a wide variety of habitat types. The degree of hydrological connectivity across the coastal marsh landscape can be a significant driver in the formation and maintenance of the ecological resources found in these habitats. Environmental factors including mean sea level, tidal cycles, and wind velocity and direction can directly influence hydrological connectivity in aquatic systems, specifically affecting water column flushing rates, salinity, nutrient supply, species diversity, and primary production (Odum et al. 1995; Bornette et al. 1998; Ward et al. 1999; Ahearn et al. 2006; Leibowitz and Vining 2003; Miller et al. 2009; Wilcox et al. 2011). With increased pressures on coastal ecosystems (e.g., storm effects, sea level rise, human impacts), it is critical to understand how these variables work in concert to influence spatial and temporal patterns of hydrological connectivity across the coastal salt marsh landscape.

The degree of hydrological connectivity plays an important role in determining the flux of energy, material, and nutrients across the salt marsh landscape. In many estuarine systems, much of the nutrient load is delivered to the salt marsh via freshwater inflow originating from upstream in the watershed. However, in marshes located farther from the mouth of the estuary, at increased distances from tidal creeks, or occurring at higher elevations in relation to mean water levels, the degree of hydrological connectivity can be the regulating factor that dictates ecosystem productivity by allowing the exchange of energy, nutrients, and organisms with the marine environment (Odum et al. 1995; Pringle 2001). In tidally driven systems, there is a clear hydrological disconnect between near tidal creek habitats and more inland marsh habitats (Ragan and Wozniak 2019). During periods of low water level (e.g., low tide), water actively drains from habitats in close proximity to tidal creeks, whereas inland marsh habitats often experience delayed or incomplete drainage due to micro-elevational changes in marsh topography, which leads to fewer points of hydrological connection and subsequent shifts in marsh water quality (Valiela et al. 1978; Prado et al. 2017).

In highly heterogeneous coastal marsh settings, there are multiple connection points, which are distributed across the landscape and sometimes independent of lateral distance from tidal waters. This results in a matrix of intermittently connected ponds—relatively small patches of inundated marsh—each often operating independently from the others that may be drawn down or completely drained during periods of low tides, low rainfall, and increased evapotranspiration (ET). These dry-down phases can persist for extended periods of time (several days to weeks) and often lead to hypersaline conditions, hydrologic isolation, barriers to the movement of aquatic organisms into and out of inland marsh ponds (Day et al. 2012; Ragan and Wozniak 2019), and the reduction of primary productivity (Zedler et al. 1980). Understanding connectivity in micro-tidal estuaries is particularly important because these patterns do not relate directly to lunar tidal cycles and are a result of interactions of a relatively flat environment and other drivers of water level fluctuation (e.g., wind, storm surge, fortnightly tides, etc.).

For salt marsh systems that provide critical ecosystem services (e.g., flood risk reduction) or contain endangered species, it is important for natural resource managers to understand how different management actions permeate through their system. However, the complexity of inland marsh hydro-connectivity patterns makes developing management strategies challenging, particularly because few predictive models have been generated for the natural resource management community. Computational models that predict marsh dynamics often do not include inland ponds (Park et al. 1989; Moorhead and Brinson 1995; Nicholls 2004; Poulter and Halpin 2008); nor do they involve complex analytical solutions that explore the geophysical properties of marshes that link to the ecology (Fagherazzi et al. 2012; Fagherazzi and Furbish 2001; Mariotti and Fagherazzi 2010). High-resolution Light Detection and Ranging (lidar) data, which is capable of distinguishing the fine-scaled topographic features affecting overland flow (Lindsay 2006), allows for the development of a rapid assessment modeling tool that simulates the seasonal and year-to-year dynamics of fine-scale water level patterns within salt marsh ecosystems.

In this paper, we describe a 13-month field study that linked hydrological connectivity patterns within a salt marsh in the Guadalupe Estuary of the Texas Gulf Coast to water levels in the adjacent San Antonio Bay. We next describe integration of these field data into a spatially explicit model that simulates hydrological connectivity at a fine spatial scale in salt marsh ecosystems. The ability of the model to simulate the trends in landscape-level patterns of hydrological connectivity was assessed by comparing simulated connectivity patterns to connectivity patterns observed in the field between a tidal creek and an inland marsh pond. By simulating the pulsing structure of salt marsh hydrology, the simulation creates the foundation on which to assess how additional drivers (precipitation, wind, freshwater inflows, etc.) can influence the distribution of nutrients, abundance of organisms, and overall coastal marsh ecology.

METHODS

Study site

The Coastal Bend region of Texas includes numerous bays and estuaries that are ecologically and economically important. One such system, the Guadalupe Estuary, which includes San Antonio Bay, is a shallow (1 meter [m] mean depth [3.28 feet {ft}]) lagoonal estuary (about 550 square kilometers [km^2] in area) located along the mid-Texas coast (Figure 1). The estuary is fed primarily by the combined discharge of the San Antonio and Guadalupe rivers and is separated from the Gulf of Mexico by Matagorda Island. Aransas National Wildlife Refuge (ANWR) occupies much of the Blackjack Peninsula that extends out into the estuary and contains nearly 2,800 hectares (ha) [6,918 acres] of salt marsh interspersed with tidal creeks, inland bays, and intermittently connected marsh ponds (Figure 2). The irregularly flooded salt marsh along the ANWR possesses a narrow fringe of *Spartina alterniflora Loisel.* (1–2 m [3.28–6.56 feet] wide) and inland habitats dominated by a mixed high-marsh vegetation community including *Distichlis spicata* L. Greene, *Lycium carolinianum* Walt., and *Salicornia virginica* L. (see Butzler and Davis 2006 for a detailed description of the vegetation community). The marsh and ponds undergo inundation and connection/disconnection at irregular intervals throughout the year, and the marsh ecosystem is characterized by compact poorly-drained mineral soils. Thus, different ponds vary in terms of water level, nutrient content, and benthic production as a result of their frequency and duration of connection to tidal waters (Miller et al. 2009).

The overall stability and production of the marsh food web is of critical importance as these marshes are the wintering habitat of the endangered whooping crane (*Grus americana*). Whooping cranes utilize the ANWR salt marsh from mid-October through mid-April, foraging primarily on Carolina wolfberry (*Lycium carolinianum* Walt.) and aquatic invertebrates (such as blue crabs [*Callinectes sapidus* Rathburn], fiddler crabs [*Uca* spp.], and clams [family Corbiculidae]). These aquatic invertebrates are readily found in the marsh ponds and are dispersed across the inland marsh landscape via hydrologic connection events (Hunt and Slack 1989; Butzler and Davis 2006; Miller et al. 2009).

This paper focuses on the Boat Ramp (BR) study site located on the Blackjack Peninsula of the ANWR (Figures 1 and 2). The BR site is comprised of an extensive tidal creek-open marsh-saltwater pond complex (Figure 2). The pond we focused

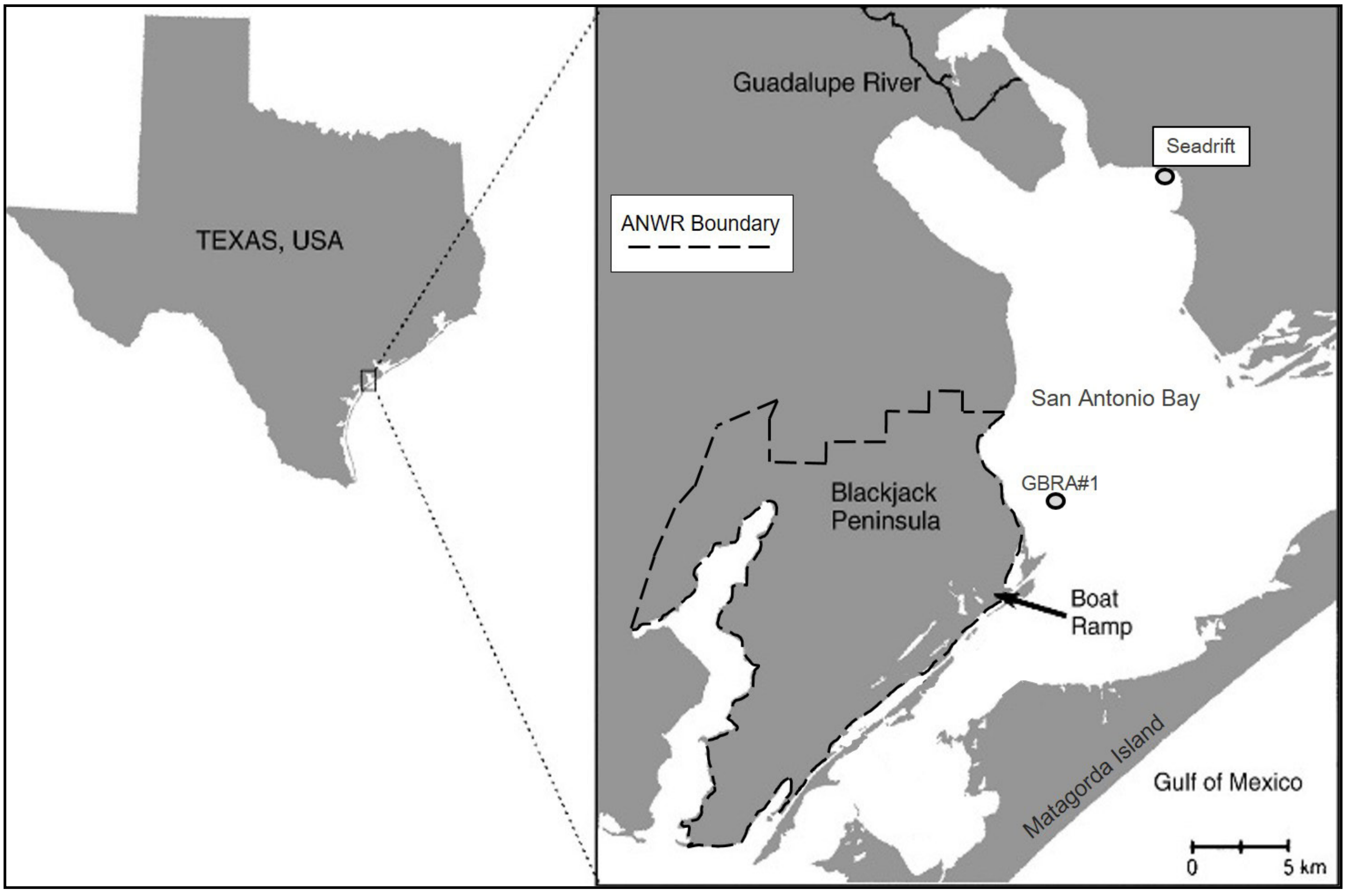

Figure 1. Map of the study system including the Guadalupe River, San Antonio Bay, and the Aransas National Wildlife Refuge (ANWR) located on the Blackjack Peninsula (boundary designated by the black dashed line). The locations of the coastal wetland research site, Boat Ramp (BR), at the ANWR and Seadrift water level monitoring station are also shown.

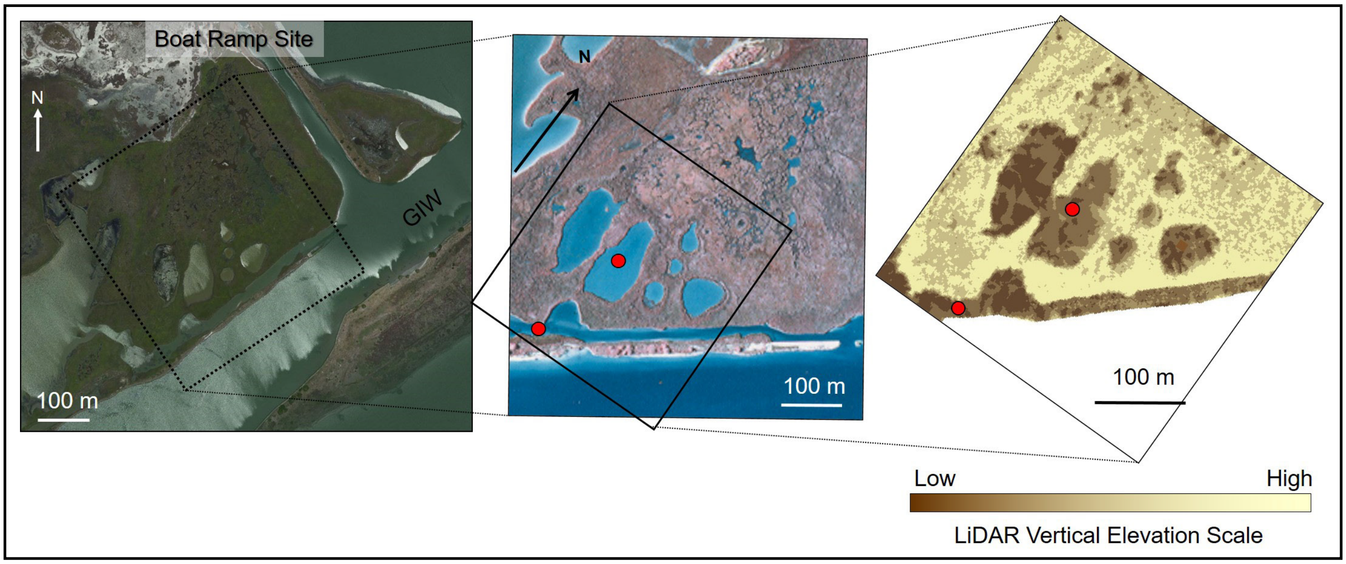

Figure 2. Left: Satellite images of Boat Ramp (BR) territory at the Aransas National Wildlife Refuge, Aransas, Texas. The box represents the approximate area chosen as the representative sample upon which Simulation of Landscape-level Oscillations in Salt Marsh Hydroperiod (SLOSH) was parameterized. Right: Lidar image of the BR territory on which SLOSH was parameterized. Green squares represent georeferenced location of water level gages used during the field studies. On the lidar image, the vertical elevation scale is shown by color with darker browns representing lower elevations and lighter tans representing higher elevations. The georeferenced locations of the tidal creek and pond water level gages are shown as red circles.

on is elliptical in shape (61 m x 137 m [200.13 ft x 449.48 ft]) and characterized by an intermittent hydrologic connection regime, becoming isolated (and at times completely dry) during periods of drought and connected with the other ponds and the greater marsh landscape during high water events. The BR tidal creek runs parallel to the Gulf Intracoastal Waterway (GIW) in a general northeast–southwest orientation. Compared to other tidal creeks along the Blackjack Peninsula, the BR tidal creek is closest to San Antonio Bay and the mouth of the Guadalupe River (approximately 26 km, or 16.2 miles to the north) and is in close proximity to the GIW (< 25 m [< 82.02 ft]). A study by Davis et al. (2009) indicated that water level fluctuations caused by barge-induced drawdown currents along the GIW were greater at the BR site compared with other ANWR tidal creeks and comparable to the diurnal tidal range (typically 10–15 cm [3.94–5.91 inches {in}]).

Simulation data sources and collection

Water level data loggers with built-in pressure sensors that compensate for changes in atmospheric pressure (accurate to +/- 0.1% of the range; Infinities USA) were placed in the tidal creek and in the nearby pond for a 13.5-month period between June 2003 and August 2004 (Figure 2). Water levels were recorded hourly, and each gage site was surveyed relative to benchmarks established within the marsh (described in detail in Miller et al. 2009). In order to determine if tidal creek water levels were influenced by bay water levels, we correlated mean daily tidal creek water levels with mean daily bay water levels, which we compiled from the Texas Coastal Ocean Observation Network water level gage data collected near Seadrift, Texas (TCOON).

Hourly tidal creek water levels during the study period were plotted and the hydrological connection point was defined as the point where the statistical relationship between tidal creek water levels and pond water levels were not statistically different from each other via comparing the slopes of the simulated and observed water levels using analysis of co-variance. Next, the tidal creek water level connection point was used to estimate the pond water level and the associated timing of connection events. Daily maximum and minimum air temperatures (°C) from the weather station at the ANWR (station ID 410305) for all dates between June 2003 and August 2004 were extracted (NCEI date). These data were used during the simulation to calculate ET rates for the inland marsh ponds. Daily solar extraterrestrial radiation was extracted from the Food and Agriculture Organization data tables (Allen et.al. 1998, Annex 2. Meteorological tables) for the latitude of the ANWR. Precipitation data were not considered because precipitation events did not alter pond water levels during the field study as the area was experiencing drought conditions.

We obtained georeferenced elevation data from lidar data of Calhoun and Aransas counties, Texas from the Texas Natural Resources Information System website (TNRIS 2019). Lidar were processed using standard procedures and projected in the North American Vertical Datum of 1988 (NAVD88) geodetic vertical datum. All geographic information system (GIS) file manipulations were done using ArcGIS v9.1.

Water level simulation model description

Based on the attributes of the BR study site and the location of the *in situ* water level loggers, we developed a grid-based, spatially explicit model that is a Simulation of Landscape-level Oscillations in Salt Marsh Hydroperiod (SLOSH). The model consists of two submodules: the first calculates the water level at which each cell in the grid is connected to the tidal creek; the second simulates a time series of water level changes over the landscape based on a regression equation that correlated the water level in San Antonio Bay (via the Seadrift, Texas gage station) with data from the BR tidal creek water level logger, solar radiation, air temperature, and the lidar data. The connection points calculated in submodule one are based solely on lidar elevations and are independent of the water level data. Similarly, observed pond water levels were not used in model parameterization and were used as the validation dataset to evaluate the ability of the model to simulate the timing of surface water connections with the BR tidal creek. The details of this process are described in the following sections and a comprehensive conceptual diagram that describes the specific flow of model/coding operations of SLOSH is presented in Figure 3.

Marsh topography

To accurately represent marsh topography in the simulation model, we created a grid of 47,607 cells (cell size: 1.4m^2 [15.07 ft^2], total area: 9.33 ha [23.05 acres]) that included the elevations extracted from the lidar layer and the georeferenced locations of the BR tidal creek and saltwater pond water gages (Figure 2). This grid was topographically and ecologically representative of the BR's salt marsh study site. This grid file containing georeferenced elevation was used as an input file for the simulation model, serving as the foundation for assessing water level fluctuation.

Model initialization

SLOSH is grid-based simulation package programmed in VB.NET (© Microsoft 2003). The simulation proceeds in two steps: (1) determine the tidal creek water level at which each cell is connected hydrologically to the tidal creek; and (2) simulate inland marsh pond hydrodynamics for a period of time defined by the user (the model runs on a daily time step by default

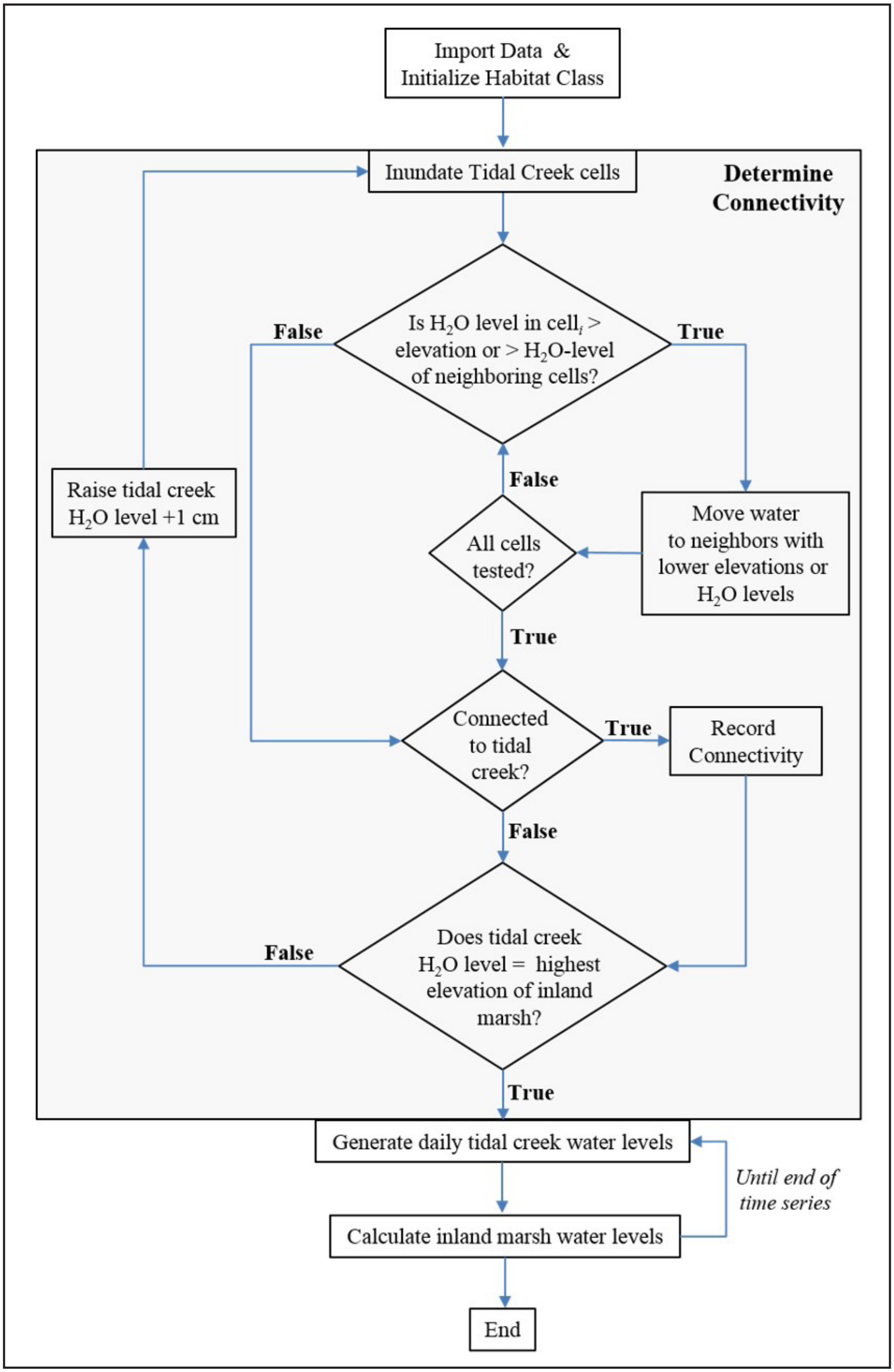

Figure 3. Flow diagram of model calculations. Rectangles indicate computations or data input/output. Diamonds indicate conditional statements. Gray box indicates the *determine connectivity* submodel.

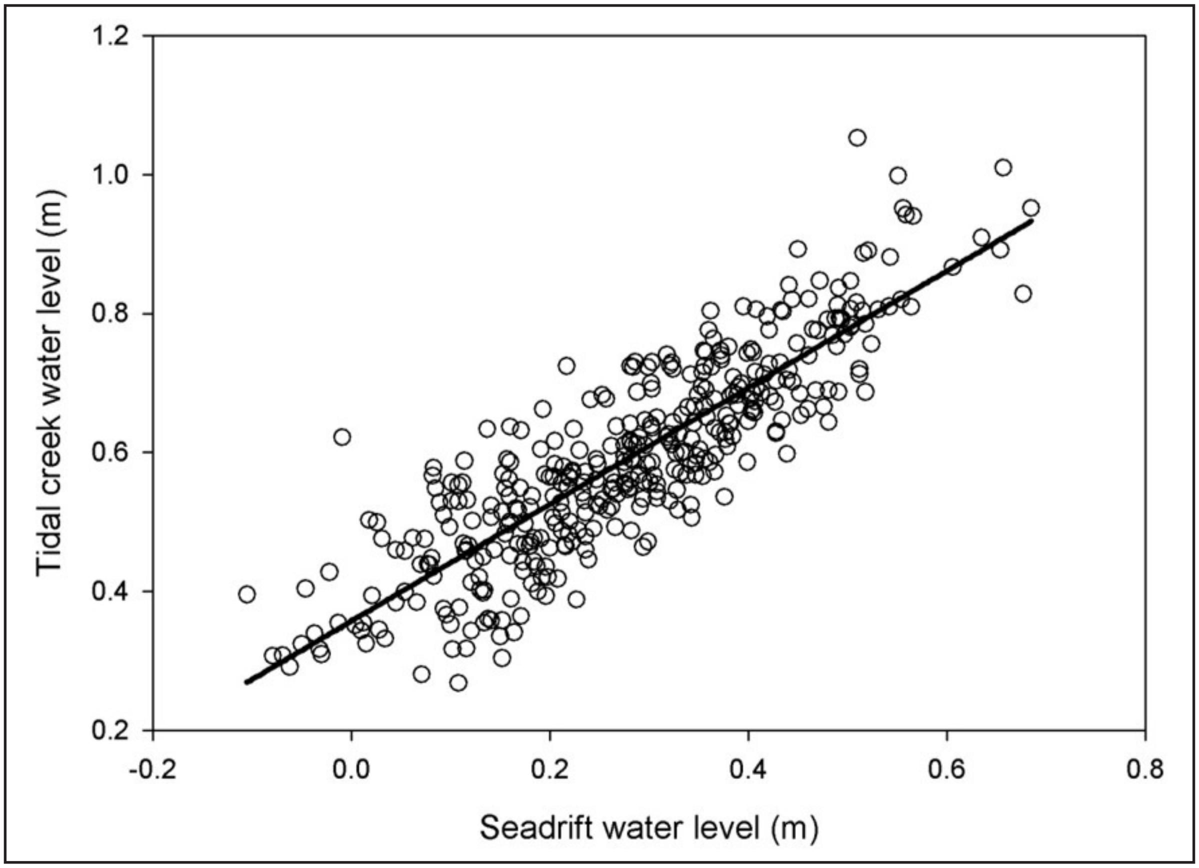

Figure 4. Correlation between mean daily water levels (meters above sea level, corrected for the NAVD88 vertical datum) calculated from water level data recorded at Seadrift (Sd_t) in San Antonio Bay (Figure 1) and mean daily water levels calculated from the hourly *in situ* data recorded at the gage in the tidal creek at the Boat Ramp study site (BR_t). Data shown are from 17 August 2003 to 24 June 2004.

but can be changed by the user). Model initialization begins with the parameterization of marsh topography (represented by grid cells inputted from a .csv file). Each grid cell is assigned its elevation value and XY coordinates, thus creating a virtual topography composed of the georeferenced cells. In addition to elevation and XY coordinates, each cell is initialized with the following three attributes: (1) current water level of the cell; (2) the BR tidal creek water level at which the cell's surface water connection to the tidal creek was established (calculated in the first step of the simulation); and (3) the concurrent water level in San Antonio Bay.

Determining hydrologic connectivity

We initialized the SLOSH with water only in those cells located within the GIW. We progressively flooded these cells by iteratively raising water levels within the initially flooded cells by 1 cm (0.39 in), then allowing the water to move into neighboring cells with lower elevations and/or water levels, until all changes in water levels within the system were < 0.1 cm (< 0.04 in). The current water level of each newly flooded cell was updated, and then the process was repeated until all the cells had been inundated across the marsh (see Figure 3 for a logic diagram of model flow). The tidal creek water level at which each cell was connected to the tidal creek was recorded (essentially, we created a lookup table that was our simulation referenced when processing tidal creek water levels) and was used as input data for the simulation of salt marsh hydroperiod. Connection levels of inland cells and the tidal creek water levels were determined and stored as an attribute of the grid cells. Specifying the surface water connection as an attribute of each cell, although computationally intensive, subsequently greatly reduced the time required to simulate the inundation regime associated with any given time series of water levels.

Simulating salt marsh hydroperiod

To initialize a simulation of salt marsh hydroperiod, we imported a time series of bay water levels from the Seadrift gage and used a linear correlation between mean daily tidal creek water levels (BR_t) and mean daily water levels at the Seadrift gage in San Antonio Bay (Sd_t) (Figure 4):

$$BR_t = 0.357 + 0.8399 * Sd_t, \ (r^2 = 0.745, \ n = 396) \quad (1)$$

The correlation between tidal creek water levels and mean daily water ($r^2 = 0.745$) was strong, and we assumed that the predicted mean would best capture the general system trends (i.e., we did not incorporate error from Equation 1 into our simulation). We simulated inland marsh hydrodynamics by iterating through the time series of bay water levels, using Equation 1 to convert the values to BR_t and then using the water level connection point for each cell (defined in section 3) to determine if the cell was hydrologically connected to the tidal creek. If it was connected, then that cell was inundated. We assumed water loss was negligible while cells were hydrologically-connected to the tidal creek. During periods of disconnection, we represented water loss from each cell due to ET (ET_t, mm day^{-1}) by parameterizing the Hargreaves equation (Hargreaves et al. 1985):

$$ET_t = 0.0023 * (((MaxT_t + MinT_t) / 2) * ((MaxT_t - MinT_t)0.5))) * Ra \quad (2)$$

where $MaxT_t$ and $MinT_t$ represent daily maximum and minimum temperatures (°C), respectively, and Ra represents mean daily solar radiation (MJ m^{-2}day^{-2}), based on the solar radiation and temperature data recorded near the study site. We used Ra values for the 15th of each month, which provide good estimates (<1.0% error) of Ra averaged over all the days within a month (Allen et al. 1998; Allen et al. 2005). ET was treated as a deterministic variable to capture general system trends. Future iterations of the model should include treating ET stochastically. We did not include water losses due to percolation of water into the marsh soils because coastal water tables are relatively high, and sandy clay soils, which are typical of the study site, have very low percolation rates (Rawls et al. 1992). We also did not include precipitation in water balance calculations, because precipitation events during the study period did not have a noticeable effect on the water balance in the marsh system relative to tidal inputs (Miller et al. 2009). However, precipitation can be incorporated into the model in future simulations of large rainfall events (hurricanes, etc.), which may result in increased precipitation-driven marsh flooding. We initialized SLOSH with a 10-year time series of values representing mean daily water levels in San Antonio Bay, mean daily solar radiation, and maximum and minimum air temperatures near the study site, from 1 January 1997 to 31 December 2007.

Simulation model verification and evaluation

We evaluated the ability of SLOSH to simulate the observed trends in surface water connections between the tidal creek and the pond by comparing simulated results to field data from a 303-day period during our field study (from 17 August 2003 to 24 June 2004). Observed pond water level data were not used in model parameterization so we could have an independent data source to verify model outputs. Field gages were not working for a 15-day period from 5 January 2004 to 19 January 2004, so simulated data representing that period were not included in the comparison. We verified that the model generated the observed temporal dynamics of mean daily water levels in the tidal creek. We compared (a) simulated to observed water levels in the marsh pond and (b) the simulated versus field-estimated tidal creek water level at which a surface water connection was established between the tidal creek and the pond. Connection points were recorded if the simulated marsh pond gage was hydrologically connected to the tidal creek. Hydrological connectivity between the simulated tidal creek and simulated marsh pond was determined using the same techniques that were used in the field.

RESULTS

Field results

Our field monitoring indicated that tidal flow from San Antonio Bay into the BR creek was the main factor leading to hydrologic connections driving inland pond water level. Daily high tides did not always lead to connection events between the creek and pond due to tides not breaching the dike of the tidal creek as well as micro-elevational changes across the marsh limiting water flow. In fact, seasonal and fortnightly tides accounted for much of the intra-annual variability in water level range (Figure 5a). Tidal creek water level was strongly correlated with water level at the Seadrift gage, located on the northeastern shore of San Antonio Bay (Figure 5, adj. $r^2 = 0.745$). A hydrological connection event occurred when the tidal creek water level was 0.7 m (2.30 ft.) and the pond water level was at least 0.37 m (1.21 ft; Figure 6). Based on this estimation, we observed 11 hydrological connections between the pond and tidal creek during the 13-month study (Figure 5b).

SLOSH verification and evaluation

Magnitude and periodicity of water level fluctuations in the tidal creek generated by Equation 1 reflected those recorded during the field study well, but water levels generally tended to be overestimated at higher tidal creek water levels (Figure 5a). Magnitude and periodicity of simulated and observed water level fluctuations in the pond were similar, but simulated pond water levels differed, on average, from observed pond water levels by 0.17 m (± 0.082 m) (Figure 5b). A hydrological connection occurred when the simulated tidal creek water level was 0.71 m (2.33 ft) and the pond water level was at least 0.57 m (1.87 ft; Figure 6). SLOSH generated 14 hydrological connections between the tidal creek and pond, which corresponded well temporally with the 11 connections observed in the field (Figure 5b). SLOSH captured all of the observed connection events but also simulated three additional events on 23

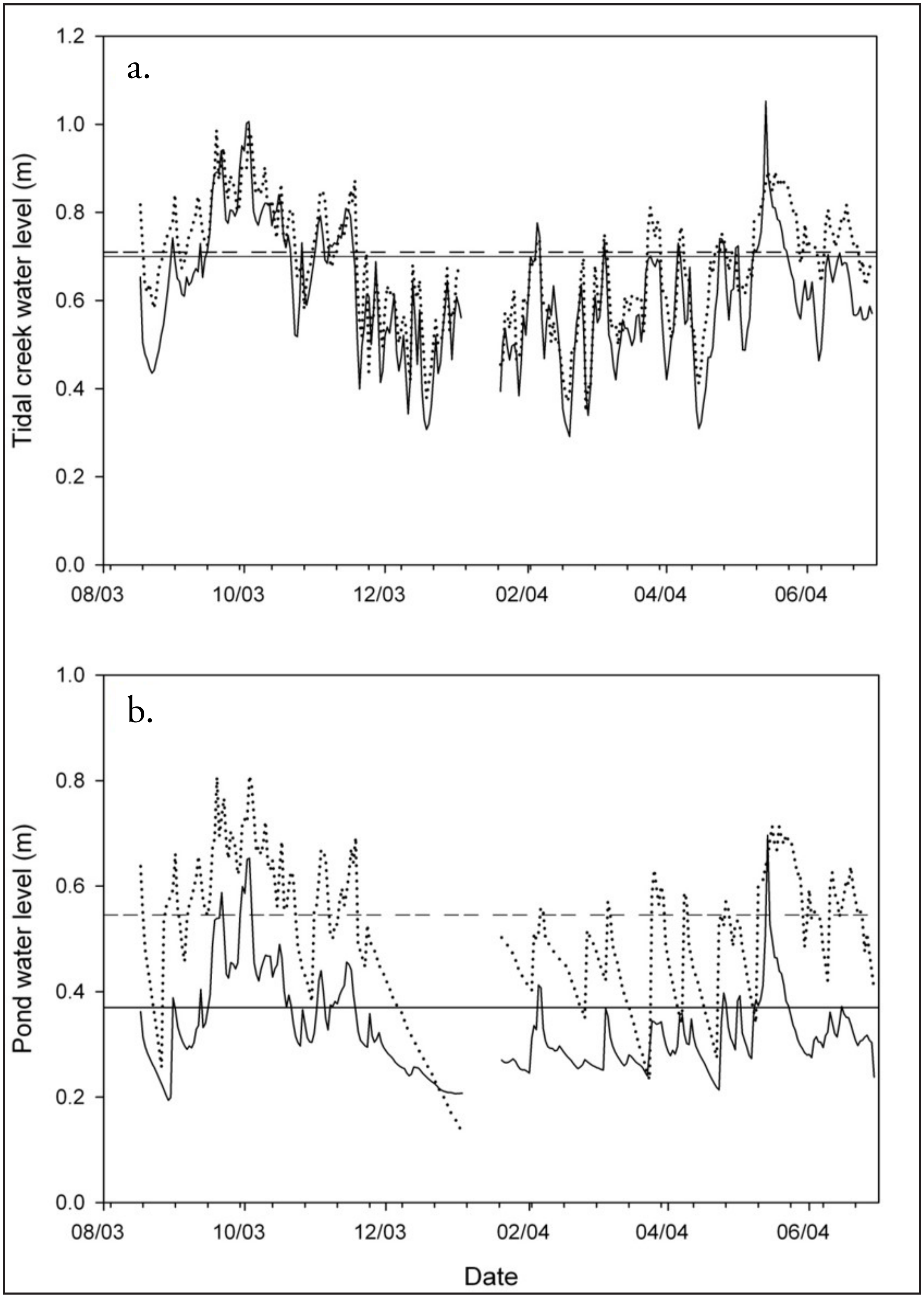

Figure 5. Observed and simulated temporal dynamics of mean daily water levels in (**a**) the tidal creek and (**b**) the marsh pond. Solid lines represent observed field data, and dotted lines represent simulated data from Simulation of Landscape-level Oscillations in Salt Marsh Hydroperiod. Straight horizontal lines represent water levels at which a surface water connection between the tidal creek and the pond was established.

