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Cover photo:
Santa Elena Canyon, Big Bend National Park, Texas.

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Commentary: Water Infrastructure and Supply Are the Backbone or Achilles' Heel of Texas' Future: The Choice is Ours

Charles Perry*[1]

Editor-in-Chief's Note: In every odd-numbered year, the Texas Legislature convenes in regular session for 140 days. With this in mind, the Texas Water Journal invited Senator Charles Perry, Chairman of the Senate Water, Agriculture, and Rural Affairs Committee to discuss his priorities and visions for Texas water and the regular session of the 88th Texas Legislature. 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, or the Bureau of Economic Geology.

Keywords: 88th Texas State Legislature, Texas Senate, Texas water policy

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With the 88th Legislative Session fully underway, I remain steadfast in my commitment to water infrastructure and water supply. It is clear: For Texas to succeed, we must have access to dependable and safe drinking water. Investing in existing infrastructure to make every drop count and pursuing new water sources must become a priority of the State.

Having grown up in West Texas, I know the value of water. As chairman of the committee overseeing water policy in the Senate since 2015, my goal has always been to extend the existing water supply and diligently search for more supply opportunities.

First, we can address our aging and leaking infrastructure through investment in our smaller systems. The state continues to grow, putting strain on rural and midsized communities. An estimated 136 billion gallons of water loss occurs annually through leaking pipes according to the Texas Water Development Board (TWDB). With an estimated 70% of water line infrastructure in Texas nearing, at, or beyond the end of its life expectancy, this is the session we can address the issue.

Second, let the nationwide recent water shortages be a warning to our state. Without setting up supply for years to come, we will be struggling with drought and communities without water. It is time to look beyond our borders. According to the TWDB, our state will be 7 million acre feet short on water supply in 50 years.

Our neighboring states have access to excess water that Texas can develop. Additionally, marine desalination has been vastly underutilized. While there are 35 brackish desalination plants in Texas, there are zero in the Gulf of Mexico. California has six active plants. Texas must "tap" every available resource by making water a biannual discussion and consideration.

I am proposing a fund that would provide needed investment in both water infrastructure and supply. On the supply side, the funding would aim to reach 7 million acre feet of projects committed in 10 years, putting Texas on track to beat that 50-year timeline.

One example of new water supply is to recover half of the 14 million barrels of water a day that comes out of the ground from oil and gas production. The Texas Produced Water Consortium is ready to conduct pilot projects and testing of this potential new water source from oil and gas production. Another example is to look to our neighbors just east of Texas. Louisiana has expressed interest in moving supply to Texas, and with the right investment, our state can start the nationwide conversation of water security for our agriculture, manufacturing, and residential uses.

Water is as much an infrastructure item as roads, bridges, and communications. The 88th Legislative Session can establish the footprint for current and future water supply development. The lack of urgency and understanding and in some cases the disbelief that water is an issue can no longer be acceptable. Our world has the same core needs as we have in the past. Where there is water, there is life.

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Low Flow Trends in Texas Stream Segments Serving Unique Hydrologic Functions

Kartik Venkataraman*[1], Narayanan Kannan[2], and Victoria Chraibi[3]

Abstract: In recognition of the unique hydrologic functions they serve, certain stream segments in Texas have been designated as ecologically significant. In this study, we evaluated low flow trends in seven hydrologically unique stream segments spanning three climatic divisions in Texas from 1970 to 2019. Despite increasing mean annual temperatures, there are no trends in low flows or other hydrologic variables in the East Fork of the San Jacinto River in the Upper Coast climatic division, likely due to local moisture surplus effects from the Gulf of Mexico. In the Edwards Plateau climatic division, annual low flows and annual baseflows are decreasing in the South Fork of the Guadalupe River, the Sabinal River and the Frio River. While increasing mean annual temperatures appear to have a role in the drying of all three of these stream segments, increasing annual potential evapotranspiration may be an additional driver in the Sabinal and Frio Rivers. Analysis of the Standardized Streamflow Index indicates that all seven stream segments experienced their worst streamflow droughts in the 2010s. As such, the watersheds draining to the gages on these stream segments have minimal anthropogenic impacts, suggesting the influence of climate on the observed stream drying.

Keywords: stream drying, ecosystem, low flow, drought index, Edwards Plateau, baseflow

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Terms used in paper

Acronym / Initialism	Descriptive Name
$7Q_{10}$	annual minimum 7–day mean flow with a 10–year return period
$7Q_2$	7–day, 2–year low flow
AMDHWL	annual mean of the daily-high water level
AMJ	spring season
CCF	cross-correlation function
CD	climatic divisions
cumecs, cms, m^3/s	cubic meters per second
CPM	critical period management
CRU	Climatic Research Unit
EAA	Edwards Aquifer Authority
EGRET	Exploration and Graphics for RivEr Trends
EP	Edwards Plateau
EPE	Edwards Plateau East
EPN	Edwards Plateau North
EPW	Edwards Plateau West
ET	Evapotranspiration
HCDN	Hydro-Climatic Data Network
JAS	summer season
JFM	winter season
km^2	square kilometers
LCMAP	Land Change Mapping Assessment and Projection
LULC	land use and land cover
mm	millimeters
MMK	modified Mann-Kendall test
NCDC	National Climate Data Center
OND	autumn/fall season
PET	potential evapotranspiration
r^2	Spearman's "rho" or correlation coefficient squared
RE	runoff efficiency
SC	South Central
Sen slope	estimator which captures the linear rate of increase or decrease of a parameter over the time period of reference
SPEI	Standardized Precipitation Evapotranspiration Index
SPI	Standardized Precipitation Index
SPI-12	12–month Standardized Precipitation Index
SRI	Standardized Runoff Index
SSI	Standardized Streamflow Index
SSI-12	12–month Standardized Streamflow Index
TAC	Texas Administrative Code

Acronym / Initialism	Descriptive Name
TCEQ	Texas Commission on Environmental Quality
TMDL	total maximum daily load
TPDES	Texas Pollutant Discharge Elimination System
UC	Upper Coast
USGS	U.S. Geological Survey

INTRODUCTION

Low flows in streams are often used in natural resource management and environmental regulation as an indicator of overall stream health. Several researchers (e.g., Hisdal et al. 2004; Jowett and Biggs 2006; Bradford and Heinonen 2008; Thomas et al. 2019) have highlighted increased stress on aquatic, riparian, and hyporheic ecosystems during low flow due to decreased water availability and habitat quality. During these intervals, low flows help maintain longitudinal connectivity in the stream (Curran et al. 2012). Changes in flow and groundwater levels due to precipitation and seasonal factors have ecological impacts on stream communities. For instance, fish in riffle or shallow-water habitats can experience habitat loss. Low flows are critical for successful reproduction as many fish species migrate upstream to spawning sites (Bradford and Heinonen 2008; Bogan et al. 2017). In water resource management, Smakhtin (2001) noted that the evaluation of low flows is necessary for water allocations for competing interests such as municipal supply, irrigation, and recreation. The impact of low flow characteristics on water availability and water security has been discussed by Stahl et al. (2008), Vorosmarty et al. (2010), and Brauer et al. (2015). From an environmental health perspective, low flows such as the $7Q_{10}$ (the annual minimum 7–day mean flow with a 10–year return period) have been used for prescribing total maximum daily loads (TMDLs) in some parts of the United States (Steinschneider and Brown 2012). In Texas, the $7Q_2$ (7–day, 2–year low flow) is used to establish water quality criteria for wastewater discharges as part of the Texas Pollutant Discharge Elimination System (TPDES) by the Texas Commission on Environmental Quality (TCEQ; TCEQ 2010).

In recognition of the critical roles that streams play in local ecosystems, the 80th Texas Legislature passed bills (e.g., Senate Bill 3 2007) to develop, manage, and preserve the water resources of the State and protect instream and freshwater inflows. The 16 regional water planning groups in Texas recommended that the State Legislature designate certain segments of streams as ecologically significant. Streams with this designation are acknowledged for their unique ecological value in serving various biological and riparian functions, for supporting endangered or threatened species and communities, and for serving important hydrologic functions, including flow stabilization and groundwater recharge (Texas Administrative Code (TAC) § 358.2 2012). Upon receiving this designation, the stream segment is protected from the construction of State-funded reservoirs. Most of the segments that have been recognized for their unique hydrologic function are located in the Edwards Plateau (EP) region of Texas and serve as above-ground recharge sources for the Edwards Aquifer, one of the most productive karst aquifers in the world (Thomas et al. 2019). The majority of the Edwards Aquifer recharge (85%) is contributed locally by the overlying watershed while the remainder is sourced from direct precipitation and below-ground flows from adjacent aquifers (Edwards Aquifer Authority [EAA] 2003).

A brief review of existing literature on low flows in Texas streams is presented to substantiate the motivation behind the current study. Poshtiri and Pal (2016) used various indicators to study the magnitude, timing, and duration of low flows in the continental United States from various starting periods to 2012. This study included several Hydro-Climatic Data Network (HCDN) stations in Texas. In general, they found a drying trend from 1980 onward (relative to pre–1980) for the Texas Gulf region. A few sites in South Texas also showed statistically significant decreasing trends in annual 7–day minimum flows. Without reference to any specific site or river basin, they reported an increase in the frequency of dry days in the Texas Gulf region. Thomas et al. (2019) used a diverse suite of hydrological indicators to assess hydroclimatic trends in ecologically significant stream segments in the Nueces River Basin from 1970 to 2014. They reported decreasing trends in annual minimum and annual median flows in four of the six gages used in the study with no corresponding conclusive trends in precipitation. They concluded that even small changes in land use and land cover in this basin, coupled with the lack of statutory oversight on water withdrawals in these segments, likely contributed to the declining trends in annual low flows. Recently, Rogers et al. (2020) evaluated trends in streamflow at selected locations in Texas as part of a larger study encompassing the southern and southeastern United States. They found statistically significant decreasing trends in flow for 1970–2015 at many ‘reference’ sites (i.e., sites with minimal anthropogenic influence) in Texas and concluded that these declines may be partially climate-driven. They also highlighted the year 1970 as being the beginning of a period of significant decline in mean streamflow and noted that analyses beginning with this year may be useful for studying climate change impacts on streamflow.

Climatic variability, specifically increasing surface water temperature (which is a function of ambient air temperature) and potential evapotranspiration (PET), has been demonstrated to influence the health of individual taxa and ecosystem functioning in streams, particularly the cycling of carbon. In situations of drying or drought, streams provide critical drought refuges such as (1) remnant or perennial pools and seeps for surface water habitats; (2) sediment or stones for resting stages, and (3) the hyporheic zone for taxa capable of vertical migration (Chester and Robson 2011; Bogan et al. 2017). These refuges can provide a critical source to support biodiversity downstream if located at headwaters (Bogan et al. 2015). However, not all taxa benefit from refuges and site-specific factors, such as substrate type or oxygen concentration. In addition, fluctuations in the pH conditions of pools can result in community structures (e.g., surface invertebrates such as aquatic insects) that are significantly different before and after recovery from drought (Acuña et al. 2005; Bogan et al. 2015). Even though some surface invertebrates do not find refuge in the hyporheic zone, both surface insect fauna and hyporheic non-insect fauna demonstrate overlap between intermittent and perennial streams (Del Rosario and Resh 2000). This suggests the ability of these fauna to re-colonize streams that are hydrologically connected via swimming, crawling, or flying (Bogan et al. 2017).

It is evident from the preceding literature that much interest has been shown in investigating the impacts of climate (both past and future) on streamflow. When watersheds undergo changes in land use or experience anthropogenic modifications, we often suspect that flow regimes may be altered and studies investigating the impact of these changes are often carried out. However, where ecologically significant stream segments are concerned, hydro-meteorological changes in their watersheds often go unnoticed. As highlighted earlier, these segments are of critical importance to the ecosystem, and yet very little literature exists on long-term changes in their hydrology. Therefore, there is an urgent need for studies that examine climate impacts on streamflow in these segments, particularly low flows. Smakhtin (2001) emphasized the need for such studies to receive more focus and recommended the use of a variety of low flow indices to understand this “dynamic concept.” Therefore, overarching goal of this study is to examine trends in low flows at seven United States Geological Survey (USGS) gaging stations in Texas using a suite of complementary hydroclimatic indicators. These stations were selected due to their location on stream segments that serve a unique hydrologic function. The selected gages are maintained by the USGS as part of the HCDN (Lins 2012) and are minimally impacted by anthropogenic factors. Specifically, we use metrics that reflect the magnitude, duration, and frequency of various types of low flows; examine the concurrent trends in associated variables such as temperature, precipitation, and evapotranspiration; and develop drought indices to evaluate low flow trends in those segments holistically and identify potential drought drivers. To the best of the authors’ knowledge, there have been no prior efforts to characterize low flow trends in segments serving such valuable hydrologic functions in Texas. Therefore, the discussion of our results in the context of potential meteorological drivers and ecohydrological implications is a novel feature of the study.

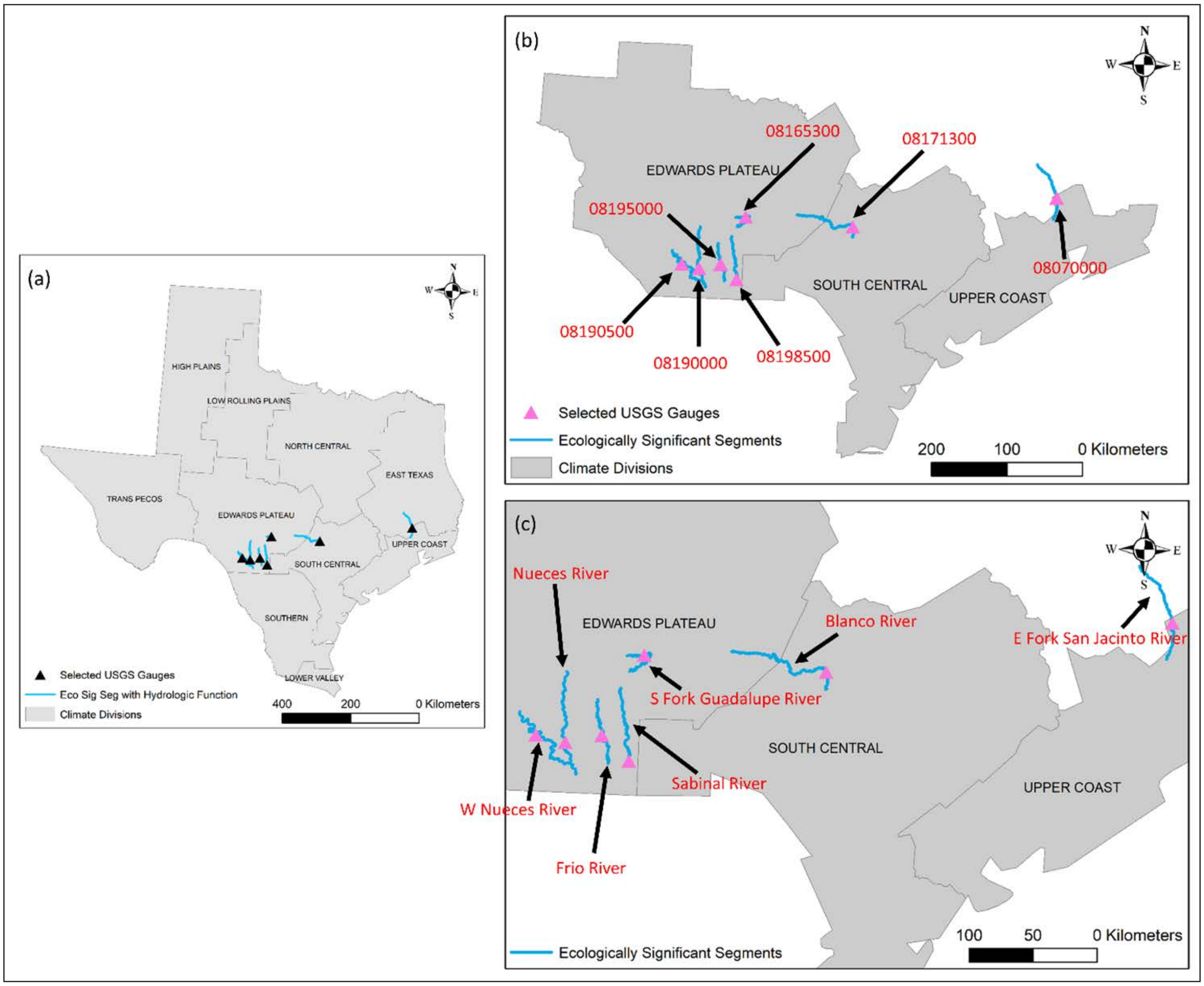

Figure 1. (a) Climate divisions of Texas; (b) location and number of USGS sites with continuous daily records from 1969-10-01 to 2019-09-30 relative to the climate divisions; (c) names of the ecologically significant stream segments in this study.