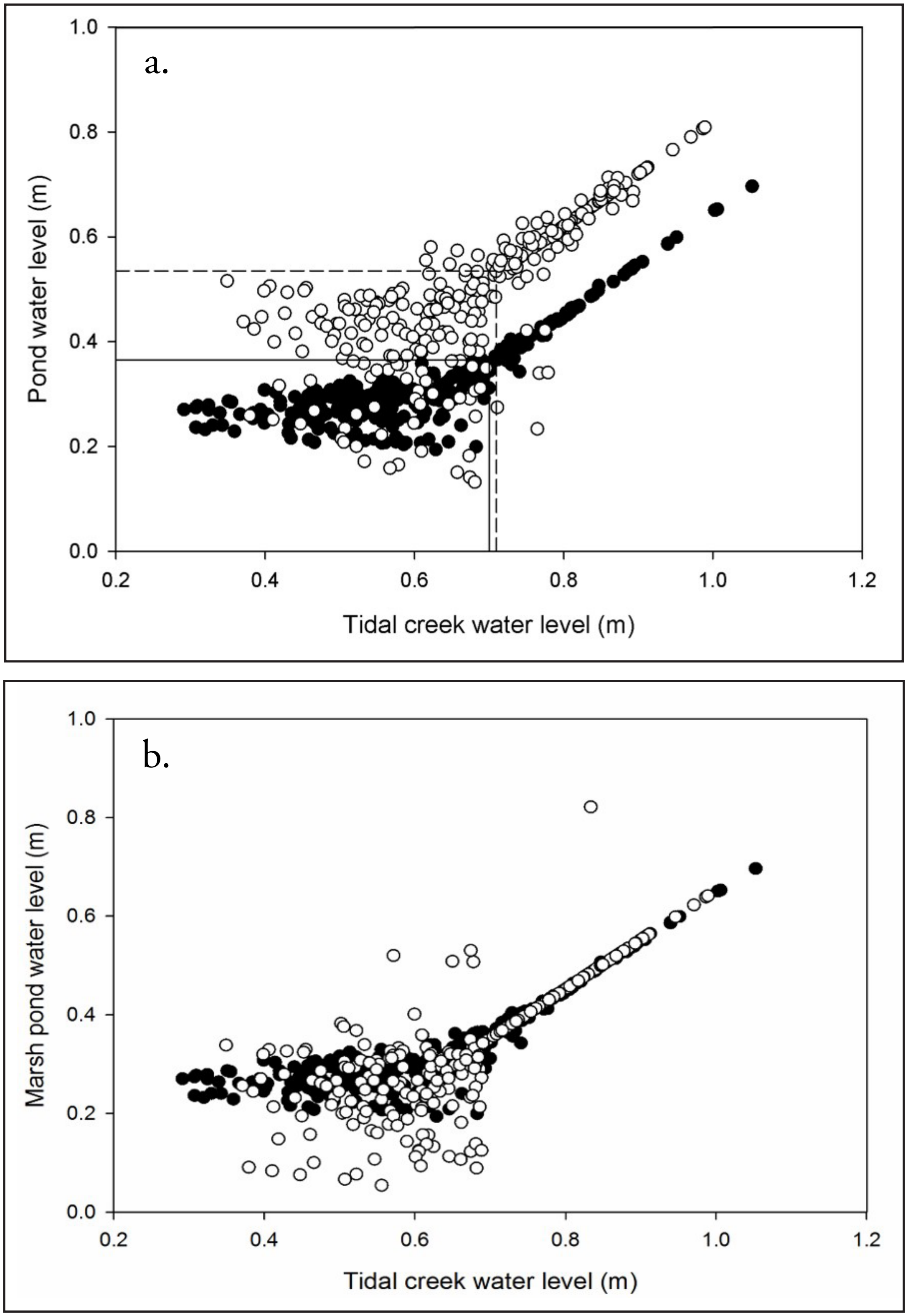

Figure 6. Observed and simulated temporal dynamics of mean daily water levels in the tidal creek and the marsh pond and the relationship between water levels in the creek and those in the pond. Solid lines and gray circles represent field data, and dotted lines and open circles represent simulated data. Straight horizontal and vertical lines represent water levels at which a surface water connection between the tidal creek and the pond was established. **6a** represents results without adjusting model elevations and **6b** represents model results after calibrating model elevations to match field values.

November 2003, 25 March 2004, and 7 April 2007 (Figure 5b) and did not simulate one event (26 October 2003) that occurred during the field study. There was also one connection event observed in the field (May 2004) that lasted for 15 days, whereas SLOSH simulated a connection event lasting 20 days (Figure 5b).

Discussion

Surface water level data from BR creek and the adjacent coastal pond indicate a clear point of connection/disconnection that allows us to better understand the timing of hydrologic connection events along a bay-tidal creek-marsh-pond continuum. These data also show that the seasonal pattern of fluctuations in bay water levels is associated with the frequency and duration of connection events across the ANWR marsh and ponds. Data from other creek-pond sites in the ANWR marsh show the same pattern, allowing for a larger-scale analysis (S. Davis unpublished data). It is important to note that the SLOSH was parameterized from a four-year field dataset when there were no large precipitation events that could impact marsh hydroperiod—this dataset provided a unique opportunity to explore marsh inundation being driven by a single factor (tides) without teasing apart other environmental interactions. In general, high creek water levels—and subsequent high frequency and duration of pond connection events—observed in the fall correspond with highest median bay water levels that typically occur in September and October of each year. The lowest creek water levels and frequency of pond connection occurred during the height of the winter (i.e., December through February) coinciding with long-term bay water level data.

Interestingly, whooping cranes historically begin arriving at the ANWR during mid-October after their nearly 2,500 mile fall migration from Wood Buffalo National Park in northeastern Alberta, Canada (Hunt and Slack 1989; Chavez-Ramirez 1996). Thus, they arrive during the period of highest connectivity between marsh ponds and the San Antonio Bay and feed heavily on the nekton resources (e.g., blue crabs) in these ponds. During these periods of high connectivity, there is a physical connection between marsh ponds and bay water, providing the potential for blue crab recruitment into marsh ponds from the bay and the continued availability of this key food resource for cranes. However, whooping cranes do not begin spring migration back to their Canadian breeding grounds until mid-April. Thus, the remainder of their stay at the ANWR coincides with the period of lower marsh-San Antonio Bay connectivity (December through February). The isolation of marsh ponds during lower water levels can lead to elevated evaporation, increased water column salinity, and lower blue crab abundance, as whooping cranes forage and remove crabs from marsh ponds. These factors, coupled with lower ambient winter temperatures, represents a critical period for the whooping cranes when thermal regulation and foraging are necessary for survival (Stehn 2003, 2004, 2005). Here, SLOSH can be used as a rapid assessment tool by coastal managers to determine the degree of hydrologic connectivity between bay water and marsh ponds, the potential shifts in connectivity patterns, and the subsequent availability of nekton food resources across the marsh landscape.

Summertime hydrology has been shown to have a clear impact on winter vegetation dynamics in the coastal marshes of the ANWR. Wozniak et al. (2012) found that mean summertime salinity in San Antonio Bay is directly linked to winter fruit production by the Carolina wolfberry (*Lycium carolinianum*), another key food resource for the whooping crane. SLOSH can be used here as an additional assessment tool to determine how summertime water levels and bay water column salinity work in concert to influence winter food resources. Specifically, SLOSH can determine if higher salinity summer water is hydrologically connected to coastal marsh ponds during periods of lower water levels; conversely, during high water level connection events, the salinity of the flooding water can be documented, as it is a critical indicator of the abundance of wolfberry fruit during the winter period (Wozniak et al. 2012).

Hydrological connectivity in salt marshes varies across both spatial and temporal scales and is controlled not only by tides but also by micro-elevational changes across the landscape. The degree of connectivity across the landscape is a significant driver for both the formation of the heterogeneous habitat types and for the distribution of energy, material, and nutrients throughout the marsh. Previous approaches to understanding landscape-level hydrologic connectivity patterns have required either long-term monitoring or spatially explicit modeling (Poulter and Halpin 2008). The former is expensive and time-consuming, while the latter has been limited by coarse-scale digital elevation models (DEM) on which to base flow dynamics (Park et al. 1989; Moorhead and Brinson 1995; Nicholls 2004). However, the increasing availability of high resolution DEMs and an increased focus on marsh response to climate change and sea level rise only improves our ability to model inundation in both riparian and coastal ecosystems (Alizad et al. 2016; Bales et al. 2007; Byrd et al. 2016; Poulter and Halpin 2008). Our study shows the potential for coupling the two approaches in a rapid assessment tool. We used a relatively short-term field data set to parameterize and evaluate a simulation model (SLOSH) that used high-resolution lidar data to determine connectivity patterns within the coastal wetlands of the ANWR.

Many hydrological processes are scale-dependent (Holmes et al. 2000; Kenward et al. 2000; Omer et al. 2003; Kienzle 2004). The spatial resolution of the lidar used by SLOSH allowed us to capture the fine-scale (i.e., micro-elevational) topographic features that can affect overland flow in the salt marsh of the ANWR. Lidar data increase the spatial resolution of elevation data by orders of magnitude compared to previously available DEMs for the ANWR (e.g., previous DEMs available mapped elevations in 30 m x 30 m cells, compared to the 1.4 m x 1.4 m [4.59 ft x 4.59 ft] cells of lidar images used here). Further, both field observations and results from SLOSH indicated that micro-topography and tidal fluctuation are driving factors for hydrological connectivity patterns at the ANWR. SLOSH captured the temporal dynamics of water fluctuations of both the tidal creek and inland marsh pond; however, the water level in the pond (i.e., pond depth) differed between the simulated and observed ponds by approximately 17 cm (6.69 in; Figure 6a). This lack of fit between simulated and observed water levels could have resulted from three sources: (1) the laser used to collect the lidar data not penetrating the water column during the initial survey; (2) an error in estimating the elevation of certain cells; or (3) the relative elevations obtained in the field not being standardized to the NAVD88 geodetic datum. Likely the error resulted from a combination of the three sources. The model can be calibrated by adjusting in-model elevation to correct for these errors (Figure 6b). It is important to note that the simulated hydrological connection point only differed by 1 cm (0.39 in) from the connection point observed in the field. From an ecological point of view, this is an acceptable range of error because we were not attempting to simulate hydrodynamics at a predictive scale but rather were attempting to capture the patterns in connectivity that could be used to infer ecological response. SLOSH is intended to be used as a rapid assessment tool to inform natural resource decision making and made several simplifying assumptions. However, SLOSH was able to capture the pattern of hydrologic connection events, providing useful insight into how hydrologic connectivity can regulate the transfer of energy, nutrients, and biota between the bay, tidal creeks, and inland marsh ponds.

Temporally, SLOSH captured all but one of the connection events between the tidal creek and the inland marsh pond; however, SLOSH generated three connection events that did not occur during the field studies. Each of the four disparate events resulted from the error associated with the regression predictions. During periods of disconnection, water loss in SLOSH was greater than observed in the field. Increased water loss in the model may have been attributed to the Hargreaves ET equation in SLOSH, which considered both temperature (observed at the ANWR) and solar radiation data (Hargreaves et al. 1985). We chose the Hargreaves equation because it was the most parsimonious of the ET equations we considered. There are several other empirical estimations of ET, including the Thornthwaite equation (Thornthwaite 1948), among others (refer to Mitsch and Gosselink 2007 for other references), and future versions of SLOSH could explore those estimations as well. Further, SLOSH only estimated water levels via regional bay water levels and losses via ET. This initial version of SLOSH was not parameterized to account for any other processes, such as direct precipitation, infiltration, or wind and/or barge effects that can affect inland marsh water levels.

We recognize that there are numerous factors affecting connectivity patterns and that overland flow is a complex phenomenon. Our goal, however, was to develop the most parsimonious model possible that captured the dynamic patterns of hydrological connectivity across a salt marsh at a relatively fine spatial scale (in this case 1.96 m^2 [21.10 ft^2]). SLOSH captured these general trends in marsh dynamics. Future research should include using SLOSH to determine at what spatial scale connectivity patterns are no longer captured and validate that with a more detailed field study as well as hindcasting marsh-pond connection events based on archived bay water level data going back to 1996. This will provide us with a better understanding of the frequency and duration of connection events that could potentially affect the abundance and distribution of food supplies and nutrients across the inland marsh landscape, which is not only important for marsh natural resource and whooping crane population management but will also allow us to have a foundation for understanding inland marsh functionality.

SUMMARY

The results from this study indicated that SLOSH has considerable potential for rapidly assessing inland marsh connectivity in salt marsh ecosystems. SLOSH is a dynamic simulation tool capable of generating connectivity patterns observed in the field with relatively little associated error, is a relatively low-cost method for capturing hydrological connectivity in inland marshes, and provides the foundation for more detailed assessments of how hydrologic connectivity events regulate the availability of critical food resources for migratory wading birds, including the endangered whooping crane. Lidar is readily available through coastal mapping programs of multiple federal and state agencies. SLOSH was parameterized from a time series of water level data that was collected when marsh inundation was being driven by tidal dynamics. As such, it provides a foundational level approach for understanding inundation during drought conditions. The SLOSH clearly captures the fine-scale hydrologic dynamics of the study site at the ANWR, which, in turn, created a spatially heterogeneous pulse-dependent landscape. Further, by modeling the pulsing structure of salt marsh hydrology, we have the underlying foundation on which to begin to understand how additional drivers (precipitation, wind, etc.) can impact the distribution and abundance of nutrients, organisms, and other natural resources across coastal marsh landscapes.

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Economically Recoverable Water in Texas: An Underappreciated Water Management Strategy?

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Abstract: Conversations about the value or "true cost of water" and the nationwide infrastructure maintenance gap encourage a reconsideration of the value of utility water losses. Water loss audit data for 2014 for two planning regions that are home to almost a third of Texas' population and include three of the five largest cities are examined to explore the value of economically recoverable water losses from a perspective that better reflects the regional scenarios under which the state water plan is developed. The volume of real and apparent losses is valued per a new regional average composite price to arrive at an estimation for the water that should be feasible to recover. Normalized values of economically recoverable losses are generated to arrive at a statewide estimate of valuation. Industry standard financial and operational performance indicators are also developed and compared to a larger, multi-state data set. Results are presented in the context of state and regional water supply planning in two ways: 1) comparing the volume of economically recoverable water to the volume of supply expected from water loss control strategies, and 2) comparing the newly assessed value of recoverable water to the estimated costs associated with water loss control strategies.
Keywords: utility water loss, economic level of loss, water audits, value of water, water supply

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Terms used in paper

Acronyms	Descriptive name
AWWA	American Water Works Association
CARL	current annual real losses
ELL	economic level of loss
gpcd	gallons per capita per day
ILI	infrastructure leakage index
IWA	International Water Association
KWEC	Kunkel Water Efficiency Consulting
TWDB	Texas Water Development Board
UARL	unavoidable annual real losses
WSP	water service provider

INTRODUCTION

The United States faces a significant need for water delivery infrastructure maintenance and repair. Historical underpricing of drinking water is one reason for the state of infrastructure disrepair (Beecher 1997). The American Water Works Association (AWWA) estimates that $1 trillion is needed to maintain and expand water service to meet demands over the next 25 years (AWWA 2012). The American Society of Civil Engineers gives the nation's drinking water infrastructure a D grade in its 2017 Infrastructure Report Card (ASCE 2017). The state of the nation's water delivery infrastructure is one reason water supply is a rising cost industry (Beecher 1999). More recently, the AWWA (2016a) declared the North American water industry at a crossroads regarding nonrevenue water—the difference between system input volume and billed authorized consumption—of which real losses from leaking pipes are a major component.

Reducing utility system water loss has traditionally been viewed as a form of water conservation. A new emphasis on utility water loss is supported by studies that reveal the potential for recovery of lost revenue (or sunk costs) and new tools for its capture. The International Water Association (IWA) and the AWWA, for example, offer a water loss audit methodology that is being used by a growing number of utilities, also referred to as water service providers, across the country (AWWA 2016b). The AWWA Free Water Audit Software complements the IWA/AWWA method and enables utility staff to improve desktop accounting for water throughout the distribution and billing systems, including their nonrevenue water.

For Texas, the grade for drinking water infrastructure is D+, an improvement over the previous D- grade, but the grade is nonetheless an assessment of the $33.9 billion needed for drinking water infrastructure over the next 20 years (ASCE 2017). At the same time, Texas' population is growing rapidly and placing increasing strain on the state's water resources (TWDB 2016). Reducing utility-side water loss therefore holds great promise as a strategy for helping to make ends meet with respect to the growing imbalance between projected water demand and existing supplies during a prolonged drought.

The purpose of this pilot study is to evaluate water loss audit data from calendar year 2014 as reported by water service providers (WSP) from two of 16 regional water planning areas to the Texas Water Development Board (TWDB). Operational and financial performance indicators are presented along with a reframing of the cost impact of apparent and real losses identified in water loss audits in order to better reflect water scarcity in Texas and its assumption in state and regional water supply planning efforts. To that end, the study estimates the economic level of loss—the level of leakage below which it is not cost-effective to invest in reducing leakage further down (Farley and Trow 2003)—for several water service providers within the two planning regions. It then normalizes that figure to produce both regional and state-level estimates of the financial impact of lost water that could be economically feasible to recover.

The cost (of supplying drinking water), price (paid by ratepayers for delivery on demand), and value of water are different yet related terms (Raucher 2005). These terms all have some bearing on the thesis of this study, which is to reconsider the financial impacts of nonrevenue water for regional planning purposes in a state that will be severely challenged for water when the next drought of record occurs.

BACKGROUND

In 2003, the 78th Texas Legislature enacted House Bill 3338, which requires retail public utilities providing potable water to conduct a water audit based on the most recent annual system water loss. The results of such water loss audits must be submitted to the TWDB once every five years. The first year for this requirement was 2005, and reports were subsequently submitted in 2010 and 2015. Additionally, any retail water supplier that has an active financial obligation with the TWDB or has more than 3,300 service connections must now submit an audit annually (Texas Water Code, Section 16.0121). The annual water loss audits covering a calendar year are due on the first of May the following year.

The TWDB collects water audit data via an online form that is based on the AWWA audit software. Data inputs can be assigned a validity score that is a modified version of what is featured in the AWWA audit software. Validity scores from the AWWA audit software are totaled and placed into one of five levels, with a maximum score of 100 points. AWWA validity score levels are characterized to provide basic loss control guidance to water service providers. The Water Loss Audit Manual for Texas Utilities (Mathis et al. 2008) has a more streamlined guidance matrix with a total of 85 points possible.[2] The guidance matrix has possible points assigned by category: water supplied (20), authorized consumption (20), apparent losses (15), real losses (10), cost data (10), and system data (10). The Texas guidance matrix does not sum points and assign data validity levels as the AWWA does but offers three scoring categories (i.e., 0-40, 41-70, 71-85) that suggest in general terms the level of accuracy and thus the usefulness of the data collected.

In 2017, the 85th Texas Legislature enacted House Bill 1573, which amends Section 16.0121 of the Texas Water Code to require that water audits be completed by a person trained to conduct water loss auditing and that the TWDB make training on water loss auditing available without charge via the Board's website. This Act took effect September 1, 2017. Given that these new requirements aim to improve system understanding and thus accuracy and validity of data reported, it is reasonable to expect higher water loss audit data validity scores in the future.[3] To quantify the extent to which this might occur, it will be necessary to consider audit data in greater detail both prior to and after this new law took effect.

WATER-PLANNING REGIONS C AND K

Two of 16 water planning regions were chosen for this pilot study. Region C includes all or part of 16 counties in north-central Texas and includes the Dallas-Fort Worth metropolitan area. The city of Dallas is the third largest city in Texas. The population of Region C was 6,477,835 or about 25% of the state's population in 2010 (U.S. Census Bureau 2017). The Dallas Water Utility, the largest in the region, serves a population of 1,232,360, while the second largest water service provider in Region C, the city of Fort Worth, serves 781,100 people.[4] Region C's population is projected to be 7,504,200 in 2020, about a 16% increase during the current decade (Freese and Nichols, Inc. et al. 2015a).

Water demand in Region C's municipal sector, 1,481,530 acre-feet per year, is projected to account for 86% of total forecasted demand of 1,723,325 acre-feet per year among the six water-use sectors during the next decade (TWDB 2016). Under a worst case drought scenario using only existing water supplies, Region C's potential water shortage is projected to grow from 125,037 acre-feet per year in 2020 to 604,016 acre-feet per year in 2040 across all water-use sectors.[5] In response, the 2016 Region C Water Plan presents a range of potential supply enhancement strategies, including 259 water loss control management strategies that could produce water savings of 26,646 acre-feet[6] per year in the decade beginning 2020 at an expected annual cost of $36,546,937 or an annual unit cost of $1,372 per acre-foot or $4.21 per kilogallon[7] (personal com-

[2] The data validity scoring scheme was modified to total 100 points beginning with the 2015 audit reports.

[3] Without third-party validation (i.e., Level 1 validation), however, self-reported data validity will remain suspect regardless of complementary efforts to improve the quality of audit reports.

[4] Population served figures come from 2014 Water Audit Reports submitted to TWDB and shared with author.

[5] Water need or potential shortage is based on projected population growth/water demand and existing supplies. Any imbalance between demand and supply is predicated on a scenario of recurrence of drought of record conditions and not implementing any water management strategies presented in regional water supply plans.

[6] Tally by author of individual water loss control strategies listed in Appendix Q, Table Q-10 of the 2016 Region C Water Plan after corrections applied as referenced in the following footnote (Freese and Nichols, Inc. et al. 2015c).

[7] The published cost of $3.74/1,000 gallons of water saved in Appendix K, Summary Table K.3, 2020 column, of Region C's approved plan is in error, per email communication with Brain McDonald, Allan Plummer Associates, July 24,2018. Appendix Q, Table Q-10 of Region C's plan also features a couple of errors, most notably with the 2020 unit cost listed for Fort Worth,

Table 1. Recommended water management strategies for Region C, Texas for decade beginning 2020 unless otherwise noted.

Strategy type	Percentage of total[a]	Volume of water[b] (acre-feet/year)	Unit cost[c] ($/acre-feet) in 2070
Municipal conservation	29.0	55,628	154
Indirect reuse	21.6	41,442	111
Other surface water	20.0	38,371	571
Other direct reuse	20.0	38,331	285
New major reservoir	6.7	12,870	563
Groundwater wells & Other	2.7	5,135	350
Totals	100	191,777	n/a

[a] and [b] Source: Texas Water Development Board, Interactive 2017 State Water Plan, Region C. https://2017.texasstatewaterplan.org/region/C

Thirty-four acre-feet are not included in this table and are expected from irrigation conservation.

[c] Source: Texas Water Development Board. 2016. Water for Texas, 2017 State Water Plan. Table 8.5

munication with Brian McDonald, Senior Project Engineer, Water Infrastructure Planning, Alan Plummer Associates, Inc., July 24, 2018, via email). This unit cost will be placed in a value-of-water context later. Here, the unit cost will be considered relative to other strategies using data points made available by the Texas Water Development Board.

First, it is instructive to note that any comparison invokes a couple of caveats. For example, investment made in water loss control results in finished water that is captured and remains available in the distribution network. Other supply-augmentation strategies result in raw water at the source. Thus, one must add the cost of withdrawal, treatment, and pumping into the distribution network to more closely compare with the unit cost of supply gained from water loss control. Furthermore, other supply strategy unit costs will vary over time: a higher unit cost calculated over the initial 20 years during which a typical loan is amortized and a lower unit cost beyond that period.

The 2017 State Water Plan (TWDB 2016) projects that the recommended water management strategies in Region C will yield an annual volume of 192,000 acre-feet during the decade beginning 2020. The capital costs of producing this water total $3,730 million for the decade or $1,943 per acre-foot per year. Accordingly, supplies gained through investment in water loss control at an annual unit cost of $1,372 per acre-foot offer significant economic appeal.[8]

which should be $1,061 rather than the $357 currently published, per the same email communication. There are 259 water loss control strategies that are estimated to produce one or more acre-feet per year during the 2020s for a total of 26,646 acre-feet of water saved at a combined cost of $36,546,937. A tally of water loss control strategies downloaded from the Interactive 2017 State Water Plan sums to 26,638 acre-feet. Costs are not included in this file. The discrepancies in water volumes listed here and in Appendix K, Table K.2 of the Region C plan are minor: less than one-tenth of 1%.

[8] Water loss cost/acre-foot calculations made by author for this study.

Table 1 illustrates the relative and absolute contributions of major categories of water management strategies that are expected to come online during the decade beginning in 2020. Table 1 also includes a column that features the unit cost of implementing these strategy categories in 2070, presumably after they have all been brought online and either fully or partially paid for.

The municipal conservation category includes water loss control, water waste prohibition, and other conservation practices (e.g., enhanced public and school education, price elasticity/rate structure impacts, and time-of-day irrigation restrictions) bundled together. Since the unit cost of water loss control has already been determined for the next decade, it is not necessary to unpack this category to arrive at unit costs for water waste prohibition or a collection of other practices simply dubbed "conservation."

The unit cost for municipal conservation in 2070 (Table 1, last column) is consistent with evidence found elsewhere (Richter 2014). Thus, conservation is the "low-hanging fruit" in economic terms and should be maximized first. Here it should be noted that indirect reuse options, unlike conservation, are not available to all utilities. Lastly, the unit costs in Table 1 reflect supplies gained and cost amortization over 50 years. The utility of this column of information is limited to comparison to other categories featured in the table at the end of the state planning horizon.

Region K includes all or part of 14 counties and generally follows the Colorado River from central Texas in the northwest part of the region to the Gulf of Mexico in the southeast. Region K had a population of 1,410,328 in 2010 (U.S. Census Bureau 2017) and is home to the city of Austin, the fourth largest city in the state. Austin Water, the region's largest water service provider, serves a population of 896,363.[9] Region

[9] *Ibid.* 4

Table 2. Water demand/supply/needs for Regions C and K, Texas in the next decade.

2020 (decade)	Texas Planning Region (acre-feet/year)	
	C	K
Projected annual water demand – all water-use sectors	1,723,325	1,183,325
Projected annual water demand – municipal water-use sector	1,481,530	306,560
Existing supplies – all sectors	1,650,227	998,867
Existing supplies – municipal sector	1,390,169	457,961
Needs (potential shortage) – all sectors	125,037	373,563
Needs (potential shortage) – municipal sector	106,718	7,881
Strategy supplies – all sectors	191,811	436,423
Strategy supplies – municipal sector	164,144	174,777

K's population is projected to be 1,737,227 in 2020, a 23% increase during the current decade (Lower Colorado Regional Water Planning Group 2015a).

Water demand in Region K's municipal sector, 306,560 acre-feet per year, accounts for 26% of total forecasted water demand of 1,183,325 acre-feet per year across all water-use sectors during the next decade. Region K's potential water shortage is projected to grow from 373,563 acre-feet per year in 2020 to 387,321 acre-feet per year in 2040 across all water-use sectors. The potential shortage in the municipal sector is small, 2% in 2020, but grows to 12% by 2040 (TWDB 2016). The Lower Colorado (K) Regional Water Plan does not present any explicit water loss control management strategies for the next decade or beyond as is done in the Region C plan. Rather, "leak reduction" is included only in the city of Austin's "conservation" water management strategy. Thus, it is not possible to determine expected savings/supply or costs associated solely with water loss control apart from the other conservation measures listed: landscaping, efficiency, etc. (Lower Colorado Regional Water Planning Group 2015b). What can be determined is the annual unit cost of securing all planned water management strategies during the next decade—$704 per acre-foot—the bulk of which, 96%, is for the irrigation and steam electric power (i.e., nonmunicipal) sectors (TWDB 2016).

Collectively, these two water planning regions capture both urban and rural areas that are located predominately in the eastern, more populated half of the state and are home to almost a third of the state population.[10] As such, conservation programs in these planning regions can offer useful examples for other water planning regions in the heavily populated Texas Triangle and Lower Rio Grande Valley, as well as larger cities in West Texas and the Panhandle. Findings from this sample of two regions are instructive about the state as a whole. Table 2 provides water supply/demand and other data for the upcoming decade taken from the 2017 Interactive State Water Plan.[11]

[10] 31.4% in 2010

WATER LOSS AUDIT DATA

In June of 2016, the author requested that the Texas Water Development Board provide water loss audit data for Regions C and K from 2014, the most recent and complete set of audits available at that time. The TWDB responded with data from the 106 (87 from Region C and 19 from Region K) WSPs that submitted a report during an off-year (i.e., audit data for 2015 by all systems per the five-year cycle were not yet available). Thus, the audits received by the author represent the WSPs that either have at least 3,300 service connections or have borrowed money from the TWDB, as these are by law required to provide annual water loss audit data to the TWDB.

From the data file for 106 WSPs, the top 27 water service providers (Table 3) were selected for many of the analyses because this subset produces 85%—333,259.83 million gallons per 1,022,735 acre-feet—of the total system input volume of 392,764.71 million gallons per 1,205,349 acre-feet distributed by the 106 WSPs. As it turns out, all but one are situated within Region C.

Other analyses use a variable "n" based on data plausibility. Thus, the sample size of each analysis is noted accordingly. The current state of data is unvalidated, but it does undergo some filtering by the TWDB staff (personal communication with John Sutton, Municipal Water Conservation Manager, Water Science and Conservation, Texas Water Development Board, July 27, 2017, via email.) Data from the two regions have been combined into one data set. Table 4 features several characteristics of WSPs that have been partitioned based on their size (i.e., population served).

[11] Interactive 2017 State Water Plan: https://2017.texasstatewaterplan.org/statewide

Table 3. Top 27 water service providers based on system input volume from 2014 in Regions C and K, Texas.

Public water service provider	Region	Public water service provider	Region	Public water service provider	Region
Dallas Water Utility	C	City of Frisco	C	City of Southlake	C
City of Fort Worth	C	City of Richardson	C	City of Coppell	C
City of Austin Water & Wastewater	K	City of Carrollton	C	City of Sherman	C
City of Arlington	C	City of Mesquite	C	City of Keller	C
City of Plano	C	Town of Flower Mound	C	City of Farmers Branch	C
City of Irving	C	City of Grapevine	C	City of Euless	C
City of Garland	C	City of Lewisville	C	City of Bedford	C
City of McKinney	C	City of Allen	C	City of DeSoto	C
City of Grand Prairie	C	City of North Richland Hills	C	City of Colleyville	C

Table 4. Public water service provider characteristics for Regions C and K, Texas in 2014.

WSP size class	No. of WSPs	Range of population served	Average population served	Average system input volume in acre-feet/year	Total system input volume in acre-feet/year	Average no. of service connections	Average production MGD/acre-feet per day	Average deliveries MGD/acre-feet per day	Average miles of main	Total miles of main
X-Large	3	781,100–1,232,360	969,941	185,715	557,145	260,047	165.80/509	142.54/437	4,089	12,268
Large	12	91,429–369,308	178,305	28,906	346,877	67,124	25.81/79	23.01/71	829	9,951
Medium	58	10,005–68,667	28,463	4,836	280,523	10,788	4.32/13	3.87/12	228	13,208
Small	33	190–8,819	2,936	336	20,805	1,168	0.30/0.92	0.25/0.76	28	1,566
Totals	106	N/A	N/A	N/A	1,205,350	N/A	N/A	N/A	N/A	36,993

Note: Average production and deliveries do not include wholesale. Averages for small water service providers are median values. All other size classes feature mean averages. MGD = million gallons per day. X-Large WSPs include Dallas, Austin, and Fort Worth. Large WSPs include Arlington, Plano, Garland, Irving, Grand Prairie, McKinney, Frisco, Mesquite, Carrollton, Richardson, Lewisville, and Allen.

Nonrevenue water, as a percentage of system input volume, can be calculated but has shortcomings as a measure of WSP operational performance (AWWA 2016b). The percentage of nonrevenue water derived is biased against WSPs with relatively lower consumption and sensitive to average operating pressures, which are often set to overcome the amount of relief present in a service area (Farley and Trow 2003). A more efficient community (i.e., lower gallons per capita per day or gpcd) with both an identical population served and an annual volume of water loss as a community with a higher gpcd will indicate a higher nonrevenue water percentage. With these caveats shared, nonrevenue-water percentages for the full data set of 106 WSPs analyzed here range from 4–47% with a median value of 16%.

The AWWA and IWA prefer use of a scaling factor where losses are expressed relative to number of service connections or miles of water main. Additionally, the infrastructure leakage index (ILI) in loss-control parlance is the ratio of current annual real losses to unavoidable annual real losses and is the best operational performance indicator for comparisons between peer systems (AWWA 2016b). Figure 1 graphs ILI values for the three extra-large WSPs—Dallas, Fort Worth, and Austin—along with eight large-sized WSPs.

As an indicator, ILI values range from 1.3 to 5.6 with an average of 3.6 that indicates current annual real losses among the largest WSPs are about three and one-half times greater on average than the reference minimum or theoretical lower limit of water loss. There is no apparent pattern based on either size WSP.

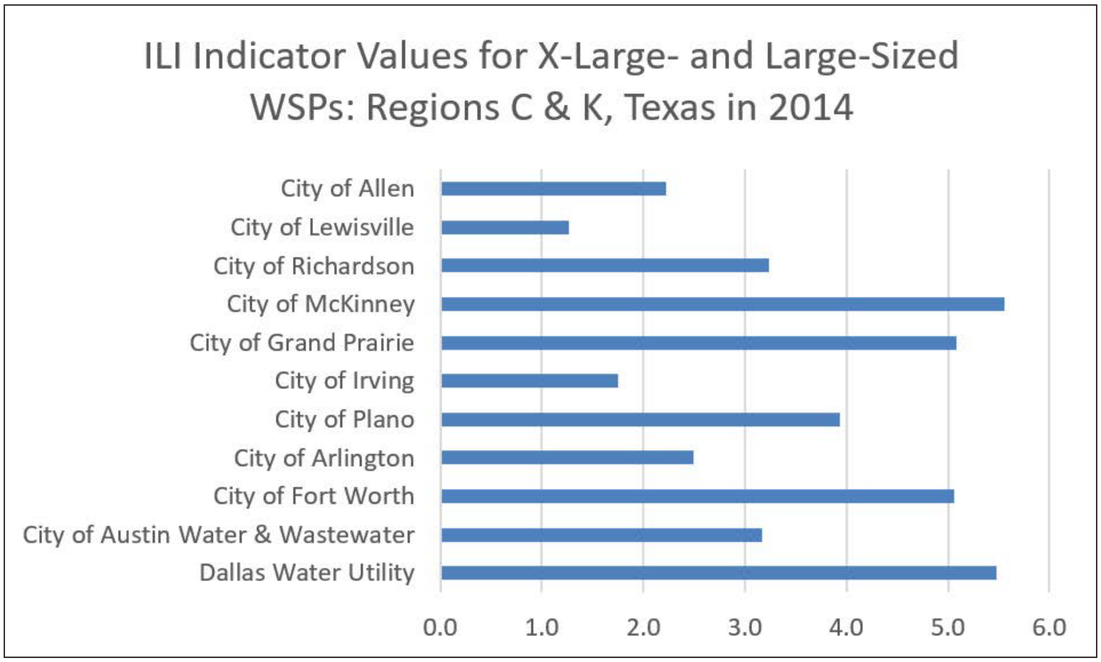

Figure 1. Comparison of infrastructure leakage index (ILI) indicator values among extra-large- and large-sized WSPs: Regions C and K, Texas in 2014.

For medium-sized water-service providers (Figure 2), ILI indicator values range from 1.0 (the lowest possible value) to 6.0 with an average of 2.7. The range among these 47 WSPs is more dynamic than that of the larger systems, and on average at least, the medium-sized systems appear to be performing a little better during the one year studied.

For the five smallest WSPs whose data led to plausible ILI indicator values (Figure 3), the range is from 1.2 to 6.2 with an average ILI of 2.9. Taken together, the 63 of 106 WSPs who reported both current and unavoidable real losses and/or plausible data (i.e., an ILI greater than or equal to one), do not yield obvious conclusions based on size alone.

Water loss is segmented into two types: real losses and apparent losses. Real losses result from actual leaks in transmission and distribution pipes, storage tanks, and on service connections up to the point of customer metering. Traditionally (i.e., IWA/AWWA water loss audit methodology), this water is valued at variable production cost, and the TWDB-approved water loss audit methodology in Texas follows this tradition. It is important to note, however, that the AWWA supports using a retail water rate to value real losses if scarcity is part of the local/regional context within which water service providers operate (AWWA 2016b). The rationale is simple: Every drop of leaked water saved can be projected as a water sale to someone using that same source.

The other type of water loss, apparent losses, results from data handling or billing errors, including faulty customer meters and unauthorized consumption (e.g., theft). This type of lost water is valued using the retail water rate because water was delivered, but revenue was not captured in return. Real and apparent losses constitute the majority of nonrevenue water, which also includes two types of unbilled authorized consumption: metered and unmetered. This study does not concern itself with unbilled authorized consumption, which was reported to be 2.5% and 4.5% of total system input (n = 106) for metered and unmetered consumption respectively.[12] This is not to say that the amount of nonrevenue water attributed to unbilled authorized consumption is inconsequential. Rather, this study is focused on real and apparent water losses and the value of such.

Audit inputs in both methodologies include a retail rate for water. The TWDB's audit guidance document acknowledges that typical utility water rate structures feature multiple tiers of pricing and guides utilities (i.e., WSPs) to use a single composite price rate to represent the retail cost of water, adding "where appropriate, use the tier with the majority of the consumption." (TWDB 2018). Yet the reported retail rates are neither calculated to reflect actual bills paid by ratepayers nor do they appear to be determined in a consistent fashion across reporting water service providers.[13] Thus, audit data likely undervalue water losses.

[12] These percentages of unbilled authorized consumption are calculated such that they are included in the nonrevenue water total for the entire data set (n = 106) calculated at 19.3% (i.e., sum of nonrevenue water volumes / sum of total system input volumes or 75,725,919,325 / 392,764,711,972).

[13] In fairness to water service providers, they are neither guided to assign a retail rate that reflects an actual water bill nor are they expected to charge the same price as neighboring communities.

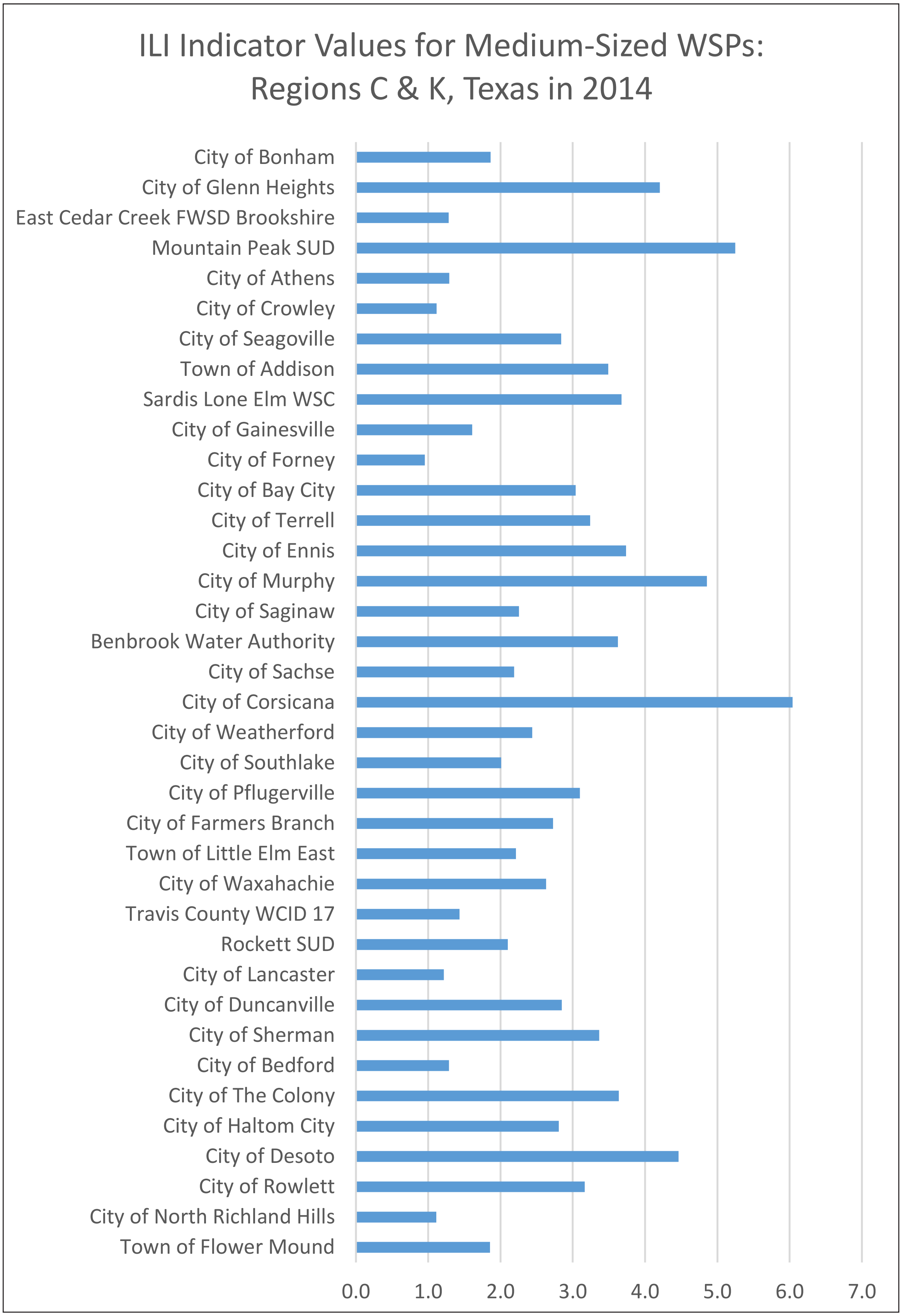

Figure 2. Comparison of infrastructure leakage index (ILI) indicator values among medium-sized WSPs: Regions C and K, Texas in 2014.

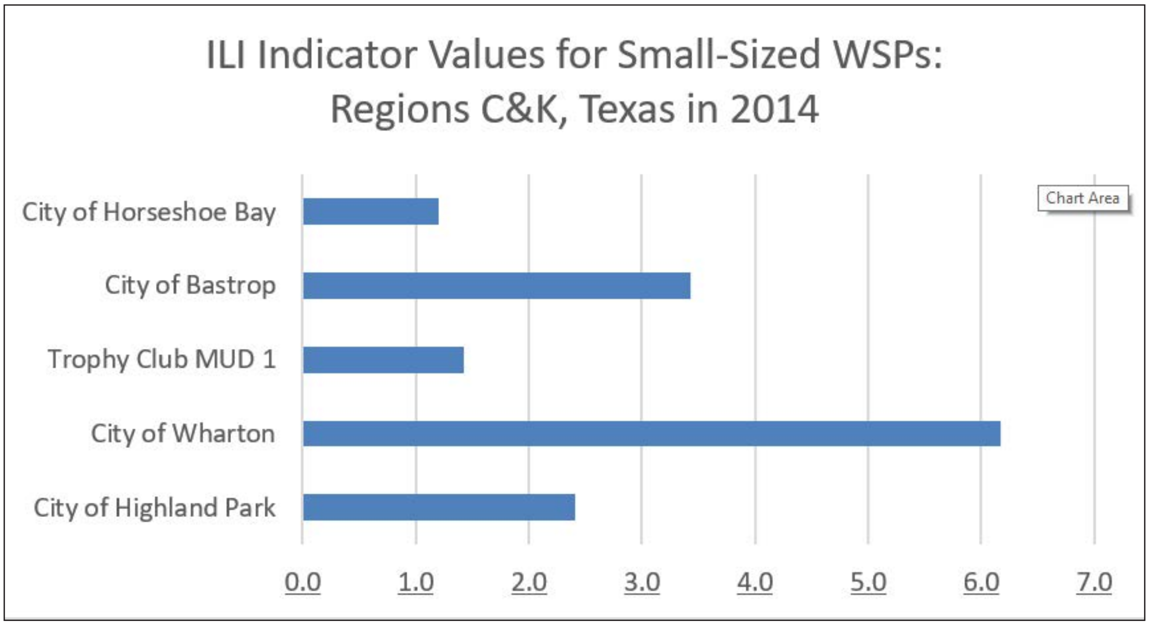

Figure 3. Comparison of infrastructure leakage index (ILI) indicator values among extra-large- and large-sized WSPs: Regions C and K, Texas in 2014.

Table 5. Retail price of water for top 26 water service providers in Texas: reported vs. calculated from current water rates.

	Water audit/average current rate ($)	X-Large WSP (3) audit/current ($)	Large WSP (11) audit/current ($)	Medium WSP (12) audit/current ($)
Retail price per 1,000 gallons	3.94/5.22	3.68/5.37	4.29/4.93	3.64/5.27
Retail price for 8,000 gallon bill	31.52/41.76	29.44/42.96	34.32/39.44	29.12/42.16

Note: Lewisville, one of the top 27 WSPs, is not included due to reported data implausibility. Thus, n = 26 rather than 27. Seventy-four percent of rate sheets were revised in 2016 or 2017, which will tend towards slightly higher current rates from those used in 2014 audits.

Valuing water losses using retail price can help planners and utility managers more realistically calculate the benefit/cost ratio of this supply option versus others, and valuation using retail price will better reflect scarcity in a drought-prone state where surface water is overallocated relative to its availability during a record drought (Sansom 2008; McGraw 2018).

Furthermore, valuation using retail price also speaks to the needs of both water service providers and the communities they serve (Beecher and Shanaghan 1999) and should come closer to capturing the opportunity cost associated with impacts of urban water use/loss on other competing uses and the environmental cost related to impacts, for example, on environmental flows (see Freebairn 2008).[14]

To examine the difference in retail price reported and a retail rate calculated from current rate sheets, an average monthly water bill was developed that is based on consumption of 8,000 gallons per residential (single-family) household.[15] Table 5 illustrates the disparity in retail price between rates reported in water loss audits and rates calculated for this study using current rate sheets in a manner consistent across water service providers.

[14] Protecting environmental flows and the aquatic species that such flows maintain in Texas is an evolving issue since passage of Senate Bill 3 in 2007 (Sansom 2008). Protecting the flow of natural springs, baseflow, and aquifers from overdraft (see, for example, Chaudhuri and Ale 2013; Sheng 2013) are other compelling reasons for pricing/valuing water to help minimize negative externalities. Elsewhere, an attempt to estimate the shadow price of system leakage as a proxy of the environmental and resource/opportunity costs of water losses is predicated on using the retail price of water, divined from utility bills, delivered to end-users (Molinos-Senante, Mocholi-Arce, and Sala-Garrido 2016). Thus, assigning a defensible retail value to real and apparent losses has value for multiple reasons.

[15] Monthly consumption is based on 2.84 persons per household (U.S. Census Bureau 2017) and 94 gallons per capita per day (statewide average) derived from Hermitte and Mace (2012). The monthly bill, from which a per 1,000 gallon rate is derived, includes any fixed or minimum charge, charge based on meter size, and applicable volumetric rates. Thus, the water bill for 8,000 gallons is what a ratepayer will receive either as an average of all 26 WSPs used in this particular analysis or an average from grouped WSPs that are similarly sized.

Table 6. Median water loss performance indicators for Regions C and K, Texas in 2014 compared to other data set.

Data	Performance indicator	TWDB 2014 median	Andrews & Strum (2016) median	Unit
Financial	Retail cost (n = 99)	4.00	4.67	$/1,000 gallons
	Variable production cost (n = 98)	1,680.00	950.00	$/MG
	Annual reported cost of real and apparent losses (n = 94)	238,921	---	$/year
	Nonrevenue water as percentage of operating cost	---	7.8	percentage
Operational	Apparent losses	5.81	5.73	gallons/service connection/day
	Real losses (normalized to service connections)	32.03	39.88	gallons/service connection/day
	Real losses (normalized to miles of main)	1,424	785.54	gallons/miles of main/day
	Real losses (normalized to pressure)	0.47	0.59	gallons/service connection/day/psi
	Infrastructure leakage index (n = 50)	2.82	2.48	dimensionless
	Data validity score	38	73.1	points out of 85/points out of 100

Note: n refers to 2014 TWDB sample only and varies due to implausibly high or low reported data or retail or variable production cost data that were deemed inaccurate. For operational performance indicators, n = 106 unless otherwise noted. MG = million gallons; psi = pounds per square inch

The average actual retail prices of the audited WSPs ranged from 15% to 46% higher than the retail rates used in their water loss audits (average difference of 32%). The calculations assumed monthly household consumption of 8,000 gallons. This difference is unlikely to be explained solely or even mostly by current rates that for the majority of the WSPs have increased during the last three years, as noted in Table 5. Dallas Water Utility, for example, reports a retail rate of $1.80 per 1,000 gallons in 2014 versus their current reported rate of $1.90 per 1,000 gallons, an increase of under 6%.

Rates calculated here do not include wastewater treatment charges that the AWWA indicates can be included in an approach to valuing real losses using retail price if wastewater treatment charges are included in the water bill. And no additional attempt has been made to more carefully estimate the environmental and resource costs (i.e., cost of negative externalities and opportunity cost alluded to above) that have been innovatively estimated by Molinos-Senante, Mocholi-Arce, and Sala-Garrido (2016) for Chilean water companies to be 32% of the delivered water price. Thus, the rates that were calculated consistently across the sample based on average household water use in Texas and presented in Table 3 might be considered conservative at capturing scarcity/opportunity, environmental, and other costs despite being greater than reported rates in the study year.

Finally, the average (median) variable production cost reported by the top 27 water service providers is $1.87 per 1,000 gallons.[16] This production cost value is a little less than half of the reported in 2014 retail price (average of $3.94) and a little more than a third of the retail price calculated from current rate sheets (average of $5.22). Applying retail price to real losses, therefore, results in a significantly higher valuation of economically recoverable water than is currently the case when its value is equated with its variable production cost.

PERFORMANCE INDICATORS

Industry standard performance indicators, both financial and operational, were calculated from audits reported to the TWDB for comparison (Table 6) to a composite water loss audit data set from five states, including Texas data from 2010 and 2013 (Andrews and Sturm 2016).

Differences in four indicators warrant comment. First, retail prices found in the Andrews and Sturm (2016) composite data set are almost 17% higher than retail rates reported in 2014 Texas water loss audits despite the former coming from mostly older data (i.e., 2010-2014). Because most of the data in the composite data set come from states other than Texas, the comparison suggests that Texas retail water rates are either set low, reported low, or both. Secondly, there is a big difference

[16] The variable production cost of $1.87, taken from the top 27 water service providers, is somewhat higher than the average taken from the 98 water service providers that reported plausible data; see Table 4.

in real losses normalized by miles of main: 1,424 gallons per mile of main per day in this study versus 785.5 gallons per mile of main per day in the Andrews and Sturm (2016) data set. This could be the result of older infrastructure that is generally in poorer condition or a reflection of a different split between urban and rural service areas among the Texas utilities. Examining this operational performance indicator alone will not explain the difference in results.

The third noticeable difference between the Texas data and the composite data set concerns data validity scores. As suggested above, Texas measured on a different scale than the AWWA method in 2014. But even when viewed as an adjusted data validity score of 45 (i.e., 38/85), the average self-reported data validity score is very low in Texas compared to the composite data set and may reflect the lack of confidence in the reliability of the available data, the auditor's inexperience with conducting an audit, or both. The composite data set includes Georgia, which benefits from third-party audit validation and technical assistance, both thought to improve audit quality and data validity score accuracy (Andrews and Sturm 2016). Finally, real losses, normalized to service connections, are nearly 20% lower in the 2014 Texas data set than what was found in the multistate composite data set. One plausible explanation is that the current study data set likely reflects a more urban/suburban and thus higher density service area than the composite data set evaluated by Andrews and Sturm (2016).

ECONOMIC LEVEL OF LOSS

Not all water loss that is technically recoverable is economically feasible to recover (US EPA 2010). The economic level of loss (ELL) is the point where the value of the water saved is less than the cost of making any additional reduction in system water losses (Farley and Trow 2003). The economic level of loss only considers the direct costs incurred by the water service provider, not the environmental and scarcity costs of urban water use that is more fully captured by another metric, the Sustainable Economic Level of Leakage, which has been proposed by Ofwat (2007), estimated by Molinos-Senante, Mocholi-Arce, and Sala Garrido (2016), and discussed by others. That said, the ELL is also a function of how water is valued and entails both a short-term ELL and long-term ELL, as elucidated by Farley and Trow (2003). Furthermore, Farley and Trow (2003) describe supply-side and demand-side options for maintaining system capacity (i.e., headroom) when considering the calculation of ELL.

While it is up to each water service provider to determine their unique economic level of loss, it is unknown how common this understanding might be among water service providers. Furthermore, the ELL is not a calculation whose result remains static. A WSP's economic level of loss will vary over time and in response to the degree of active leakage control that is implemented (Farley and Trow 2003). In any event, it is a best management practice for water service providers to pursue water loss control to the point where they reach an economic level of loss, at a minimum. Such a level of loss exists somewhere between unavoidable annual real losses (UARL) and current annual real losses (CARL) per the IWA/AWWA water loss audit methodology (AWWA 2016b).

Here, two techniques are considered for estimating the ELL. First, a simple midpoint between CARL and UARL volumes is selected, given the regional scale nature of the analysis. A second estimation technique is detailed in a report that evaluated water audit data for Pennsylvania water utilities (Kunkel Water Efficiency Consulting (KWEC) 2017). In short, this technique considers median values of customer retail unit cost of water (for apparent losses), variable production cost (for real losses), and normalized apparent/real loss indicators. Utilities with values for these three variables that are found to be greater than the median values calculated from the full data set of utilities were thought to have the greatest economic incentive for recovering apparent and real losses.

Both approaches were applied to the top 27 WSPs. Eighteen of the 27 WSPs qualified for further calculations when applying the midpoint technique. Applying the KWEC technique (tested on real losses only) resulted in a smaller sample size (n = 7) and given the greater-than-median-value criteria involved, did not capture the three largest utilities. Thus, given the pilot nature of this study, small resultant sample size from applying the KWEC method, and the argument made in this study for using retail price rather than variable production cost for identifying the economic value of real losses, the author chose to apply the simple midpoint method: a volume of water that is halfway between UARL and CARL. The midpoint method is applied in Table 7.

EXTRAPOLATION OF REGIONAL RESULTS

Table 7 illustrates several normalized loss values, economically recoverable loss estimates, and more. Results from Regions C and K data analysis are shown in one column and extrapolated statewide as shown and explained in the notes below the table. The purpose of Table 7 is to arrive at an approximation of the combined annual financial impact of both apparent and real losses in utility operations statewide that are estimated to be economically feasible to recover.

Table 7. Population, water usage, loss, and value estimates for Regions C and K and State of Texas.

	Regions C and K in 2014	State of Texas in2010
Population served	6,816,020[a]	25,260,000
Total system inputs (MG/acre-feet)	392,764/1,205,348[a]	1,456,350/4,469,374[b]
Average economically recoverable real losses (gallons/person/year)[c]	2,519	(assumes 2,519 gallons/person for entire population)
Value of economically recoverable real losses/ person/year[d]	Calculated for water (1,000 gallons) valued at: a) variable production cost: $4.71 b) audit reported retail: $10.08 c) current rate retail price: $13.15	
Value of economically recoverable real losses/ year based on population served	a) $32,103,454 b) $68,705,482 c) $89,630,663	$118,974,600–$332,169,000
Average economically recoverable apparent losses (gallons/person/year)[a]	590	(assumes 589.85 per person for entire population)
Value of economically recoverable apparent losses/person/year	$2.36–$3.08 Calculated for water valued at audit reported retail ($4.00/1,000 gallons) and by the current rate retail price ($5.22/1,000 gallons)	
Value of economically recoverable apparent losses per year based on population served	$16,085,807–$20,993,342	$59,613,600–$77,800,800
Average economically recoverable real and apparent losses (gallons/person/ year)	3,109	(assumes total loss of 3,109 per person for entire population)
Value of economically recoverable real and apparent losses/person/year	$12.44–$16.23 Calculated for water valued at reported retail ($4.00/1,000 gallons) and by current-rate price ($5.22/1,000 gallons) for Regions C and K.	
Total volume (MG/acre-feet) economically recoverable real and apparent losses	21,191.01/65,033	78,533.34/241,010
Total value of economically recoverable real and apparent losses/ year	Applying retail rates only: reported: $84,791,289 -current: $110,624,005	$314,234,400–$409,969,800

[a] includes full data set from Regions C and K (2014; n = 106) unless noted otherwise. MG = million gallons

[b] Source: Maupin et al. 2010 (public water supply sector only)

[c] n = 52 because negative (CARL-UARL) values in data set led to exclusion of 54 WSPs. Real loss volume of 27,565.12 MG * 0.50 = economic level of loss volume of 13,782.56 MG/population served (n = 52) of 5,471,921.

[d] n = 52 as in c. above. Range of value was calculated by multiplying 2,518.78—the average economically recoverable real loss per person per year—by the median reported retail price ($4.00/1,000 gallons) and by the average retail price calculated from current rate sheets ($5.22/1,000 gallons).

DISCUSSION AND CONCLUSIONS

This is a regional-scale study of nonrevenue water and the portion of such water that is estimated to be economically recoverable. A regional average water bill has been calculated for assigning a consistent retail value to economically recoverable water losses, to more appropriately value the water in question.

The author's analysis of water loss audit data submitted by the WSPs to the TWDB suggests that the water loss audit methodology employed—assigning a variable production cost rather than a retail price—underestimates the value of economically recoverable water leaking out of their distribution systems by nearly a factor of three. The volume in question was assessed to be worth approximately $32.1 million using a variable production cost per gallon versus the $89.6 million that it would be worth using a regional average retail rate per thousand gallons (Table 7). Given this difference in assigned values, it seems fair to ask about the potential consequences of this undervaluation. Might the undervaluation suppress investment in reclaiming water lost to leakage and by comparison lead to overinvestment in other supply strategies? Perhaps the answer to that question depends in part on the volume of water loss that can be economically recovered.

The total volume of economically recoverable water from the two regions in 2014, both real and apparent losses, is 21.19 billion gallons per 65,032 acre-feet (Table 7). For perspective, the volume of economically recoverable water estimated here for Regions C and K is over 22% of projected annual water demand (all water-use sectors) in 2020 for both regions.[17] More strikingly, the recoverable water estimate represents over 36% of projected annual water demand within the municipal water-use sector of both regions in 2020 where the leaky infrastructure is situated.

More aggressive investments aimed at capturing nonrevenue water could form an important pillar of many WSPs' water supply strategies in coming years. Region C alone projects municipal water supply savings of 8.682 billion gallons per 26,646 acre-feet per year during the next decade from enhanced water loss control programs (i.e., as planned water management strategies; Freese and Nichols Inc., et al. 2015b). For perspective, this volume of water planned for recovery in Region C is sufficient to meet the residential needs of a city sized between Lubbock (population 247,323) and Laredo (population 255,305) for one year.[18] While positive, the amount of water supply planned for recovery in Region C is less than half—41%—of what is estimated to be economically recoverable from both regions. Furthermore, the unit cost of capturing this water is a relative bargain compared to the unit cost of securing other water supplies.

Water savings from Region K's water loss control strategies are unknown because they are included in the more comprehensive category of conservation. But there is little reason to believe that the city of Austin's investment in water loss control will yield a volume of water sufficient to make up the difference between the economically recoverable water volume estimated here, 21.191 billion gallons per 65,033 acre-feet (Table 7), and the amount planned for recovery in Region C.

The economically recoverable nonrevenue water from the two planning regions has been estimated to have a retail value of over $110 million in the one year examined. This estimated value is three times the amount of $36.5 million that is planned to be spent on water loss control strategies in Region C each year over the course of the next decade. The loss-control costs expected to be incurred by Region K, including the City of Austin, are not detailed in the Region K plan and are thus unknown to the author. That said, it is likely that even if the two regions were considered together and the City of Austin's cost for water loss control implementation was included to enable an "apples-to-apples" comparison, the yawning gap between the value of economically recoverable water and funds planned for water loss control in the larger of two regions studied would not materially narrow.

The statewide impact of ignoring the nonrevenue water that could be economically feasible to recover ranges from $314 million per year using the audit reported retail price of water to as much as $400 million annually using a retail price that is derived from a regional average of ratepayer bills calculated for this study (Table 7). While these numbers are based on 2014 data, they are very likely to be similar—and perhaps higher—for each of the years since then.

Given the magnitude of infrastructure repair needs, robust population growth in Texas, and the proposed cost of implementing myriad water management strategies to make drinking water ends meet, it does not serve the public interest to either ignore the economically recoverable portion of nonrevenue water or underestimate its value. This is especially true given that recovering nonrevenue water, particularly real losses, is now considered a source of new water in state and regional water supply planning efforts. There is an urgent economic and environmental case for realistically valuing nonrevenue water in order to incentivize water service providers to reduce losses to the point where they reach an economic level of loss.

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[17] The 2017 State Water Plan projects annual water demand in 2020 for both Regions C and K will be 2,906,000 acre-feet across all water-use sectors and 1,788,090 acre-feet for the municipal water-use sector alone.

[18] This assumes the same gpcd of 94 as used to derive average household use and the resultant monthly water bill. City population estimates are from U.S. Census Bureau via Texas Demographics by Cubit https://www.texas-demographics.com/cities_by_population

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Commentary: 86th 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 five 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 2019 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:
- Sierra Club, Lone Star Chapter and Save Our Springs Alliance
- Texas Water Conservation Association
- Texas Alliance of Groundwater Districts
- Texas Rural Water Association
- Texas Water Infrastructure Network

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Terms used in paper

Abbreviation	Name
ASR	aquifer storage and recovery
BGPZ(s)	brackish groundwater production zones
BRA	Brazos River Authority
CCN	Certificate of Convenience and Necessity
FIF	Flood Infrastructure Fund
GAM(s)	Groundwater Availability Models
GCD(s)	groundwater conservation district(s)
GCWA	Gulf Coast Water Authority
GLO	Texas General Land Office
GO	general obligation
HB	House Bill
HJR	House Joint Resolution
HUB	Historically Underutilized Business
JOC	job order contracting
MSA	metropolitan statistical area
NCTMA	North Central Texas Municipal Water Authority
NESC	National Electrical Safety Code
PUC	Public Utility Commission
RWPG(s)	regional water planning groups
SB	Senate Bill
SUD(s)	special utility districts
TAGD	Texas Alliance of Groundwater Districts
TCEQ	Texas Commission on Environmental Quality
TxDOT	Texas Department of Transportation
TDEM	Texas Division of Emergency Management
TIRF	Texas Infrastructure Resiliency Fund
TRWA	Texas Rural Water Association
TWCA	Texas Water Conservation Association
TWDB	Texas Water Development Board
TXWIN	Texas Water Infrastructure Network
WAM(s)	water availability models
WSC(s)	water supply corporations

WATER IN THE 86TH TEXAS LEGISLATURE: FLOODING DOMINATES BUT WATER MANAGEMENT ISSUES PERSIST

By Ken Kramer, Water Resources Chair for the Lone Star Chapter of the Sierra Club, and Christopher Mullins, Staff Attorney for Save Our Springs Alliance

Immediate crises or recent catastrophes have a remarkable way of focusing the attention of politicians and policy-makers. This phenomenon was apparent in how the regular session of the 86th Texas Legislature addressed water issues. Flooding and damages from Hurricane Harvey and floods elsewhere in Texas in 2017 and 2018 depleted the oxygen from most other water topics in the session.

Approximately one-fourth of the over 200 pieces of water-related legislation introduced in the Texas House and Senate in the spring of 2019 dealt with flood issues or related emergency and disaster response and preparedness. Along with the volume of such bills introduced, the scope of the flood-related legislation the Legislature passed emphasized the focus on flooding.

Drought—too little water—has usually been the driver of major new water legislation in Texas. The historic drought of record in the 1950s led to creation of the Texas Water Development Board (TWDB) and a round of dam building, the dry years of the mid-1990s produced the regional water (supply) planning process, and the drought of 2011 (and beyond 2011 for some) prompted creation of the State Water Implementation Fund for Texas (SWIFT).

This session: Action prompted by "Too much water!"

In 2019, however, it was concern about too much water in the wrong places that prompted fairly sweeping legislation on disaster management and recovery, flood project funding, and a new state and regional flood planning process, among other enactments. Of course, given the impact of Hurricane Harvey on the Texas coast and other recent flooding experiences—combined with the potential for more such extreme events as a result of climate change (yes, Texas Legislators, the climate is changing)—the question remains whether the 2019 legislative response to flooding will prove sufficient.

Even a $1.6+ billion withdrawal from the state's "rainy day fund," as was done by Legislators to provide new funding for flood projects and related flood work, may not be enough to meet the challenge, even combined (as it is intended to be) with local government funds and as a match for federal funding. The state flood assessment prepared by the TWDB in 2018 estimated statewide flood mitigation costs over the next ten years to be more than $31.5 billion, with $18 billion–$26.6 billion needing to come from state or federal sources. Moreover, the estimate did not include "projects associated with Hurricane Harvey recovery, other large federal projects such as the Coastal Spine, or rehabilitation of high hazard dams within the state."

In addition, moving forward with some projects will depend on voter approval of a proposed state constitutional amendment. Success will also depend, as it always does, on how efficiently and effectively the new flood project funding mechanisms and planning processes are implemented by state, regional, and local government entities.

Moreover, are Texas state and local officials willing at some point to impose real estate development measures to avoid the mistakes of the past that have exacerbated flooding in many areas? Legislators did not take that approach this session. Money and infrastructure alone, however, are not the answers to reducing and managing flooding. Finally, what happens if parts of the state are hit by major floods in the near term before new projects are completed or local measures enacted? Will that dramatically increase the price tag for flood control and recovery, and, if so, will future Legislatures be blessed with a robust state revenue scenario to allocate those additional dollars?