MATERIALS AND METHODS

Study area characteristics and data overview

The State of Texas comprises ten distinct climatic divisions (CDs; Figure 1; National Climate Data Center [NCDC] 2015). Regions that fall within the same CD are similar in seasonal weather patterns as well as in characteristics of hydroclimatic variables such as temperature and precipitation. Therefore, we selected CDs as the basis for our assessment of spatial hydrodynamic trends.

The USGS maintains a network of HCDN gages across the United States that represent streams with minimal or no anthropogenic disturbance or influence. As these streams are unimpaired by damming, artificial storage, and channel diversion for withdrawal and use, an analysis of their streamflow records allows assessment of hydrologic response to climate. As of 2009, there are 39 gaging stations in Texas that are continuously monitoring streamflow discharge (Lins 2012). Of these 39 stations, seven were selected for the present study based on the following criteria: (1) the gaging stations must be located on ecologically significant stream segments that serve a hydrologic function; and (2) daily streamflow records for the water year 1970 to water year 2019 (October 1, 1969 to September 30, 2019) must be available. The locations of these seven gages on their respective stream segments and the climate division they are contained within are shown in Figure 1. These seven gages span three CDs: site 0807000 is located in the Upper Coast (UC) CD, site 08171300 is located in the South Central (SC) CD, and sites 08165300, 08190000, 08190500, 08195000, and 08198500 are located in the EP CD. It must be noted that while site 08070000 is located in the UC CD, over 90% of its contributing watershed lies in the East Texas CD.

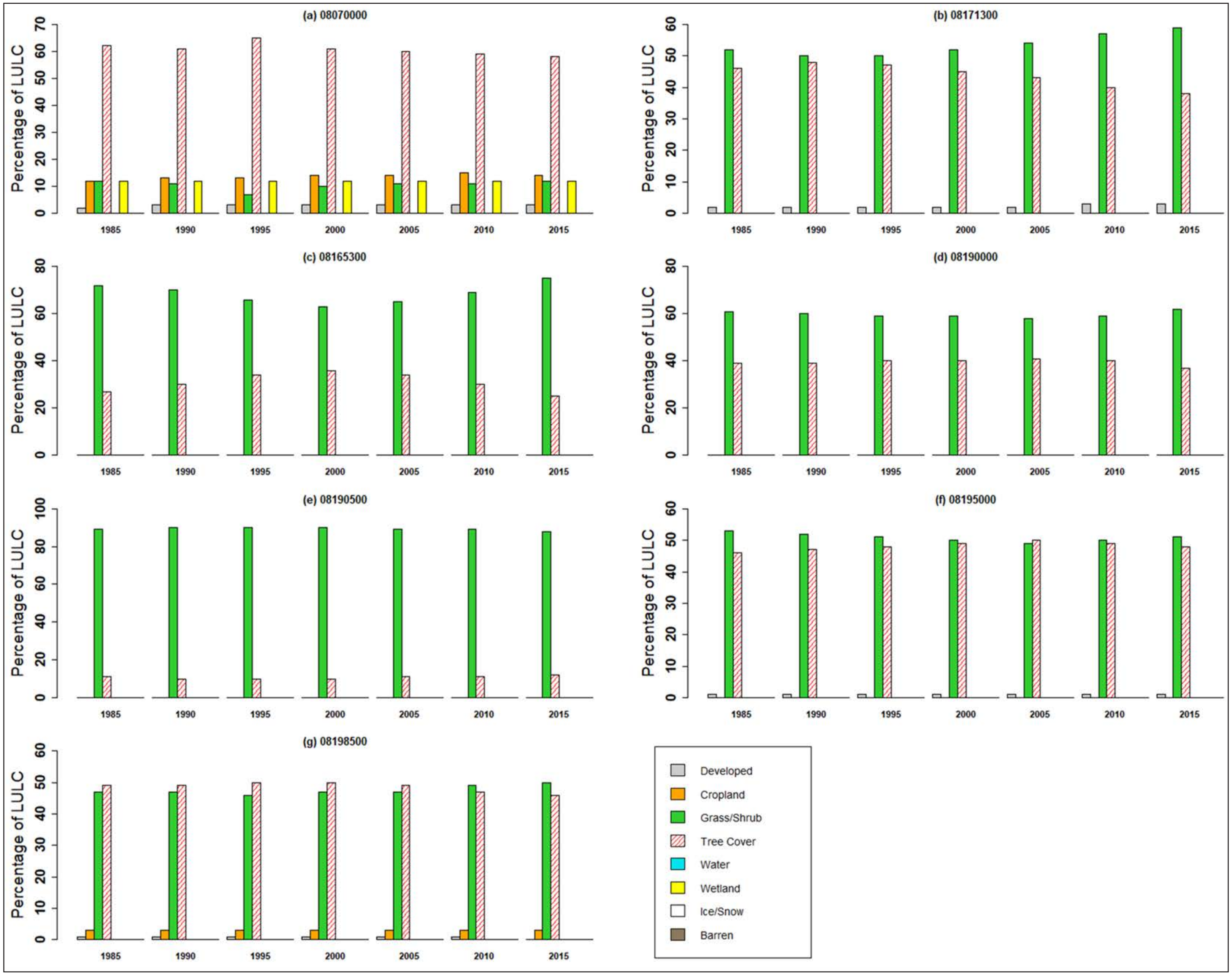

Figure 2. Annual change in LULC for select years from 1985 to 2015 for the watersheds contributing to the seven selected gages (gage IDs are shown above each figure).

Table 1. Descriptions of the hydrologic function and other functions served by the stream segments monitored by the USGS HCDN gages utilized in this study.

USGS Station ID	Station Name	Drainage Area, square kilometers (km2)	Climate Division	Significant Segment Name	Hydrologic Function	Biological Function	Threatened or Endangered Species and Unique Communities	High Water Quality or Exceptional Aquatic life and Aesthetic Value	Riparian Conservation Area
08070000	East Fork San Jacinto River near Cleveland, Texas	841	UC1	East Fork San Jacinto River	Groundwater recharge of the Chicot Aquifer	Aquatic habitat value due to high biodiversity		Diverse benthic macroinverterbrate and fish communities	Sam Houston National Forest
08171300	Blanco River near Kyle, Texas	1067	SC2	Blanco River	Edwards Aquifer recharge zone			Overall use	
08165300	North Fork Guadalupe River near Hunt, Texas	436	EP3	North Fork Guadalupe River	Groundwater discharge of the Edwards Aquifer			High water quality and exceptional aquatic life	Kerr Wildlife Management Area
08190000	Nueces River at Laguna, Texas	1961	EP3	Nueces River	Edwards Aquifer recharge zone	Texas Natural Rivers System nominee and Top 100 Texas Natural Areas list		Exceptional aesthetic value	
08190500	West Nueces River near Brackettville, Texas	1799	EP3	West Nueces River	Groundwater discharge and recharge of Edwards Aquifer		Texas snowbells		
08195000	Frio River at Concan, Texas	1028	EP3	Frio River	Edwards Aquifer recharge zone	Texas Natural Rivers System nominee		Exceptional aesthetic value and overall use	Garner State Park
08198500	Sabinal River at Sabinal, Texas	624	EP3	Sabinal River	Edwards Aquifer recharge zone	Texas Natural Rivers System nominee		Exceptional aesthetic value	

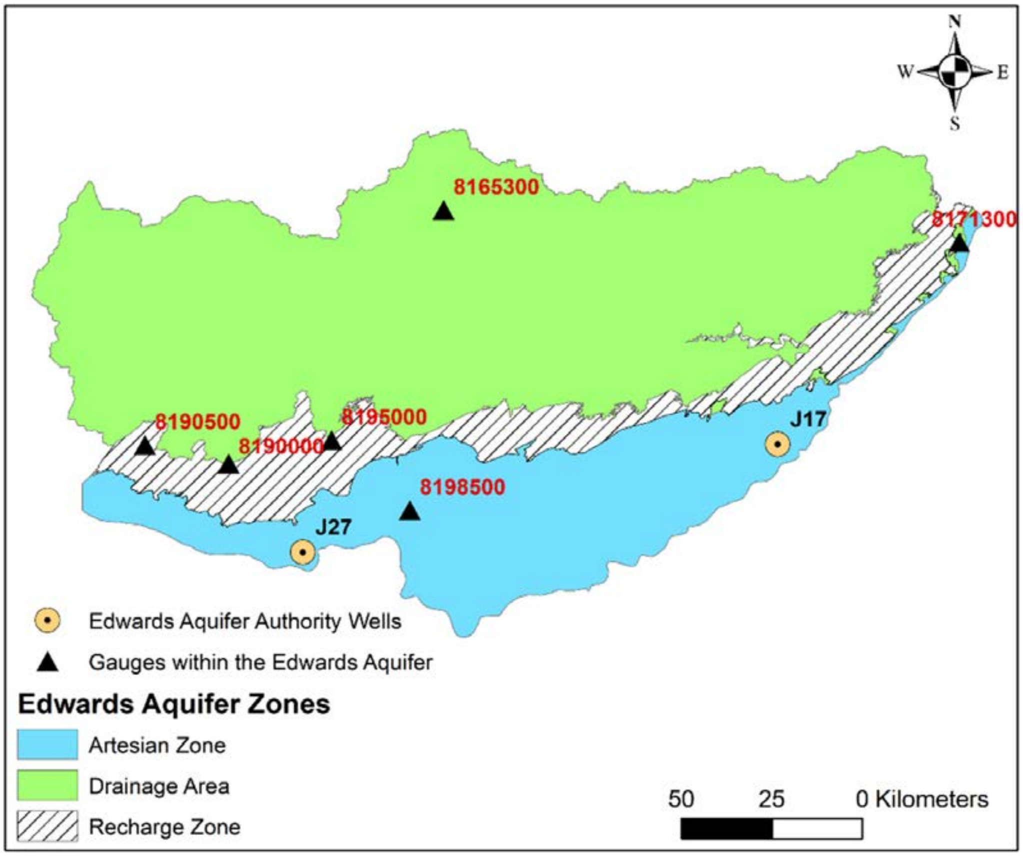

Figure 3. Location of six of the seven selected gage sites and the two Edwards Aquifer Authority (EAA) monitoring wells relative to the Edwards Aquifer recharge zone. The ArcGIS shapefiles for the aquifer zone maps were retrieved from the Edwards Aquifer Authority 2021a. The leading zeroes in the gage IDs have been omitted.

Daily discharge data were compiled for the seven gages using the EGRET (Exploration and Graphics for RivEr Trends) software package (Hirsch and De Cicco 2015) developed for use with RStudio (RStudio Team 2019). The FlowScreen package (Dierauer and Whitfield 2017) was used to develop and analyze baseflow statistics such as minimum, mean, and maximum baseflow at the gages for a user-defined period. The Eckhardt digital filter method (Eckhardt 2012) built into this package (which has been recommended by Xie et al. (2020) for the contiguous United States) estimates baseflow from streamflow discharge.

The watershed draining to each of the seven gages was first delineated. Then, the land use and land cover (LULC) characteristics and temporal changes of the seven watersheds were evaluated at 5-year intervals. The purpose of this exercise was to verify that the watersheds had undergone minimal LULC change, albeit over a 33-year timeframe, as only data from 1985–2017 were available from the USGS Land Change Mapping Assessment and Projection Datasets (USGS 2021). Nonetheless, validation of LULC changes further aids the attribution of hydrologic trends. If minimal or no LULC changes were present at the gages, we can attribute the hydrologic trends observed to changes in climate (Lins 2012). Eight types of LULC are described in these datasets — developed, cropland, grass/shrub, tree cover, water, wetland, ice/snow, and barren. Ice and snow cover do not exist for any of the watersheds examined. The temporal trends in LULC for the seven watersheds are shown in Figure 2. It should be noted that only LULC for 5¬–year intervals beginning with the year 1985 are shown in this Figure. Developed land use is minimal (≤3%) and is only observed in watersheds draining to gages 08070000, 08171300, 08195000, and 08198500. In all four watersheds, there is no temporal change in the percent of the watershed area under developed use. The only watershed with any appreciable agriculture is that draining to gage 08070000. Cropland cover in this watershed shows very little change, ranging from 12% to 15% of the overall area depending on the time period of interest (Figure 2a). Overall, with the exception of the watershed draining to gage 08171300 in the SC CD, where a slight increase (from 50% in 1985 to 60% in 2017) in grass/shrub cover occurred at the expense of tree cover, there was no notable change in LULC at any of the seven sites.

The location of the hydrologically unique stream segments (Figure 1c) and the description of the functions they serve are shown in Table 1. All seven stream segments serve as sources of recharge for the respective aquifers they overlie. The East Fork of the San Jacinto River recharges groundwater to the Chicot Aquifer (which is part of the larger Gulf Coast Aquifer system), while all remaining segments overlie the Edwards Aquifer. Four gages (08171300 on the Blanco River, 08190000 on the Nueces River, 08190500 on the West Nueces River, and 08195000 on the Frio River) directly overlie the sensitive recharge zone of the Edwards Aquifer (Figure 2). In addition to serving critical hydrologic roles, each of these seven stream segments is unique for one or more of the following reasons: (1) serving vital biological functions, (2) housing threatened or endangered species or unique communities, (3) providing high water quality or exceptional aquatic life use and aesthetic value, and (4) acting as a riparian conservation area (Table 1; TAC § 358.2 2012).

In addition to daily streamflow records, water level data from two groundwater wells (also referred to as "index wells") maintained by the EAA were compiled and included as part of the hydroclimatic assessment (EAA 2021b). As part of this monitoring effort, daily high water level data are available from two index wells: J17, representative of the "San Antonio Pool," and J27, representative of the "Uvalde Pool." Although daily-high data are available from 1932 for J17 and from 1942 for J27, only the daily-highs for the water years 1970–2019 were used in this analysis. Well J17 is located in the SC CD while J27 is in the EP CD (Figure 3). Spring flows in the Aquifer help sustain seven endangered and one threatened aquatic species. Water withdrawals by pumping can detrimentally impact these flows and threatened species. Therefore, continuous monitoring of groundwater levels using these index wells is mandated. The EAA jointly uses the water level data from these wells and discharge data from two springs, the Comal Springs and the San Marcos Springs, to enforce groundwater withdrawal restrictions during periods of drought based on set criteria (EAA 2021b).

Monthly total precipitation, monthly total potential evapotranspiration (PET), and monthly average temperature were compiled from the University of East Anglia Climatic Research Unit (CRU)'s high-resolution gridded data, version 3.26 (Harris and Jones 2019). This dataset is presented at 0.5° x 0.5° resolution and has been widely used in catchment-scale studies (e.g., Demaria et al. 2013; Hajihoseini et al. 2015; Mahmood et al. 2019; Mutti et al. 2020). The weather data from observation stations reported by the National Climate Data Center (NCDC) were either discontinuous, sparse, or not available for part of our study area. As a result, the CRU dataset, which includes PET data, was used as an alternate source. Harris and Jones (2019) reported that while temperature and precipitation are primary variables based on observations, PET is a derived variable, computed from temperature, vapor pressure, and cloud cover. This dataset presents month-by-month variations in these climate variables for the period January 1901 to December 2017.