These uncertainties aside, the Legislature deserves credit for taking important steps this session to address flooding and related issues. Several bills had implications for flood control and response, but the most significant ones were three bills making numerous statutory changes, a supplemental appropriations bill, and a proposed state constitutional amendment.

Senate Bill (SB) 6

SB 6 requires the Texas Division of Emergency Management (TDEM) to undertake several tasks related to disaster response and recovery. SB 6 also establishes a "wet debris study group" to "study issues related to preventing the creation of wet debris and best practices for clearing wet debris following a disaster, including: … (1) the creation of maintenance programs for bodies of water in this state." The study group is required to submit a report with recommendations to the Legislature by November 1, 2020.

SB 7

SB 7 revises and adds to the state's mechanisms for funding flood mitigation and flood infrastructure projects. Article 1 defines eligible "flood control planning" activities. Article 2 creates a new Flood Infrastructure Fund, defines eligible projects to receive assistance from the fund, and sets out in detail how the TWDB is to administer the fund. However, Article 2 will only take effect if the voters of Texas approve the state constitutional amendment proposed in House Joint

Resolution (HJR) 4. That vote will come in November 2019. Once a state flood plan is adopted (see below), this fund may only be used to provide financing for projects recommended in that plan.

Article 3 establishes a separate fund called the Texas Infrastructure Resiliency Fund, with a Floodplain Management Account, a Hurricane Harvey Account, and a Federal Matching Account. These accounts are structured to apply to different types of projects. The TWDB is the primary administrative body for the resiliency fund, but the TDEM has a lead role in financing projects funded out of the Hurricane Harvey Account. This new fund and its separate accounts are in effect now—voter approval of a constitutional amendment was not required.

SB 8

SB 8 establishes a new state and regional flood planning process, similar to the water supply planning process created by SB 1 in 1997. Under the guidance of the TWDB, the state will be divided into flood planning regions, and planning groups with diverse representation will be created in each region. Their regional plans will be submitted to the TWDB for review and approval, and the TWDB will aggregate those regional plans into a state flood plan. The first state flood plan must be adopted no later than September 1, 2024 and must be revised every five years. SB 8 also requires the State Soil and Water Conservation Board to prepare a separate plan for repair, rehabilitation, and maintenance of dams under its jurisdiction and to revise that plan every decade.

Statutory changes are important, but implementation of statutes requires, with some exceptions, legislative appropriation of dollars. This time the supplemental appropriations bill, SB 500, was the primary vehicle for allocating funds to the TWDB to carry out most of its revised flood responsibilities. Almost $1.5 billion was taken out of the rainy day fund and appropriated to the TWDB for flood programs. Another $200 million out of that fund was given to the General Land Office to match federal funds for studies and projects of the U.S. Army Corps of Engineers, apparently to support a potential coastal barrier project touted as protecting vulnerable parts of the Texas coast from storm surge from tropical storms or hurricanes.

Some interesting aspects of the legislative action on flooding deserve special attention:

- "Nonstructural" flood projects (including "projects that use nature-based features to protect, mitigate, or reduce flood risk" or "natural flood control strategies"—the terms vary among the new funds) are expressly eligible for funding. This could be a boon for green infrastructure, including preservation of open space to reduce flooding.
- Some new funding mechanisms will provide grants as well as loans, somewhat of a departure from the usual legislative preference that financial assistance for water projects be paid back by political subdivisions over time.
- The Legislature is interested in flood projects that might also serve a water supply purpose.
- The Legislature intends to play an active role in shaping and overseeing implementation of the flood legislation, not only by the usual oversight but through legislative advisory committees providing input to rulemaking and perhaps ongoing administration.

How the flood legislation works out in practice remains to be seen. The bottom line, however, is that the 86th Legislature made flooding a high priority for the first time in decades, and that priority affected legislative attention to other water issues.

A biennial favorite water topic: Surface water and groundwater management

Despite the focus on flooding, some other water issues did get attention. The next most significant water policy issue was a biennial favorite: how to manage surface water and groundwater.

Most, if not all, Legislators and policy wonks agree that surface water and groundwater management should balance production with conservation and the long-term needs of all users, including the environment. However, this session's water bills exemplified two major trends that threaten achievement of this balance: (1) major policy decisions on water management are being made without careful consideration of critical, problematic details in the legislation and (2) the regulatory process is being "streamlined" via legislative dictates and procedural shortcuts.

Several bills were aimed at facilitating aquifer storage and recovery (ASR) and brackish groundwater development. ASR is absolutely a promising technology. However, policy questions about how and where the technology might be used raise numerous practical, technical, and ecological issues requiring consideration before Texas goes all in on ASR. One bill that passed—**House Bill (HB) 720**—failed to consider these crucial factors. HB 720 creates a system to incentivize and expedite ASR projects to capture "unappropriated [surface water] flows" during wet years for underground storage, allegedly for flood mitigation and for later retrieval for water supply.

HB 720 was enacted despite public testimony identifying potential ecological impacts and major legal, planning, and engineering challenges to the viability of such ASR projects. The bill was based on the questionable premise that there are unappropriated volumes of water in streams in excess of what is needed for the environment. In reality, most of the surface water rights in Texas were granted prior to any conditions required for "environmental flows," environmental flow standards set by the Texas Commission on Environmental Quality are considered inadequate, and the state's surface water availability models (WAMs) in major river basins need to be updated (one bill passed this session, **HB 723**, requires WAMs to be updated for some basins: the Neches, Brazos, Red, and Rio Grande).

Similarly, a brackish groundwater bill, **HB 724**—which did not pass—ignored some critical issues. The bill would have automatically granted a bed and banks authorization to use surface streams to discharge, convey, and divert treated brackish groundwater. However, the bill had no provisions to limit withdrawal of brackish groundwater in situations where that underground resource contributes to surface flows. Surface water-groundwater interaction should be considered in any water management strategy. HB 724 exemplified both trends noted above: It failed to consider all relevant factors, and it would have required automatic approval of permit applications.

Numerous bills affecting groundwater conservation districts (GCDs)—the state's preferred method of groundwater management—were filed this session, and most exemplified the "streamlining" trend. Those wishing to profit from the groundwater gold rush continue to seek passage of bills undermining GCD regulation, seen as an impediment to moving groundwater around Texas. The result, if the state is not careful, will be a massive statewide system of water pipelines, nicknamed "Gridzilla"—a beast in the mold of the deeply flawed California water model.

Past efforts to bring "Gridzilla" to life with statewide legislation failed. However, state water grid supporters are seeking to assemble it piece by piece like a T-Rex in a museum. Several bills this session were the legislative equivalent of the glue needed to put the creature together. For example, **SB 1010** would have moved Texas towards a one-size-fits-all style of groundwater management, and **SB 851** would have incentivized parties to sue GCDs, effectively chilling districts' regulatory effectiveness (both bills failed). **HB 1066**, set to go into effect in September, requires almost automatic renewal of groundwater transport permits by GCDs and eliminates meaningful public participation.

Overall, this session's surface water and groundwater management bills, apart from those involving studies, were steps in the wrong direction. One notable exception: **SB 942**, which did pass, would have allowed the TWDB to provide state financial assistance for conservation easements and other strategies to reduce nonpoint source pollution (which affects both surface water and groundwater quality). By and large, however, the Legislature is failing to give adequate scrutiny to proposed changes in surface water and groundwater management and is undermining a healthy regulatory balance in managing water resources.

Conclusion

In addition to flooding and water management, the 86th Texas Legislature enacted about 20 other bills relating to water topics such as conservation and desalination, among others. The Legislature also proposed a state constitutional amendment to authorize additional bonds to finance water, wastewater, and (now) drainage projects in economically distressed areas. However, water topics ebb and flow from one session to another. This time flooding swept most of those other topics away, but the issue of managing surface water and groundwater continues to bubble and apparently will not decline soon, even though some aquifer water levels and environmental flows may.

TEXAS WATER CONSERVATION ASSOCIATION 86TH LEGISLATIVE SESSION WRAP-UP

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

After a fast and furious 140 days, the 86th Legislature has adjourned *sine die*. In 2019, Legislators filed 7,324 bills, the most in a decade. And 1,429 of those bills passed both chambers by *sine die*, providing for a relatively high 19.5% bill passage rate. Governor Abbott then vetoed 58 bills, the most of his tenure so far and the most of any governor since 2001.

Legislators spent the bulk of their time this session on school finance, tax and lobby reform, and flood response. As in past sessions, the Texas Water Conservation Association (TWCA) closely followed bills of possible interest to its members. Staff tracked 522 bills in 2019, up by nearly 15% from 2017, and designated 169 of those bills as high priority. Nearly 23% of our tracked bills made it to the finish line, and summaries for the most significant bills that may be of interest to water professionals are provided below.

Flood and emergency response

In advance of this session, the TWCA convened a Flood Response Committee to work toward educating lawmakers on flood-related policy issues and developing a set of guiding principles related to flood legislation. The committee was chaired by Bob Brandes, a water resources consultant, and Matt Phillips, of the Brazos River Authority, led a legislative subcommittee. The educational paper and guiding principles can be found on TWCA's website.

Though Legislators filed dozens of bills related to flooding during the 86th session, four bills made up the largest funding opportunities for flood response in the state:

- **Senate Bill (SB) 7: Funding of Flood Planning, Mitigation, and Infrastructure (Creighton/Phelan)**
- **SB 8: State and Regional Flood Planning (Perry/Larson)**
- **House Joint Resolution (HJR) 4: Flood Funding Constitutional Amendment (Phelan/Creighton)**
- **SB 500: Supplemental Appropriations (Nelson/Zerwas)**

Together, these bills provide for and direct the spending of more than $1.8 billion in flood-related dollars. SB 7 specifically creates two new funds at the Texas Water Development Board (TWDB): the Flood Infrastructure Fund (FIF) and the Texas Infrastructure Resiliency Fund (TIRF).

SB 500 appropriates $793 million to the FIF, dependent on passage of HJR 4, which will go before voters in November. The fund, if approved, will provide low-interest loans and grants to water districts or authorities, municipalities, or counties for flood projects, including planning, design, regulatory approvals, and construction. Grants are authorized only for projects serving an area outside of a federally designated metropolitan statistical area (MSA),[1] for projects where the eligible political subdivision does not have the ability to repay the loan or to provide matching funds to enable participation in a federal program for a flood project. Applications must include an analysis of whether the proposed flood project could use floodwater capture techniques for water supply purposes. Upon adoption of an initial state flood plan by the TWDB as required by SB 8, the initial provisions for use of the FIF expire, and the TWDB may use it only to finance projects in the state flood plan.

SB 500 also appropriates $685 million to the TIRF, which is not dependent on the passage of HJR 4 and consists of four accounts:

- the Floodplain Management Account to provide financing for flood planning, the collection and analysis of flood-related information, and other flood activities (this account already exists but is transferred here);
- the Hurricane Harvey Account to provide grant and loan financing through the Texas Division of Emergency Management (TDEM) to eligible political subdivisions for flood projects related to Hurricane Harvey;
- the Federal Matching Account to provide matching funds for federal money; and
- the Flood Plan Implementation Account to provide financing for projects in the state flood plan required by SB 8, once adopted.

SB 7 provides guidance to the TWDB to prioritize funding requests and creates an advisory committee to provide further guidance and oversight. As mentioned, SB 8 calls for a new state flood plan, which borrows from the state's regional water planning groups' model and requires TWDB to prepare and adopt the plan in conjunction with regional flood planning groups.

In SB 500, the Legislature also provided $200 million to the Texas General Land Office for matching funds for U.S. Army Corps of Engineers studies and projects and $150 million to the Texas State Soil and Water Conservation Board for dam repair and maintenance.

[1] An MSA is defined by the Office of Management and Budget as one or more adjacent counties that have at least one urban core area of at least 50,000 population, plus adjacent territory, that has a high degree of social and economic interaction with the core.

Other bills that address flood and emergency response include:

House Bill (HB) 5 (Phelan/Kolkhorst)

HB 5 requires the TDEM to develop a catastrophic debris management plan and model guide for use by political subdivisions in the event of a disaster as well as a model contract for debris removal services to be used by political subdivisions. The bill also requires the Texas A&M Engineering Extension Service to establish a training program on the use of trench burners in debris removal and creates groups to study wet debris and local restrictions that impede disaster recovery efforts.

HB 26 (Metcalf/Nichols)

HB 26 requires the owner or operator of a state-regulated dam that has a spillway with gates used to regulate flood waters to notify local emergency operation centers in downstream communities when spillway releases are made to regulate floodwaters, according to the Texas Commission on Environmental Quality (TCEQ) action plan guidelines. Emergency operation centers must then provide prescribed information to the public.

HB 137 (Hinojosa/Perry)

HB 137 requires the TCEQ to provide a biannual report of the condition of dams classified as high or significant hazard to designated city and county officials and councils of government in which the dam is located. The TCEQ must also report on a dam that has had a change of hazard classification within 30 days of the designation.

HB 1059 (Lucio III, Rodriguez)

HB 1059 requires the TCEQ to appoint a Green Stormwater Infrastructure and Low Impact Development Report Group to prepare biennial reports.

HB 2305 (Morrison/Kolkhorst)

HB 2305 requires the TDEM to study and develop a proposal for training and credentialing state and local emergency management personnel.

HB 2320 (Paul/Taylor)

HB 2320 requires the TDEM, in collaboration with other entities, to include private wireless communication, internet, and cable service providers in the disaster planning process and identify methods for hardening utility facilities and critical infrastructure to maintain essential services during disasters. The bill also requires the Public Utility Commission (PUC) to promote public awareness of bill payment assistance available during a disaster for electric, water, and wastewater services.

HB 2325 (Metcalf/Hancock)

HB 2325 requires the TDEM, in collaboration with other entities, to coordinate state and local government efforts to make 911 emergency service capable of receiving text messages, develop standards for the use of social media as a communication tool after a disaster, develop a mobile application for wireless communication during a disaster, use data analytics software to integrate data, and conduct a study on the use of a standard communication format by first responders.

HB 2345 (Walle/Hinojosa)

HB 2345 creates the Institute for a Disaster Resilient Texas at Texas A&M University, charged with a variety of analytical tools and information to support disaster planning, mitigation, response, and recovery.

HB 3815 (Morrison/Huffman) and SB 339 (Huffman/Morrison)

These bills require a seller's disclosure notice for residential property to include information about whether the property has flood insurance, has been previously flooded, is located within the 100 year or the 500 year flood plain or a floodway, as defined, or within a reservoir or flood pool of a reservoir operated by the U.S. Army Corps of Engineers.

SB 6 (Kolkhorst/Morrison)

SB 6 requires the TDEM to develop a disaster response guide for local officials and a catastrophic debris management plan. The Texas A&M AgriLife Extension Service is required to establish a training program on the use of trench burners for debris removal. A wet debris study group and an emergency management work group are created.

Groundwater

TWCA's longstanding Groundwater Committee, chaired by Hope Wells of the San Antonio Water System and Brian Sledge, an attorney in private practice, again worked during the interim to develop consensus-based legislative proposals in advance of the 86th Legislature. More than 80 TWCA members served on the committee, which took up issues ranging from groundwater conservation district (GCD) rules, attorneys' fees, groundwater mitigation, permits, and abandoned wells.

The TWCA supported **HB 722 (Larson/Perry)**, related to brackish groundwater, and **HB 1066 (Ashby/Perry)**, related to renewal of export permits, both of which will be effective on September 1. HB 722 is intended to provide greater access to brackish groundwater by simplifying procedures, expediting processing, reducing expenses, and providing flexibility to certain applicants within a GCD. The bill authorizes (and in the case of a petition from a groundwater owner, requires) a GCD to adopt and implement special permitting rules relating to the completion and operation of electric generation or municipal wells for the withdrawal of brackish groundwater within brackish groundwater production zones designated by the TWDB. The legislation contains comprehensive requirements for the content of rules and the processing of applications, which includes a technical review by the TWDB.

HB 2378 was a TWCA-initiated bill that aimed to clarify legislation from 2015. That session, the 84th Texas Legislature passed SB 854, allowing for automatic renewals of certain groundwater operating permits when conditions have not changed. However, many GCDs also require export permits to accompany an operating permit when groundwater will be exported out of the GCD. This bill clarifies that any export permit issued by a GCD in conjunction with an operating permit must be renewed consistent with the corresponding operating permit, effectively marrying the two permits so that they run concurrently once the original export permit period has expired.

Other bills that address groundwater management include:

- **HB 720 (Larson/Perry)** authorizes the appropriation of water for aquifer recharge. It also authorizes the holder of a water right authorizing storage that has not been constructed or that has lost storage to sedimentation to amend the right to include aquifer storage and recovery (ASR), taking into account evaporation credits. The bill prescribes procedures for consideration of an application for an aquifer recharge project and requires the TCEQ to adopt rules to implement the legislation.
- **HB 721 (Larson/Perry)** adds aquifer recharge projects to TWDB's study and survey requirements related to ASR and provides more specificity about how a report is to be prepared.
- **HB 1311: Geoscientist Sunset Bill (Thompson/Watson)** continues the existence of the Texas Board of Professional Geoscientists until September 1, 2025.

Water planning and surface water rights

TWCA's Surface Water Committee, chaired by Lyn Clancy of the Lower Colorado River Authority and Bob Brandes, was not active in advance of the 86th session but continued to support updated funding for water availability models (WAMs) at TCEQ. **SB 723 (Perry/Larson)** requires TCEQ to obtain or develop updated water availability models for the Brazos River, Neches River, Red River, and Rio Grande basins by December 1, 2022. The Legislature appropriated just over $2 million to obtain or develop the models.

Other bills that address water planning and surface water rights include:

HB 807 (Larson/Buckingham)

HB 807 requires the TWDB to create an Interregional Planning Council consisting of members of each regional water planning group to improve coordination, facilitate dialogue, and share best practices among regions. The bill also requires plans to identify drought response strategies, assess ASR opportunities, and set goals for water use per capita in certain instances.

HB 1052 (Larson/Perry)

HB 1052 requires at least 50% of the money from the State Participation Account to be used for interregional water projects and authorizes the TWDB to use the account to provide financial assistance for a desalination or ASR projects, including state ownership in such a facility, limited to $200 million in bonds.

HB 1964: (Ashby/Creighton)

HB 1964 expressly exempts certain applications for a minor amendment to a surface water permit from requirements for a notice and hearing or technical review.

HB 2846 (Larson/Huffman)

HB 2846 requires the City of Houston to enter into a contractual agreement with the Brazos River Authority (BRA) on or before January 1, 2020 to transfer the city's ownership interests in the Allen's Creek Reservoir project to the BRA, including the associated water right permits. The contractual agreement must include provisions for the transfer of not to exceed $23 million from the BRA to the city.

HB 3339 (Dominquez/Creighton)

HB 3339 establishes minimum requirements for a water conservation plan that an applicant must meet to be eligible for financial assistance under various provisions of Chapters 15, 16, and 17 of the Texas Water Code. The plan must include specific, quantified five-year and ten-year targets for water savings, including goals for water loss programs and municipal use measured in gallons per capita per day. Data submitted to the TWDB may not be the only factor considered by the TCEQ in determining the highest practicable level of water conservation for an application for an interbasin transfer. Certain exemptions are provided, including for financial assistance for not greater than $500,000. The TWDB is required to establish a program to assist political subdivisions in developing water conservation plans.

SB 2272 (Nichols/Metcalf)

SB 2272 clarifies decertification provisions and prohibits a holder of a Certificate of Convenience and Necessity (CCN) that is the subject of an expedited release petition from borrowing money under a federal loan program until the PUC issues a decision on the petition. The bill also establishes a process for an independent appraiser to make a binding determination of compensation for decertification, and requires that the PUC ensure that the landowner pay the required compensation to the certificate holder.

Other bills of interest

The TWCA also saw some additional bills that may impact its members.

HB 305 (Paul/Nelson)

HB 305 requires a political subdivision with the authority to impose a tax that at any time on or after January 1, 2019 maintained a publicly accessible Internet website to post prescribed information on the website. The legislation contains exceptions for certain counties, cities, and school districts.

HB 1999 (Leach/Creighton)

HB 1999 prescribes actions a governmental entity must take before bringing a claim against a contractor or design professional for an alleged deficiency in the design or construction of certain improvements to real property.

HB 2202 (Miller/Kolkhorst)

HB 2202 authorizes a commissioners' court that created a levee improvement district with three appointed directors and a population of 2,000 or more to increase the total number of directors to five.

HB 2849 (Canales/Hughes)

HB 2849 requires local governments to allow any member of the public who desires to address the body on an agenda item to do so. The governmental body may adopt rules to limit the total amount of time that a member of the public may speak. A governmental body may not prohibit public criticism of the governmental body.

HB 3001 (Morrison/Birdwell)

HB 3001 addresses how special purpose districts may satisfy requirements to make financial information available to the public, including financial information addressed in Chapter 49 of the Texas Water Code.

HB 3834 (Capriglione/Paxton)

HB 3834 requires the establishment of state certified cybersecurity training programs. State agencies must identify employees who use a computer at least 25% of the time and require those employees and each elected or appointed officer of the agency to complete a certified cybersecurity training program at least once each year. Local government employees who have access to a local government computer system or database, elected officials of the local government, and contractors who have access to a state computer system or database must also complete a certified cybersecurity training program.

SB 2 (Bettencourt/Burrows)

This is an omnibus 147-page tax reform bill that establishes revenue caps for taxing entities. Sections 87, 88, and 89 include changes to the Texas Water Code. Rollback rate limitations for water districts vary from 3.5% to 8% depending on whether a district levies a tax of 2.5 cents or less per $100 valuation and whether a district meets the definition of "developed district." An unused increment rate provision may allow tax levies to exceed the 3.5% threshold if a district has not levied at the full 3.5% rate in any of the previous three years.

SB 65 (Nelson/Geren)

This comprehensive bill amends various sections of the Texas Government Code related to state agency contracting procedures. Significantly for local governments, the bill requires a political subdivision that contracts with a state agency for consulting services to post certain information on its website regarding contracts for lobbying activities.

SB 239 (Nelson/Button)

SB 239 requires a district with a population of 500 or more and subject to Chapter 51, 53, 54, or 55 of the Texas Water Code, upon written request by a district resident, to make an audio recording of a public hearing to consider the adoption of an ad valorem tax rate and to provide the recording to the resident in an electronic format after the hearing. The district is then required to maintain a copy of the recording for at least one year and post minutes of the meeting on the district's website if the district maintains a website. The bill also amends Chapter 49 of the Texas Water Code, relating to the procedures for holding meetings outside of a district and to require a district providing potable water or sewer service to include certain language on a customer's water bill about information available on the Comptroller's Special Purpose District Public Information Database or the district's website.

SB 530 (Birdwell/Wray)

SB 530 increases the maximum penalty per day for violations of laws protecting drinking water from $1,000 to $5,000.

SB 700 (Nichols/Geren)

SB 700 changes the definition of a Class B Utility and a Class C Utility and creates a new Class D Utility. The bill also addresses provisions for issuing emergency orders, temporary rates, ratemaking methodologies, a statement of intent for a rate increase, and rate application requirements.

SB 943 (Watson/Capriglione)

SB 943 adds a definition for "contracting information" to the Public Information Act and requires governmental bodies to release contracting information to the public except where excepted by law.

SB 944 (Watson/Capriglione)

SB 944 amends the Public Information Act to include protected health information not subject to disclosure and to address the maintenance and ownership of public information by an officer or employee of a governmental body. The bill also authorizes a governmental body to designate one email address and one mailing address for receiving public information requests.

Looking ahead

Due to the focus on flooding, popular policy topics such as groundwater took a back seat this session, even though numerous groundwater bills were filed and discussed. We expect a renewed focus on these issues in 2021, especially with respect to GCDs over the same aquifer adopting similar rules, attorneys' fees, permit moratoriums, consideration of a water provider's service area in groundwater permitting, and the standard of review for an appeal of GCD's decision on a groundwater permit. TWCA also hopes to continue working with stakeholders and policy-makers on funding and policies related to abandoned wells.

TEXAS ALLIANCE OF GROUNDWATER DISTRICTS 86TH LEGISLATIVE WRAP-UP

By Leah Martinsson, Executive Director, Texas Alliance of Groundwater Districts

The overarching themes of property tax and school finance reform dominated the 86th Texas Legislature, while the legislative response to Hurricane Harvey in the form of flood and disaster planning was the primary focus of discussions on water. Ultimately, significant legislation was passed in these areas. This resulted in a somewhat decreased focus on groundwater management during the 86th Legislative Session.

There were 15 bills filed that sought to make substantive changes to the provisions of Chapter 36 of the Texas Water Code. This represented fewer bills than in prior sessions. Nevertheless, the changes sought by many of the bills would have been significant. There were also a number of other bills filed that implicated groundwater policy and groundwater management districts (GCDs). In total, the Texas Alliance of Groundwater Districts (TAGD) identified 20 statewide priority groundwater bills for tracking during the session. Of those 20 bills, only five crossed the finish line.

Throughout the 86th Legislative Session, TAGD tracked over 130 bills of interest to groundwater conservation districts. In addition to the 20 statewide priority groundwater bills, TAGD tracked selected bills affecting individual GCDs, general water, study/planning, and administrative law/governance of political subdivisions for its membership. Those that passed and have or will become law are listed at the end of this article.

The substance of many of the 86th Legislative Session's groundwater bills reflected various themes that emerged during a busy legislative interim. And as is frequently the case, the session's groundwater policy dialogue was as affected by what didn't pass as by what did. This article briefly describes key groundwater bills that passed by topic area. It then discusses selected pieces of ultimately unsuccessful groundwater-related legislation that were the subject of significant attention this session.

Groundwater bills that passed

Brackish groundwater

Two of the groundwater bills that passed during the 86th Legislative Session address development of brackish groundwater resources. **Senate Bill (SB) 1041** extends the time by which the Texas Water Development Board (TWDB) must identify and designate brackish groundwater production zones (BGPZs) until December 1, 2032. This was necessary because the TWDB may otherwise have not been able to meet the prior 2022 deadline to identify and designate those BGPZs due to inadequate funding and limited availability of qualified contractors. In addition to this extension, the Legislature approved $2 million and two FTEs for the TWDB Brackish Resources Aquifer Characterization System, aimed at accelerating the mapping and characterization of brackish aquifers.

Once such BGPZs are identified, the passage of Chairman Larson's **House Bill (HB) 722** creates a separate GCD permitting system for the production of brackish groundwater in BGPZs. This may be the most notable change to Chapter 36 and GCD permitting as a result of the 86th Legislative Session and reflects a continuation of Chairman Larson's prior efforts to encourage further development and utilization of brackish groundwater.

Specifically, HB 722 provides that a GCD located over any part of a TWDB-designated BGPZ may adopt separate rules to govern the issuance of permits for wells to produce brackish groundwater from that BGPZ. If such GCD receives a petition from a person with a legally defined interest in groundwater in the district, that GCD must adopt such rules governing the issuance of permits for the withdrawal of brackish groundwater within 180 days.

HB 722 details certain requirements for applications for BGPZ operating permits. This includes a requirement that the TWDB investigate each such application and issue a report on potential adverse impacts from operation under the proposed BGPZ permit. Permits shall be for 30-year permit terms and shall include requirements for monitoring of water levels and water quality on the permit as may be recommended by the TWDB.

These BGPZ rules must provide for production in addition to the amount of managed available groundwater under Section 36.108 of the Texas Water Code. HB 722 further provides that permits shall be issued, to the extent possible, up to the point that the total exempt and permitted brackish production equals the amount that may be produced annually under the TWDB's BGPZ designation. While providing for separate BGPZ rules, HB 722 also requires that GDCs provide greater access to brackish groundwater by simplifying procedure, avoiding delay, and providing greater flexibility in permitting.

Export permits

Another noteworthy change to Chapter 36 resulted from the passage of Representative Ashby's **HB 1066**. This bill was initiated by the Texas Water Conservation Association (TWCA) groundwater committee and was a re-file of the 85th Legislative Session's HB 2378, which was vetoed by the Governor. This bill was described as essentially cleaning up a piece that had been overlooked in the passage of SB 854 by the 84th Legislature in order to align the timing of renewals of transfer permits and operating permits in those districts where both are issued separately.

Aquifer storage and recovery

The 86th Legislative Session saw passage of a handful bills to encourage further development and use of aquifer storage and recovery (ASR) and managed aquifer recharge projects.

HB 720 amends portions of Chapters 11 and 27 of the Texas Water Code to allow appropriations of state water for recharge into aquifers through ASR or an aquifer recharge project if certain conditions are met and the Texas Commission on Environmental Quality (TCEQ) determines that the water is not needed to meet instream flow needs. HB 720 also allows for amendments to convert certain qualifying appropriations for storage in a reservoir to storage in an ASR project. The bill also contains provisions for the TCEQ to adopt rules to protect groundwater quality through requirements for recharge injection wells and injection water quality.

Also intended to encourage the development of ASR projects, **HB 721** directs the TWDB to conduct studies on ASR projects in the state water plan and to conduct a survey to identify the relative suitability of various aquifers for use in ASR projects by December 15, 2020. The Legislature appropriated $500,000 in funding and three FTEs for the TWDB to complete this work.

Rounding out the bills designed to encourage further development of ASR projects, **HB 1052** authorizes the TWDB's State Participation Fund account to be used for interregional projects and for desalination and ASR projects that are not in the state water plan.

State and regional water planning

HB 807 makes changes to the regional water planning process aimed at encouraging greater cooperation between regional water planning groups (RWPGs), which include representation from groundwater management areas. HB 807 directs the TWDB to appoint an interregional planning council of representatives from every RWPG. The purposes of the council include improving coordination among the state's 16 RWPGs and the TWDB, as well as helping facilitate dialogue on water management strategies and best practices that could affect multiple planning areas. The bill also expands the requirements for information that RWPGs must provide in their regional water plans. This includes a requirement that regional water plans include opportunities for large-scale desalination projects for brackish groundwater and for regional water plans to include any legislative recommendations to facilitate voluntary water transfers.

Also, of significant interest in the groundwater community was the Legislature's approval of $1 million in funding and four FTEs for the TWDB to update the Groundwater Availability Models from outdated, unsupported software and code to current best practice standards. This allows the TWDB to develop and refine essential tools and information to address evolving water planning needs and provide critical inputs for the state water planning process and groundwater management.

Groundwater bills that did not pass

Many of the bills that would have most affected GCD powers and duties under Chapter 36 and attracted the most attention during the 86th Legislative Session ultimately failed to make it to *sine die*. The topics of many of these bills were subject to charges and hearings over the interim.

GCD rules and uniformity

Increasing uniformity between GCDs was a topic that received attention over the interim and had grown out of the dialogue that started with the failed SB 1392 from the 85th Legislative Session. Over the interim, a number of groundwater management areas (GMAs) undertook efforts to look at the rules of the GCDs within that GMA to compare their rules for similarities and differences. The TWCA groundwater committee proposed an amended SB 1392 for the 86th Legislative Session, which included language aimed at increasing GCD coordination of their rules through the GMA planning process. In filing **SB 1010**, however, Chairman Perry proposed a different approach.

SB 1010 sought to prohibit GCDs overlying a "common aquifer" and located within the same GMA from making or enforcing rules that are not similar to another GCD "that… regulate levels of groundwater production similar to the level the district regulates," with certain exceptions. A GCD could have rules that are not similar if it was specifically authorized to do so by its enabling legislation or if it provides an explanation of the district's reasoning to support its rule in its management plan. While SB 1010 passed the Senate, it was not voted out of the House Natural Resources Committee in the face of significant concerns.

Another bill, Representative Harris' **HB 2123**, sought to codify a petition process whereby a person with groundwater ownership and rights could petition a GCD to adopt a rule or modify a rule. HB 2123 included notice and hearing requirements that would need to be followed by the petitioner and the GCD and would have required the GCD to issue an explanation of its reasoning if it did not grant the petition. While it was voted favorably from the House Natural Resources Committee, this bill did not receive a vote on the floor of the House.

Retail public utility service area

Two bills both sought to modify Section 36.116(c) of the Texas Water Code. This section grants GCDs the permissive authority to consider the service needs or service area of a retail public utility when regulating groundwater production by tract size or acreage. While nearly identical in their captions, **HB 2122** and **HB 2249** sought to replace a GCD's discretion with opposing mandates. HB 2122 (Representative Harris), along with its companion **SB 800**, would have prohibited consideration of service needs or service area unless the retail public utility had obtained rights through purchase or lease to groundwater or otherwise obtained permission from the landowner. Conversely, HB 2249 (Representative Lucio III) would have required GCDs to consider the service area in granting permits to retail public utilities, subject to reductions for operating permits within the service area. While **SB 800** was favorably voted on in the Senate, none of these bills were voted out of the House Natural Resources Committee.

Attorney's fees

The subject of attorney's fees awards to GCDs was again at issue during the 86th Legislative Session. There were two bills filed that would have altered the provisions that award attorney's fees to a prevailing GCD when lawsuits are filed against a GCD. Representative Burns' **HB 2125** sought to modify the mandatory nature of the award of attorney's fees to prevailing GCDs and instead make that award of attorney's fees permissive.

Chairman Perry filed a more aggressive bill on the same subject, **SB 851**, which would have made the award of attorney's fees permissively available to the prevailing party in lawsuits. It went one step further and would have also removed the mandatory award of attorney's fees to GCDs in enforcement actions and allowed for recovery in those enforcement actions to the prevailing party.

There was no appetite in the House for any changes to the attorney's fees provisions of Chapter 36, however. While SB 851 was voted favorably by the Senate, neither bill went further than the House Natural Resources Committee.

Surface water and groundwater interaction

The interaction between groundwater and surface water has been and will likely continue to be the subject of conversations in the water community. Chairman Larson's **HB 4570** sought to create a nine-person advisory board charged with studying the extent of surface water and groundwater interaction, challenges arising therefrom, and potential approaches to mitigating those challenges and delivering a report prior to the 87th Legislative Session. While ultimately this bill suffered at the hands of the clock and did not come up for a vote in the House, one can reasonably expect to see this subject discussed in the interim and beyond.

De novo review

While not the subject of any interim discussion, Chairman Perry's **SB 2027** proposed to make a dramatic change to the standard of review applied by reviewing courts to GCD decisions. SB 2027 would have changed the deferential "substantial evidence" standard of review that is applied by reviewing courts to GCD—and essentially all administrative agency—decisions to a *de novo* standard of review. Amid significant concerns, Senator Perry did not call for a vote on SB 2027 in the Senate Water and Rural Affairs Committee. Instead, he promised to hold a hearing on this issue during the interim.

Omnibus

Chairman Larson filed **HB 726** with an omnibus caption to address a number of proposed changes to Chapter 36. HB 726 had four primary elements: (1) clarifying GCD considerations in granting or denying permits, including consideration of registered exempt wells; (2) clarifying that the rules in place at the time of a permit application govern consideration of the permit; (3) authorizing GCDs to issue 90-day moratoriums under certain circumstances only after a notice and hearing process has occurred; and (4) prohibiting a district from issuing a separate export permit from an operating permit.

A number of these proposed changes to Chapter 36 were re-files of bills that were met with the Governor's veto pen in the 85th Legislative Session. It would be unsurprising if one or more bills are filed again next session to make some, if not all, of these proposed changes.

Summary

TAGD's positions on the 20 statewide priority groundwater bills ultimately resulted in its support for nine bills, a neutral position on four bills, and opposition to seven bills. Broadly speaking, these numbers are representative of the GCD community's willingness to engage in productive dialogue and work toward solutions to identified concerns.

Looking ahead, one can anticipate more discussion both inside and outside the Texas Legislature on the topics of bills that did not pass into law during the 86th Legislative Session, particularly on the areas of surface water and groundwater interaction, GCD uniformity, attorney's fees, and judicial review.

List of TAGD-tracked bills passed into law

The following is a summary list of those bills of possible interest to GCDs that were tracked by the TAGD for its members and ultimately have been or will become effective. It is not intended to represent an exhaustive list and should not be relied upon as such.

HB 720

Relating to appropriations of water for use in aquifer storage and recovery projects. Effective 6-10-19.

HB 721

Relating to the duty of the TWDB to conduct studies of and prepare and submit reports on aquifer storage and recovery. Effective 6-14-19.

HB 722

Relating to the development of brackish groundwater. Effective 9- 1-19.

HB 723

Relating to a requirement that the TCEQ obtain or develop updated water availability models for certain river basins. Effective 9- 1-19.

HB 807

Relating to the state and regional water planning process. Effective 6-10-19.

HB 1052

Relating to the authority of the TWDB to use the State Participation Account of the Water Development Fund to provide financial assistance for the development of certain facilities. Effective 9- 1-19.

HB 1066

Relating to extensions of an expired permit for the transfer of groundwater from a groundwater conservation district. Effective 9- 1-19.

HB 1311

Relating to the continuation and functions of the Texas Board of Professional Geoscientists. Effective 9- 1-19.

HB 1495

Relating to authorization for the creation of a county ethics commission in certain counties. Effective 6-14-19.

HB 2018

Relating to required notice for municipal management districts that annex or exclude territory. Effective 9- 1-19.

HB 2729

Relating to the administration, duties, and operation of the Edwards Aquifer Authority. Effective 9- 1-19.

HB 2771

Relating to the authority of the TCEQ to issue permits for the discharge into water of this state of produced water, hydrostatic test water. Effective 9- 1-19.

HB 2840

Relating to the right of a member of the public to address the governing body of a political subdivision at an open meeting of the body. Effective 9- 1-19.

HB 3001

Relating to the fiscal transparency of special purpose districts and other political subdivisions. Effective 9-1-19.

HB 3339

Relating to requirements for programs of water conservation and water conservation plans. Effective 9-1-19.

HB 3656

Relating to the transfer of certain permitted irrigation water rights related to a certain portion of the Edwards Aquifer. Effective 9- 1-19.

HB 4172

Relating to the nonsubstantive revision of certain local laws concerning water and wastewater special districts, including conforming amendments. Effective 4-1-21.

HB 4705

Relating to the territory of the Sutton County Groundwater Conservation District. Effective 9-1-19.

SB 2

Relating to ad valorem taxation. Effective 1-1-2020 (certain sections with separate effective dates).

SB 27

Relating to recovery of damages, attorney's fees, and costs related to frivolous claims and regulatory actions by state agencies. Effective 9-1-19.

SB 65

Relating to state contracting and procurement. Effective 9-1-19.

SB 239

Relating to the requirements for meetings of certain special districts. Effective 9-1-19.

SB 241

Relating to certain required reports received or prepared by state agencies and other governmental entities. Effective 9-1-19.

SB 483

Relating to permits for certain injection wells that transect a portion of the Edwards Aquifer. Effective 6-10-19.

SB 520

Relating to the storage and recovery of water in a portion of the Edwards Aquifer. Effective 9-1-19.

SB 669

Relating to the date for the confirmation election for the Southwestern Travis County Groundwater Conservation District. Effective 5-20-19.

SB 872

Relating to the composition of the board of directors of the Gateway Groundwater Conservation District. Effective 5-7-19.

SB 911

Relating to the supervision of water districts by the TCEQ. Effective 9-1-19.

SB 943

Relating to the disclosure of certain contracting information under the public information law. Effective 1-1-20.

SB 944

Relating to the public information law. Effective 9-1-19.

SB 1041

Relating to the deadline by which the TWDB is required to identify and designate brackish groundwater production zones for certain areas of the state. Effective 9-1-19.

SB 1574

Relating to the duties of the TWDB. Effective 9-1-19.

TEXAS RURAL WATER ASSOCIATION SUMMARY OF THE 86TH LEGISLATIVE SESSION

By Trent Hightower, Assistant General Counsel, Texas Rural Water Association

Water issues are always a hot topic at the capitol when the Texas Legislature convenes every other year, and the 86th Legislative Session was no exception. As a statewide trade association serving the interests of more than 750 rural water and wastewater utilities, the Texas Rural Water Association (TRWA) tracked more than 400 bills this session with the potential for affecting the quality and affordability of water for more than 3 million Texans. The TRWA's membership consists of nonprofit water supply corporations (WSCs), special utility districts (SUDs), various other types of districts, small cities, and investor-owned utilities, each with their own unique challenges and regulatory frameworks. While other organizations in this journal will be covering bills with broader impacts on water law and policy in Texas, the TRWA has identified the following bills as having the most impact on the rural water industry in Texas.

Water utility issues

Compensation to utilities after Certificate of Convenience and Necessity (CCN) decertification

As Texas continues to grow, conflicts have arisen between urbanizing areas and areas traditionally served by rural water systems. In response, the Legislature passed Senate Bill (SB) 573 in 2011, which effectively allows landowners to automatically decertify land from a utility's CCN area. Since that time, many water utilities have seen high-growth areas of their service area decertified, but due to the current language in the Texas Water Code, the Public Utility Commission of Texas (PUC) has not awarded these utilities any compensation for their stranded investment. After several legislative cycles of the TRWA working to amend this legislation, the issue was included as an interim charge by the House Natural Resources Committee. Through this process, stakeholders were able to agree that systems should be fairly compensated for investments made to support future growth in areas that are subsequently removed from their service area.

Compromise legislation, **SB 2272** by Senator Robert Nichols, was passed into law with the support of stakeholders on both sides of the issue. The bill removes the requirement in current law that systems only receive compensation for property that has been rendered "useless and valueless" by decertification, language that has long been a barrier to utilities receiving compensation. All stakeholders agreed that their intent was to ensure a fair compensation process after decertification, and they pledged to work cooperatively on a letter to that effect to assist the PUC in the forthcoming rulemaking process.

Groundwater permitting for water utilities

Groundwater conservation districts (GCDs) are responsible for managing production from aquifers within their geographic boundaries by requiring permits for the production. The law currently allows, but does not require, GCDs to take into account a utility's service area when deciding how much water the utility is authorized to produce. While many GCDs have rules taking a utility's service area into account, others base permit allocations on the acreage owned by the utility or the contiguous acreage owned by the utility at its well site. For utilities in this type of GCD, these ownership requirements can be burdensome, as systems typically do not own or need large tracts of land to serve their customers.

This session, two bills were filed with opposite approaches for groundwater permitting for water utilities. The first, supported by the TRWA, was **House Bill (HB) 2249** by Representative Eddie Lucio, III. This bill would have mandated that all GCDs consider a utility's service area, with an exclusion for land within that area that is served by another permitted well. The opposition bill, **SB 2026** by Senator Charles Perry and **HB 2122** by Representative Cody Harris, would have removed the provision in Chapter 36 of the Texas Water Code that currently allows GCDs to consider a utility's service area if they so choose. The House Natural Resources Committee heard HB 2249 and HB 2122 concurrently in March, but neither bill was voted out of the committee. Senator Perry's bill passed the Senate by a vote of 19-12, but did not receive a hearing in the House.

Rate increases for investor-owned utilities

Since jurisdiction over water rates was transferred to the PUC, both the agency and stakeholders have expressed concern that current law imposes burdensome requirements on small investor-owned utilities when seeking rate increases. The Legislature sought to alleviate those difficulties this session with **SB 700**, which restructures rate classes for investor-owned utilities. Currently, the Class B Utility designation is quite broad, encompassing utilities with 500 to 10,000 connections. The new law would raise the lower threshold for a Class B utility to 2,300 connections while maintaining that 10,000-connection upper threshold. Utilities with 500 to 2,300 connections will now be classified as Class C utilities, and the bill creates a new category of Class D utilities for those with fewer than 500 connections. The law goes on to require the PUC to implement rules that are less burdensome for each class of utilities compared to the next-higher category. The bill also amends current law by requiring the PUC to determine the duration of temporary rates when a nonfunctioning utility is acquired by another utility.

Nonfunctioning investor-owned utilities

HB 3542 requires investor-owned utilities with fewer than 10,000 connections to provide additional financial, managerial and technical reports to the PUC if they violate a Texas Commission on Environmental Quality (TCEQ) order relating to capacity, minimum pressure, and accurate water quality testing. The law also provides a model for placing a valuation on an investor-owned utility during the process of its acquisition by a Class A or Class B utility.

Increase in maximum penalty for violation of TCEQ rules

Under current law, the TCEQ may assess penalties against a person who causes, suffers, allows, or permits a violation of drinking water health standards in Chapter 341 of the Health and Safety Code in an amount ranging from $50 to $1,000 per violation. **SB 530** by Senator Brian Birdwell raises the upper limit for such penalties to a maximum of $5,000 per violation.

Public notification of defluoridation of water supply

HB 3552 by Representative J.D. Sheffield amends the Health and Safety Code to require public water systems who furnish fluoridated water to provide customers with at least 60 days written notice before permanently terminating the fluoridation of the water supply.

Effect of criminal background on operator licensing

SB 1217 by Senator Carol Alvarado removes a barrier many Texans have found to inhibit their ability to obtain a variety of professional licenses. Currently, the TCEQ requires applicants for a new or renewal water or wastewater operator's license to attest that they have no arrests, convictions, deferred adjudications, or dismissals for any charges above a Class C misdemeanor. Under the new law, licensing authorities such as the TCEQ can no longer consider arrests not leading to a conviction or placement on deferred adjudication in determining an applicant's fitness to receive a license.

Open government

Nonprofit WSCs and water districts of all types are subject to the Texas Open Meetings Act and the Texas Public Information Act. The Legislature was active in this area in the 2019 session, and the following new laws will change the way water utilities operate in Texas:

Meeting notice and minutes (districts)

SB 239 by Senator Jane Nelson requires all districts to include in their meeting notices justification for the meeting's location if it will be held at a location more than 10 miles outside the district's boundaries. It also requires all districts to include the following mandated language with their water bills as part of their normal billing process: "For more information about the district, including information about the district's board and board meetings, please go to the Comptroller's Special Purpose District Public Information Database (or district's Internet website if the district maintains an Internet website)." The statement may be altered to provide the current website address of either the Comptroller's database or that of the district.

The new law also requires water control improvement districts, fresh water supply districts, municipal utility districts, and water improvement districts with a population of more than 500 people to post their meeting minutes on their website if the district maintains a website. The law also allows any district resident to request a recording be made of any hearing to consider the adoption of an ad valorem tax rate. The request must be made at least three days before the hearing, and the recording must be made available within five days after the hearing. Further, the district must maintain the recording for a period of one year after the hearing.

Meetings notice and response to Public Information Act requests during emergency

SB 494 by Senator Joan Huffman, which applies to all entities subject to the Open Meetings and Public Information Acts, reduces the notice requirement for an emergency meeting from the current two hours to one hour. It also provides examples of "reasonably unforeseeable situations" that would authorize an emergency meeting, bringing clarity to a term that is currently undefined in statute. Under the new law, "reasonably unforeseeable situations" include:

- fire, flood, earthquake, hurricane, tornado or wind, rain or snowstorm;
- power failure, transportation failure or interruption of communication facilities;
- epidemic; or
- riot, civil disturbance, enemy attack or other actual or threatened act of lawlessness or violence.

The new law also allows the attorney general to bring a mandamus or injunction action to stop, prevent or reverse a violation or threatened violation of the Open Meetings Act's emergency provisions.

Finally, the bill temporarily suspends requirements under the Public Information Act for requests during a period of "catastrophe," which is defined the same as "reasonably unforeseeable situation" above. When utilizing this provision, governmental entities must provide notice to the attorney general and the public that it is currently being impacted by a catastrophe and has elected to suspend the applicability of the Public Information Act. The initial suspension period may not be longer than seven consecutive days but may be extended one time for no more than seven more days if the governing body determines that the organization is still impacted by the same catastrophe. Public Information Act requests received during the suspension period are deemed to have been received on the first day the suspension is lifted, and they must be timely addressed at that time in the usual manner.

Disclosure of contracting or bidding information

The Public Information Act generally requires governmental bodies to disclose information to the public upon request, unless that information is excepted from disclosure. **SB 943** by Senator Kirk Watson creates such an exception for information that, if released, would give an advantage to a competitor or bidder. The law also imposes recordkeeping and disclosure requirements on nongovernmental entities that contract with governmental entities and forbids governmental entities from accepting a bid for a contract with entities that have failed to comply with those requirements in past bids. The governmental body may also terminate a contract if it becomes aware of such failures by a nongovernmental entity after it has contracted with the entity.

Information maintained by a temporary custodian

SB 944 by Senator Kirk Watson provides a process for a governmental body to retrieve public information held by a temporary custodian, which is defined as an officer or employee of a governmental body who, in the transaction of official business, creates or receives public information that they have not turned over to the organization's public information officer. Notably, the term specifically includes a former officer or employee of the organization who made or received information during their affiliation with the organization. The law imposes a duty on temporary custodians to preserve information and turn it over on request and makes clear that the individual has no private ownership interest in the information, even if it is maintained on their personally owned device.

Public Participation at Open Meetings

Prior to this session, the board of an entity subject to the Open Meetings Act was not required to allow the public to speak at an open meeting but had the discretion to allow public comment if they elected to do so. **HB 2840** by Representative Terry Canales amends the law by requiring all organizations subject to the Act to allow members of the public to speak on any properly noticed agenda item at their meetings. The law requires this comment period to occur before or during the board's consideration of the item, and it allows the board to adopt reasonable rules regarding the public's right to comment, including rules that limit the total amount of time that a member may speak.

"Walking quorums" under the Texas Open Meetings Act

In February, the Texas Court of Criminal Appeals struck down the provision of the Open Meetings Act that provides for criminal penalties for public officials who conspire to circumvent the Act. The court held that the statute was unconstitutionally vague as written, because it was unclear as to the specific conduct that would subject an individual to prosecution. The Legislature responded by passing **SB 1640** by Senator Kirk Watson, which more clearly describes the concept of a "walking quorum" as the prohibited action. Under the revised statute, a quorum of board members may not engage in a series of communications in numbers that are less than a quorum to discuss matters within the body's jurisdiction. Any member who engages in any such communication with knowledge that it is part of a series that would or could constitute a quorum is subject to criminal liability under the Act.

TEXAS WATER INFRASTRUCTURE NETWORK
THE 86TH REGULAR SESSION OF THE TEXAS LEGISLATURE

By Perry L. Fowler, Executive Director, Texas Water Infrastructure Network

Perhaps the most meaningful achievements of the session with respect to the water infrastructure market and the Texas economy reside in key bills providing for new planning and funding for flood control and disaster recovery. In the post-Harvey era, what was accomplished by the Legislature to address these issues will have profound impacts on our state taking a more comprehensive view and approach to policy, planning, and the provision of funding for billions of dollars in immediate and long-term infrastructure planning needs. The Texas Water Infrastructure Network (TXWIN) actively supported many if not all of these efforts.

Two key bills supported by the TXWIN, **House Bill (HB) 2585** by Chairman Jeff Leach (R- Plano) and **HB 2135** by Representative Hugh Shine (R-Temple), did make significant progress this session and succeeded in garnering significant support as they made their way through the House. Both bills represented significant changes to public works policy related to contracting and administration of retainage for public works construction. Both bills passed unanimously out of the House State Affairs Committee and were scheduled for consideration by the full House. HB 2585 specifically was voted out of the House (139-8) and received a hearing in the Senate Business and Commerce Committee.

The progress of both bills represented significant steps forward in raising awareness in industry and the owner community on key issues that impact the water infrastructure market in Texas. It is also noteworthy that both of these bills contain sound and fair practices that public owners should be encouraged to adopt in the interim as permitted under current law.

It should also be noted that approximately 80 bills impacting operations of individual utilities and water utilities also passed this session. Approximately 50 bills authorized new municipal utility or other special districts that will create additional infrastructure and water supply needs in Texas.

Key statistics to consider:

- Of the 7,324 House Bills and Senate Bills (SB) introduced, only 1,429 (19% including companions) passed.
- The Governor vetoed 56 bills before the June 16, 2019 deadline.
- 20% of House Bills passed. 25% of Senate Bills passed.
- 3,335 bills never received a hearing in the house of origin.
- 1,192 bills had hearings and did not pass out of committee.
- 725 House Bills referred to calendars were not scheduled for consideration for a vote on the House Calendar.
- 108 bills died as a result of deadlines on the House Calendar.
- 78 bills were scheduled on the Senate Intent Calendar and were not heard or died as a result of deadlines.

Selected notable and priority legislation that passed

Contracts and procurement

HB 985 (Parker/Hancock)

HB 985 relates to the effect of certain agreements with a collective bargaining organization on certain state-funded public work contracts. The bill prohibits project labor agreements on state-funded construction projects, including issuance of debt guaranteed by the state from entities such as the Texas Water Development Board (TWDB). TXWIN SUPPORTED.

HB 1542 (Martinez/Hinojosa)

HB 1542 relates to changes made by certain design-build contractors to the design-build team for transportation projects. The bill prohibits changes to design-build teams for transportation projects with certain exceptions reflecting industry best practices. TXWIN SUPPORTED.

The 86th by the numbers:

86th Regular Session - 2019										
Status	**HB**	**HCR**	**HJR**	**HR**	**SB**	**SCR**	**SJR**	**SR**	**Total HB & SB**	**Total**
Introduced	4765	186	147	2217	2559	68	70	865	7324	10877
Passed	969	102	7	2155	460	23	3	862	1429	4581
Vetoed	41	2	N/A	N/A	15	0	N/A	N/A	56	58

SB 124 (West/Sherman, Sr.)

SB 124 relates to the authority of a county to require electronic bids or proposals for competitive bidding. The bill allows counties to require electronic bidding. VETOED.

SB 943 (Watson/Capriglione)

SB 943 relates to the disclosure of certain contracting information under the public information law. SB 943 is an omnibus bill regarding provision of contracting information under public information law. The bill does not materially affect construction contracting information but adds protections for confidential and proprietary information. The bill also enhances document retention requirements for governmental entities and may result in need to sign affidavits declaring compliance with the law. TXWIN IMPACTED.

SB 1510 (Schwertner/Muñoz, Jr.)

SB 1510 relates to the apportionment of infrastructure costs in regard to certain property development projects. The bill amends appeals process for developer reimbursables for infrastructure.

SB 1512 (Flores/Martinez)

SB 1512 relates to payment of costs related to the relocation of certain political subdivision utility facilities for state highway projects. The bill clarifies financial responsibility and availability of funding for relocation of utilities in connection with state highway construction.

Disaster planning, response, and recovery

SB 6 (Kolkhorst/Morrison)

SB 6 relates to emergency and disaster management, response, and recovery. SB 6 is an omnibus disaster recovery bill. The bill provides for disaster response training for political subdivisions, development of a "disaster response guide" in concert with the Texas A&M Engineering Extension Service, development of a catastrophic debris management plan and model guide for use by political subdivisions including contracting and debris removal standards, and various study and work groups with reports due by November 2020. The bill creates a "disaster recovery loan account" and fund with various capitalization options. The bill also instructs a rulemaking. TXWIN SUPPORTED.

HB 5 (Phelan/Kolkhorst)

HB 5 relates to debris management and other disaster recovery efforts. The bill requires the Texas Division of Emergency Management (TDEM), in consultation with any other state agencies, to develop a catastrophic debris management plan and model guide for use by political subdivisions in the event of a disaster. The bill sets out the required components of the plan and requires the Texas A&M Engineering Extension Service to establish a training program for state agencies and political subdivisions on the use of trench burners in debris removal. The bill requires the TDEM, in consultation with the Federal Emergency Management Agency, to develop and publish a model contract for debris removal services to be used by political subdivisions following a disaster. The bill also requires the TDEM to consult with the Comptroller of Public Accounts to establish appropriate contracting standards and contractor requirements for the model contract and include a contract for debris removal services on the schedule of multiple award contracts or in another cooperative purchasing program administered by the Comptroller. The bill establishes that the wet debris study group is required to submit a report containing recommendations on those issues to each member of the Legislature not later than November 1, 2020. TXWIN SUPPORTED.

HB 6 (Morrison/Kolkhorst)

HB 6 relates to developing a disaster recovery task force to assist with long-term disaster recovery. The bill amends the Texas Government Code to require the TDEM to develop a disaster recovery task force to operate throughout the long-term recovery period following natural and man-made disasters by providing specialized assistance for communities and individuals to address financial issues, available federal assistance programs, and recovery and resiliency planning to speed local-level recovery efforts. The bill also authorizes the task force to include and use the resources of any appropriate state agencies, including institutions of higher education and organized volunteer groups. The bill requires the task force to develop procedures for preparing and issuing a report listing each project related to a disaster that qualifies for federal assistance and requires a report to be submitted to the appropriate federal agencies as soon as practicable after any disaster. The bill requires the task force to provide a quarterly briefing to members of the Legislature, legislative staff, and state agency personnel on the response and recovery efforts for previous disasters and on any preparation or planning for potential future hazards, threats, or disasters. TXWIN SUPPORTED.

HB 7 (Morrison/Huffman)

HB 7 relates to disaster preparation for state agencies and political subdivisions. The bill requires the Office of the Governor to compile a list of statutes and rules that may require suspension during a disaster. The bill also requires the TDEM to develop a plan to assist political subdivisions with executing contracts for services commonly needed after a disaster. The plan must include training on the benefits of these contracts, recommendations on what services are likely to be needed after a disaster, and assistance in finding capable persons to provide such services. The bill requires the TDEM to consult with the Comptroller of Public Accounts regarding contracts for debris management and infrastructure repair on the schedule of multiple award contracts developed under Subchapter I, Texas Government Code Chapter 2155. TXWIN SUPPORTED.

HB 2320 (Paul/Taylor)

HB 2320 relates to services provided during and following a disaster. The bill requires telecommunications providers to establish temporary facilities for provision of services after natural disasters. The bill also requires that utilities investigate ways to improve the hardening of utilities and facilities; improve oversight, accountability, and availability of individuals in the building trades offering services to disaster survivors; and increase utility customers' awareness of utility payment relief programs.

HB 2340 (Dominguez/Johnson)

HB 2340 relates to developing a disaster recovery task force to assist with long-term disaster recovery. The bill encourages federal-state partnerships to reduce red tape and streamline federal policies to be better prepared for future disasters and makes recommendations to improve federal laws and policies related to responding to a disaster, housing assistance, information sharing, and federal disaster assistance programs. The bill also creates an information sharing work group to develop recommendations for improving the way electronic information is stored and shared among state agencies to improve response to a disaster. The bill creates an unmanned aircraft study group to recommend changes to state law that would allow a more effective use of unmanned aircraft during response and recovery of a disaster. TXWIN SUPPORTED.

HB 2345 (Walle/Hinojosa)

HB 2345 relates to resources to facilitate disaster mitigation, response, and recovery. The bill establishes the Institute for a Disaster Resilient Texas at Texas A&M University. TXWIN SUPPORTED.

SB 300 (Miles/Thompson)

SB 300 relates to indefinite quantity contracts for the provision of certain services to declared disaster areas following a natural disaster. The bill requires the Texas General Land Office (GLO) to enter into indefinite quantity contracts with vendors to provide information management services, construction services, including engineering services, and other services the GLO determines may be necessary to construct, repair, or rebuild property or infrastructure in the event of a natural disaster. The bill requires compliance with Texas Government Code 2254. It does not exempt indefinite delivery, indefinite quantity contracts from requirements under Texas Government Code 2269. TXWIN IMPACTED.

Liability

HB 1999 (Leach/Creighton)

HB 1999 relates to certain construction liability claims concerning public buildings and public works. HB 1999 is a construction defect/statute of repose bill for public works projects. The bill exempts transportation, residential, and civil works projects as defined in Texas Government Code 2269.351. The bill requires an inspection of the affected improvement, and for a period during which the potentially liable parties may correct any alleged defects, before a suit may be filed. The bill does not prevent a public owner from filing a construction defect suit, nor does it prevent an owner from hiring someone else to fix the alleged defect. The bill requires that the original parties who had a hand in the design and construction of the building project be given the opportunity for an inspection and a chance to address the defect prior to the suit being filed. TXWIN SUPPORTED.

HB 2826 (Bonnen/Huffman)

HB 2826 relates to procurement of a contingent fee contract for legal services by a state agency or political subdivision. HB 2826 would require political subdivisions entering into contingency fee agreements for legal services to approve the contract in an open meeting that discusses the need for obtaining the service, the terms of the contract, the qualifications of the attorney or firm, and the reasons the contract is in the best interests of the residents of the political subdivision. The bill also subjects a political subdivision's written findings in approving the contract and the contract itself to public disclosure laws, and the bill requires that the contract be submitted to the Office of the Attorney General for approval. If the political subdivision fails to comply with the bill's public notice and hearing requirements, the Attorney General may refuse to approve the contract.

HB 2899 (Leach/Hinojosa)

HB 2899 relates to civil liability and responsibility for defects in the plans, specifications, or other documents for the construction or repair of roads, highways, and related improvements. The bill provides that a contractor is not civilly liable or responsible for design defects in a design prepared by certain government entities or their designers. This legislation does not apply to a private owner or any governmental entity not specifically listed in the proposed legislation. This legislation also does not eliminate a contractor's liability or responsibility for design defects in a design prepared by the contractor or a designer working for the contractor. This legislation is applicable only to public, governmental entities authorized to construct road or highway projects under the Texas Transportation Code.

SB 1928 (Fallon/Krause)

SB 1928 relates to a certificate of merit in certain actions against certain licensed or registered professionals. The bill amends current law relating to a certificate of merit in certain actions against architects and engineers.

Water

SB 7 (Creighton/Phelan)

SB 7 relates to flood control planning and the funding of flood planning, mitigation, and infrastructure projects. SB 7 is an omnibus flood planning and mitigation bill. The bill defines “food control planning contracts” and establishes a flood infrastructure fund to be administered by the TWDB. The bill defines applicable purposes and capitalization sources in the form of loans and grants with subsidized and deferred interest. It requires that political subdivisions have conducted appropriate planning and regional planning activities, meet technical requirements, and conduct public meetings. The bill establishes an advisory committee with reporting and rulemaking instruction authority. The bill also establishes the Texas Infrastructure Resiliency Fund (TIRF), which includes the Hurricane Harvey Account, to provide funds to the TDEM flood plain management account. The bill also contains Historically Underutilized Business (HUB) utilization reporting requirements and additional reporting and transparency requirements for funding recipients. The TWDB is required to adopt application, award, and prioritization standards and initial rule proposal within 90 days of effective date. The bill establishes a “flood plan implementation account.” House Joint Resolution (HJR) 4, the associated constitutional amendment, will capitalize with $1.7 billion from the “rainy day fund.” TXWIN SUPPORTED.

SB 8 (Perry/Larson)

SB 8 relates to state and regional flood planning. The bill establishes new state flood plan process. Key features include a 5-year planning cycle that addresses flooding preparation and response measures, a guide for state and local flood control policy, a required evaluation of flood control infrastructure, ranking of projects and strategies, an analysis of projects undertaken, a 100-year floodplain analysis, and development of legislative recommendations. The TWDB will coordinate and develop guidance principles with the Texas Commission on Environmental Quality (TCEQ), Texas Parks and Wildlife Department, GLO, TDEM, and the Texas State Soil and Water Conservation Board. TWDB will develop planning parameters, financial assistance to planning groups, and guidance for adopting and amending regional plans. The TWDB will designate representatives to regional groups. The bill contains public meeting requirements and elements that regional plans must contain. The bill also requires that interregional strategies are not in conflict and the TWDB must approve the final plan. The bill establishes a 10-year dam repair and maintenance plan with annual progress reports. The bill also establishes a “State Flood Plan Implementation Advisory Committee” with rulemaking instruction authority. The TWDB must adopt guidance principles for regional planning by September 2021, and regional groups must submit their first plan by January 2023. TXWIN SUPPORTED.

HB 720 (Larson/Perry)

HB 720 relates to appropriations of water for use in aquifer storage and recovery (ASR) projects. The bill allows unallocated state water to be used to recharged aquifers or in ASR projects including storm water and flood water. The bill includes special provisions for water in the border region subject to international law. Water rights may be amended with conditions surrounding ASR projects. The bill defines ASR projects in Chapter 27 of the Texas Water Code and grants jurisdictional authority to the TCEQ for permitting. TXWIN SUPPORTED.

HB 721 (Larson/Perry)

HB 721 relates to the duty of the TWDB to conduct studies of and prepare and submit reports on ASR. The bill directs TWDB to study the suitability of Texas’ major and minor aquifers for use in ASR and aquifer recharge projects. TXWIN SUPPORTED.

HB 722 (Larson/Perry)

HB 722 relates to the development of brackish groundwater. The bill amends the Texas Water Code to authorize a groundwater conservation district located over any part of a designated brackish groundwater production zone to adopt rules to govern the issuance of permits under the bill’s provisions for the completion and operation of a well for the withdrawal of brackish groundwater from a designated brackish groundwater production zone. The bill authorizes a person to obtain a permit under the rules for projects, including a municipal project designed to treat brackish groundwater to drinking water standards for the purpose of providing a public source of drinking water and an electric generation project to treat brackish groundwater to water quality standards sufficient for the project needs. The bill also prohibits a district from adopting rules limiting access to the production of groundwater within a designated brackish groundwater production zone to only such a municipal project or electric generation project. TXWIN SUPPORTED.

HB 807 (Larson/Buckingham)

HB 807 relates to the state and regional water planning process. The bill creates interregional councils to address issues between water planning regions to decrease conflicts and promote regional water planning approaches in the state water plan. The bill also adds ASR to water planning strategies.

HB 1052 (Larson/Perry)

HB 1052 relates to the authority of the TWDB to use the state participation account of the Texas Water Development Fund to provide financial assistance for the development of certain facilities. The bill adds ASR and desalination projects to those that may receive funding from the TWDB State Participation Program, which the state provides funding to in exchange for ownership and revenues until projects have been completed and the state has been reimbursed. The bill encourages private investment in conjunction with the State Participation Program and caps annual bond sales to $200 million. TXWIN SUPPORTED.

SB 2452 (Lucio/González)

SB 2452 relates to the provision by the TWDB of financial assistance for the development of certain projects in economically distressed areas. The bill amends the Texas Water Code to authorize the TWDB, with respect to provisions relating to assistance to economically distressed areas for water supply and sewer service projects, to maximize the effectiveness of certain authorized additional general obligation (GO) bonds by using the additional bonds in conjunction with other sources of financial assistance, including nonpublic funds, to provide financial assistance to political subdivisions for the construction, acquisition, or improvement of water supply and sewer services. The additional bonds can also be used to promote and support public-private partnerships that the TWDB determines are financially viable. The bill will diversify the methods of financing available for water supply and sewer services and will reduce reliance on the issuance of bonds supported with general revenue. The bill requires the TWDB to rank and prioritize projects and post project information on the Internet. There is an accompanying constitutional amendment on the ballot in November 2019 authorizing issuance of up to $200 million in GO bonds. TXWIN SUPPORTED.

HB 4690 (Thompson/Taylor)

HB 4690 relates to the territory, powers, and administration of the Gulf Coast Water Authority (GCWA). The bill expands the geographic territory and authority of the GCWA to develop projects. The bill contains exemptions to public bidding and procurement requirements if industrial facilities paid for with private funds require infrastructure on their premises to connect the GCWA infrastructure.

HB 1806 (King/Campbell)

HB 1806 relates to the use of water withdrawn from the Edwards Aquifer by certain entities. The bill expands the ability of Edwards Aquifer (via the San Antonio Water System) to sell at least 1,500 but not to exceed 5,000 acre-feet of wholesale water to Kendall County. VETOED.

HB 1964 (Ashby/Creighton)

HB 1964 relates to the procedure for action on certain applications for an amendment to a water right. The bill streamlines the water rights permitting process of the TCEQ by eliminating notice and the possibility of a hearing for a specific category of water rights applications that have no impact on the environment or other water rights.

HB 3542 (Phelan/Lucio)

HB 3542 relates to the provision of water and sewer services by certain retail public utilities. The bill changes the water utility valuation process by the Public Utility Commission (PUC) and establishes a process by which a Class A public utility providing retail water or sewer service could acquire a retail public utility, or the facilities of a utility, and recover investments made to acquire a water or wastewater system. This legislation may enhance the ability to regionalize water utilities through the acquisition of other utilities.