Data from the CRU grid that encompassed each watershed were compiled. In some instances, a watershed spanned two 0.5° x 0.5° grids; in these cases, climate data from the two grids were aggregated by area-weighted averaging. Data that were averaged in this fashion are still referred to in the singular (as "grid") for simplicity. The resulting pairing of gages and the CRU dataset is as follows: gage 08070000 is paired with the UC grid, gage 08171300 is paired with the SC grid, gage 08165300 is paired with the Edwards Plateau North (EPN) grid, and gage 08190500 is paired with the Edwards Plateau West (EPW) grid. The watersheds draining to gages 08190000, 08195000, and 08198500 are adjacent to each other and are all encompassed by the Edwards Plateau East (EPE) grid. The ncdf4 package (Pierce 2015) was used within RStudio to extract and analyze the precipitation, PET, and temperature datasets. Finally, Spearman's rank correlation was performed between streamflow depth (as calculated using Equation 1) and the three CRU climate variables to investigate the strength of their linear relationship. Spearman's "rho" or correlation coefficient was squared to give the coefficient of determination (referred to as r^2 in this study) to determine the variance in streamflow depth that can be explained by the climate variables.

$$d_{streamflow,annual} = \frac{Volume_{streamflow,annual}}{Area_{watershed}} \quad (1)$$

Hydroclimatic change indicators and metrics

To capture the magnitude and duration of the streamflow (low) extreme, the annual minimum of 1–day means and annual minimum of 30–day means were selected. These metrics represent the lowest single-day value in a water year and the lowest consecutive 30–day or monthly average occurring in that year. Considering that streamflow discharge measured at a gage comprises above-ground and below-ground components, averaging flows over monthly (or longer) time periods helps buffer short-term, or sudden, fluctuations and provides a means of analyzing the persistence of drier conditions. Additionally, a metric such as the 30–day minimum also represents a measure of a more prolonged hydrologic and, consequently, environmental stress. The next metric was the number of days below the low flow threshold, defined as the number of days in that year that the daily mean falls below the 25th percentile of the daily means of the entire period of the study (in this case, the water year 1970 to the water year 2019) at that location. The 25th percentile was adopted as the low flow threshold following the recommendations of The Nature Conservancy's Indicators of Hydrologic Alteration User Manual (2009). The aforementioned indicators are also a select subset of hydrologic alteration statistics prescribed by Richter et al. (1996).

In addition to these indicators, the runoff efficiency (RE) of the watershed was also computed as shown in Equation 2. RE is a measure of the fraction of precipitation that is converted to runoff and changes in this parameter may reflect climate variability (i.e., changes in temperature, precipitation, and PET). This metric was included in the current study as a tool for evaluating the nature of the precipitation–runoff relationship. To compute RE, the discharge data from the gages and precipitation data from the CRU dataset were paired in the same manner as described in Section 2.1. Lastly, the FlowScreen package was used to perform baseflow separation from the daily mean discharge data. The annual minimum, annual mean, and annual maximum baseflow were included as indicators in this study.

$$RE = \frac{d_{streamflow,annual}}{d_{precipitation,annual}} \quad (2)$$

Data Analysis

The modified Mann-Kendall test (MMK) proposed by Hamed and Rao (1998) accounts for autocorrelation by modifying the variance of the original Mann–Kendall test. It has been widely used in hydrologic studies for the detection of non-stationarity (e.g., Wahl et al. 2015; Venkataraman et al. 2016; Machiwal et al. 2019; Alashan 2020) and is employed in this study for the detection of monotonic trends. For the sake of brevity, the MMK test has not been discussed here (see Hamed and Rao 1998 for a comprehensive treatment).

The MMK was applied to the following hydroclimatic indicators: (1) for streamflow — the annual and seasonal 1–day minimum of means, the annual and seasonal 30–day minimum of means, the number of annual days below the low flow threshold, and the annual RE; (2) for baseflow — the annual minimum, the annual maximum, and the annual mean; (3) for groundwater levels — the annual minimum of, the annual mean of, and the annual maximum of daily-high water levels; and (4) for climate variables — the annual and seasonal mean temperature, the annual and seasonal total precipitation, and the annual and seasonal total PET. The significance of linear trends was assessed at $p \leq 0.05$. Additionally, the magnitude of the trends for the streamflow, baseflow, and groundwater levels were characterized using the Sen slope, an estimator which captures the linear rate of increase or decrease of a parameter over the time period of reference (Sen 1968). While the MMK helps ascertain whether a monotonic trend is present, the Sen slope helps compare the magnitude of this trend between different gages and climate divisions.

Drought Indices

Several standardized indices have been widely used in hydrological studies to investigate the length and severity of droughts. These include the Standardized Precipitation Index (SPI) (McKee et al. 1993), the Standardized Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano et al. 2010), the Standardized Runoff Index (SRI) (Shukla and Wood 2008), and others. The general procedure for the development of these indices involves identifying the probability distribution that best fits the time series aggregated over a period of interest (e.g., 1–month, 6–months, 12–months, etc.) and subsequently transforming this distribution to a normal distribution with zero mean and unit variance. In this study, the 12–month SPI (henceforth referred to as SPI-12) was computed for each of the five CRU grids. The SPI package in the R software environment (Neves 2013) was employed to compute the SPI-12. As the CRU dataset was available only until 2017, the SPI-12 was computed for water years 1970–2017. Values of this index that fall within -1 to +1 indicate "normal," or average, precipitation conditions, while those values that exceed +1 or are smaller than -1 indicate abnormally wet/above-average precipitation periods and abnormally dry/below-average precipitation periods, respectively. A similar procedure was followed for developing an index for streamflow, also referred to as the Standardized Streamflow Index (SSI) (following Vicente-Serrano et al. 2012), with zero mean and unit variance. The SSI was also computed on a 12-month scale and is hereafter referred to as SSI-12. For both the SPI-12 and the SSI-12, the number of months in each decade falling above- or below-average conditions was computed to compare drought severity.

RESULTS

Trends in climate variables

The trends in mean temperature, total precipitation, and total PET at both the annual and seasonal time scales for water years 1970 to 2017 were assessed using MMK (Table 2). Annual mean temperatures show significantly increasing trends in all five CRU grids. From a seasonal perspective, mean temperatures for all five grids for all four seasons are rising except the autumn and winter mean temperatures for the UC grid, as shown in Table 2. There are no significant trends in annual precipitation, but spring totals show declining trends in the EPE grid and the EPW grid. Finally, annual PETs show increasing trends in both the EPE and EPW grids. At these two grids, spring and summer PETs are also increasing. Additionally, autumn PETs show increasing trends in the EPN and EPE grids.

The strength of the linear relationship between annual streamflow depth in millimeters (mm) and the three climate variables, i.e., annual mean temperature, annual total precipitation (in mm), and annual total PET (in mm), is shown in Figure 4. For an explanation of the pairing of streamflow gages and CRU grids, please refer to Section 2.1; gage 08195000 was selected to represent the EPE grid. Annual streamflow is positively correlated with annual precipitation at all grids. The coefficient of determination for all five grids is statistically significant; the SC, EPE, and UC grids show the strongest cor-

Table 2. Trends in climate data from the CRU dataset for the water year 1970 to water year 2017 period from the MMK test. Sen slope values are shown in parentheses where trends were statistically significant (significance assessed at p≤0.05).

Climatic Research Unit (CRU) Grid	Annual	Winter season (JFM)	Spring season (AMJ)	Summer season (JAS)	Autumn/fall seaason (OND)
Temperature in degrees Celsius (°C)					
UC Grid	↑ (0.02)	-	↑ (0.02)	↑ (0.02)	-
SC Grid	↑ (0.03)	↑ (0.04)	↑ (0.03)	↑ (0.02)	↑ (0.02)
EPN Grid	↑ (0.03)	↑ (0.04)	↑ (0.03)	↑ (0.03)	↑ (0.03)
EPE Grid	↑ (0.04)	↑ (0.05)	↑ (0.04)	↑ (0.04)	↑ (0.03)
EPW Grid	↑ (0.04)	↑ (0.04)	↑ (0.04)	↑ (0.04)	↑ (0.03)
Precipitation in millimeters (mm)					
UC Grid	-	-	-	-	-
SC Grid	-	-	-	-	-
EPN Grid	-	-	-	-	-
EPE Grid	-	-	↓ (-1.85)	-	-
EPW Grid	-	-	↓ (-1.55)	-	-
Potential evapotranspiration (PET) in millimeters (mm)					
UC Grid	-	-	-	-	-
SC Grid	-	-	-	-	-
EPN Grid	-	-	-	-	↑ (0.46)
EPE Grid	↑ (2.71)	-	↑ (0.88)	↑ (0.79)	↑ (0.62)
EPW Grid	↑ (2.76)	-	↑ (0.85)	↑ (0.78)	-

CRU: Climatic Research Unit; UC: Upper Coast; SC: South Central; EPN: Edwards Plateau North; EPE: Edwards Plateau East; EPW: Edwards Plateau West; JFM: winter season; AMJ: spring season; JAS: summer season; OND: autumn/fall season; ↓: decreasing trend; ↑: increasing trend; °C: degrees Celsius; mm: millimeters; PET: potential evapotranspiration;

relation between streamflow and precipitation, as indicated by the r^2. As for PET, the annual streamflow in the SC, EPN, EPE, and EPW show a negative correlation, with the EPE showing the strongest r^2 of 0.52, indicating that just over half the variance in streamflow can be explained by PET. However, PET does not display a significant correlation with streamflow in the UC. Lastly, annual streamflow shows a negative correlation with annual mean temperature in the SC, EPN, EPE, and EPW, with the EPE again displaying the strongest r^2 of 0.37. Temperature seems to have no impact on the variance in streamflow in the UC, as shown in Figure 4.

Trends in streamflow and baseflow

The trends in annual and seasonal 1–day and 30–day minimum flows were assessed for the water years 1970–2019

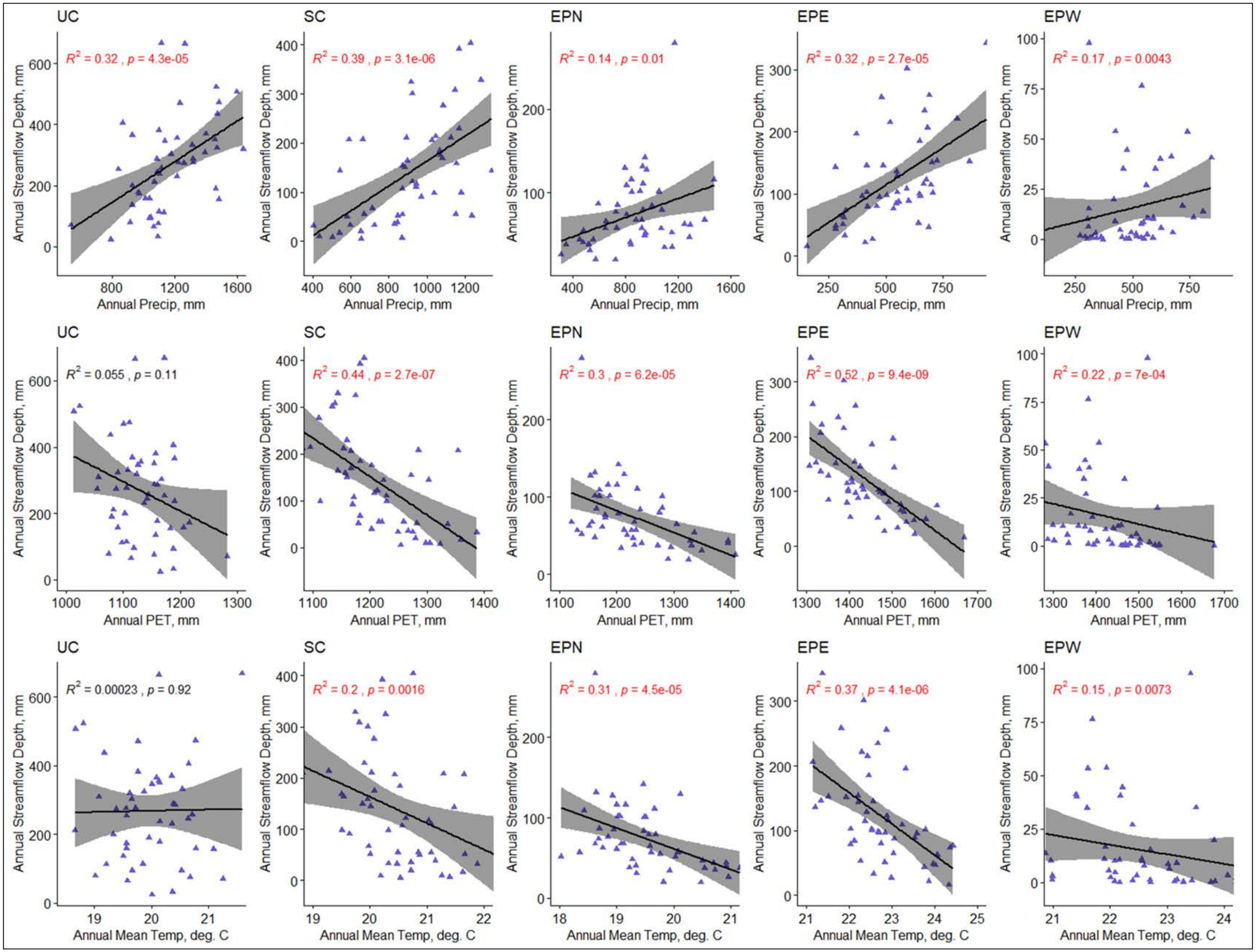

Figure 4. Spearman correlation between annual streamflow volume (expressed as depth) and CRU climate variables. The gray bands show the 90% confidence limits (coefficient of determination r^2 are shown in red where p≤0.05; gage 08195000 is used to represent the EPE grid.)

Table 3. Summary of annual and seasonal trends at the selected sites analyzed using the MMK test. Sen slope values are shown in parentheses where trends were statistically significant (significance assessed at p≤0.05; centimeters [cm] or cubic meters per second [m^3/s]).

Gage ID / Climatic division	Annual	Winter season (JFM)	Spring season (AMJ)	Summer season (JAS)	Autumn / fall seaason (OND)
1–day Minimum in centimeters (cm)					
08070000 / UC	-	-	-	-	-
08171300 / SC	↓ (-0.08)	-	-	↓ (-0.20)	-
08165300 / EP	↓ (-0.18)	-	-	↓ (-0.16)	↓ (-0.26)
08190000 / EP	-	-	-	-	-
08190500 / EP	-	-	-	-	-
08195000 / EP	↓ (-0.66)	↓ (-0.90)	↓ (-0.76)	↓ (-0.69)	↓ (-0.97)
08198500 / EP	↓ (-0.01)	↓ (-0.02)	↓ (-0.01)	↓ (-0.01)	↓ (-0.02)
30–day Minimum in centimeters (cm)					
08070000 / UC	-	-	-	-	-
08171300 / SC	↓ (-0.22)	-	-	↓ (-0.21)	-
08165300 / EP	↓ (-0.16)	-	-	↓ (-0.15)	↓ (-0.22)
08190000 / EP	-	-	-	-	-
08190500 / EP	-	-	-	-	-
08195000 / EP	↓ (-0.84)	↓ (-0.88)	↓ (-0.75)	↓ (-0.72)	-
08198500 / EP	↓ (-0.01)	↓ (-0.01)	↓ (-0.01)	↓ (-0.01)	↓ (-0.02)

UC: Upper Coast climatic division; SC: South Central climatic division; EP: Edwards Plateau climatic division; JFM: winter season; AMJ: spring season; JAS: summer season; OND: autumn/fall season; ↓: decreasing trend; cm: centimeters;

at a significance level of 0.05 (Table 3). The UC CD (site 08070000) shows no significant trends in the 1–day or 30–day minimums at the annual or any of the seasonal scales. Likewise, the two westernmost sites in the EP CD (gages 08190500 and 08190000) show no trends at any time scale. It must be noted that gage 08190500 in the EPW frequently experiences several zero-flow days in a year. In 21 of the 50 water years included in this study, there were at least 60 days per water year with zero mean flow. However, analysis of daily mean flows at gage 08190000 did not reveal any zero-flow days for any of the water years chosen for the study. For other sites, the results are mixed. The SC CD (gage 08171300) shows significant declining trends in annual 1–day and 30–day minimum flows while, at the seasonal scale, summer 1–day and summer 30–day minimums show declining trends (Table 3). In the EP, sites 08165300, 08195000, and 08198500 all show declining annual 1–day and 30–day minimums. Site 08198500 shows significant declining trends for all four seasons of the year for all three low flow metrics while adjacent site 08195000 shows an identical pattern, albeit with autumn/fall (OND) 30–day minimums alone showing no significant trends (Table 3). Gage 08165300 experienced significant declines in summer (JAS)

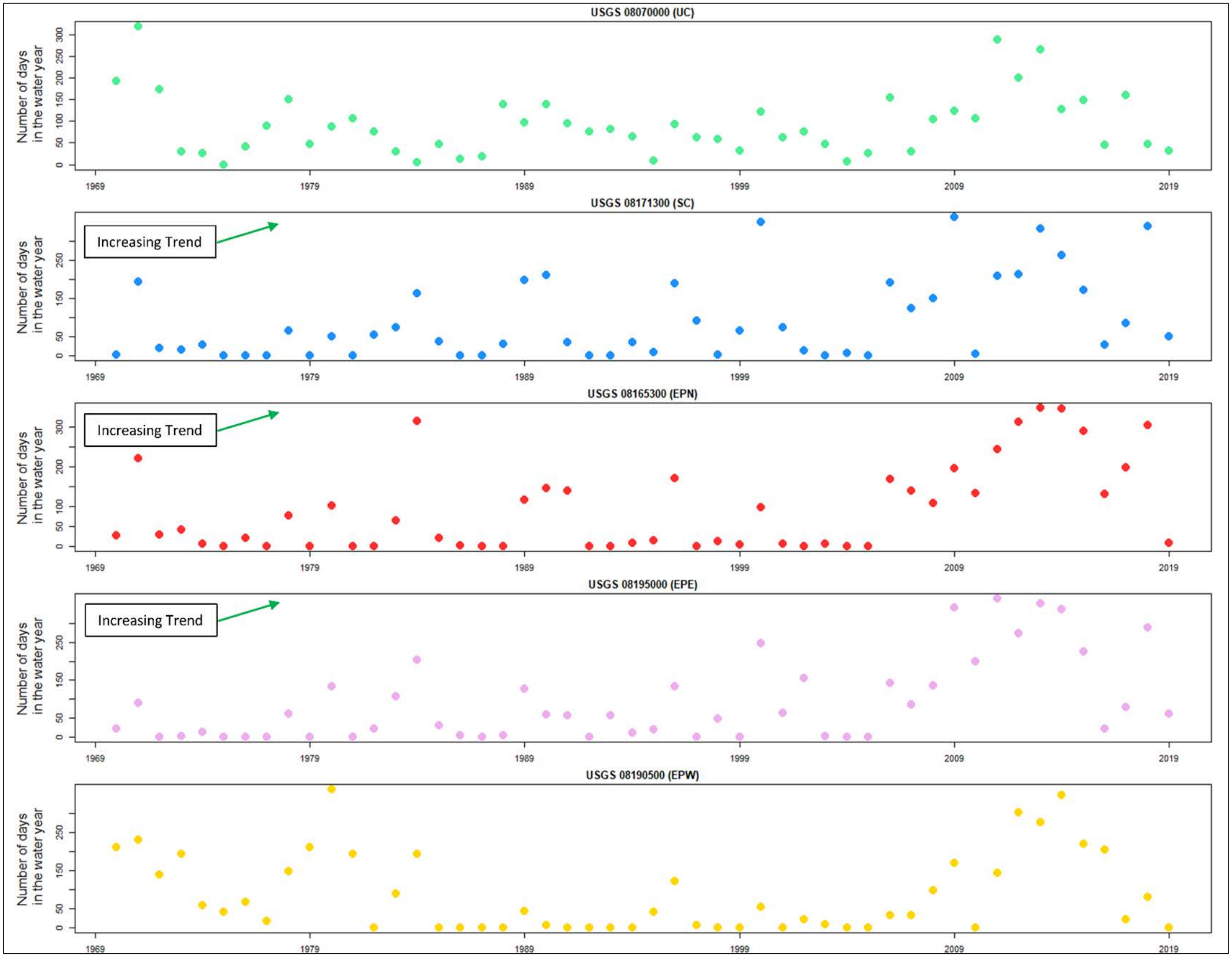

Figure 5. Trends in the number of days below the low flow threshold, defined as the number of days in the water year with daily mean flow below the 25th percentile of the overall time period (gage 08195000 is used to represent the EPE grid.)

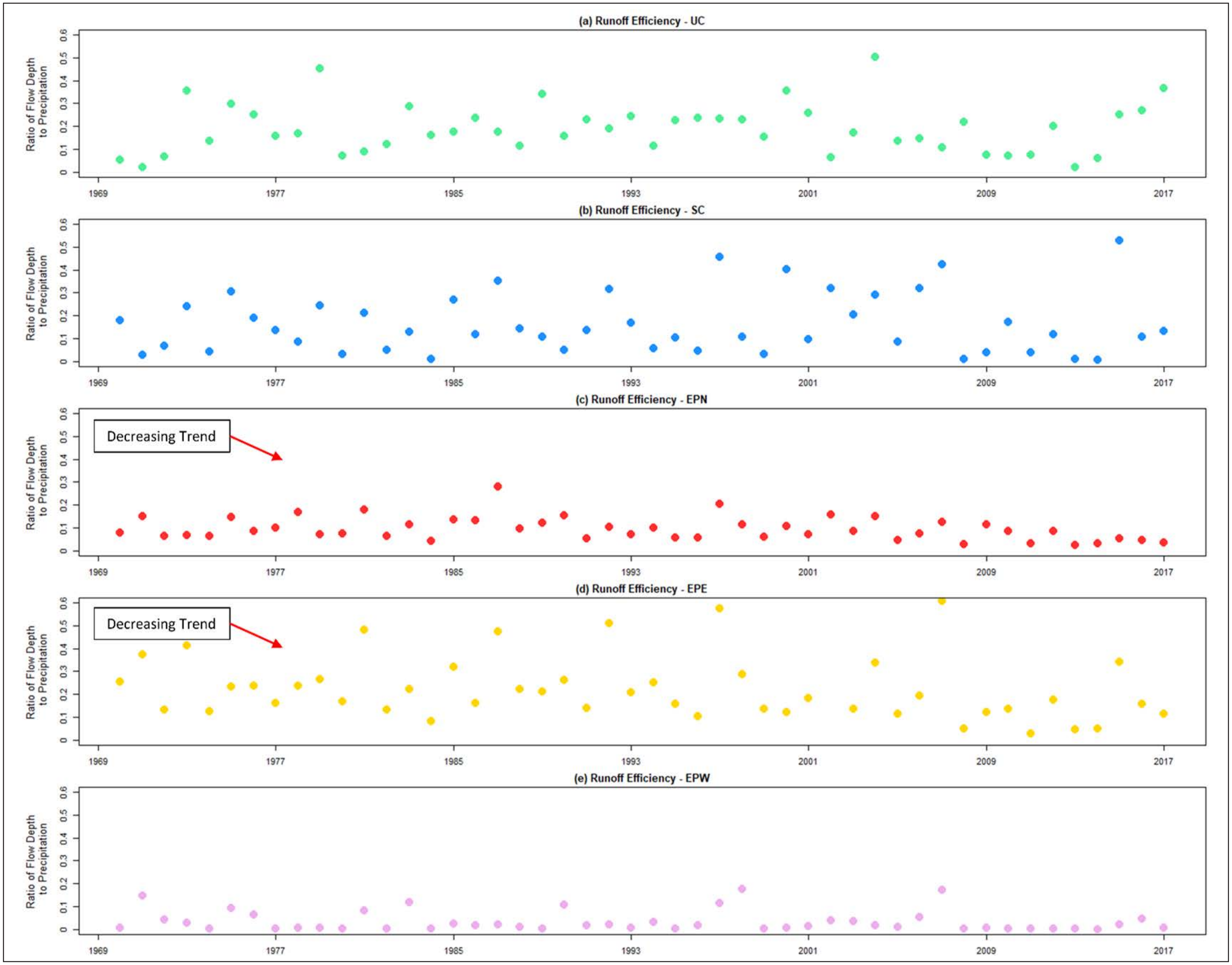

Figure 6. Runoff efficiency (ratio of annual streamflow to annual precipitation, both expressed in depth units) trends (gage 08195000 is used to represent the EPE grid.)

Table 4. Summary of trends in annual minimum, mean, and maximum baseflows (significance assessed at p≤0.05). Sen slope values are shown in parentheses; the units of flow are cumecs or m³/s.

Site ID/ Climatic division	Annual minimum	Annual mean	Annual maximum
08070000/UC	-	-	-
08171300/SC	↓ (-0.07)	-	-
08165300/EP	↓ (-0.15)	↓ (-0.24)	↓ (-2.54)
08190000/EP	-	-	-
08190500/EP	-	-	-
08195000/EP	↓ (-0.57)	↓ (-1.16)	↓ (-8.32)
08198500/EP	↓ (-0.01)	-	-

UC: Upper Coast climatic division; SC: South Central climatic division; EP: Edwards Plateau climatic division; ↓: decreasing trend

and OND 1–day and 30–day minimums, but there were no trends at this site in the winter season (JFM; Table 3). As for the magnitude of trends, despite showing significant declines in all annual and seasonal low flow metrics, site 08198500 had the lowest Sen slopes of all seven sites. In contrast, adjacent site 08195000 in the same EPE grid experienced the sharpest declines, with the OND and JFMs showing the largest slopes. On an annual basis, the Sen slope for the 30–day minimum flows is larger than the 1–day counterpart at site 08171300, but on a seasonal basis, the Sen slopes for the summer 1–day and 30–day minimum flows are nearly identical.

Trends in the number of days below the low flow threshold are shown in Figure 5. All sites except site 08070000 in the UC CD and site 08190500 in the EP CD show increasing trends (Figure 5). The annual RE was computed for each of the five CRU climate grids, with gage 08195000 being representative of the EPE grid for water years 1970–2017. Patterns in annual RE are shown in Figure 6 and locations where this metric showed a statistically significant trend (using MMK at a significance level of 0.05) are indicated. At the EPW grid, which encompasses the westernmost site 08190500, the maximum RE observed was nearly 0.2, indicating that, at best, 20% of annual precipitation is translated to runoff (Figure 6e). The RE in the majority of the years is <0.1 in the EPW, which is explained by the number of low flow threshold days (Figure 5). The largest interannual variability in RE is shown in the EPE grid (Figure S2; violin plots showing the kernel density, median, and interquartile range are presented as supplementary material). Although the largest REs (slightly more than 0.6) were recorded at this site, this metric shows declining trends here as well as in the EPN grid (Figures 6c, 6d). Interannual variability in RE is also pronounced in the SC grid, albeit with no statistically significant trends (Figure 6a). The UC grid shows no significant trends either (Figure 6b). We note that the averages of the REs for the five grids over the chosen 48-year duration are similar to the long-term REs computed by McCabe and Wolock (2016) for the period 1951–2012 for the hydrologic units they fall within.

The MMK test for annual minimum, annual mean, and annual maximum baseflow showed no significant trends in these three metrics in the UC CD site (08070000) or in the two westernmost sites in the EP CD, i.e., gages 08190500 and 08190000 (Table 4). The three remaining sites in the EP CD (gages 08165300, 08190000, and 08190500), as well as the SC CD (gage 08171300), all show declining annual minimum baseflows. Two EP sites (08165300 and 08195000) show significant declining trends in annual mean and annual maximum baseflows (Table 4).

Trends in well water levels

Trends in the annual maximum, mean, and minimum of daily-high water levels recorded at wells J17 (SC CD) and J27 (EP CD) were assessed at a significance level of 0.05. There were no significant trends in any of the three water level metrics at well J17. However, the annual maximum, annual mean, and annual minimum of daily-high water levels all showed significant decreasing trends at well J27. On a comparative basis, the Sen slope of the annual minimum of daily-high water levels was larger than the annual mean and annual maximum of daily-high water levels at this well.

From Figure 3, it is evident that well J27 lies in the artesian zone downgradient of gages 08190000 and 08195000, as well as in the same EPE grid as these two gages and gage 08198500. Water levels here are possibly influenced by the hydrology of the upgradient streams (losing streams) located in the recharge zone as well as climate variables such as temperature, precipitation, and PET. To further explore these relationships, cross-correlations and Spearman correlations were performed to estimate the r^2. The cross-correlation functions (CCFs) between the annual mean of the daily-high water level (AMDHWL) at well J27 and the three climate variables (on an annual scale) are shown in Figures 7a-7c. While precipitation appears to have no cross-correlation with the AMDHWL (Figure 7b), both temperature and PET show negative CCFs with a lag of approximately 1–2 years, indicating that above-average annual temperatures and PETs precede below-average groundwater levels by approximately 1–2 years. An even stronger CCF is found between annual mean streamflow at the upgradient gages (08190000 and 08195000) and the AMDHWL, as seen in Figures 7d and 7e. The CCFs are positive and peak at a 1–year lag, suggesting the influence of recharge to well J27 from above-ground flows at these two gages. A similar pattern is evident with the annual mean baseflows at these two gages (see Figures 7f and 7g). The strength of the linear relationship between the AMDHWL and the related hydrological variables is demonstrated using the r^2 metric in Figure 8. The negative correlation between the AMDHWL and both annual mean temperature and annual total PET are evident from Figure 8; the r^2 for both climate parameters is roughly the same (0.18) and is statistically significant. Weak positive correlations between the AMDHWL and annual mean streamflows as well as baseflows are also evident (Figure 8). The strongest r^2 occurs at gage 08195000 upgradient of well J27; 32% and 40% of the variance in AMDHWL are explained by streamflow and baseflow, respectively.

Analysis of drought indices

The percent of each decade spent under abnormally dry (i.e., below-average) and abnormally wet (i.e., above-average) conditions according to the SPI-12 and 12–month Standardized Streamflow Index (SSI-12) was computed and is shown in Figure 9. Abnormal conditions are defined as periods when the index exceeds +1 or drops below -1, while normal, or "average," conditions are characterized by values of the index between -1 and +1. Figure 9b shows that very little of each decade leading up to the 2010s was characterized by below-average flows in the EPN and EPE grids. However, more than 66% of the 2010s (water years 2010–2017) were characterized by below-average flows at these two grids. This observation is in stark contrast to the trends in the SPI-12 for these two grids (Figure 9a), where only 15% or less of the 2010s are classified as drier-than-average, suggesting a pronounced impact of temperature-influenced drying. Another interesting observation is the lack of above-average flow periods at the gages in the EPN and EPE during the 2010s, despite experiencing wetter-than-average conditions at least 15% of the time (Figure 9b and 9a, respectively). The temporal variations in the SPI-12 and the SSI-12 are shown as supplementary material (Figure S4).

DISCUSSION

Hydroclimatic trends, drivers and implications

At site 08070000 located in the UC CD, it appears that the increasing trend in annual mean temperatures has not impacted PET or streamflow. Although this gage is located in the UC CD, its contributing drainage basin is almost entirely located in the adjacent East Texas CD. Jiang and Yang (2012), Venkataraman et al. (2016), and Crawford et al. (2019) note that the eastern extreme of Texas (which encompasses the watershed contributing to gage 08070000) benefits from moisture surplus due to proximity to the Gulf of Mexico and generally suffers milder droughts relative to the rest of the State.

In the SC CD, statistically significant increases in annual and seasonal mean temperatures were detected at the SC grid, yet there were no trends in precipitation or PET. This gage (08171300) overlies the Edwards Aquifer recharge zone, where low flows and baseflows have been decreasing over the 50–year period beginning in 1970. Nearly one-third of the 2010s was spent in below-average SSI conditions — the worst among the five . However, in comparison with other CDs, this site endured the fewest below-average flow months in the 2010s. As such, the decrease in low flows and RE at this location may be temperature-driven, but modeling studies that explicitly account for the influence of temperature on streamflow are needed for further validation.

For the EP CD, generalizations cannot be made about any hydroclimatic variables except that annual and seasonal mean temperatures show increasing trends. While annual 1–day minimum and 30–day minimum flows exhibit decreasing trends at gage 08165300 on the South Fork of the Guadalupe River (in the EPN) and gages 08195000 on the Frio River and 08198500 on the Sabinal River (both in the EPE), gage 08190500 on the West Nueces River (EPW) shows no trends whatsoever; the same patterns are exhibited in baseflow. It appears that the West Nueces River in the EPW is intermittent, experiencing many zero flow days in a year. Consequently, there are no trends in any of the streamflow metrics or baseflow (which was separated from the streamflow data) despite increasing annual mean temperatures and PET. In fact, long periods of zero flow days, some lasting five consecutive months, have been reported in the West Nueces River (Thomas et al. 2019; Hackett 2019).