HB 3663 (Frank/Perry)

HB 3663 relates to the powers and duties of the North Central Texas Municipal Water Authority (NCTMA). The bill amends authority of the NCTMA to develop groundwater projects.

SB 520 (Campbell/Kuempel)

SB 520 relates to the storage and recovery of water in a portion of the Edwards Aquifer. The bill allows the City of New Braunfels to withdraw the measured amount of water actually injected or artificially recharged via ASR. The bill adds a set of conditions under which the Edwards Aquifer Authority may contract with a political subdivision for injection or artificial recharge of the aquifer for subsequent retrieval, if provision is made for protecting and maintaining the quality of groundwater.

HB 2846 (Larson/Huffman)

HB 2846 relates to the sale of the Allens Creek Reservoir project. The bill requires the City of Houston, notwithstanding any other provision of this article (relating to the creation of the Allens Creek Reservoir project), to enter into a contractual agreement with the Brazos River Authority (BRA) not later than January 1, 2020, to transfer to the BRA all of the city's ownership interests in the Allens Creek Reservoir project, including all required water right permits, along with the responsibility to construct the project in accordance with all associated statutory requirements and deadlines.

Safety

HB 864 (Anchia/Birdwell)

HB 864 relates to pipeline incident reporting requirements for gas pipeline operators. The bill details information operators must provide to the railroad commission after an incident. The required information includes the operator's name and telephone number, the location of the incident, the time of the incident, and any other significant facts relevant to the incident. Other details may include facts related to ignition, explosion, rerouting of traffic, evacuation of a building, and media interest. The bill also requires operators to notify the railroad commission of any incident within one hour of incident discovery and for the railroad commission to keep incident investigation records perpetually. The bill will require a rulemaking for implementation.

HB 865 (Anchia)

HB 865 relates to the replacement of certain gas pipelines with plastic pipelines. The bill requires natural gas operators to replace all cast iron pipelines by December 31, 2021. In addition, operators would be prohibited from installing new lines made from cast iron, wrought iron, or bare steel. The bill also requires pipeline operators to replace 8% of their highest risk pipelines every year.

Utility other

HB 2422 (Anderson/Perry)

HB 2422 relates to the coordination of certain broadband projects by the Texas PUC. The bill requires the Texas Department of Transportation (TxDOT) to provide notice of ongoing and planned highway construction projects for which the TxDOT will provide voluntary joint trenching opportunities in the state's right-of-way for broadband providers. A broadband provider may collaborate with the TxDOT to deploy broadband conduit or other broadband facilities in those rights-of-way and assist political subdivisions in taking advantage of voluntary joint trenching opportunities.

HB 4150 (Paddie/Hughes)

HB 4150 relates to safety and inspection reporting requirements for certain utilities. The bill requires an electric utility, municipally owned utility, or electric cooperative to meet the minimum clearance requirements specified in Rule 232 of the National Electrical Safety Code (NESC) Standard ANSI (c)(2) in the construction of any transmission or distribution line over certain lakes. The bill requires each electric utility, municipally owned utility, and electric cooperative that owns or operates overhead transmission or distribution assets to submit to the PUC a report that includes a summary description of hazard recognition training documents provided by the utility or electric cooperative to its employees related to overhead transmission and distribution facilities. The report must also include a summary description of training programs provided to employees by the utility or electric cooperative related to the NESC for the construction of electric transmission and distribution lines.

Constitutional amendments

The following joint resolutions will appear on the November 5, 2019 Ballot

House Joint Resolution (HJR) 4 (Phelan/Creighton)

HJR 4 proposes a constitutional amendment providing for the creation of the flood infrastructure fund to assist in the financing of drainage, flood mitigation, and flood control projects. The resolution works in conjunction with SB 7 and provides that the flood infrastructure fund is created as a special fund in the state treasury outside the general revenue fund. The resolution authorizes money in the flood infrastructure fund, as provided by general law, to be administered and used, without further appropriation, by the TWDB or that board's successor in function to provide financing for a drainage, flood mitigation, or flood control project, including: planning and design activities, work to obtain regulatory approval to provide nonstructural and structural flood mitigation and drainage, and construction of structural flood mitigation and drainage infrastructure. The resolution authorizes separate accounts to be established in the flood infrastructure fund as necessary to administer the fund or authorized projects. TXWIN SUPPORTED.

Senate Joint Resolution (SJR) 79 (Lucio/González)

SJR 79 proposes a constitutional amendment providing for the issuance of additional GO bonds by the TWDB to provide financial assistance. The resolution allows the TWDB to issue GO bonds to fund the Economically Distressed Area Program not to exceed $200 million at any time. TXWIN SUPPORTED.

Notable and priority legislation that did not pass

HB 2135 (Shine)

HB 2135 related to retainage requirements for certain public works construction projects. The bill passed unanimously out of committee and was scheduled for consideration by the Texas House. The bill was set on the last House HB Calendar and did not receive a vote before the midnight deadline. The intent of the bill was to ensure excessive retainage was not withheld on public works projects and to promote the fair and reasonable administration of retainage to promote project completion and conflict resolution. Key features of the bill included provisions which limited the amount of retainage that could be withheld, establishment of contract language describing circumstances under which partial retainage could be released, and "right to cure" language. A committee substitute for consideration on the floor was negotiated with the Texas Municipal League and water utility owners. TXWIN SUPPORTED.

HB 2585 (Leach/Zaffirini)

HB 2585 related to civil works projects and other construction projects of governmental entities. The bill passed unanimously out of committee and passed Texas House by vote of 139-8. The bill was referred and heard in Senate Business and Commerce Committee. The bill established guidelines for contractor prequalification for competitive bidding, created a debrief process for unsuccessful offerors, established minimum price weighing requirements for competitive sealed proposal procurements, and increased the time period to file for injunctive relief and bid protests. The bill was left pending in committee. TXWIN SUPPORTED.

HB 1752 (Clardy)

HB 1752 related to the construction manager-at-risk method of contracting for governmental construction projects. The HB and its Senate companion both passed out of committee. The HB was postponed with point of order on the final House HB Calendar and was killed by clock. The SB passed, was referred to a house committee and did not make final calendar. TXWIN SUPPORTED.

HB 2579 (Thompson)

HB 2579 related to the authority of the TxDOT to use the construction manager-at-risk project delivery method for state highway improvement projects. The bill was not scheduled for hearing in committee.

HB 2752 (Martinez)

HB 2752 was a job order contracting (JOC) bill removing limits on JOCs. The bill was heard in committee and left pending.

HB 2795 (Capriglione)

HB 2795 related to the use of JOC method by certain joint airport boards. The bill passed out of committee and was placed on the House local calendar. The bill was killed on local calendar.

HB 2882 (White)

HB 2882 related to recovery in a civil action of damages attributable to excavation activities. The bill would have allowed enhanced penalties for knowingly violating excavation safety law. The bill was referred from the House Judiciary Committee and died in the Calendars Committee.

HB 2901 (Leach)

HB 2901 related to civil liability and responsibility for the consequences of defects in the plans, specifications, or related documents for the construction or repair of an improvement to real property. The bill was referred from the House Judiciary Committee and died in the Calendars Committee. TXWIN SUPPORTED.

HB 3439 (Patterson)

HB 3439 related to the authority of a municipality or county to require a labor peace agreement as a condition of engaging in a commercial transaction with the municipality or county. The bill was dead by procedural action on the House floor. HB 3439 would have amended the Local Government Code to prohibit a municipality or county from adopting or enforcing a measure that requires a person to enter into an agreement with the person's employees or an entity that represents or seeks to represent those employees that limits or otherwise interferes with the person's rights under federal labor law or to waive or limit any of the person's rights under that law as a condition of being considered for or awarded a contract or otherwise engaging in a commercial transaction with the municipality or county. TXWIN SUPPORTED.

HB 3673 (Capriglione)

HB 3673 related to the application of the Underground Facility Damage Prevention and Safety Act to Class B underground facilities. It would have mandated water utilities (Class B underground facilities) participate in 811 "Call Before You Dig" system. The bill was heard in committee and left pending. TXWIN SUPPORTED.

HB 3674 (Capriglione)

HB 3674 related to an opportunity to cure a bid, proposal, or offer that does not include a required HUB subcontracting plan when HUB goals not met. The bill was heard and left pending in committee. TXWIN SUPPORTED.

HB 4288 (Morrison)

HB 4288 related to the use of a program manager for certain public works projects. The bill created a "Program Manager" procurement/project delivery method in Texas Government Code 2269. The bill was heard and left pending in committee.

HB 4432 (Perez)

HB 4432 related to a prohibition on certain contracts for construction projects by governmental entities. The bill was a broad expansion of JOC method for public works. The bill was referred to committee but not heard.

SB 621 (Nichols/Lambert)

SB 621 related to the transfer of the regulation of plumbing to the Texas Department of Licensing and Regulation, following recommendations of the Sunset Advisory Commission. The bill passed both chambers and died in conference committee. Governor Abbot issued an Executive Order extending the operation of the Plumber's Licensing Board.

SB 771 (Hughes)

SB 771 related to certain agreements by architects and engineers in or in connection with certain construction contracts. The bill limited designer liability for defects. The bill was referred to committee and was not heard.

SB 1137 (Watson)

SB 1137 related to the applicability of certain public works contracting requirements to a metropolitan rapid transit authority. The bill expanded the capability to utilize design-build for rapid transit projects. The bill was not heard.

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Transboundary Water Sharing: Risk Perceptions Held by Texas Border Decision Makers

Lindsay Sansom, Ph.D.[1]*

Abstract: Despite transboundary water resource management issues being a source of tension between neighboring states, little research has addressed what causes cooperation or conflict between differing governments along borders. For the most part, natural hydrological boundaries do not fall easily within political boundary delineations, so governance structures and management approaches are often very different once political jurisdictions are crossed, underscoring the importance of proper management of transboundary water resources. In order to better understand what drives cooperative or conflictual behavior among transboundary stakeholders, a cross-sectional study was conducted along the Texas-Mexico border. Questionnaires were collected (N=168) from Texas water managers along the southern border on issues related to their Mexican counterparts. The results revealed that a lack of trust for binational counterparts is correlated ($p<0.001$) with a decrease in willingness to cooperate; likewise, as trust decreased, perceptions of risk increased. This approach can help identify a plausible intervention strategy that could target activities that build trust between individuals on both sides of the border to mitigate individuals' perceptions of risk.

Keywords: Transboundary water sharing, risk perception, trust, cooperation, conflict, Texas, Mexico

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Terms used in paper

Acronyms	Descriptive name
CPR	Common pool resource
IBWC	International Boundary and Water Commission
NAFTA	North American Free Trade Agreement
USMCA	United States, Mexico, and Canada Agreement

INTRODUCTION

Water is necessary for sustaining life, growing economies, and maintaining healthy ecosystems. However, for the most part, natural hydrological boundaries do not fall easily within political boundary delineations, so governance structures and management approaches are often very different once political jurisdictions, especially international boundaries, are crossed. Mismatches in governance occur frequently with water management precisely because of water's flowing nature across political jurisdictions. Surface water and groundwater resources cross political boundaries all the time, creating immense challenges for peaceful and efficient management. There are 263 transboundary rivers and lake basins worldwide, comprising slightly less than half of the Earth's land surface, and approximately 608 transboundary aquifers (Wolf et al. 2007; Conti 2014; UN Water 2018). These global hydrological and political realities create complicated social, economic, and environmental challenges for countries, which can hinder bilateral or multilateral cooperation regarding shared transboundary water management.

The sheer number of competing water uses within and across municipal jurisdictions can make it difficult to manage water flows from one city to the next within Texas, particularly in places where water is managed by multiple institutions without coordination. Management of water that crosses international boundaries requires careful balance of issues related to national sovereignty, equity, and accountability. While there are challenges associated with sharing scarce resources across borders, there is also an opportunity for cooperation to generate shared benefits and increased regional security. Cooperation can lead to more safe and secure regions by ensuring that both sides of the border are accommodating each country's respective needs to generate growth and stability.

Transboundary water issues include problems associated with a lack of coordination, lack of appropriate institutional structures, and lack of international agreements or problems with monitoring, enforcement, and sectioning associated with those agreements. These issues have become more prevalent around the world for a variety of reasons, including water scarcity, population growth, climate change, environmental degradation, and mismanagement across borders resulting from complex governance systems. The challenges associated with modern transboundary water management can be summed up as follows: Water is a necessary element for human survival and economic growth; there is limited supply, which is exacerbated by increased demand; management decisions about use, allocation, and distribution are made by different institutions at different scales, which impacts availability.

This study fills important gaps within the broader literature by combining a variety of theoretical approaches to address the problems associated with understanding how decision makers within different institutional settings choose to engage in cooperative or conflictual behaviors over shared transboundary waters. While transboundary water sharing has a long history rooted in international relations literature, little is known about the driving factors for individual decision makers (nested within institutional settings) to engage in cooperation or conflict over international transboundary water issues. Substantial efforts have gone into conceptualizing key metrics of successful cooperation over internationally shared water resources; however, most do not have a strong empirical approach or rigorous empirically grounded theoretical underpinnings, and most only focus on how institutions can encourage cooperation or conflict, ignoring the role of individuals within institutions. Additionally, most of the literature is focused on surface water sharing. Drivers of cooperation or conflict over transboundary groundwater resources are poorly understood, partially due to the complicated nature of the hydrological system and partially due to the complex historical progression of laws governing water. International relations literature offers clear conceptual approaches to understanding issues of water security, power dynamics, and nation-to-nation cooperation and conflict (Rowland 2005; Zeitoun and Warner 2006; Zeitoun and Mirumachi 2008; Berardo and Gerlak 2012; Subramanian et al. 2012, 2014). However, it does not consider the role that individual decision makers play from within institutions responsible for executing international treaties and agreements. Common pool resource (CPR) theory is ideal for exploring the relationships between individual resource users in a given system; however, this approach has not often been applied to large-scale transboundary resources and does not consider the role of individual decision makers nested within larger institutional settings (Fleischman et al. 2014; Villamayor-Tomas et al. 2014; Garrick et al. 2018). Instead, CPR theory offers insight into resource-user decisions based on institutional constraints. Risk perception and trust literature has been traditionally applied to understand how stakeholders within a system use risk perceptions to respond to specific hazards or make specific decisions (Lopes 1994; Siegrist et al. 2000; Siegrist et al. 2005; Earle and Siegrist 2008; Earle et al. 2010; Subramanian et al. 2012, 2014). While this approach offers a model for understanding individual perceptions to physical hazards, it does not consider how those perceptions can be aggregated by institutional setting nor how those perceptions may drive willingness to cooperate or engage in conflict over shared binational waters. This study bridges these issues by combining several theoretical concepts to understand how perceptions of risk and trust held by individuals within larger institutional settings can be aggregated to predict willingness to cooperate or engage in conflict over transboundary water resources in an international setting.

This article looks more in-depth at the complexities surrounding transboundary water sharing, with a particular focus on what variables drive decision makers to engage in cooperative or conflictual behaviors over transboundary water sharing across an international border. The study tests the following two hypotheses: 1) Trust will be positively correlated with willingness to cooperate, and 2) Risk perception and trust will be inversely correlated; as risk perception increases, trust decreases. Transboundary water management and sharing issues are timely all over the world, where surface water is becoming overallocated, polluted, or scarce. Due to this reality, many countries are turning to groundwater resources to make up for the lack of available surface water. While countries generally have treaties in place for surface water that crosses international boundaries, the same cannot be said for groundwater. In many ways, customary international groundwater law is still in a nascent state, and countries are struggling to identify the best ways to share this precious resource across international boundaries.

A case study on the Texas-Mexico border is provided to illuminate many of the potential directions for positive relationships, as well as many of the potential pitfalls. This region offers an ideal study location owing to the United States' and Mexico's long history of surface water-sharing treaties. Despite this long history of cooperation over surface water, there is still not a legal treaty mechanism in place for bilateral groundwater sharing. As in many places around the globe, stakeholders on both sides of the Texas-Mexico border are feeling the negative impacts of surface water scarcity; this is because by the time the Rio Grande reaches Texas, it is often overallocated, polluted, and/or suffering from severe drought conditions (Nava and Sandoval Solis 2014). In most places along this border, stakeholders are turning to groundwater sources to fill the demand gap. Globally, most countries, including the United States and Mexico, do not fully understand the complex transboundary nature of shared aquifers. Lacking knowledge, legal precedent, and/or experience, many countries are leery of the risks associated with formal cooperation. This study examines risk perceptions held by decision makers in Texas regarding transboundary surface water and groundwater cooperation with Mexico. This case serves as a pilot project to test the identified concepts and is intended to offer an approach for doing comparative analysis in binational or multinational settings. The outlined approach offers a promising new metric for understanding potential bottlenecks to transboundary cooperation along the U.S.-Mexico border and globally.

BACKGROUND

In Texas, we have a saying: "Whiskey is for drinking and water is for fighting over." Water availability ranges drastically from East Texas, where water is more plentiful, to arid West Texas. The Texas-Mexico border is made up by the Rio Grande, which stretches for nearly 2,000 miles from the tip of West Texas to the Gulf of Mexico in South Texas. While Mexico and the United States have a long history of promoting cooperation over surface water, arid conditions consistently threaten political-diplomatic relations and there is mounting evidence

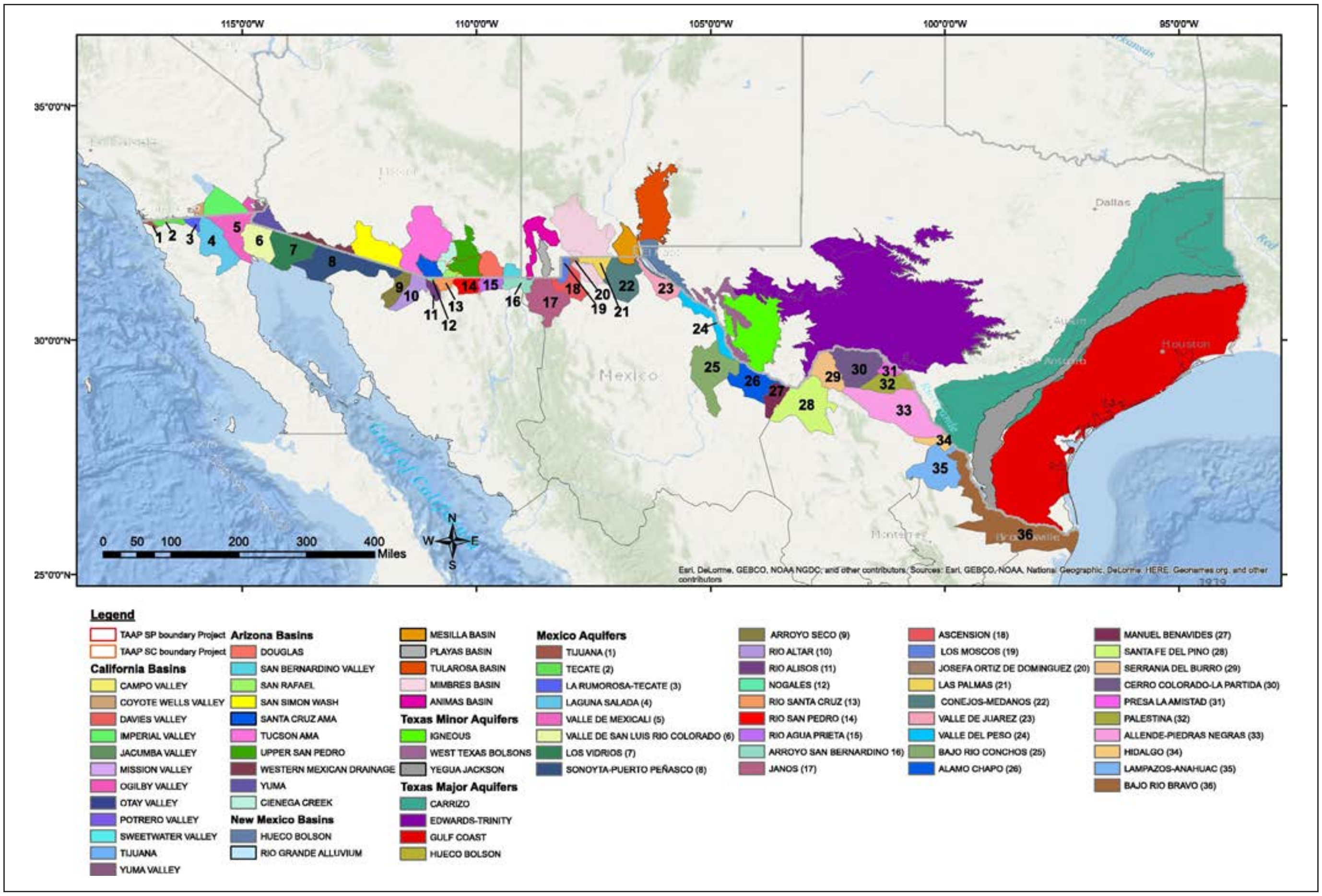

Figure 1. Rotential transboundary aquifers between the United States and Mexico (Sanchez et al. 2016).

of tensions bubbling beneath the surface, particularly considering the ever-increasing demand at state and local levels (Nava and Sandoval Solis 2014).

Current research asserts that cross border tensions over water represent serious challenges to water security and international diplomacy (Subramanian et al. 2012, 2014). The primary U.S.-Mexico institutional framework for dealing with transboundary water issues is the 1944 U.S.-Mexico Water Treaty for the Utilization of Waters of the Colorado and Tijuana Rivers and of the Rio Grande (hereafter, referred to as 'the Treaty'), which created the International Boundary and Water Commission (IBWC). Since that time, the IBWC has focused much attention on shared surface water, especially the water of the Rio Grande/Rio Bravo. However, in addition to the surface waters of the Rio Grande/Rio Bravo, there are considerable underground water resources, which are not fully covered under the Treaty (Figure 1).

Along the nearly 2,000-mile border sit approximately 36 potential transboundary aquifers, with only 11 officially recognized as transboundary and only four designated as priority aquifers for data sharing (Sanchez et al. 2016). Currently, there is no formal binational governance mechanism in place to manage these transboundary aquifers. Additionally, a number of other geopolitical challenges complicate water-sharing relations. From current trade disagreements to tensions over new U.S. immigration reform, there are several social, economic, and political obstacles that are considered higher political priorities and can complicate U.S.-Mexico relations over transboundary water-sharing arrangements. The following section will provide some insight into current U.S. affairs on the U.S.-Mexico border in order to provide context and political background information, which could confound or alter perceptions of risk and trust for this Texas-Mexico case study.

Social, economic, and political settings

There are numerous diplomatic constraints along the border that serve as a barrier to further development of transboundary water management. The U.S.-Mexico relationship over issues surrounding trade, immigration, and complications from the drug war has changed dramatically over the last two decades and has influenced perceptions of risk.

There has been a long-standing power asymmetry between the United States and Mexico, where the United States is a hegemonic leader. This asymmetry is largely a result of how historical treaties have been negotiated between the two countries. Despite the asymmetry of power between the two countries, there was a maturing relationship spurred along in the mid-1990s with the North American Free Trade Agreement (NAFTA), which was designed to allow for easier economic exchange between the United States, Mexico, and Canada (Villareal and Fergusson 2017). In the summer of 2017, President Donald Trump's Administration announced that it would be renegotiating NAFTA. In the fall of 2018, an agreement was reached. The new agreement is known as the United States-Mexico-Canada Agreement, (USMCA). It is still unclear whether environmental agreements negotiated under NAFTA will apply under this new agreement, and it will take time for policy-makers and researchers to sort through the new language. This level of uncertainty influences perceptions regarding the efficacy of environmental cooperation with Mexico.

Reforming the U.S. immigration policy, deporting undocumented immigrants, and taking more active measures along the Mexico border has been a central thrust of the Trump Administration (Rogers 2018). A series of executive orders on immigration were signed by President Trump focusing on drastically expanding the border wall and increasing law enforcement along the border. Recent changes in rhetoric and policies has led to a serious degradation in relationships between the United States and Mexico. Despite claims by the Trump Administration, more Mexicans having been leaving the United States than arriving, and border apprehensions are at a 40-year low (Seelke 2019). However, there has been significant negative press over Trump's policy to separate families at the border. Tensions over immigration policy reform have been very high on both sides of the border, which impacts how decision makers in the United States and Texas perceive their binational counterparts.

The U.S.-Mexico border has been a focal point of the war on drugs since Richard Nixon's presidency five decades ago. The border drug war has undergone several reorganizations and strategies over this time, but little progress has been shown. Well-organized, funded, and armed illegal drug cartels have formed and operated, moving an estimated $19 to $29 billion in drug revenue annually into the United States (U.S. Department of Homeland Security 2010). In 2007, U.S. President George W. Bush and Mexican President Felipe Calderón enacted a cooperative initiative, called the Merida Initiative, in order to share in the responsibilities and solutions in curbing narcotics trafficking. The U.S. Congress pledged up to $1.4 billion in appropriations (U.S. Department of State 2008). The success of this initiative has been limited; the most violent year on record related to drug cartels occurred in 2017, and the Trump Administration is likely to rethink several key provisions of this partnership in the years to come (LaFranchi 2017).

All of these social, political, and economic issues are at the forefront of the media discussion. As controversy stirs over immigration reform and trade, water management has taken a political back seat. However, massive media coverage of these issues often has a polarizing impact and has the potential to influence previously held perspectives on risk and trust. Within the broader context of these major issues, water managers on both sides of the border must still come together to address the challenges of transboundary water management.

METHODS

Site location

The Texas-Mexico border was chosen as an appropriate case study to pilot this novel approach to exploring the potential drivers of cooperation and conflict, which are vital for understanding what leads to improved water security outcomes. This socio-ecological system is complicated politically, socially, economically, and environmentally. Clear delineations of the surface water system, the Rio Grande/Rio Bravo, are present, and a polycentric governance system is in place for this resource. However, there are still issues of overdraft, pollution, and poor collective management owing to a lack of consistent monitoring, effective sanctioning, and enforcement of the rules in place (Milman and Scott 2010; Nava and Sandoval Solis 2014). Additionally, management along this massive system is very disjointed, leaving gaps in management as well as overlaps in jurisdiction (Eckstein 2012; Nava and Sandoval Solis 2014). Transboundary groundwater offers a larger challenge still due to the vastly different approaches to groundwater management on both sides of the border. Not only are boundaries not clearly delineated, but in some cases the aquifers are still poorly understood, or lack data, or the approach to data collection is completely different on both sides of the border, making data-sharing efforts even more challenging (Sanchez and Eckstein 2017). Additionally, there are no transboundary groundwater-sharing agreements in place on the Texas-Mexico border, and there is little to no political incentive to negotiate such an agreement. Thus, there are no clear boundaries, there are not adequate rules or procedures in place for management, and there is no monitoring, sanctioning, or enforcement. In short, transboundary aquifers along the Texas-Mexico border are an ideal example of a CPR that is vulnerable to the "tragedy of the commons" (Hardin 1968). Water managers and decision makers in the border region offer an ideal case to study how perceptions of risk and levels of trust influence willingness to cooperate or engage in conflict. By starting initially with decision makers in Texas, this new approach can be piloted to test potential correlations.

Study design

A cross-sectional study design was used to collect and analyze survey data from known transboundary water decision makers in Texas along the border with Mexico. Decision makers were defined based on governance tier and included participants from local, state, and federal levels of governance. Participants were selected from each Texas county that borders Mexico and included representatives from all agencies with relevant water management decision making capacity. The response rate for elite surveys is extremely important in establishing the external validity of the resulting data; this study was designed to follow a protocol expected to maximize the response rate (Dillman et al. 2009). The result is a quantitative analysis that combines elements of political science, international relations, social psychology, and sociology. The survey was designed to help explain when and why decision makers at various tiers of governance make the decision to cooperate or engage in conflict either formally or informally over surface water and groundwater resources. Data was collected regarding individual perceptions of risk and trust, individual levels of engagement in binational cooperative efforts, and individual attitudes toward cooperative or conflictual behavior. Data was aggregated into institutional settings and analyzed by looking at different tiers of governance to provide a deeper understanding of how individual behavior is aggregated at the institutional level.

Questionnaire development

The survey was developed in order to measure participants' perception of risks and levels of trust on decisions to engage in binational water cooperation and/or conflict. Cooperation and conflict were considered central dependent variables for measuring the independent variables of risk perception and trust. Within the measures of cooperation and conflict, several questions asked about risks associated with groundwater and surface water to capture possible differences in perceptions and trust regarding the two sources. The questionnaire also included general positional questions, such as experience cooperating with binational counterparts (stakeholder engagement), time worked in position, perceived reliance on groundwater, and perceived transboundary nature of border aquifers. Demographic information was collected on age, gender, race, educational background, and political affiliation. For the initial pilot study, surveys were only distributed on the Texas side of the border in order to determine proof of concept. For this approach to be fully applied, future studies should include both sides of the border to identify potential bottlenecks for cooperation and allow for comparative analysis.

The questionnaire was administered using mixed modes. The initial survey was mailed with a pre-paid return envelope. The mailed survey included, in the cover letter and at the top of the questionnaire, a web link to an online version of the questionnaire that had the exact same content as the paper questionnaire. This provided participants with the option of responding online or in print. For those respondents whose email addresses were known, follow-up notices were sent out two weeks after the paper questionnaire was sent.

Surveys were administered to all appropriate local, Texas state, and federal water decision makers with official responsibilities for water policy and management along the Texas-Mexico border. An initial list of 755 officials was compiled, consisting mainly of municipal, county, regional, statewide, and federal officials. Approximately 85% of the list of potential participants were local public officials and 15% were state or federal officials.

Descriptive statistics were calculated for each variable. Composite scores for trust, perceptions of risk, and willingness to cooperate were calculated by summing the total scores of the five ordinal questions related to each category. For instance, for trust, five different variables were created to measure different aspects of trust, and those variables were combined to create a composite score in order to capture one overarching metric for trust. This process was repeated for risk perception and willingness to cooperate. Creating a composite score for each set of metrics allowed for measuring the statistical relationships between categories. A scatterplot, r^2 value and corresponding p-values were reported to estimate the impact that levels of trust had on an individual's perceived risk or willingness to cooperate over shared transboundary issues.

RESULTS

A total of 755 decision makers were contacted on the Texas-Mexico border; owing to undeliverable mail, a net number of 707 recipients were ultimately contacted. The sample included a comprehensive list of decision makers in Texas that operate at the local, state, and federal level to make decisions about water management in the border region. Out of 707 net surveyed recipients, 168 responded either online or via mailed response for a total response rate of 23.8%. During the data collection phase, there was massive flooding on the border, particularly in cities of the Rio Grande Valley during June of 2018 (Alamdari 2018). This could have influenced the response rate for city officials and for utilities or other types of water managers, who are often the primary agencies to respond to these types of hazards. Another limitation to data collection was the limited availability of public data on emails for local and special district officials. This is in part due to the nature of these districts, which do not have much interaction with the public; thus, the need for transparency is lower.

Table 1. Sample characteristics.

Sample characteristics	N (%)
Gender	
Male	119 (77.8%)
Female	34 (22.2%)
Race	
Non-Hispanic White	72 (47.4%)
Hispanic or Latino	72 (47.4%)
Other	8 (5.3%)
Age in groups	
< 35	7 (4.6%)
36 – 54	54 (35.1%)
55 – 74	81 (52.6%)
75+	12 (7.8%)
Education	
At least some college	29 (18.9%)
Associates degree	8 (5.2%)
Bachelor's degree	57 (37.3%)
Graduate degree	43 (28.1%)
Terminal or professional degree	16 (10.5%)
Political ideology	
Very liberal	9 (5.9%)
Slightly liberal	15 (9.9%)
Moderate	45 (29.8%)
Slightly conservative	54 (35.8%)
Very conservative	28 (18.5%)

The sample was comprised of 77.8% men and 22.2% women (Table 1). This gender composition is not a surprise, as it is well known that men dominate the water management field, as well as elected positions in government, though this trend is starting to change. The sample population was 47.4% Non-Hispanic White, 47.4% Hispanic, and 5.3% "Other." As seen in Table 1, the sample population was also older and more well-educated, with 60.4% 55 years or older and over 75% having a bachelor's degree or higher. Within the sample, there were more conservatives than liberals, with 54.3% (N=82) conservative-leaning, 29.8% (N=45) moderates, and 15.8% (N=24) liberal-leaning.

Overall, respondents believed that benefits of cooperation outweighed potential costs. Most respondents were willing to cooperate and were less willing to accept conflict, even in the face of severe water shortages. The only deviations from this trend were found in one measure of conflict, which asked respondents if they were willing to withhold water from the Colorado River in protest to failed Mexican deliveries to the Rio Grande. In response to this question, most were willing to accept this type of conflict. It is suspected that this result is due to more recent negative experiences with inconsistent Mexican deliveries out of the Rio Conchos during times of severe drought. "Trust" revealed more mixed responses. Most respondents expressed that, in general, people were trustworthy; however, the majority did not think that Mexican water managers could be trusted to manage water efficiently. Respondents also believed that international rules for groundwater sharing were inadequate. Over 32% of the respondents reported that their communities relied heavily or somewhat heavily on groundwater resources. While respondents reported that they were willing to participate in binational stakeholder engagement efforts, very few actually had participated in these types of efforts.