The drying trend in the EPN and EPE is further evident in the increasing number of days below the low flow threshold and

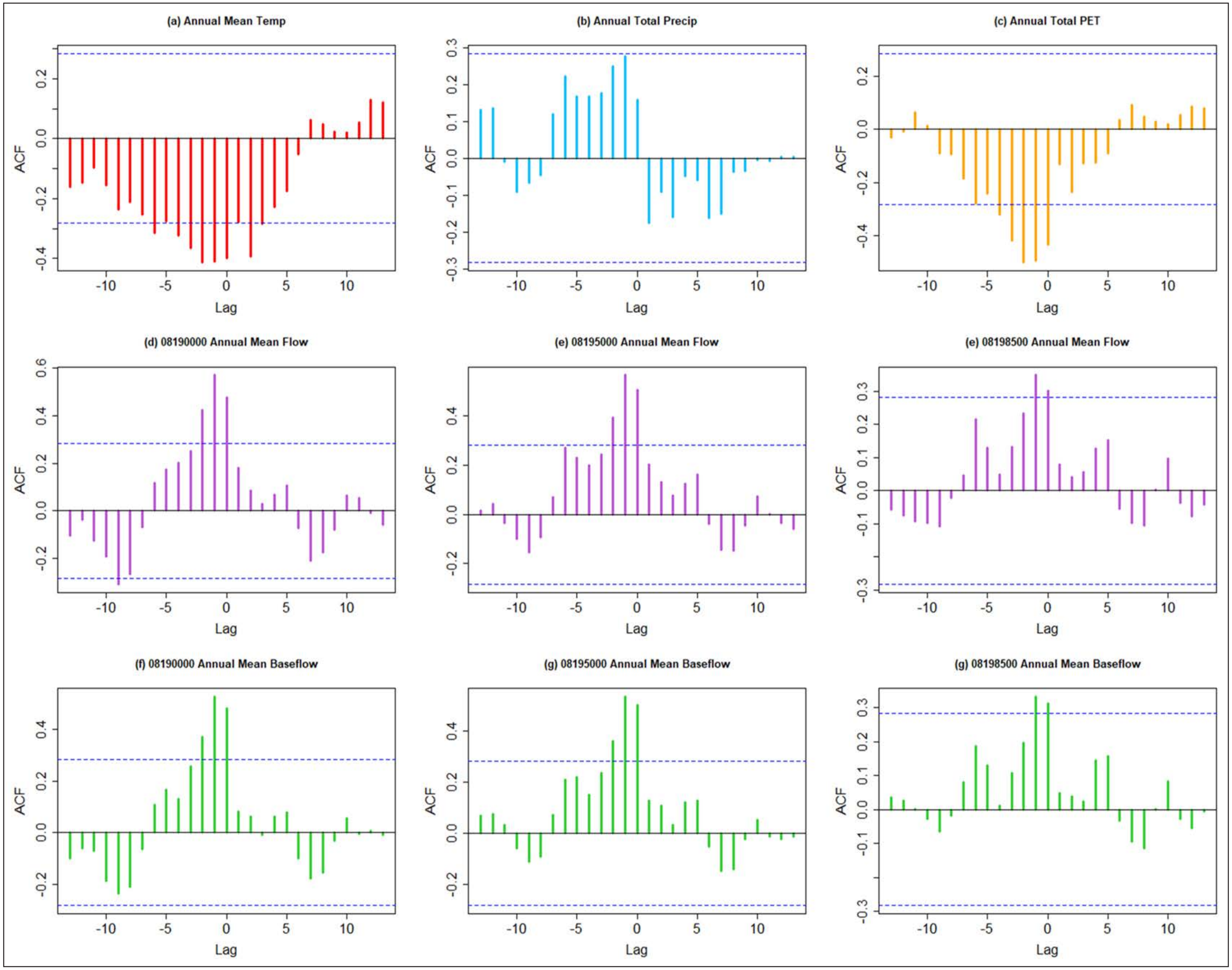

Figure 7. Cross-correlations between the annual mean of daily-high water levels at well J27 and (a) – (c): CRU variables in the EPE grid, (d) – (e): annual mean flows and (f) – (g): annual mean baseflows in upgradient gages.

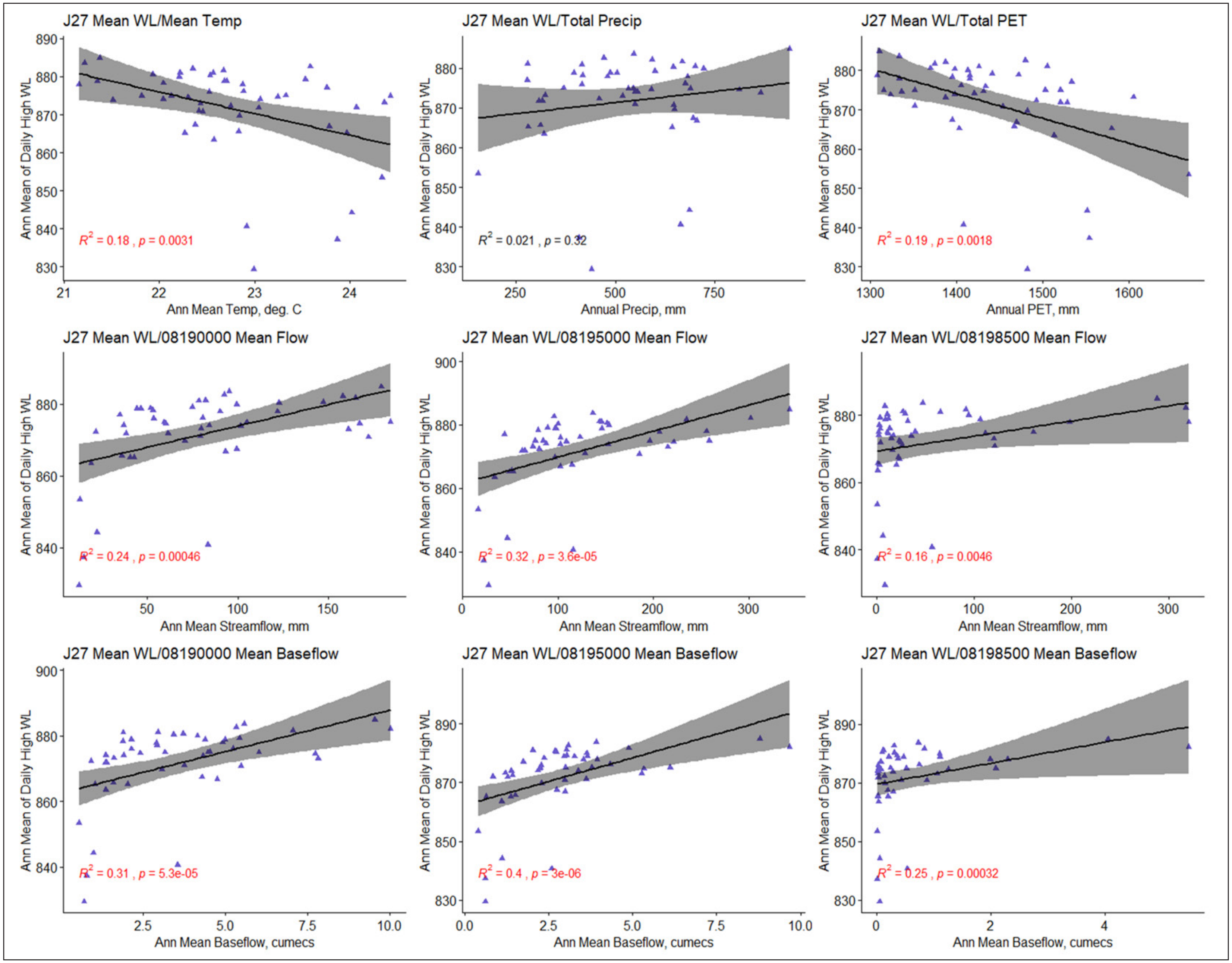

Figure 8. Regression analysis between the annual mean of daily-high water levels at well J27 and CRU variables in the EPE grid and annual mean flows and annual mean baseflows in upgradient gages (r^2 is shown in red where $p \leq 0.05$; the gray bands show the 90% confidence limits; cumecs = m^3/s).

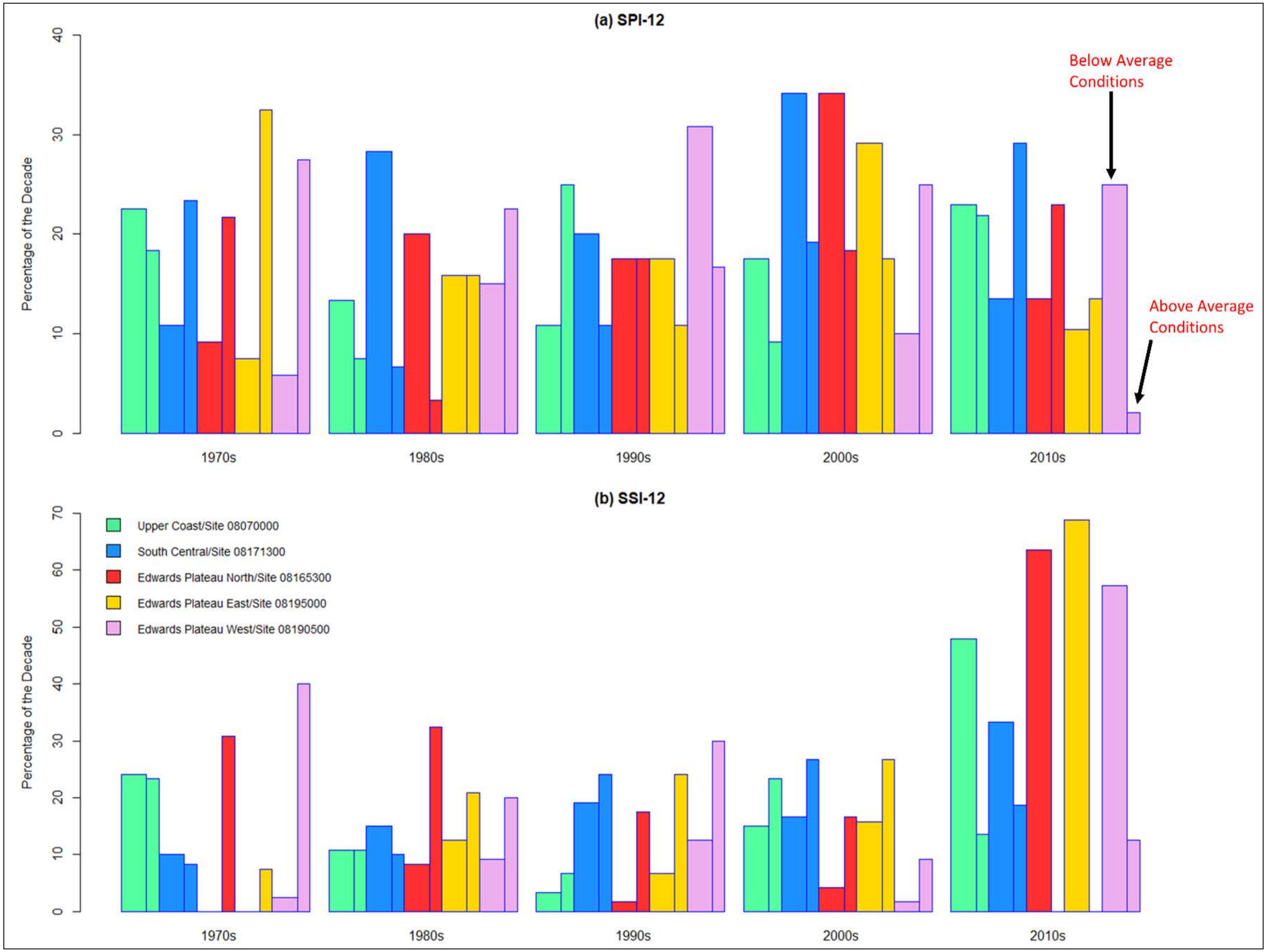

Figure 9. Total percent of the water year decade with below and above average (a) SPI-12, and (b) SSI-12 (the thicker bars show below-average conditions and the thinner bars show above-average conditions.)

decreasing runoff efficiencies. The EPN and EPE grids experienced no wetter-than-average months in the 2010s, and of the five chosen grids, experienced the worst streamflow droughts, as indicated by the percentage of the 2010s in below-average SSI conditions. The drying pattern in the EPE is particularly worrisome considering its moderate influence on daily-high water levels in well J27 located in the same climate grid. Lindgren et al. (2004) reported no long-term declines in water levels in the Edwards Aquifer, but their study was limited to the 20th century. They mentioned that water levels showed rapid recoveries after periods of drought and that the highest water levels were observed in the 1990s. Although we included only two wells in the Edwards Aquifer as part of our study, one of which (J17) showed no trends in daily-high water levels, there is evidence that daily-highs in well J27 have been decreasing since 1969. From a natural resource management perspective, water levels in the J17 and J27 wells are used by the EAA as the criterion for distinguishing stages of drought as part of a critical period management (CPM) plan. In Uvalde County, the water level of well J27 has been reported to be the most suitable indicator of drought severity by Green and Bertetti (2010), as river discharge did not appear to be useful. However, the cross-correlation at a 1-year lag between mean flows at gages 08190000 and 08195000, and the mean of daily-high water levels at well J27, as well as the moderately strong but statistically significant r^2 between the two, suggest that discharge at these two gages merits consideration for an early warning or preliminary drought trigger system for Uvalde County.

Although annual minimum flows and annual baseflows are decreasing in the EPN and EPE, the magnitude of these declines is higher in the EPE. This difference between the two grids is likely due to the combined effect of increasing temperature and increasing PET in the EPE as opposed to increasing temperature alone in the EPN. It is also worth noting that spring precipitation is decreasing in the EPE. Precipitation regimes in the EP CD are generally bimodal, with spring (May) and end-of-summer (September) accounting for the majority of annual precipitation. Therefore, decreasing spring precipitation possibly has a role in the drying observed here. Thomas et al. (2019) found similar drying patterns in streamflow in parts of the Upper Nueces River Basin, portions of which overlap our study area. They did not find any conclusive trends in ET in what is essentially the EPE grid of our study area for the period 1970–2015. However, their findings are based on ET data developed on a continental scale. Using the CRU climate dataset, which allows for analysis at a more localized scale, we have found increasing PET trends in the EP. The results of the correlation analyses also showed that the EPE grid had the highest r^2 between streamflow and PET as well as temperature of the five chosen climate grids. These r^2 (0.52 for PET and 0.37 for temperature) suggest the moderate influence of these meteorological parameters on streamflow. Considering the minimal anthropogenic impact on these watersheds, the stream drying observed here may be climate-driven.

As for secondary factors involved in the drying pattern observed in the EPN and EPE, we first consider the karst landscape of the EP and its impact on rainfall-runoff relationships. Wilcox et al. (2008) reported that where soils are shallow and underlain by impermeable limestone in this region, overland flow dominates subsurface flow. Additionally, they highlighted the presence of overland flow zones in areas with certain types of vegetation, i.e., woody plants versus grass and shrub cover. Wilcox and Huang (2010) further suggested that degradation of karst landscapes may result in declines in groundwater recharge and, subsequently, baseflow, but above-ground river flows may recover with an increase in woody plant cover. The implications of these two studies are that in the EP, particularly the EPE grid, spatial variations in the karst landscape may result in (a) a greater fraction of overland flow versus subsurface flow, which may lead to greater exposure to the elements in a drying climate; or (b) reductions in baseflow where these landscapes may be degraded. Lindgren et al. (2004) emphasized that the recharge zone of the Edwards Aquifer is characterized by a "dual- or triple-porosity nature" and that groundwater flow in this zone is poorly understood. Recent studies, such as Kromann (2015) and Hackett (2019), report that the nature of streamflow losses and gains in these segments and their subsequent role in drying patterns are unclear and merit further research. The last factor that cannot be ignored is the role of surface water governance. Although groundwater use in the Edwards Aquifer is strictly regulated by the EAA, all surface water in this watershed is owned by the State of Texas and appropriated to users through a system of water rights permits. Thomas et al. (2019) noted that withdrawal of surface water beyond the allocated quota may occur in parts of the EP CD (which fall under the EAA's jurisdiction), particularly in times of low streamflow. Such violation of the honor system (which involves self-reporting of water extraction) may go unnoticed and unreported. It must be added that the Blanco River in the SC climate division may suffer from the same exploitation of water rights since it does not fall under the purview of a Watermaster system.

Ecological implications

Regarding ecological implications, the reduction in baseflow we note in our study may influence stream communities of the EP and may provide a preliminary indication of a changing flow regime. Reduced baseflow and drying events/droughts have demonstrated effects on the communities of other streams. For example, even though the low presence of riffles in streams with intermittent flows can lead to lower species richness than in perennial streams, macroinvertebrate communities are still found to be diverse (Santos and Stevenson 2011). Interestingly, the communities of streams with intermittent flows can be distinct from perennial streams in terms of functional feeding groups and benthic communities (Santos and Stevenson 2011), rare and endemic niche specialists (Stubbington et al. 2017), and a combined biodiversity composed of aquatic and terrestrial species due to the dry–wet regime of the system (Bunting et al. 2021). Streams with intermittent flows have diverse and shifting communities during lentic (flowing), lotic (ponding), and dry phases such that they contribute greatly to the overall biodiversity of the entire catchment, both aquatic and terrestrial (Stubbington et al. 2017; Hill and Milner 2018). In the EP, hydrological connectivity of the streams is critical to the resilience of the basin community, as baseflow is apt to decline as drought worsens. Moreover, the dry–wet phases of a stream require that both aquatic and terrestrial communities be characterized and considered in management, as they are both affected and can colonize a streambed quickly in either flow regime (Bogan et al. 2017; Bunting et al. 2021). This suggests that even terrestrial species of ecological concern in EP, such as the Texas Snowbell (*Styrax platanifolious* ssp. *texanus*), could potentially be influenced by changing flow regimes.

The management and conservation of ecologically significant stream segments ideally focus on maintaining ecological resilience (here defined as the ability of an ecosystem to maintain structure and function in the face of disturbance, per Holling 1973). The findings of this study agree with those of others that climate exerts a high-order environmental control on low- and no-flow stream conditions. However, regional-scale climatic, physiographic, and anthropogenic factors play important roles in determining the flow regime of streams (Reynolds et al. 2015; Hammond et al. 2020). Drought protection of ecologically significant stream segments should consider habitat diversity to preserve ecological functions. For example, perennial pools and flowing reaches provide drought refuges and habitat for newly colonizing taxa (Chester and Robson 2011; Hill and Milner 2018), and headwaters, especially in forested catchments, host high biodiversity (Storey et al. 2011; Bogan et al. 2015). In general, knowledge of the spatial distribution of perennial and intermittent river channels in a river basin would optimize such protection plans (González-Ferreras and Barquín 2017). Furthermore, an ecological understanding of the life history traits of the organisms relying on drought refuges, especially endangered species (Robson et al. 2011), would help provide targeted conservation management plans for ecologically significant stream reaches.

CONCLUSION

Investigation of low flows is a critical part of evaluating the overall health of a stream and is imperative for long-term natural resource management. In this study, we have used a variety of metrics to assess the low flow characteristics of stream segments in Texas that serve a unique hydrologic function for the period covering water years 1970 through 2019 using discharge data from seven USGS gages. Although annual mean temperatures have been increasing in all climate divisions chosen in this study, critical inter- and intra- climate division differences highlight the spatially diverse nature of the State of Texas. As such, there are no significant streamflow trends in the gage located in the UC CD, the watershed for which lies in the East Texas CD, likely due to proximity to the Gulf of Mexico. The Blanco River in the SC CD, and the trio of the South Fork of the Guadalupe River, the Frio River and the Sabinal River in the EP CD have undergone pronounced drying since the water year 1970. We performed LULC analysis of the watersheds contributing to these gages and confirmed that they have undergone little to no change over time, indicating minimal anthropogenic influence. Therefore, the results of the correlation analysis with climate variables and the comparison of drought indices suggest that the drying we have observed may be climate-driven. It must be noted that our findings and interpretations are based on a small subset of stream gages confined to three climate divisions in the State, and therefore far-reaching conclusions or generalizations about regional patterns or trends cannot be made.

Overall, in planning for changes associated with climate change and human water demand, several studies concur that intermittent streams are critical components of a river basin in terms of biodiversity, community dynamics, biogeochemical cycling, ecosystem services, and ecological resilience, even during dry phases. This study finds evidence of increasing temperature, declining spring precipitation, increasing PET, and declining minimum flows and daily-water level highs for the EP, although there are seasonal and physiographic differences in these trends among sites. In general, if the EP were to experience more temperature-driven drying and drought conditions in the future, the streams would provide important drought refuges at perennial pools and hyporheic zones in addition to the habitat and ecosystem services they already provide as flowing waterbodies. Moreover, the role of streams in recharging the Edwards Aquifer will remain important even when the streams do not have surface flow. The EP streams investigated in this study will likely remain ecologically significant in the future and the use of climatic and land use variables to monitor and predict conditions in the region will be critical for their conservation and management.

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SUPPLEMENTARY MATERIAL

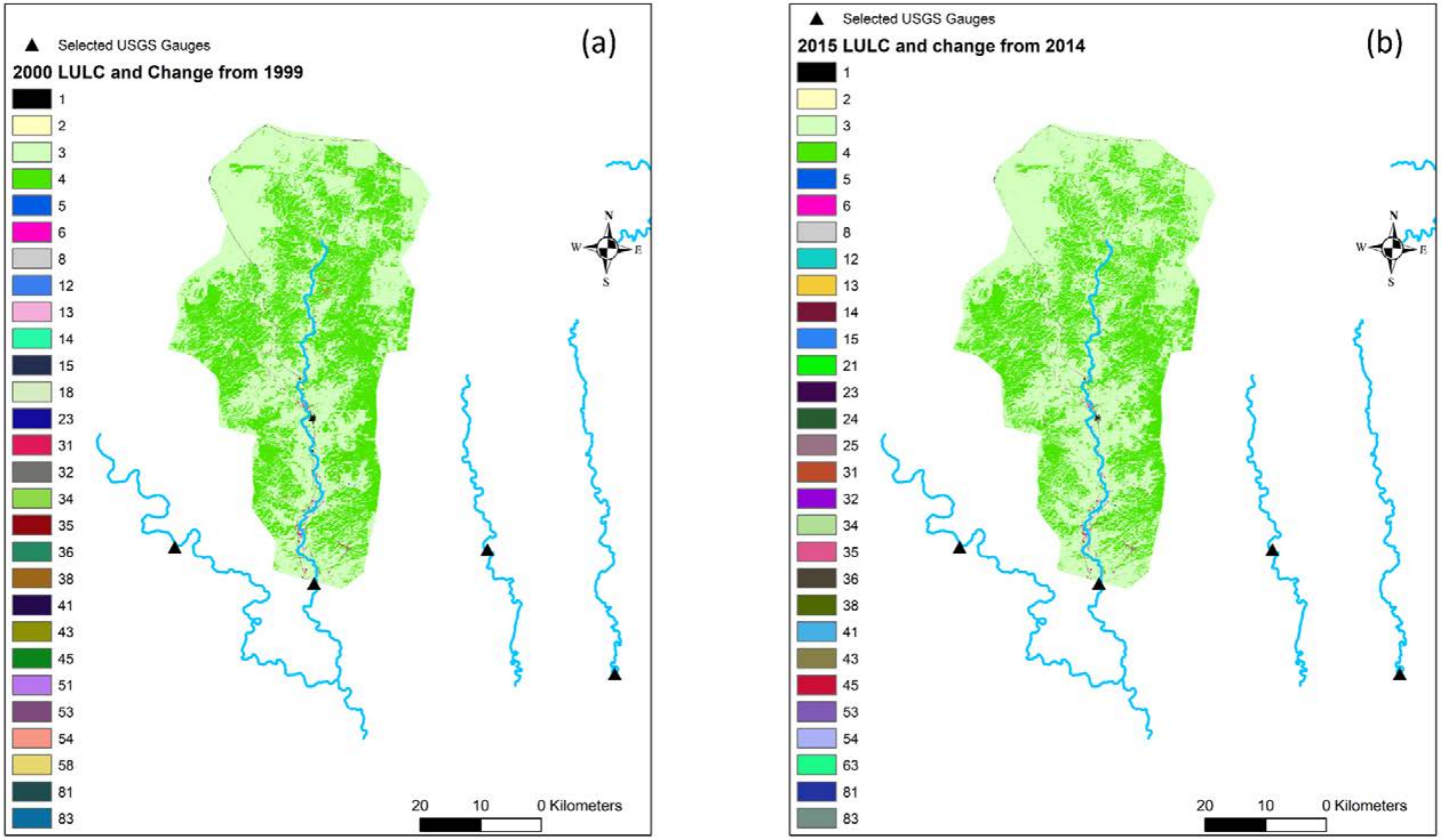

Figure S1. Figure S1. Land use land cover (LULC) for the watershed contributing to site 08190000: (a) in the year 2000 and change relative to 1999, (b) in the year 2015 and change relative to 2014. Site 08190000 is shown as a representative sample of the seven gages while years 2000 and 2015 are shown as representative samples of the LULC temporal dataset.

LULC codes: 1 – developed land; 2 – cropland; 3 – grass/shrub cover; 4 – tree cover; 5 – water; 6 – wetland; 8 – barren; double digit codes show change from one category to another. For example, 12 indicates change from class 1 (developed) to 2 (cropland) during that 1-year time frame.

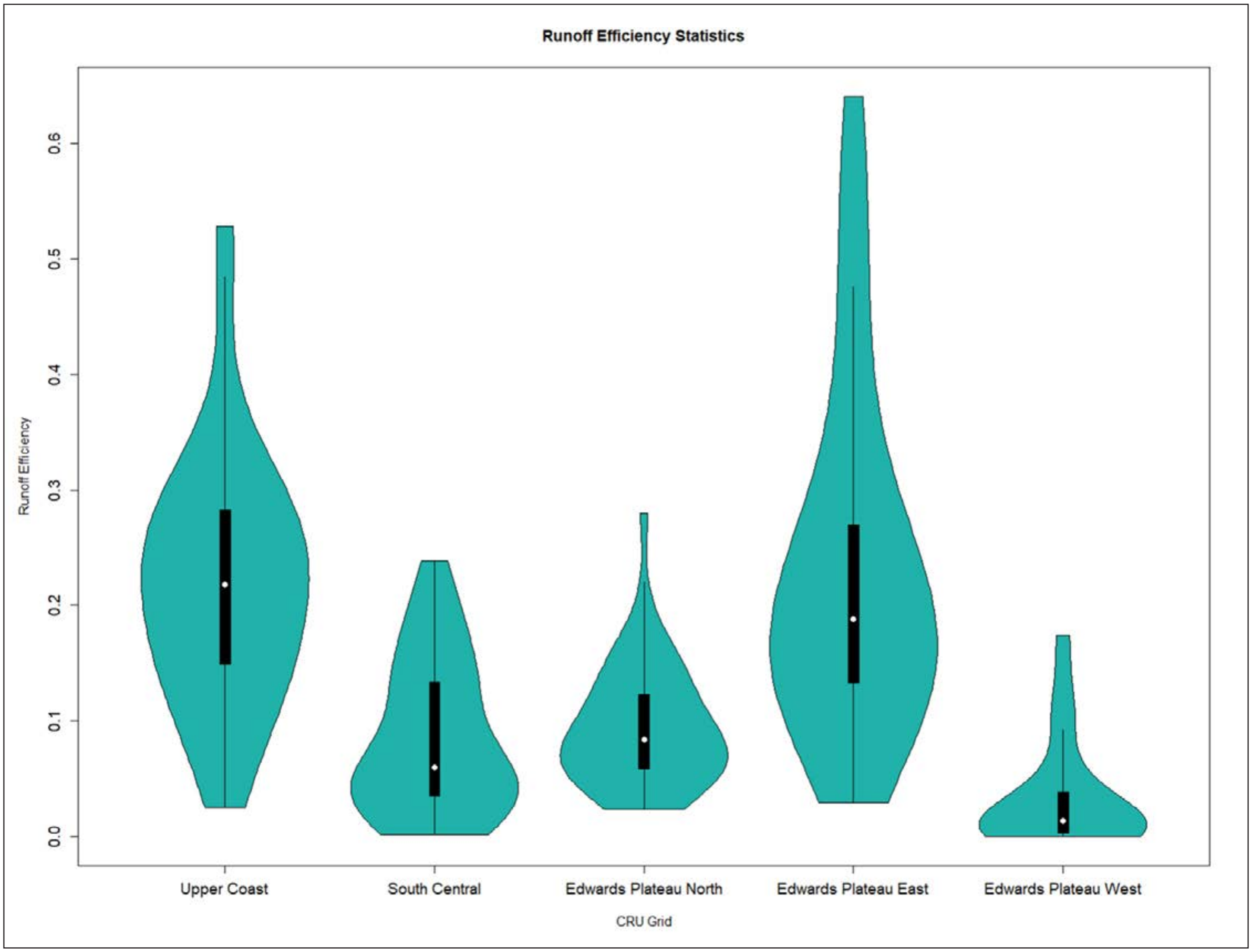

Figure S2. Runoff Efficiency (ratio of annual streamflow depth to annual precipitation) Statistics.

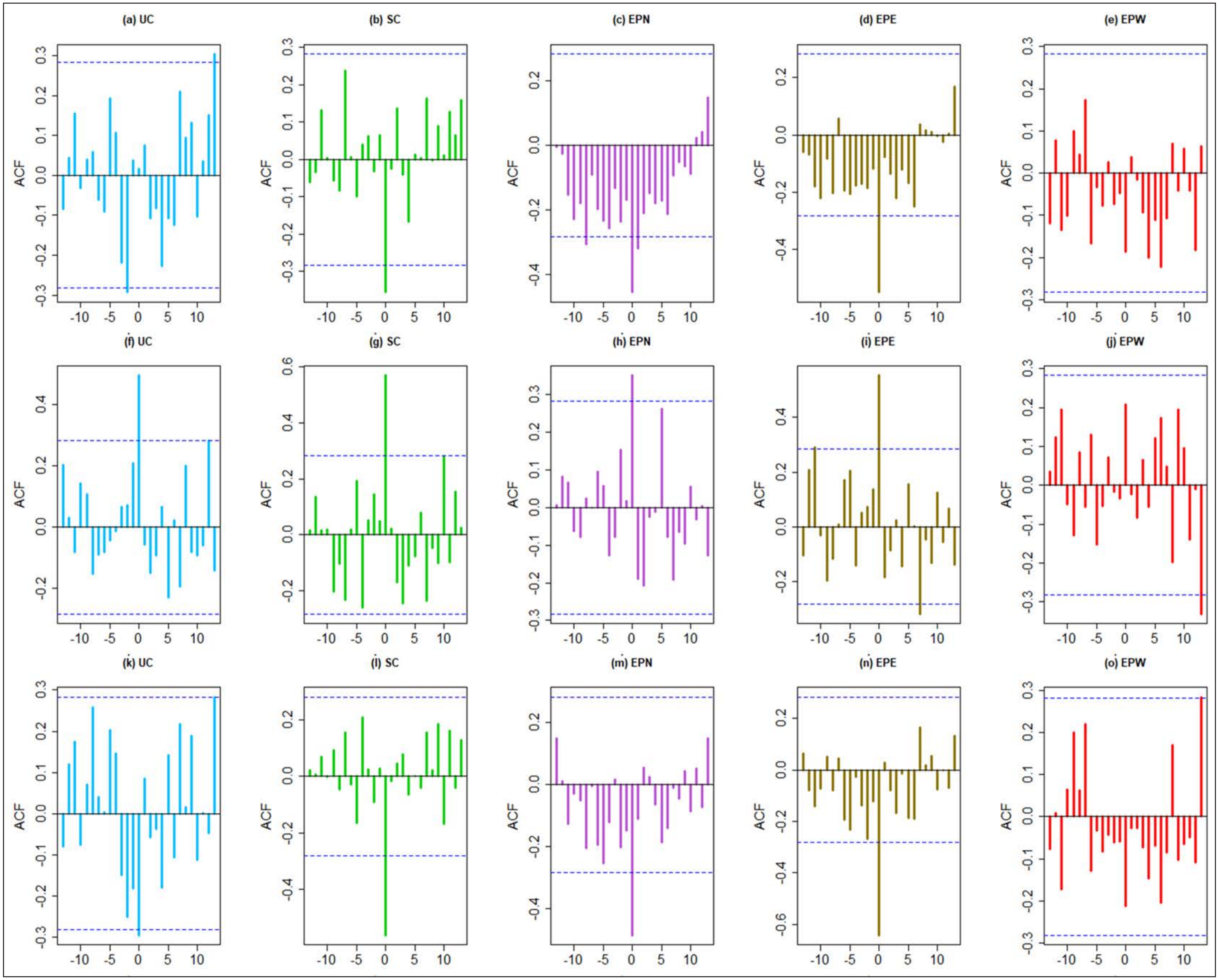

Figure S3. Cross-correlation between annual streamflow depth (in mm) and (a)-(e): annual mean temperature, (f)-(j): annual total precipitation, in mm, (k)-(o): annual total PET, in mm.