The first hypothesis tested expected that trust would be positively correlated with willingness to cooperate. Figure 2 visualizes this relationship with a scatterplot and a fitted ordinary

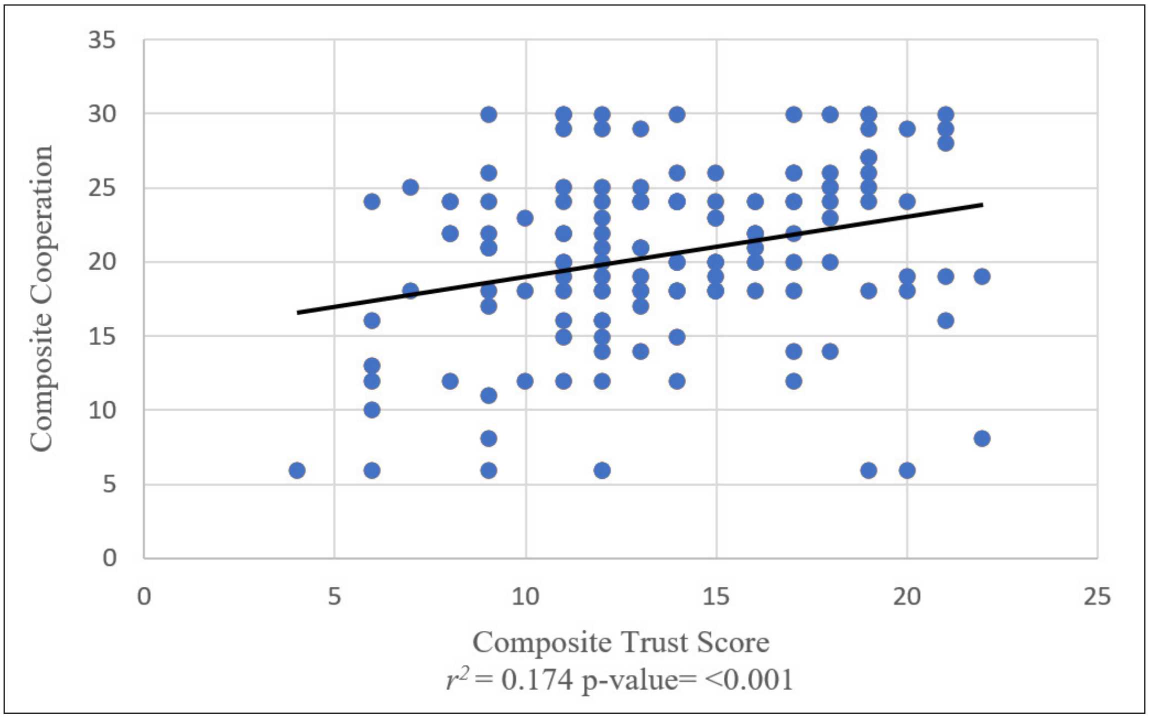

Figure 2. Composite cooperation score by composite trust score.

least squares regression trend line. While the regression model only accounted for 17.4% of the variance (r^2=0.174), it was highly significant (p-value=<0.001). This finding suggests that as trust rises, so does willingness to cooperate. Though this study was not designed to be able to measure a causal relationship, the correlation does provide evidence to support the hypothesis.

The second hypothesis predicted that risk perception and trust would be inversely correlated: as levels of trust increased, perceptions of risk would decrease. As seen in the scatterplot shown in Figure 3, there is an inverse correlation between the composite score of risk perceptions and the composite score of trust.

Figure 3 shows that as perceptions of risk increase, trust decreases, which supports the hypothesis. This relationship is highly statistically significant, with an r^2 value of 0.295 and a p-value of <0.001.

CONCLUSIONS

Managing water across borders is complex and fraught with political, social, economic, and environmental challenges. However, the challenges of cooperative management of transboundary water are increased by issues of state sovereignty, increased pressures from population growth and competing water uses, uncertainties from climate change, and difficulties associated with modelling complex hydrological realities. Managing water resources that cross an international boundary has often created multilateral relationships that are characterized by tension or tenuous cooperation, and these tensions are often exacerbated by power asymmetries. Transboundary water governance presents one of the most complex and challenging issues of coupled human-natural systems anywhere in the world, and it is valuable to study the characteristics that influence decision making in transboundary water-sharing settings.

Institutions are comprised of individuals, and the role of individuals within institutional settings have been understudied. The results of this study show that perceptions of risk and levels of trust held by individual decision makers nested within institutional settings can offer insight into how decisions are made regarding willingness to cooperate or engage in conflict over shared transboundary water resources. The case study between Texas and Mexico was an ideal political, institutional, and geographic setting for testing these concepts. Results showed a positive relationship between trust and willingness to cooperate; as trust increased, willingness to cooperate also increased. As predicted, there was an inverse correlation between risk perceptions and trust; as trust increased, risk perceptions decreased. These findings are useful for understanding what influences cooperative and conflictual behaviors over shared transboundary waters.

In the U.S.-Mexico region, an expanded study could be performed by adjusting the questionnaire to make it more appropriate for local settings on each side of the border. Comparative studies could then be performed to analyze different perceptions of risk and levels of trust to identify points of contention

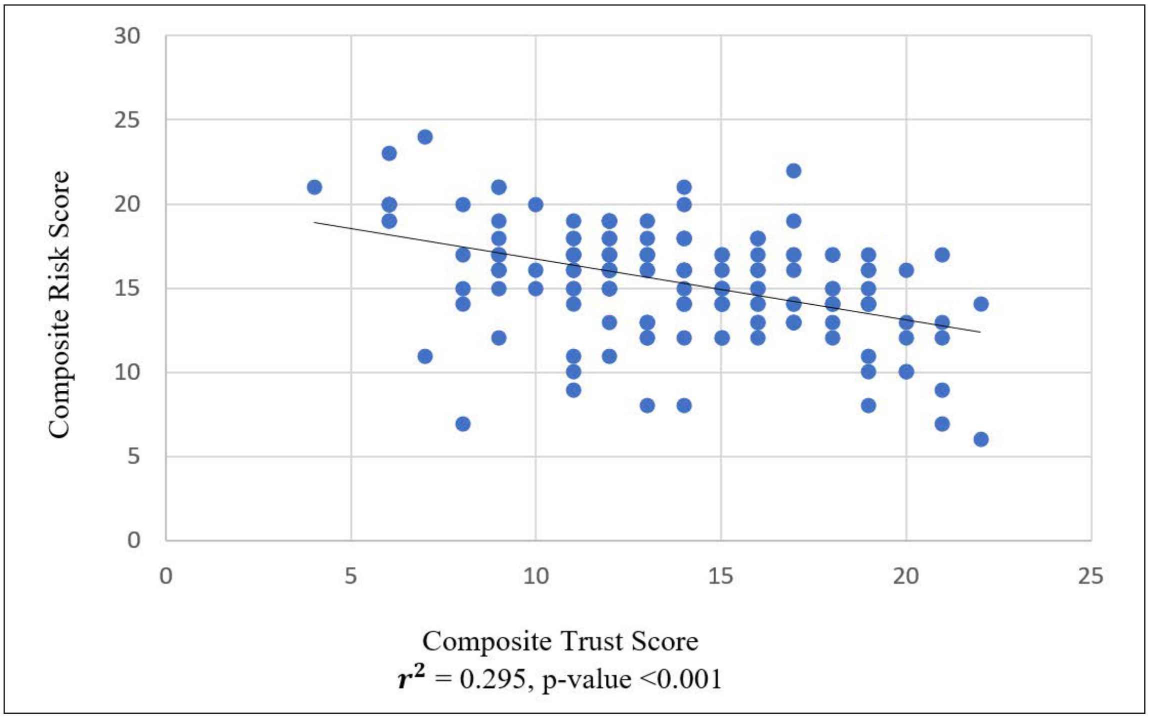

Figure 3. Scatter plot of risk perception composite score and trust composite score.

between binational counterparts within different states. This information would be very useful for designing appropriate intervention strategies to improve levels of trust and reduce perceptions of risk. One finding that is particularly relevant for designing interventions is that as respondents participated more frequently in binational stakeholder engagement efforts, levels of trust increased and perceptions of risk decreased. This indicates that individual decision makers operating within their respective institutional settings are influenced by experience, knowledge, and frequency of interaction with binational counterparts. Future interventions could be designed at the most appropriate governance levels to increase bilateral interactions.

Implications for future studies and other global questions

Not only can this approach be applied to the broader U.S.-Mexico border region, but it could be very useful for international transboundary water-sharing settings all over the world. The survey approach is designed to be flexible and take into consideration different socio-political contexts and governance structures. This approach is designed to enable comparative analysis regarding perceptions held in distinctly different social, economic, political, and environmental settings. Results from this study show promise for a new quantitative study design, which tests how perceptions of risk and levels of trust held by individual decision makers within institutional settings could influence willingness to cooperate over shared transboundary waters, in particular groundwater. Future studies could use this novel approach in more contentious international water-sharing settings to gain a deeper understanding of potential barriers to cooperation from distinctly different perspectives. The approach used within this study could provide additional insight into the institutional barriers by analyzing individual decision makers' perceptions of risk to cooperation and levels of trust in bilateral or multilateral counterparts. Additionally, this can reveal perceived challenges from power asymmetries and perceived problems with current international treaties, agreements, or other procedures for water management. This study also offers support for the idea that the degree of governing structures, rules in use, and procedures in place have the ability to impact or influence perceptions of risk and level of trust for cooperating over surface water versus groundwater. When combined with a strongly CPR approach, this quantitative measurement of decision maker perspectives has a potential to increase understanding on the role of trust and risk perceptions in making cooperative decisions over shared natural resources. Future studies could also use this approach to explore perceptions of water value, water-trade links across borders, and other issues that come up between counties that share valuable water resources. To conclude, the novel approach utilized by this study has great potential for identifying and addressing barriers to cooperation or barriers to overcoming conflictual relationships in many different international transboundary water-sharing settings.

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Interjecting Economics into the Surface Water Dialogue

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Abstract: This paper applies the conceptual lens of economic efficiency as a criterion by which to evaluate surface water in Texas. We identify two major problems. First, Texas has a water allocation problem limiting the ability to substitute groundwater for surface water to move water between river basins and to facilitate transfers within a river basin. Second, surface water is both underpriced and unresponsive to drought conditions preventing it from being used at its highest and best use. We propose a variety of partial solutions, which include facilitating greater reliance on water markets as well as a water tax that would vary across regions and over time to encourage conservation.

Keywords: surface water regulations, surface water allocation, surface water tax

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Terms used in paper

Acronym	Descriptive term
CFS	cubic feet per second
CIF	Community Involvement Fund
GDP	gross domestic product
GCD(s)	groundwater conservation districts
LCRA	Lower Colorado River Authority
MSB	marginal social benefit
MSC	marginal social cost
MWD	Metropolitan Water District
PVID	Palo Verde Valley Irrigation District
PDSI	Palmer Drought Severity Index
SWIFT	State Water Implementation Fund for Texas
TCEQ	Texas Commission on Environmental Quality
TWDB	Texas Water Development Board
WAM	Water Availability Model

INTRODUCTION

Paradoxically, while Texas is a leader in the science of modelling surface water flows (see Wurbs 2015), economic efficiency has taken a back seat to other criteria in the surface water policy dialogue. These other criteria can include protecting existing stakeholders, guaranteeing environmental flows to bays and estuaries, protecting water for local use, and so forth.[1] Each criteria yields separate, and often conflicting, policy recommendations around which various interest groups coalesce. The result is an emotion-charged political patchwork fashioned during severe droughts. In the past, ignoring economic criteria was relatively costless because Texas had an abundance of both surface water and groundwater. But with population growing from 11.2 million in 1970 to an estimated 29.1 million by 2019[2] and the state's gross domestic product (GDP) topping all but 10 countries,[3] we can no longer afford to exempt Texas' water resources from economic scrutiny. Griffin (2017) offered a critique of groundwater policy from an economics perspective. This sequel paper offers an economic critique of surface water regulation and is based on a 2017 Bush School Capstone report (Vaca et al. 2017) to State Comptroller Glenn Hegar.

By adopting the conceptual lens of "economic efficiency" as this paper's evaluation criterion, further justification is in order. Economic efficiency requires that for the last tranche of water consumed, the marginal social cost (MSC) of providing water just equals its marginal social benefits (MSB).[4] Note that the terms "social" costs and "social" benefits implies that we adopt a holistic approach looking at society as a whole in which environmental costs are factored in. Economic inefficiency can occur either with too little (MSC>MSC) or too much (MSB<MSC) water consumption. Particularly, when water is misallocated from high-valued uses to low-valued uses, the welfare loss (or efficiency loss) to society as a whole would be measured by the difference between the two. For example, if surface water is diverted from an industrial user willing to pay $1000/acre-foot to a cotton farmer only able to pay $100/acre-foot, then the welfare loss from this misallocation is $900/acre-foot. Note that this calculation is value neutral between

[1] Other examples include protecting: touristic areas, animals and wildlife, other economic activities.

[2] Texas State Demographer. https://uspopulation2019.com/population-of-texas-2019.html

[3] This ranking is obtained by comparing the GDP of countries from the World Bank Data (2018) and the Texas GDP from the Texas Comptroller 2018 website.

[4] See Gruber (2013).

the choice of producing cotton or producing industrial products. Normally in the absence of significant externalities in the form of environmental effects, the market value for water used in cotton versus industrial production will prescribe that the water should flow to its highest valued use.[5]

This papers proceeds as follows. First, it will go over the case for adopting economic efficiency as an evaluation criterion, which will set the basis to justify our later policy recommendations. Second, we will explain two main problem areas for economic efficiency in surface water that arise from current regulations and policies and propose alternative solutions to each of these problems.

THE CASE FOR ADOPTING ECONOMIC EFFICIENCY AS AN EVALUATION CRITERION

Opposition to adopting the economic efficiency criterion rests primarily on the notion that some group or groups will be negatively impacted. Economists have long recognized that the policies promoting economic efficiency will produce winners and losers. This is called the equity versus efficiency tradeoff.[6] Even though society as a whole is a net winner from efficiency-enhancing policies, some individuals and groups may be worse off. Particularly, if a policy severely impacted the poorest segments of society, policy makers should seek ways to compensate the disadvantaged group and if that was not possible, the efficiency-enhancing policy might be scrapped. Likewise, with water, emotional fears of running out of water, whether grounded in reality or imagination, can raise strong equity concerns. Thus, "equity" and economic efficiency can be in conflict. Even though the winners gain more than the losers lose, there may be no simple way to compensate the losers and equity trumps efficiency. For example, on efficiency grounds a universal poll tax avoids all the labor-leisure distortions resulting from the progressive income tax; yet, there is little support for such a tax because of its impact on the poor. At the other extreme, we have antitrust laws designed to curb the exercise of monopoly power. Clearly, in this case, the disadvantaged group from antitrust prosecution is the monopolist; yet the public shows little sympathy to the monopolist. Efficiency trumps equity.

In struggling to reconcile equity versus efficiency, economists look at the following three things:[7] (1) the magnitude of the efficiency gains; (2) the identity and magnitude of the loss to the disadvantaged group; and (3) the feasibility of compensating the losers.

First, are the efficiency gains potentially large? Going back to the cotton/industrial product example, is the difference in value between the two, $900/acre-foot or only $10/acre-foot? At a $900/acre-foot difference, the efficiency gains are potentially large, particularly if there are substantial quantities of water being relegated to low-valued uses.

Second, who would lose from the efficiency-enhancing policy and how much? Both the identity and the magnitude of the loss are relevant. Clearly, there are situations where the affected group deserves no consideration, such as a monopolist losing his monopoly profits due to antitrust prosecution. The case of the cotton farmer is more problematic. Is there a national security justification for subsidizing cotton production by providing cheap water? Are there other justifications such as cotton farmers representing a unique culture that is worth preserving? And if so, how much of a subsidy is justified to maintain this culture?

Third, when equity concerns are real and a severe impediment to economic efficiency, policy makers should look to find ways of compensating the losers so that everyone is a winner. As an example, in a Brady et al. (2016) analysis of groundwater, they proposed a mitigation fund for rural homeowners who might find their well dry.

Ultimately, the political process will answer these questions and choose a trade-off between equity versus efficiency, but that is not the focus here. By choosing to look only at the economic efficiency attributes in this paper, we avoid the subjective and value-laden calculus of determining when equity considerations trump efficiency.

There is an important word of warning regarding the excessive use of equity justifications to block efficiency-enhancing policies in cases where it is not feasible to compensate the losers. Excessive concern for equity can become a mantra for the status quo, which may lead to even worse problems in the future. In a vibrant market economy with continual technological advances, new products, and changing consumer tastes, some investors and some workers routinely find themselves the victims of these unforeseen events. Certainly, one would not want to stifle change in general, because when balanced over time, rising standards of living have made all of us better off. Unfortunately, in many instances the feasibility of compensating every individual for his/her bad fortune (and thereby making everyone winners) may be impractical.

A final attribute of using economic efficiency as a metric to evaluate policy options is that market prices can often provide valuable common sense signals. In a properly functioning market, prices send signals of relative abundance or extreme scarcity. In turn, consumers respond to high prices by reducing con-

[5] In the event there are significant environmental externalities that are not internalized in the costs of producing the cotton or the industrial products, the values for each would be adjusted accordingly.

[6] See Gruber (2013)

[7] See Pascual et al. (2010) and Martini (2007)

sumption while producers respond by increasing production. By examining water prices during periods of droughts and abundance, we can see if prices are sending the proper signals to conserve and increase supplies. The absence of the proper price signals forms a prima facie case for economic inefficiency. Because of the importance of markets sending the proper price signals, this report will frequently center on markets and the price signals being sent.

PROBLEM AREAS AND SOLUTIONS

Our study of surface water (Vaca et al. 2017) identified two basic sources of economic inefficiency. The first problem is that Texas has a water allocation problem with significant impediments to moving water from low-valued uses to high-valued uses. The second problem is that surface water in Texas is underpriced and inflexible in the face of droughts. The current pricing practices do not include a scarcity premium for raw water.[8] Gold commands a scarcity premium far in excess of the basic cost to mine and refine the ore. Yet, Texas surface water, a far more essential resource, commands no such scarcity premium. Especially during a drought, it is critical for prices to rise, encouraging conservation.

Problem area 1: Texas has a water allocation problem

The state has abundant water resources in certain locations where they are being relatively underutilized and relative scarcity in other areas. If low-cost mechanisms can be found to move water to the areas of greater need, Texas can delay having to implement high-cost alternatives like seawater desalination in the near term. It is useful to think of improving water allocation through three avenues: (1) greater conjunctive use of groundwater and surface water (2) reallocation of water resources within a river basin and (3) reallocation of surface water between river basins.

Problem 1.1: Limited transfers between groundwater and surface water

As there is a hydrological interconnection between surface water and groundwater,[9] there is also an economic relationship of substitutability between both of them. For instance, for many raw water uses, such as municipal, industrial, and agricultural uses, there is no major quality difference between surface water and groundwater. To the extent there are quality differences, inexpensive treatment costs may make the two equivalent.[10] Consequently, in the case that groundwater and surface water are equally available, the choice of which one to use should fall almost exclusively on costs.[11] However, from a policy perspective, the independent regulation of surface water and groundwater often overlooks this substitutability. Specifically, even though the State owns the surface water and landowners own the groundwater, there is no inherent reason that regulatory constraints should prevent their substitution particularly during droughts.

The fact that groundwater is generally available with greater certainty,[12] while surface water is intermittent and characterized by uncertainty, means that allowing emergency conjunctive use of groundwater and surface water can bring major efficiency gains for consumers and the environment. Let us consider the case of a very severe drought that affects many surface water streams and their users. Currently, there is no policy that incentivizes groundwater owners to react to droughts by increasing groundwater pumping to sources normally supplied by surface water. Usage-based groundwater conservation district (GCD) regulations effectively preclude an irrigator from selling his groundwater to a nearby municipality or power plant whose surface water is facing curtailment or depletion (Brady et al. 2016). Yet, during this hypothetical drought, the economic benefits of the conjunctive use would be very large: surface water users would benefit from water that would not be available otherwise, and groundwater users would be very highly compensated from selling their water. In addition, added groundwater would augment stream flows stressed by the drought helping to alleviate environmental effects (McKinney 2012).

Solution: Eliminate usage-based regulations by the GCDs and Texas Commission on Environmental Quality (TCEQ).

In order for these transfers to occur, the usage-based regulations by the GCDs and TCEQ should be eliminated for short-term transfers. If groundwater is going toward a beneficial use as specified by the Texas Water Code[13] and the transfer is specified for a short period of time as during a drought, there should be no further regulation on where a groundwater right holder can use their water.

[8] Some drought contingency plans do include a surcharge if a contract holder does not reduce usage when required under the plan. For example, the Gulf Coast Waster Authority's plan includes the surcharge. In effect, if a user does not reduce its use, the cost for water is higher.

[9] See Winter (1998), Sophocleous (2002).

[10] For an overview of different treatment options and costs, see Bhojwani et al. (2019).

[11] By this cost, we refer to a total cost of using surface water or groundwater including any treatment necessary to get a certain quality of water.

[12] The one exception is for the Edwards Aquifer, which is subject to mandatory cutbacks during droughts.

[13] Texas Water Code Chapter 11 defines "beneficial use" to include domestic and municipal, agricultural and industrial, mining, hydroelectric, navigation, recreation and pleasure, public parks and game preserves.

Problem 1.2: Restrictions on interbasin transfers

According to former TCEQ Commissioner and Texas Water Development Board (TWDB) Chairman Carlos Rubinstein, Texas will not be able to fix its water problems until we can successfully move water from "where it is, to where it is not" (Personal Communication in January 16, 2017 meeting). One way to do this is through interbasin transfers, moving water from abundant areas in East Texas to Central and West Texas. A major issue that arises when discussing interbasin transfers is the junior rights provision included in Senate Bill 1. When a transfer outside of the basin occurs, the junior rights provision changes the water right's original priority date and becomes the most junior prior appropriation. In the current prior appropriation system,[14] this provision is intended to protect the basin of origin. However, the junior provision can reduce economic efficiency by degrading the value of a water right and thereby reducing the incentive for interbasin transfers.

How does the junior rights provision affects economic efficiency?

The junior rights provision affects economic efficiency because the value of the water is greatly diminished when the priority date is changed. This reduction in the value of water rights minimizes the incentives to sell or buy water from other basins, even when there are economic gains from doing so.[15] For instance, buyers can be reluctant to invest in a costly pipeline that might only be used a fraction of the year or only during very wet years, when junior right holders can divert. It is important to note that when there is plenty of water in the basin of origin, the junior provision becomes irrelevant and would not prevent any transfer from happening. However, it is the combination of uncertainty about drought conditions and a loss of priority that reduce the incentives to buy water from another basin under the junior rights provision. A system created to pump water out of one river and transport it through a pipeline is very expensive. If the system can only be used when there is abundant water in the basin of origin, the system could sit idle for years. The cost per acre-foot of water for the project would become untenable. Consequently, the change in priority date favors the basin of origin regardless of the fact that the benefits of the transfer can outweigh its costs. Even though there is no explicit proof that the junior rights provision has prevented transfers from happening, Votteler et al. (2007) show that there is a reduction in the number of non-exempt interbasin transfers after the junior rights provision was passed in Senate Bill 1 in 1997. Before that year, a total of 28 interbasin transfers had occurred over the period 1980 to 1996. After Senate Bill 1, only three transfers have occurred in the period between 1997 and 2006.[16] Since 2006, we found only one interbasin transfer for water already owned by the City of Houston.[17] These data strongly support the conclusion that the junior rights provision has definitely reduced interbasin transfers.

Since supporters of the junior rights provision rest their support for it on equity grounds, it is important to ask the three questions outlined earlier regarding the case for economic efficiency:

1. *Are the efficiency benefits of interbasin transfers likely to be large?*

Let us consider an example of a basin where its municipal users are desperately in need of more water than the basin can supply. A study by Cai and McCarl (2007) develops an integrated economic-hydrological model to examine proposed interbasin transfers in Texas and find that they can alleviate water shortages issues, especially for large cities. As additional water would greatly benefit all these users, their willingness to pay for water will be very high. For the basin of origin, let us assume there are some irrigators holders that would be willing to sell their water at a price above its agricultural uses. For these sellers, they are fully compensated so that seemingly if the municipality is willing to pay a higher price than the irrigators' reservation price, economic efficiency dictates that the transfer occurs.

According to a report by R.W. Beck, Inc. for the TWDB in 2006 (R. W. Beck 2006), interbasin transfers in Texas can have significant net economic benefits and that "while the economic impacts are more than offset by the economic benefits which accrue to the Basin of Origin, all competing policy objectives must be considered in pursuing such transfers." So the answer to the first question is that the efficiency benefits of interbasin transfers are potentially quite large.

2. *Who are the affected parties in the basin of origin?*

Next, let us turn to the question of the identity and magnitude of the loss to the disadvantaged group. In the above example, the party selling their water rights are voluntarily selling their rights, so they cannot claim injury. Nevertheless, as Gould (1988) points out, third party effects on other downstream users in the area of origin can be substantial. Moreover, they are not normally compensated. For example, with the irrigator's water leaving the basin of origin, downstream users under the prior appropriation doctrine are deprived of runoff that returns to the basin of origin. At issue then is the magni-

[14] A system with no clear compensation mechanism established for the basin or origin.

[15] This argument is particularly applicable to run of the river rights. For transfers from reservoir storage, the impacts of the junior rights may be substantially diminished.

[16] Figure 1 of Votteler et al. (2007).

[17] The Luce Bayou Interbasin Transfer Project that is currently under construction transfers "existing surface water rights previously held by the City of Houston in the Trinity River to Lake Houston in the San Jacinto basin" (TWDB 2018). The amendments for this transfer were tied to permits and interbasin transfers granted before Senate Bill 1 so the Junior Provision did not apply in this case.

tude of the return flow and the economic consequence of its absence on third parties.

3. Can the losers be compensated and how?

While we support the elimination of the junior rights provision, we recognize the necessity for providing compensation for the area of origin. We propose that river basins and communities in Texas use an arbitrator to create their own context-specific mitigation funds. The first part of this mitigation process would consist of requiring monetary compensation for the basin of origin. For instance, some western states require compensation to be paid to the local governments within the basin of origin (Castleberry and Acevedo 2017). These payments can be done through mitigation funds. Mitigation funds can be established in different ways and can be set to compensate the losers affected by the transfer including economic and environmental costs. Hanak et al. (2011) explains that these funds should consider potential employment losses, increases in social service costs and reductions in tax revenues.

There are several examples of successful mitigation funds from surface water transfers in other states. For example, in an interbasin water contract in California between the Metropolitan Water District (MWD) and the Palo Verdo Valley Irrigation District's (PVID), the MWD (buyer) provides a Community Involvement Fund (CIF) to address community effects (Hanak et al. 2011). The CIF compensates the area of origin in the form of training programs for community members, support for small business, and cash per acre-foot of water diverted (WGA 2012). In Nevada, areas of origin simply impose a $10 fee/acre-foot on all water that is transferred out of the county (WGA 2012).

Another example of how a mitigation fund could work could be based on the compensation fund established after the Gulf Coast oil spill in 2010. In 2012, Congress passed the RESTORE Act that dedicated 80% of all penalties from responsible parties to a Gulf Coast Restoration Trust Fund (Restore the Gulf 2018). It is clearly outlined how the resources from the fund can be used to restore and protect the natural resources and the economy of the Gulf Coast. Similar mitigation funds can be created for interbasin transfers, where the percentages of the funds are clearly established to compensate the economic and environmental costs of the transfers.

Problem 1.3: Inadequate intrabasin transfers

Transfers of water within a river basin face several regulatory impediments as well. The primary impediment to transfers within a river basin is the complicated regulatory process imposed by the TCEQ in its effort to comply with legislative and legal constraints. The amendment process of a permit to change the use or diversion point requires the TCEQ to perform a technical review using the Water Availability Model (WAM) dataset to see how the amendment will affect water right holders in the basin. The objective of this process is to avoid any negative effect of amending a permit to other users. However, in the commitment to avoiding injury and respecting seniority, the bureaucratic process has become impractical and time consuming for potential buyers and sellers particularly in responding to droughts. According to the instructions of the TCEQ, an application is typically processed in 300 days.[18] This amendment process is particularly troublesome during a drought when permit holders not using their full allocation would like to lease (temporarily sell) their water to another party at a different diversion point.[19] As surface water becomes scarce and the demand for water expands, the inability to easily transfer water rights (either by short-term leases or outright sales of water rights) limits the market from allocating water to its highest value uses.

How to increase the number of intrabasin transfers?

In order to promote intrabasin transfers, we basically need to facilitate the transaction process. Vaca et al. (2017) propose three alternatives in which the transaction process can be simplified to increase the number of intrabasin transfers. In this paper we will briefly discuss the first two alternatives and will focus on a detailed explanation of the third alternative.[20] The first of these alternatives consists of changing and shortening some of the current procedures that are required to amend a water right.[21] As described in Vaca et al. (2017), this would involve using Web 2.0 technology to inform potentially impacted parties and to accelerate the process for impacted third parties to prove up their claim for damages. Particularly for short-term leases to deal with drought situations, this process could cut through the red tape. This can incentivize more buyers and sellers to participate in intrabasin transfers as they would know that they can get the water they need by the time they need it.

The second alternative outlined in Vaca et al. (2017) involved the implementation of watermasters in other basins. Currently,

[18] TCEQ (2017a) Instructions for Completing the Water Rights Permitting Application. Note that this very long period is in part created by the applicants themselves who occasionally file a permit as a placeholder and leave it pending as leverage in a water dispute or for other reasons.

[19] It is important to note that during drought emergencies, river authorities have been able to amend some of their rights temporarily as part of their Water Management Plan (see TCEQ Emergency Order for the LCRA in 2013). However, other users (i.e. not river authorities) that wish to sell their water would have to go through the normal amendment process. In addition to emergency amendments, Senate Bill 1430 approved in 2017 allows for "expedited amendments for existing water rights permits where the permit holder is off-setting freshwater use with desalinated seawater" (TCEQ 2018, SB 1430). Senate Bill 1430 intends to encourage seawater desalination.

[20] For a more detailed explanation of the other alternatives, see Vaca et al. (2017).

[21] House Bill 1964 attempts to shorten the process, but even slight changes in point of diversions require WAM analysis.

in addition to the highly successful Rio Grande Watermaster Program, there are an additional three[22] watermasters covering various segments of river systems in the state. Watermaster systems are probably not a panacea. While popular in some areas, in others there is opposition because it is costly to administer. In essence, the administrative costs may be overshadowing the efficiency gains that it generates, particularly in water abundant river systems. The third alternative is the implementation of a "Watermaster Lite System" designed to reduce the administration costs.

Watermaster Lite

The goal of the Watermaster Lite System is to ensure that water can be transferred quickly by bypassing some of the regulatory burdens set forth by the TCEQ permitting process but does so at a much lower cost than a full-blown Watermaster System. In proposing this alternative, we recognize that its implementation would require legislative action to modify the prior appropriation doctrine as well devising an entire new set of bureaucratic procedures. We also recognize that elaborating and proposing solutions to these issues could easily entail a lengthy study in itself. In the spirit of this paper, our focus is to describe how such a novel system might work and what the economic efficiency gains it might confer. Clearly, the Watermaster Lite System should be tried on an experimental basis to ensure it is effective before being implemented elsewhere. The economic efficiency gains of this system are intended to dramatically shorten the TCEQ processing time, increase market transactions, reduce transaction costs, and require less financial resources to administer than the traditional Watermaster System requires.

1. *How to implement the Watermaster Lite?*

The river will be divided into segments and each segment will have flow detectors installed to measure stream flow. Within each segment of the river basin, the basin's water right holders will then be divided and assigned a color based upon their seniority and their permitted acre-feet. By grouping rights by seniority into color categories, the process to make an intrabasin transfer will be simplified and at the same time, the prior appropriation doctrine will still be respected by group. In addition, in case of an extreme drought, right holders can still make a priority call within their color categories and thus the basic features of the prior appropriation system are maintained. The Watermaster Lite System will require the TCEQ to calculate all of the total water permits in the basin based off their acre-feet withdrawal limits. For example, in the Brazos River Basin there is a total of 7,932,481 acre-feet allocated to divert.[23] Thereafter, water right holders would be divided into five groups. The most senior quintile of the 1,983,120 acre-feet would be categorized into the color "black;" the second most senior quintile of the 1,983,120 acre-feet would be categorized in the color "red;" the third set of junior diverters will be categorized into "orange;" the next quintile would be "yellow;" and the most junior 1,983,120 acre-feet would be categorized into "green." Under this system, the whole river basin will be grouped by the acre footage and seniority of its diverters. Additionally, each river segment will be assigned a minimum flow rate corresponding to the different color categories.

This system aims to create a spot market based off short-term (less than a year) changes in diversions that will be automatically granted provided three conditions are met. (1) The first condition is the flow rate in their river segment and permit type is satisfied within a 10% margin of error. The flow rate will incorporate TCEQ's adopted environmental flow standards, which is the flow restriction TCEQ would apply to moves of diversion points under the current permitting system. (2) A second condition is that the change in diversion will incorporate stream flow losses (including evaporation effects). For example, if the original permit called for a diversion rate of 10 acre-feet daily and there was a 10% evaporation and transportation loss, the recipient would only be entitled to divert 9 acre-feet daily. (3) The permit would be subject to curtailment in the event of a senior right call.

This system is better stated with an example. Suppose we are dealing with a lower segment of the river basin where the stream flows are greater. Diverter A, from Figure 1, is the most senior water right holder in the basin and is allowed to divert 100 acre-feet annually. Thereby, Diverter A is assigned the color "Black," which means he/she can divert water even when the flows are less than 936 cubic feet per second (CFS). However, Diverter B is a more junior water right holder and assigned the color "Yellow," which indicates that when the flow rates are below 2000 CFS, he/she cannot divert water. In this scenario, Diverter B is no longer allowed to divert water; however Diverter B needs an additional 75 acre-feet for his/her crops. Meanwhile, Diverter A only needs 25 acre-feet. Since Diverter A has a senior water right and is not using all of his/her allocated share of water, under this system Diverter A could lease the remaining 75 acre-feet to Diverter B. Such transactions would be allowed to take place on a monthly basis. For example, for a 30-day transfer, the annual rate would be prorated to the daily equivalent of the permit's allocated amount.

The Watermaster Lite System is proposed as an experimental option. Its application would no doubt require addi-

[22] The other three watermasters are Brazos Watermaster Program, Concho River Watermaster Program, and South Texas Watermaster Program. (Nueces, San Antonio, and Guadalupe Rivers).

[23] The total number of permitted acre-feet is based on TCEQ (2017b). For the purpose of this exercise, we assume that all of the water rights are allocated for consumptive uses.

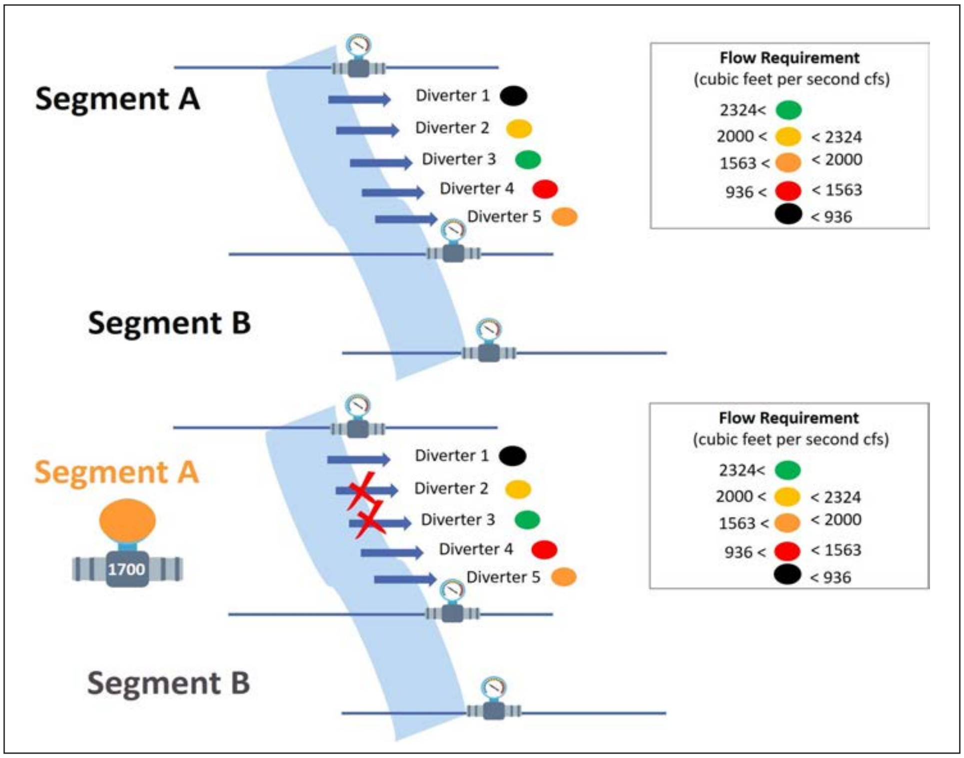

Figure 1. Example of Watermaster Lite System: segments and diverters by color.

tional adjustments and should first be refined for a particular river basin with abundant water.[24] The system would also need adjustments for periods of drought. To succeed during a drought, the Watermaster Lite System must be cheap to administer and have the flexibility to allow temporary changes in diversion points.

The attraction of the Watermaster Lite System is that it retains many of the features of a watermaster system, but would be potentially much cheaper to administer and would have desirable self-policing attributes. Also, permit holders are likely to view it as less intrusive[25] than a watermaster system.

Problem area 2: Water prices are artificially cheap and inflexible

A reoccurring theme within the literature and our surface water policy research (Vaca et al. 2017) revolves around the underpricing of water in Texas (Griffin 2011). The current price scheme of surface water is not economically efficient because it does not reflect how much water is available to use, i.e. it does not include a scarcity premium and thus water prices are artificially low. The main reason why there is no scarcity premium is related to the large amount of permitted water that river authorities sell to their customers at regulated rates based on historical costs. In many basins, river authorities typically control the bulk of diversion permits within a river basin.[26]

Currently, the regulated nature of surface water pricing by river authorities leads to the underpricing of water for two reasons. First, it omits altogether a scarcity premium to reflect the inherent scarcity of water. Second, as quasi-governmental entities, river authorities are constrained to charge rates[27] that only recover their costs. Consequently, the market prices observed in transactions between river authorities and their customers

[24] For example, the number of colors could vary depending on the volume of water rights in adjoining groups. The beauty of the system is that within a color group, all pumpers are treated equally, eliminating conflicts. Nevertheless, conflicts can exist if that pumper was assigned to a different group that would have gained access but was prevented by the original assignment of colors and stream flow limits.

[25] This system can be less intrusive than a watermaster because it would not require the site visits and users would not be required to call in their diversions and get permission to divert.

[26] A prominent exception is the Trinity River Basin where various municipalities already own significant appropriations.

[27] Raw water sold by river authorities or potable water provided by municipalities are based on an average of current and past infrastructure costs. This allows for water to remain underpriced. Neither do they include a scarcity premium. The presence of regulated rates for the transportation, treatment, and local delivery of water is a good thing by protecting consumers from the exercise of monopoly power by wholesale providers. Nevertheless, a byproduct of this regulatory scheme is that prices are too low and inflexible. [Another byproduct is that water is not being conserved because the incentives are lacking.]

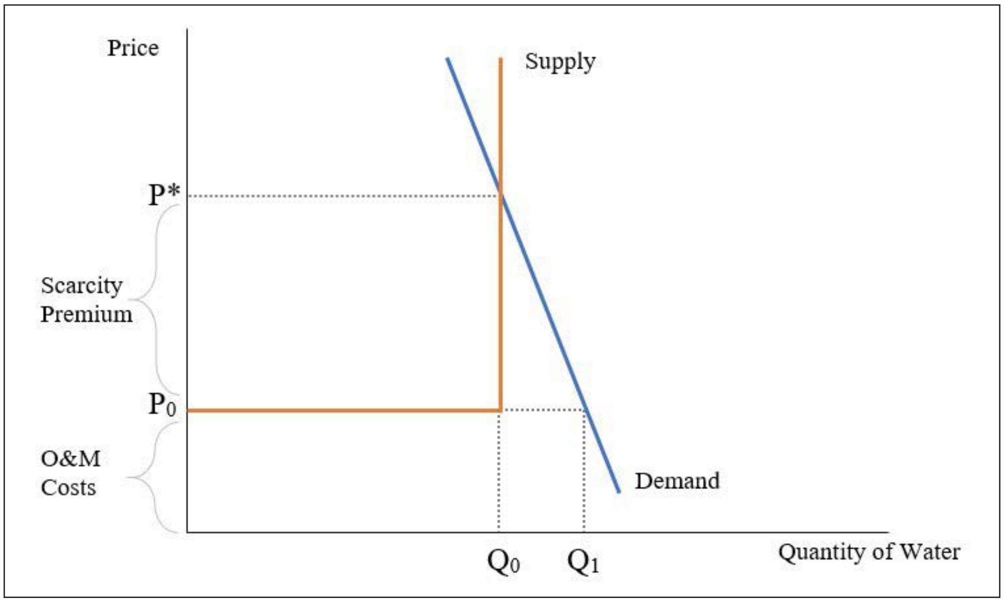

Figure 2. Regulated vs. economic efficient prices.

fail to account for true scarcity and often create a shortage of unmet demand at that regulated price. Figure 2 illustrates the problem. Assume in the example that the river authority has available only Q0 of water available, which it offers for sale to municipal users at the regulated price P0, which covers its operation and maintenance costs. Note that at this price there is unmet demand equal to Q1 – Q0. Typically, to deal with the shortage, the river authority will exercise curtailments across its customer base.

Economic efficiency would dictate that the water goes to its highest valued uses. If in Figure 2, the transaction price were allowed to rise to P*, only users who were willing to pay this price or higher would receive the water. The difference between the regulated price P0 and P* measures in this case the true scarcity premium of the water as shown on Figure 2. From an economic efficiency viewpoint, allowing the price P* to occur guarantees that only the higher valued uses—between 0 and Q0—get the water and the lower valued uses—between Q0 and Q1—are excluded. The alternative of curtailing all uses proportionally has no mechanism to filter out the lower valued uses.

The key takeaways are that if observed market prices do not include the scarcity premium, they understate the true value of water. The regulated prices coupled with rationing are neither efficient nor useful as guides for policy. Price signals from properly functioning markets should fluctuate in response to droughts and furthermore should trend upward in response to population growth and economic activity. Figure 3 shows an example of how prices do not vary according scarcity. This figure shows the regulated rate charged by the Lower Colorado River Authority (LCRA) to its municipal customers over the period 2010 to 2016. Figure 3 also shows the Palmer Drought Severity Index (PDSI) drought index showing the most severe drought in history in 2011. Note that LCRA's prices, which were based solely on operational and infrastructure costs,[28] showed no response to the drought. Paradoxically, when water was abundant in 2015-16, regulated rates actually increased.

In contrast, Figure 4 shows in theory how prices should behave in response to economic growth and droughts. Prices should increase sharply during droughts while maintaining a relative stable but gradual trend when there are no droughts. Population and economic growth should increase the demand of water over time, which means that prices should have an upward trend.

The second reason that surface water prices do not include a scarcity premium refers to limited opportunities to trade surface water rights. As explained in the water allocation section, there are regulatory barriers that can reduce the number of transfers of water. Not allowing these transactions during a drought and relying mostly on river authorities (with regulated rates) prevents water to be priced at its true scarcity price (P* in Figure 2).

In order to promote economically efficient pricing of surface water, policy makers have one of two options. The first option is to create the conditions that give rise to a vibrant water market by doing the three things outlined above: (1) encouraging conjunctive use of groundwater and surface water (2) promoting interbasin transfers, and (3) promoting intrabasin transfers.

[28] LCRA (2014) shows that its rates are calculated as the ratio of cost of services divided by the number of billing units. The costs of services include labor, operation and maintenance, and debt service. By regulation, river authorities such as LCRA are not allowed to charge rates that reflect water scarcity per se but only to recover their operational and infrastructure costs.

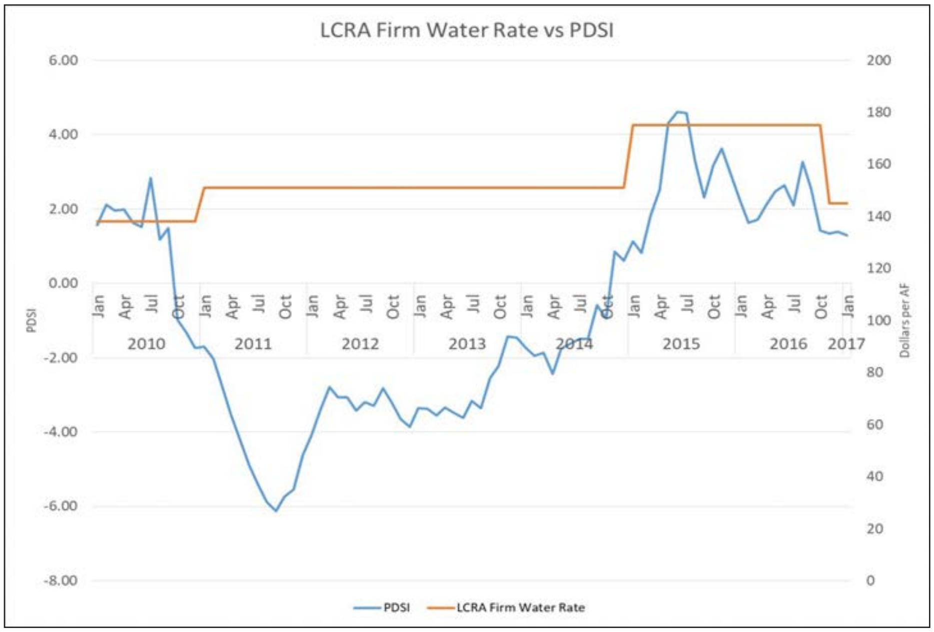

Figure 3. LCRA firm water rate vs. PDSI. Source: [LCRA 2015](), [LCRA 2017](), [Water Data for Texas 2017]().

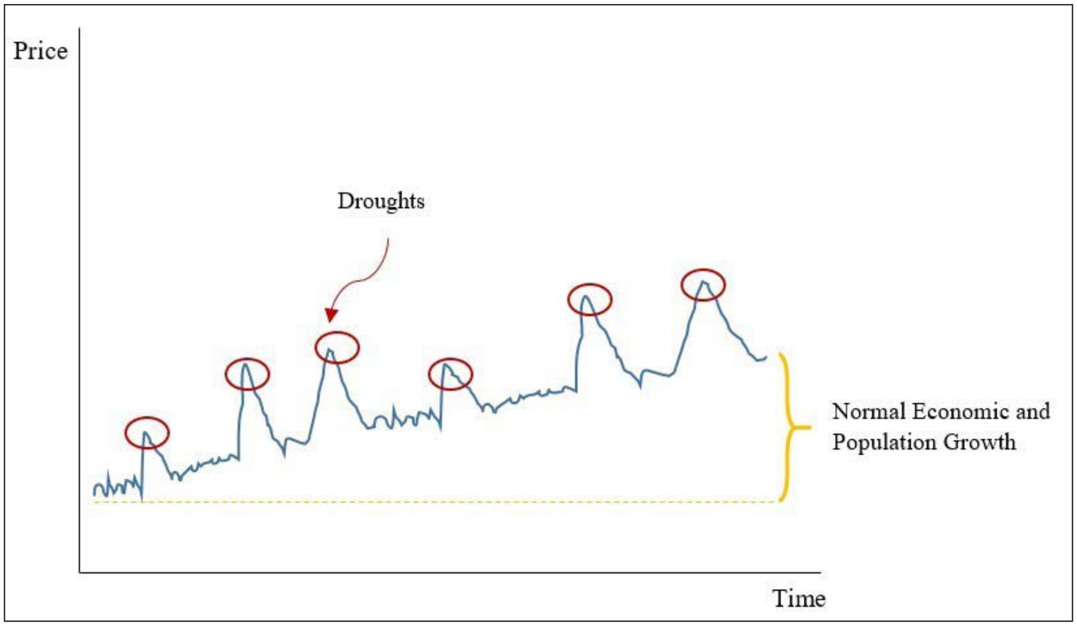

Figure 4. Hypothetical price fluctuations in a well-functioning market.

With the addition of these added sources of supply, market prices should more likely approximate Figure 4 instead of Figure 3.

There is, however, another option that, while less preferable to the authors, will nevertheless promote economically efficient pricing. Let us now turn to the option of a water tax.

Regional water taxes: that vary with water availability by region.

A water tax is designed to address the problem that water prices are artificially cheap and inflexible during droughts. First, the water tax can solve the lack of a scarcity premium because it would vary with water availability by region and can be altered by the State accordingly to address long-term water needs. Second, as the value of the tax will automatically vary

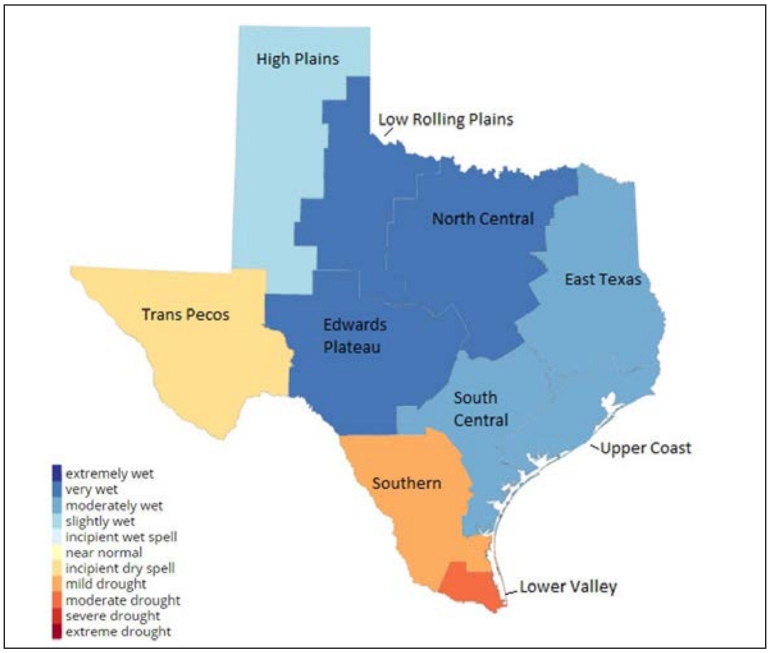

Figure 5. Texas regions for PDSI. Source: Water Data for Texas – PDSI October 2016.

with monthly water availability, it will increase water prices during droughts. Thus, a water tax will act as a water scarcity signal and create incentives to conserve.[29] In fact, Olmstead et al. (2009) suggest that using price mechanisms to allocate scarce water supply is more cost effective than implementing other programs for water conservation. It is important to emphasize that the water tax will not solve the water allocation problem because it will not directly incentivize water transactions nor will it remedy existing administrative problems. Its sole function is to promote conservation.

1. *How the tax would work*

a) The tax should vary with water availability

The most important characteristic of the tax is that it must vary with water availability, reflecting the true value of water in the short and long term. This means that the tax should increase when there is less water available like in the case of a drought.

Another feature is that the tax should vary regionally to reflect water availability. As shown in Figure 5, a regional drought indicator, the PDSI can be used as a measure of water availability to determine the value of the tax.[30] According to Water Data for Texas (2017), the PDSI index is "a meteorological drought index based on recent precipitation and temperature and is used to assess the severity of dry or wet spells of weather." The PDSI generally varies between -6 and +6, where negative values denote dry spells. In recent years, the lowest value that the PDSI has reached in Texas was in September 2011 in the Low Rolling Plains (-6.99).

The proposed tax contemplates one major exemption.[31] The proposed tax offers an 80% discount for agricultural users. Charging a lower tax for agricultural users can be justified by the fact that agricultural users usually face lower water rates (e.g. from interruptible contracts with river authorities), which would mean that even if they had the same price elasticity as that of other consumers, the price increase due to the tax will affect them disproportionally.

[29] Note that this proposal differs fundamentally from the increasing block tariff schedules implemented by many cities whereby high use residential users pay more per thousand gallons. The increasing block tariffs typically do not vary with overall water availability as our tax would and instead act as a mechanism to spread high fixed costs onto high residential users with swimming pools and large lots with sprinkler systems. The latter do not vary over time to incentivize conservation during droughts.

[30] Although the PDSI may not be the hydrologically perfect measure of water supply considering the water in reservoirs, the PDSI does track in advance the changes in water availability in reservoirs. For example see Figure A1 in appendix 1. As an alternative to the PDSI based on nine regions, one could consider computing a PDSI type index for the sixteen state water planning jurisdictions because it might facilitate better water planning and administration. Thus, the illustration here is simply designed to lay out how such an index could be used to determine tax rates that vary regionally.

[31] In addition to an exemption to agricultural users, we propose that the Rio Grande Watermaster be exempt from the tax because it is a basin that works differently from other basins in Texas. It does have a functioning water market, which means that the price of water in this region already implicitly includes a scarcity premium. We also propose to exclude 1 acre-feet of water/month to all permit holders. This exemption reduces the impact and administration burden on small users

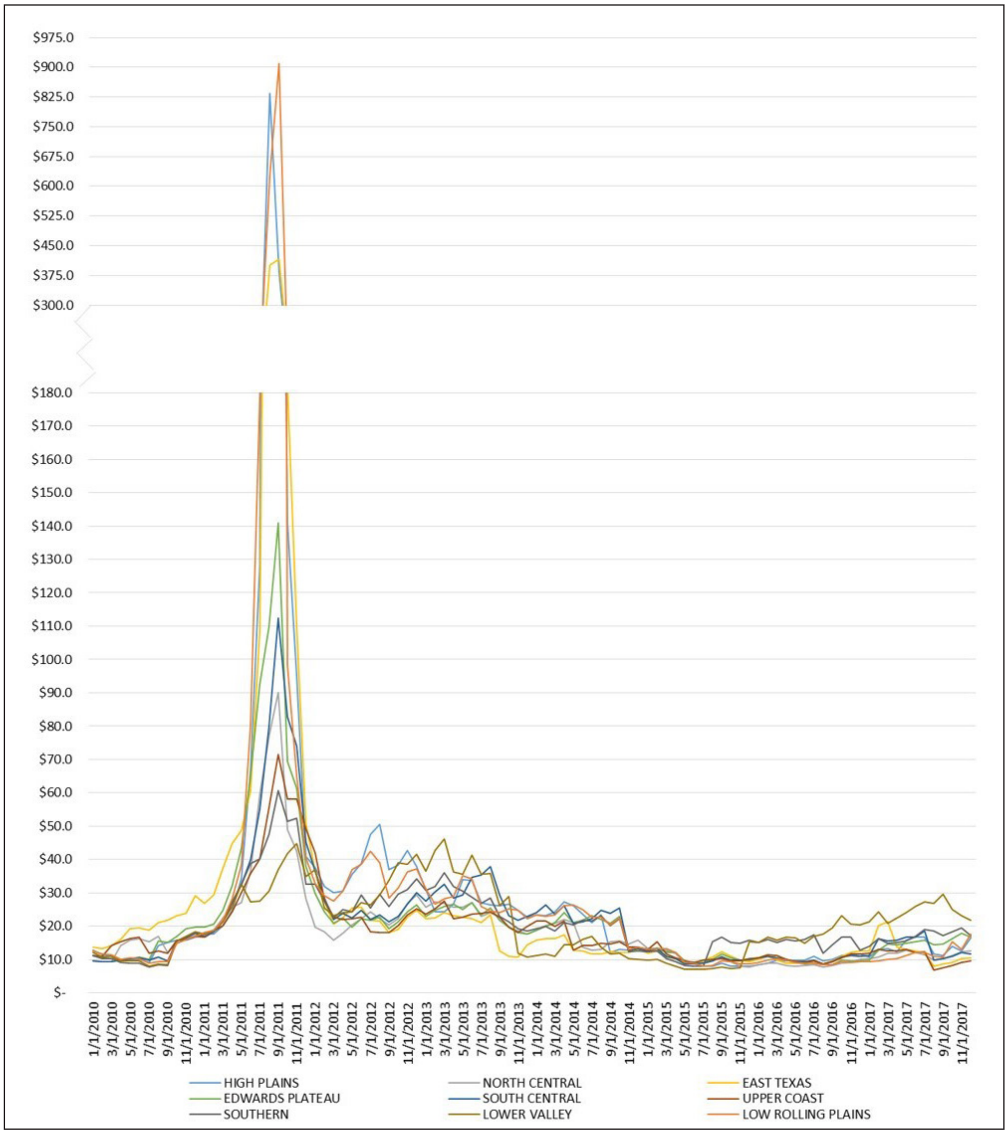

Figure 6. Tax values by region (2010 – Jan 2017) Y=100. Source: Capstone Team Estimations.

b) Payment options and enforcement mechanisms

In order to facilitate payments and revenue collection, all water users will have access to an online account where they will report their monthly water consumption to the TCEQ, who will act as the tax collector.[32] This account will show the tax rate for that month and the total amount owed by the user. To have the optimal effect on users' behavior, monthly bills, rather than quarterly or annual bills, are preferable.

2. *Tax formula and estimation of scenarios*

The main objective of the tax is to reflect the true scarcity of water and thereby encourage the optimal level of conservation. The proposed tax can be calculated using Equation 1. This equation shows that the value of the tax depends on three factors: (1) the numerator (*Y*), (2) a fixed parameter (*Z*) in the denominator, and (3) the PDSI. After simulating with different parameter numbers, we use a value of 7.1 for (*Z*), which in absolute values is slightly larger than the lowest PDSI (during the drought of 2011). In Vaca et al. (2017) we calculated three base scenarios with values of *Y* of 50, 100, and 200. For expositional purposes here, we adopt Y=100.

$$Tax_{rt}=Y/(Z+PDSI_{rt}) \qquad \text{Equation 1}$$

In equation 1, *Tax* represents the water tax per acre-foot for a region *r* in a month *t*. The tax for agricultural users will follow the same equation but be only 20% of the calculated value generated by Equation 1. We estimate the corresponding tax values, water conservation, and revenue that would have been

[32] The funds could be used for general revenue purposes or earmarked for special purposes

generated in the period 2010–2016 for the nine[33] regions in Texas.

a) Tax values

The estimation of the tax that each region would have faced since 2010 shows two important points. The first is that the tax structure allows the value to vary considerably with water availability and that the starting value of the tax has an important effect in the average values and level of variability of the tax. The variability of the tax with water availability is also showed graphically as the tax values dramatically increase in 2011 (the year of the drought) and the values decrease in wet years like 2016 (See Figure 6).

The second important conclusion from these estimations is that most of the time, when water is abundant, the tax is relatively low. Whereas, during drought conditions the value of the tax can reach very large values, which is a desirable feature of the tax. If water is scarce, it should cost more to encourage consumers to conserve. Although the tax can reach high values, these peaks rarely occur, and the majority of the regions would face low tax values each month since 2010. For a Y=100, 83.3% of tax values would have been less or equal to $30/acre-foot.[34] Conversely, the tax exceeded $100/acre-foot in only 2.2% of the cases.

b) Water Conservation

Applying a water tax will allow users to face the real scarcity cost of water in their region, which will result in water conservation.[35] This means that the tax will achieve one of its objectives, which is to reduce water consumption, especially in drought conditions like 2011. Based on the values of the tax previously calculated, we can estimate the percentage reduction in water consumption for each month. Equation 2 shows that water conservation depends on the price elasticity of demand for water, the value of the tax and the original water price.[36]

$$\textit{Conservation (\%)} = \textit{elasticity} \times (\textit{Tax}/(\textit{Water Price}) \times 100\% \qquad \text{Equation 2}$$

For this estimation, the short run water price elasticity[37] used is 0.38.

Water conservation resulting from the tax can be equivalent to increasing water supply by a certain percentage as it decreases the water deficit. For instance, in 2011 a tax with a *Y=100* would have been equivalent to an increase in supply of surface water by 13.7% for non-agricultural uses and 11.9% for agricultural users. The average water savings for non-agricultural users based on the estimations of the period 2010 to 2017 is 4.4%.

Clearly, Figure 6 shows that a state water tax that varies regionally and monthly could solve the problem that water prices are artificially underpriced and inflexible during droughts. The resulting conservation (Figure 7) during droughts will go a long way toward forcing society to use water more efficiently.

c) Tax revenue collection

As any other tax, the water tax will generate revenue for the state of Texas. As the primary purpose of the tax is to reflect water scarcity and promote conservation during droughts, how revenues of the tax are spent is not the main priority and what agency collects the tax does not have an impact on whether the tax is an economically efficient tool or not. However, we propose that the tax be collected by TCEQ as it is the primary regulatory agency for surface water. In addition, as the revenue comes from water users, it would be good to use these resources for water purposes. One alternative would be for the tax revenues to be put in a fund to cover operational expenses for agencies like TCEQ and TWDB. Another alternative would be to place all revenues of the tax in a fund like State Water Implementation Fund for Texas (SWIFT) that is used for financing water infrastructure projects.

CONCLUSIONS

The intention of the Vaca et al. (2017) report, Surface Water Regulation in Texas: Problems and Solutions, was to stimulate discussion on the pressing policy issues of surface water management in Texas. For purposes of policy analysis, we have adopted the conceptual lens of economic efficiency. We recognize that the inability to fully compensate the losers may cause policy makers to choose equity over economic efficiency. It is, nevertheless, a useful exercise to apply the conceptual

[33] As the Rio Grande is exempted from the fee, the estimations exclude the Trans Pecos regions, which mean that estimations are done only for nine of the 10 regions.

[34] For a starting value of $50, 91% of the tax values would have been below $20/acre-foot and for a starting value of $200, 73.7% of the tax values would have below $50/acre-foot.

[35] There are other policy alternatives that can result in conservation, such as mandatory rationing. As rationing can achieve a precise percentage of conservation, the fact that everyone had to conserve the same proportion makes it economically inefficient. For example, let's consider the mandatory effect of rationing for two users. The first user is an environmentally concerned citizen and has already reduced her water consumption to a minimum. The second user is not so concerned with environment: has inefficient irrigation practices for his yard and sometimes even leaves the faucet running because he forgot. Rationing would force equally both users to conserve an x%, which would be nearly impossible for user 1 while user 2 could conserve more than that %. The tax solves this problem by making water more expensive and thus leading water to its highest and best use automatically.

[36] For this estimation we use an approximation of wholesale water rates for residential users ($3/1000 gallons) and for other users we use the LCRA rates.

[37] See Espey et al. (1997).

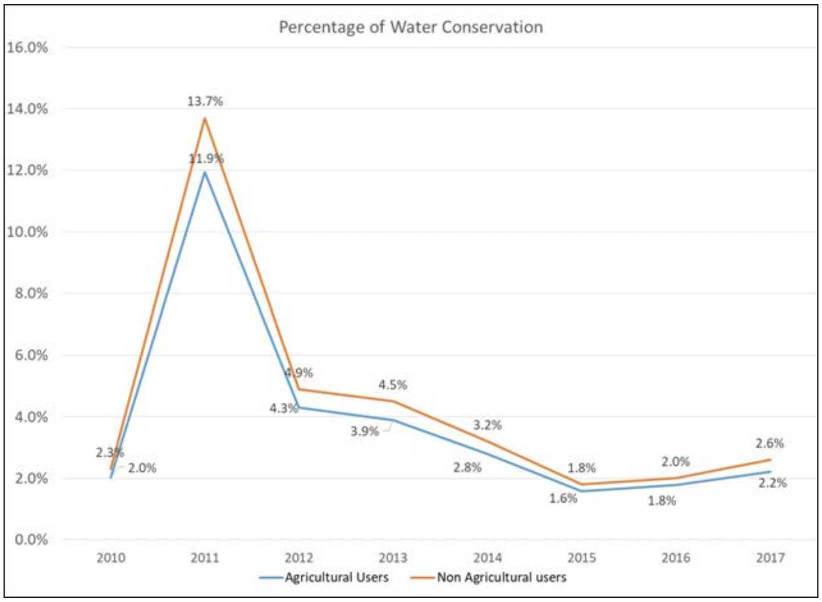

Figure 7. Percentage of water conservation across all regions (2010 – Jan 2017) (Y=100). Source: Capstone Team Estimations.

lens of economic efficiency to surface water policy to look at the benefits foregone to protect various interest groups. This paper focuses on how we can use existing water supplies more efficiently by improving water allocation and water pricing. To improve water allocation and to move water from lower valued uses to higher valued uses, we identified the following three mechanisms: (1) encouraging conjunctive water use, (2) removing roadblocks to interbasin transfers and (3) facilitating intrabasin transfers. The latter proposed a Watermaster Lite System.

To correct the current water pricing system that undervalues water and is inflexible to droughts, we present two alternatives—a water tax and an active water market. In contrast to the current artificially low and inflexible pricing system, water taxes that vary regionally in response to drought conditions could be a powerful force for conservation. The other alternative, creating an active water market, is perhaps an even more daunting task since it will require reforming legal and administrative procedures to facilitate trading of water. Nevertheless, we believe that a vibrant water market is superior to a tax because it will solve both the issues of water pricing as well as the water allocation problem.

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APPENDIX 1

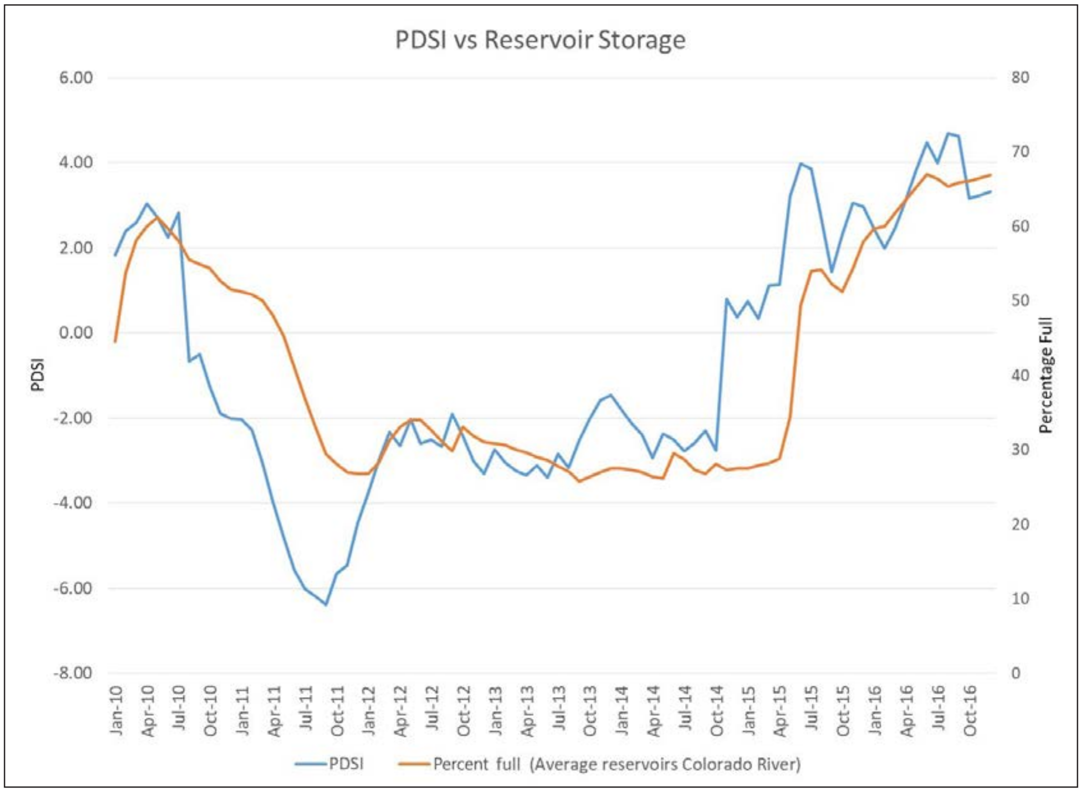

Figure A.1 PDSI and Reservoir Storage. Source: Date from Water Data for Texas 2017.

Although the PDSI may not be the hydrologically perfect measure of water supply considering the water in reservoirs, the PDSI does track in advance the changes in water availability in reservoirs. Figure A.1 shows how that the PDSI moves in the same direction as the Reservoir Storage. The correlation coefficient between these two variables is 0.73 and is statistically significant at the 1% level. In addition, Table A.1 shows the results of two simple regressions between these variables. The first line shows the results for the regression of the PDSI on Reservoir Storage with an R2 of .542. The second line also includes the lag of the PDSI (1 month before) on Reservoir Storage and the R2 increases to .64, which means that PDSI has power to predict the next month of Reservoir Storage.

Table A.1. Regression Analysis of PDSI and Reservoir Storage.

Regression	R2
Percentage Storage on PDSI	.542
Percentage Storage on PDSI and One Month Lagged PDSI	.640