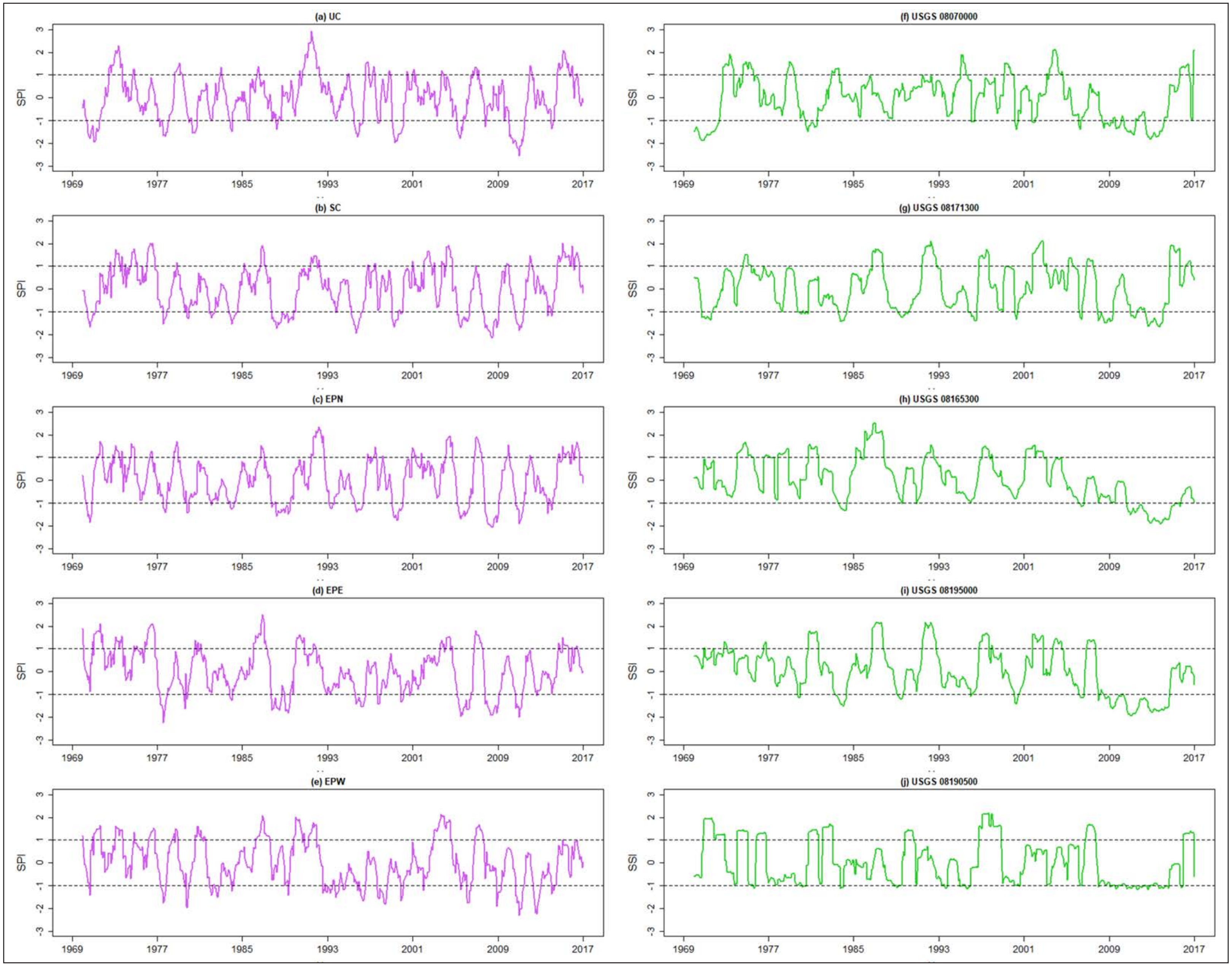

Figure S4. (a) - (e): SPI-12 (from CRU dataset) and (f) - (j): SSI-12 (from USGS gages).

Table S1. Summary of trends and changepoints in annual minimum, mean, and maximum of daily-high water levels at wells J17 and J27 (significance assessed at $p \leq 0.05$). Sen slope values are shown in parentheses.

Well ID	Annual minimum	Annual mean	Annual maximum
J17	-	-	-
J27	↓ (-0.19)	↓ (-0.15)	↓ (-0.09)

↓: decreasing trend

Table S2. Time scale for various metrices and indices.

Parameter	Analysis	Metric / Index	Timescale / temporal resolution
Temperature	Correlation with streamflow	r^2	Annual
	Trend analysis	modified Mann Kendall test (MMK)/Sen Slope	Annual and Seasonal
	Cross-correlation with well water level	cross correlation function (CCF)	Annual
Precipitation	Correlation with streamflow	r^2	Annual
	Trend analysis	MMK3/Sen Slope	Annual and Seasonal
	Drought index	SPI-12	Aggregation of monthly precipitation on a 12-month scale
	Cross-correlation with well water level	CCF	Annual
PET	Correlation with streamflow	r^2	Annual
	Trend analysis	MMK3/Sen Slope	Annual and Seasonal
	Cross-correlation with well water level	CCF	Annual
Streamflow	Trend analysis	MMK/Sen Slope	Annual 1-day minimum, Annual 30-day minimum Seasonal 1-day minimum, Seasonal 30-day minimum
	Number of days below the low flow threshold	MMK	Annual
	Runoff efficiency	MMK	Annual
	Correlation with well water level	r^2	Annual
	Drought index	SSI-12	Aggregation of monthly mean flow on a 12-month scale
Baseflow	Trend analysis	MMK	Annual minimum, annual mean, annual maximum
	Cross-correlation with well water level	CCF	Annual mean
Well water level	Trend analysis	MMK	Annual mean, minimum and maximum of daily-high water level

PET: Potential Evapotranspiration; CCF: cross correlation function; MMK: modified Mann Kendall test; SPI-12: 12–month Standardized Precipitation Index; SSI-12: 12–month Standardized Streamflow Index;

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The Use of Historical Data and Global Climate Models to Assess Historical and Future Surface Water and Groundwater Availability in the Trinity River Basin in Texas

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Abstract: As part of the Integrated Water Availability Assessment Program, the U.S. Geological Survey (USGS) and local partners, compiled historical data and developed surface-water (1980–2099) and groundwater (1949–2087) models to assess changes in recent historical and future water availability in the Trinity River Basin in Texas. A Trinity River Basin surface-water model and a Trinity River alluvium aquifer groundwater model were created to evaluate future water availability and long-term trends under different global climate model scenarios. The Trinity River Basin is divided into two regional water planning groups: Region C Water Planning Group and Region H Water Planning Group. Trend analyses using historical data (1900–2017) indicated an increase of annual precipitation on the watersheds that drain into the reservoirs in Region C Water Planning Group. However, the global climate model ensemble mean for the Trinity River Basin surface-water model indicates a downward trend in annual precipitation, resulting in a downward trend in Hortonian runoff. Additionally, the global climate model ensemble mean for the Trinity River Basin surface-water model and the Trinity River alluvium aquifer groundwater model both indicate a downward trend in recharge. The results show that the change in future water availability that can be attributed to climate change is small, assuming the average of the ensembles is the best predictor of the future.

Keywords: water availability, surface water, groundwater, water budget, trends, Trinity River

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Terms used in paper

Acronym / Initialism	Descriptive Name
CMIP5	Coupled Model Intercomparison Project Phase 5
GCM	Global Climate Model
gSSURGO	Gridded Soil Survey Geographic Database
HRU	Hydrologic Response Unit
IWAA	Integrated Water Availability Assessment
LLNL	Lawrence Livermore National Laboratory
LOCA	Localized Constructed Analogs
m/day	Meters per day
NetCDF	Network Common Data Form
NHM	National Hydrologic Model
NOAA	National Oceanic and Atmospheric Administration
PRMS	Precipitation-Runoff Modeling System
RCP	Representative Concentration Pathway
RWPG	Regional Water Planning Group
SWB	USGS Soil-Water-Balance Code
TRA	Trinity River Authority
TRAA	Trinity River alluvium aquifer
TRB	Trinity River Basin
TWDB	Texas Water Development Board
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey

INTRODUCTION

In 2019, the U.S. Congress provided the U.S. Geological Survey (USGS) Water Availability and Use Science Program with resources to implement Integrated Water Availability Assessments (IWAAs). The purposes of the IWAAs are to provide nationally consistent assessments of water availability and identify factors that limit water availability. The IWAAs are designed to meet the following six objectives: (1) provide accurate assessments of available water resources, (2) determine the quantity of water available for human and ecological needs, (3) quantify long-term trends in water availability, (4) provide assessments of changes in water availability, (5) explore factors that limit water availability, and (6) forecast water availability for economic development, energy production or conservation, and environmental or other in-stream uses (USGS 2021a). The Trinity River Basin (TRB) in Texas was selected as one of 10 basins to support development of IWAAs with state and local partners using cooperative matching funds (USGS 2021b).

The TRB is a major source of water for large, rapidly growing metropolitan areas in Texas. Maintaining the quantity and quality of water resources is vital to meeting the water demands of the greater Dallas-Fort Worth metropolitan area and downstream metropolitan areas such as the Houston metropolitan area, which are among the fastest growing cities in the United States (U.S. Census Bureau 2020a, 2020b). In response to current (2022) water demands and increasing demand requirements associated with population growth, an improved understanding of current and future water availability is needed to help resource managers efficiently manage water resources in the TRB and plan for future needs. To gain a better understanding of water availability, the USGS entered into a cooperative agreement with the following entities that manage water resources in the TRB: Trinity River Authority (TRA), City of Dallas, North Texas Municipal Water District, and Tarrant Regional Water District.

Purpose and Scope

The purpose of this study was to assess TRB water availability, quantify long-term trends, and forecast future TRB water availability. This was done using surface-water and groundwater models to evaluate future conditions under different global climate scenarios. This assessment builds on a recently completed study that evaluated historical long-term trends in streamflow and other hydrologic properties for the TRB as well as other water-supply basins in Texas (Harwell et al. 2020). In this study, those historical long-term trends were used to forecast climate scenarios, and the results were used to inform a surface-water model (Precipitation-Runoff Modeling System [PRMS] model) and groundwater model (MODFLOW numerical groundwater-flow model). The water-availability assessment was done by using historical and recently collected data to assess possible changes in future TRB water availability. The surface-water and groundwater models were used to evaluate future conditions under different existing global climate models (GCMs) through 2099 and 2087, respectively. Using historical data and GCMs provided a means for comparison of various climate projections in the TRB.

The GCMs that were used were published as part of the Localized Constructed Analogs (LOCA) downscaling Coupled Model Intercomparison Project Phase 5 (CMIP5; LLNL 2021). To help account for the inherent uncertainty associated with GCMs, 30 different GCMs were chosen to simulate the ranges of possible values for climatic variables such as precipitation and temperature for surface-water and groundwater predictive models. An ensemble mean was computed for each climatic variable from these ranges of possible values.

Study Area

The Trinity River's headwaters are in north-central Texas, west of the Dallas-Fort Worth metropolitan area. From there, the river flows approximately 550 miles southeast into the Gulf of Mexico, east of Houston, Texas (TWDB 2019). South of the Dallas-Fort Worth metropolitan area, four main tributaries join to form the main stem of the Trinity River: Clear Fork Trinity River, West Fork Trinity River, Elm Fork Trinity River, and East Fork Trinity River (Figure 1; TRA 2021). The TRB covers 17,913 square miles and is the largest river basin contained entirely in Texas (TWDB 2019). The Texas Water Development Board's (TWDB) regional water planning groups (RWPGs) divide Texas into different regions for water-management purposes (TRA 2021). Most of the TRB (81%) is included in either RWPG C (hereinafter referred to as Region C) or RWPG H (hereinafter referred to as Region H). Region C includes the upstream part of the TRB, whereas Region H includes the downstream part of the TRB. The Trinity River provides water to more than half the population of Texas. As of July 2016, the populations of regions C and H were 7.23 and 6.80 million, respectively, and are projected to increase to 14.0 and 11.7 million, respectively, by 2070 (TRA 2021). Municipal water demands accounted for 90% of the total use in Region C in 2016 and 55% in Region H in 2015 (TRA 2021). About 90% of the water supply in Region C is from surface water, mostly from reservoirs, and about 71% of the water supply in Region H is from surface water (TRA 2021).

There are 32 reservoirs in the TRB, with a total of about 7.0 million acre-feet of conservation storage (TRA 2021; TWDB 2019). As of 2022, the USGS operates 24 lake and reservoir water-surface elevation stations in the TRB (USGS 2022). Of the 32 reservoirs, 14 were analyzed in Harwell et al. (2020) for historical long-term trends, and these 14 reservoirs represent 74% of the total storage in the TRB.

Harwell (2020) divided the TRB into five sections; section 1 was the most downstream, and section 5 was the most upstream section. Within Harwell et al.'s (2020) five defined sections, the mean annual precipitation from 1900 through 2017 was 51.28, 44.87, 38.55, 37.38, and 34.53 inches for sections 1, 2, 3, 4, and 5, respectively (Figure 2). Annual precipitation and annual reservoir surface evaporation indicate that for most of Texas, evaporation exceeded the mean annual precipitation: annual evaporation during 1954–2013 averaged 55.1 inches, while the mean annual precipitation during 1940–2014 averaged 39.4 inches (Wurbs and Zang 2014; Wurbs 2021; TWDB 2021a).

Although surface water accounts for 90% of Region C's water supply, groundwater is an important source of municipal water supply in some of Region C's rural areas (TRA 2021). Within Region H, groundwater accounts for about 28% of water supply (TRA 2021). One groundwater source, the Trinity River alluvium aquifer (TRAA), underlies the Trinity River and its adjacent stream corridor and tributaries (Figure 1). The TRAA consists of alluvium and terrace deposits of gravel, sand, silt, and clay of Quaternary age (Hanko and Brikowski 2009; USGS 2014) and covers about 5,265 square miles, or 29% of the TRB. Groundwater–surface-water interactions take place between the alluvium and terrace geologic units that contain the TRAA and the overlying Trinity River and its tributaries, indicating that groundwater resources can be affected by changes in streamflow. Although TWDB does not recognize the TRAA as a major or minor aquifer in Texas, it is recognized as a viable aquifer by Groundwater Management Area 14, Region H, and the Bluebonnet Groundwater Conservation District (Groundwater Management Area 14 et al. 2016; Region H Water Planning Group et al. 2020; Williams 2010). Although few data related to the TRAA were available as of 2021 for model input and calibration (TWDB 2021b), modeling of the groundwater in the alluvium was included in this study to better understand future water availability.

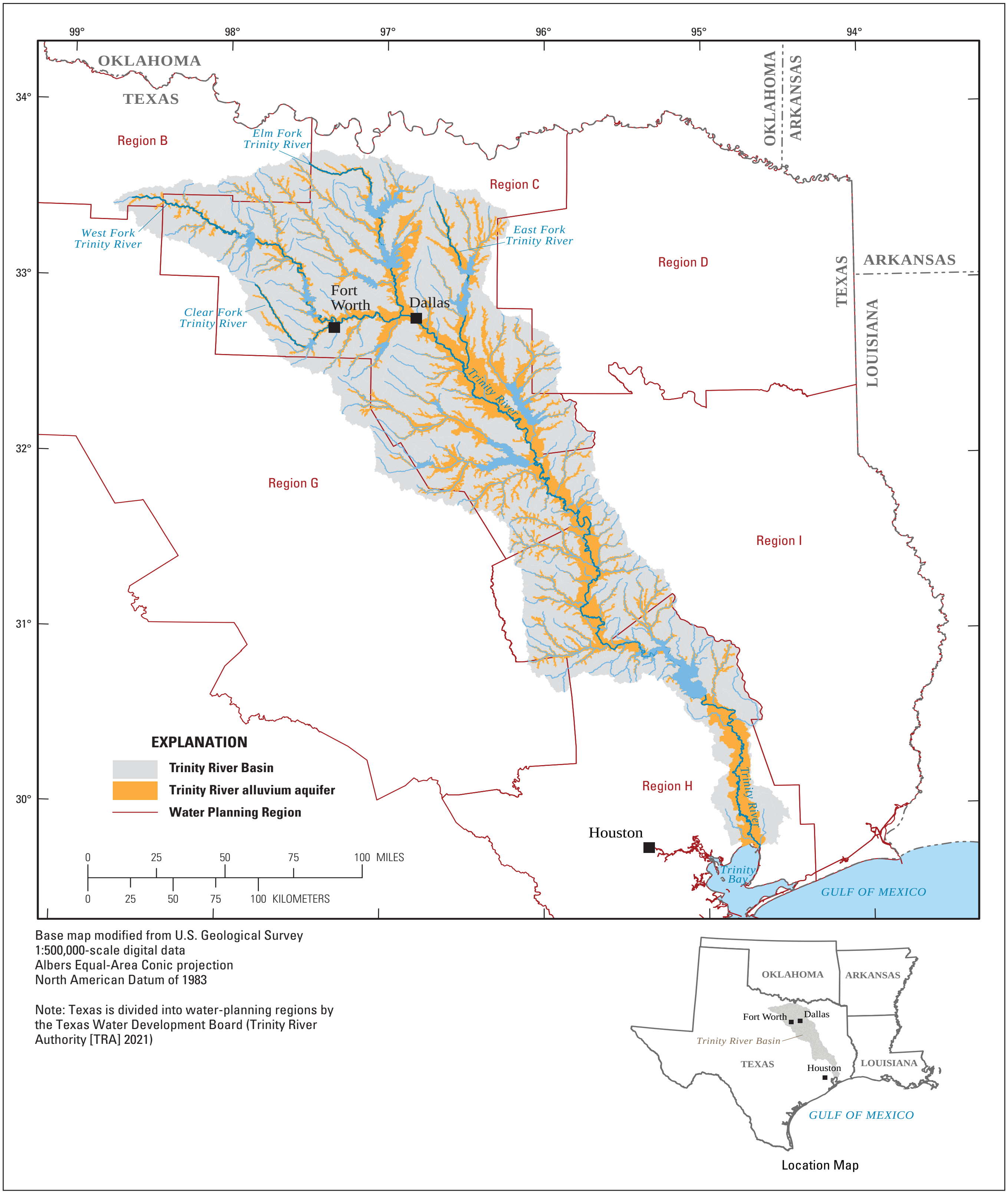

Figure 1. Trinity River Basin study area, Trinity River Alluvium aquifer (TRAA) extent, and regional water planning group extents.

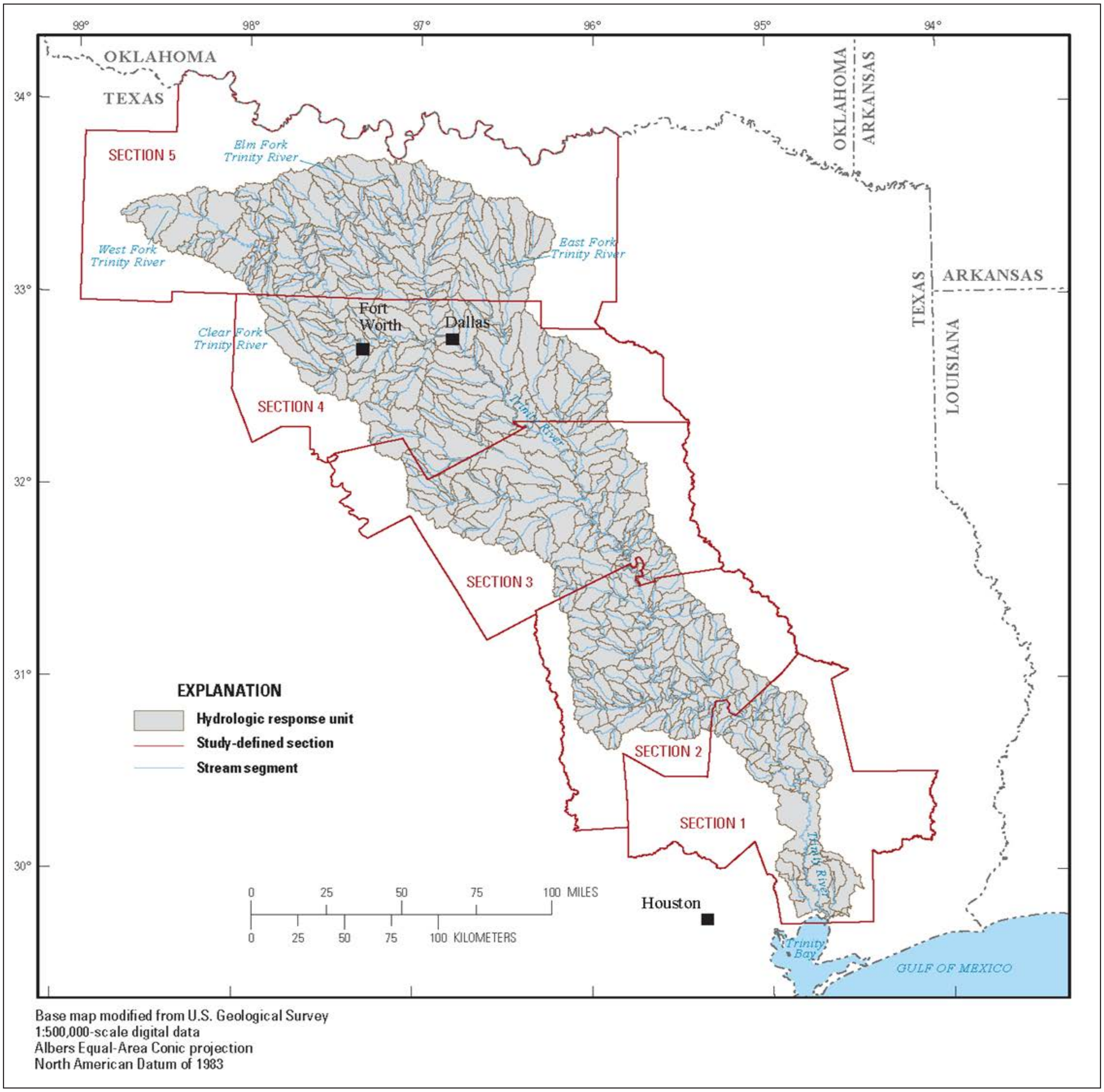

Figure 2. Trinity River Basin PRMS model extent showing 1,192 hydrologic response units and 620 stream segments (Hay 2019) and showing sections used in long-term trend analysis (Harwell et al. 2020).

METHODS

The following methods were used to better understand water availability: a statistical analysis of hydrologic trends and the development of surface-water and groundwater models for forecasting purposes. A surface-water model of the TRB was developed by using the PRMS (Leavesley et al. 1983). A numerical groundwater-flow model of the TRAA was developed by using MODFLOW-NWT (Niswonger et al. 2011), which is a modified form of the MODFLOW-2005 groundwater-flow model (Harbaugh 2005). The surface-water and groundwater models were then used for forecasting climate scenarios. Historical precipitation and air temperature values, as well as GCMs, were used to simulate current and projected water-budget components. The methods for each approach and the methodology for selecting the GCMs are discussed below.

Long-term Trends

Using the same methods used in Harwell et al. (2020), Kendall's *tau* was used to detect upward or downward trends in precipitation, groundwater levels, and streamflow. Kendall's *tau* is a rank-based correlation coefficient that measures the strength of the monotonic relationship between two variables. The relationships between precipitation and streamflow and between streamflow and storage were also assessed using Kendall's *tau*. Multiple regression equations with periodic functions were developed to test the statistical significance of any changes in annual mean air temperature over time at the 95% confidence level (p-value ≤ 0.05; Helsel et al. 2020).

The approach used by Harwell et al. (2020) to analyze for trends in different sections of the TRB was also used in this study. The previously mentioned five sections defined by Harwell et al. (2020) were created by making roughly equal divisions of the aggregated counties that overlap the TRB. These sections were used for analyzing historical long-term trends (Figure 2). This accounted for possible latitudinal and longitudinal climate differences across the TRB with respect to precipitation trends. An area-weighted daily mean precipitation total was computed for each section from the daily precipitation data (NOAA 2021). The area-weighted daily mean precipitation totals were analyzed for temporal trends in precipitation over monthly, seasonal, and annual time steps (McDowell et al. 2020). The trends from Harwell et al. (2020) informed scenarios for the surface-water and groundwater modeling.

Where Harwell et al. (2020) detected statistically significant monotonic historical long-term trends in annual or seasonal precipitation, this study used the Theil slope estimate to calculate the seasonal or annual change in precipitation quantities to estimate additional future reservoir water volume gains or losses. The Theil slope, a nonparametric estimate of a regression slope (Helsel et al. 2020), was also used to quantify projected water-budget components from modeling results.

Nonparametric tests were used to facilitate statistical comparisons of datasets that might differ from a normal distribution (Helsel et al. 2020). The Mann-Whitney rank sum test was used to test for differences in decadal data. The Mann-Whitney test indicates whether one group—or decade in this case—tends to produce larger observations than a second group (Helsel et al. 2020). No assumptions were made about the distributions of the data in either group.

Surface-water Model: Precipitation-Runoff Modeling System

PRMS is a deterministic, distributed-parameter, physical-process-based modeling system developed to evaluate watershed-scale hydrologic responses to various combinations of climate variables (Markstrom et al. 2015). Hydrologic simulations are done on a daily time step with daily input data, and the model outputs are designated by the user as daily, monthly, or annual time steps.

Model Inputs and Parameters

Hydrologic simulations for the TRB were done by using past and projected climate data as inputs to the PRMS model. Climate input variables—daily precipitation, daily minimum air temperature, and daily maximum air temperature—were used in the hydrologic simulations to evaluate annual hydrologic response to changes in climate variables from 2018 to 2099. Outputs of the model include annual water budget variables such as precipitation, actual evapotranspiration, surface runoff, and groundwater recharge. In the PRMS model, surface runoff is generated when the precipitation rate exceeds the infiltration rate of soil that may not be saturated; this type of surface runoff is referred to as "Hortonian runoff" (Horton 1933).

To account for the complexity of the hydrologic cycle, several inputs and parameters are required to compute hydrologic simulations in PRMS. A full list of required components is provided in Markstrom et al. (2015). In conjunction with the PRMS software, the surface-water model used in this study includes the USGS National Hydrologic Model (NHM) data infrastructure, which is designed "to fill the gap between the detailed local models used in engineering hydrology and global land-surface models." (p. 193 in Regan et al. 2019). The NHM data infrastructure was configured for use with PRMS and allows for extraction of one or more watersheds or hydrologic response unit (HRU). This data infrastructure provides a standardized modeling platform for model distribution, comparability, and interoperability; a consistent geospatial structure; and default parameter values (Regan et al. 2018).

NHM-PRMS can be used to compute hydrologic-simulation results of the temporal and spatial distribution of water availability and storage across the continental Unites States using national-scale datasets. These datasets include hydrography,

Table 1. Statistically significant historical monthly precipitation trends (in inches/year) for the Trinity River Basin-trend scenario from Harwell et. al. (2020). -- indicates no value was reported (months with no reported value did not have a statistically significant trend).

	Section 1	Section 2	Section 3	Section 4	Section 5
January	--	--	0.0106	--	--
February	--	--	--	--	0.0063
March	--	--	--	0.009	0.0099
April	--	−0.016	--	--	--
May	--	--	--	--	--
June	0.0172	0.0128	0.0139	--	0.0112
July	--	--	--	--	--
August	--	--	--	--	--
September	0.0156	0.0129	--	--	--
October	--	--	0.0138	--	--
November	0.0175	--	--	--	--
December	--	--	--	--	--

solar radiation, evapotranspiration, geology, soils, land cover, topography, snow-covered area, and snow-water equivalent. NHM-PRMS is currently configured with the Daymet Version 3 dataset (Thornton et al. 2016), which includes daily values of precipitation, minimum air temperature, and maximum air temperature from January 1980 through December 2016. A national PRMS model, referred to as the "NHM-PRMS, by HRU Calibrated Version" was recently published (Hay 2019) and was used in this study. This surface-water model includes PRMS parameter values calculated using the calibration procedure from the NHM-PRMS, by HRU Calibrated Version. The multiple-objective, stepwise, automated calibration procedure was used to identify the optimal set of parameters for each HRU using historical climate data from 1980 to 2016.

The historical climate inputs used in the surface-water model weredaily precipitation, daily minimum air temperature, and daily maximum air temperature on a sub-watershed or HRU scale. As shown in Figure 2, the model consists of 1,192 HRUs and 620 stream segments and has an area of 11,471,544 acres (Yesildirek et al. 2023). The model also includes daily streamflow inputs of 71 streamgaging stations from 1980 through 2016, selected for the national PRMS model. Parameters comprise values calculated geospatially by HRU or stream segment with a monthly time step or for the duration of the model-simulation period, depending on the parameter type.

PRMS hydrologic outputs are computed using methods based on physical laws and/or empirical relations. Climate outputs for the model are calculated by HRU and then geographically weighted within the model to provide an average for the TRB. The actual evapotranspiration output in the model is the computed rate of water loss, which reflects the availability of water to satisfy potential evapotranspiration; specifics of the computation are presented in Leavesley et al. (1983). To calculate Hortonian runoff, the "srunoff_smidx" module was used (Regan et al. 2018). In PRMS, recharge is the current available water in the soil recharge zone; details for calculating recharge are presented in Leavesley et al. (1983).

Model Scenarios

The surface-water model runs consist of 32 scenarios for the period from 2018 to 2099 (Table 1). The scenarios used were 30 downscaled LOCA GCMs (LLNL 2021), one forward run using climate data from 1980 through 2016 for the TRB (TRB-fwd), and one trend run applying historical long-term trends from Harwell et al. (2020) to TRB-fwd climate data (TRB-trend). Climate data used in the scenarios were daily precipitation, daily minimum air temperature, and daily maximum air temperature calculated by HRU.

The TRB-fwd scenario was generated by repeating 1980–2016 Daymet data from Thornton et al. (2016) starting in 2017 until the year 2099. Because precipitation progressively increases from the northern extent of the TRB to the southern extent, the TRB-trend scenario was generated using TRB-fwd precipitation and then applying statistically significant historical monthly precipitation trends (Table 1) from Harwell et al. (2020) by section (Figure 2) from 2018 to 2099. Additionally, temperature inputs for the TRB-trend scenario used a statistically significant upward trend in historical basin air temperature of 0.02 °F per year from Harwell et al. (2020) applied to TRB-fwd minimum and maximum air temperatures.

Numerical Groundwater Model

The numerical groundwater-flow model (McDowell et al. 2023) uses MODFLOW-NWT (Niswonger et al. 2011) to simulate steady-state and transient groundwater flow, recharge, and discharge across the TRB. The full model grid consists of 909 rows, 788 columns, and two layers for a total of 716,292 cells per layer, of which 54,551 are active in each layer, with a total area of approximately 3,369,961 acres. Model grid-cell dimensions, which were selected to align with the 1,000-meter USGS National Hydrogeologic Grid (Clark et al. 2018), are 500 meters in both directions, which equates to slightly less than 62 acres per model cell. The historical groundwater simulation period starts in 1949 (designated as a steady state simulation to obtain initial conditions) and continues through 2018. The future scenarios start in 2018 (designated as a steady state simulation to obtain initial conditions) and continue through 2087.

The surficial extent of the model was set to the surficial exposure extent of the alluvium and terrace deposits containing the TRAA (USGS 2014). Unique model cell values were selected for Quaternary alluvium and terrace geologic units underlying the Trinity River and its tributaries; drain cells (model cells where water leaves the model to the Trinity River and its tributaries); each major lake in the TRB; and all major and minor aquifers underlying the alluvium and terrace deposits containing the TRAA.

The top layer of the model represents the TRAA, and the bottom layer represents underlying geologic units that contain major and minor aquifers (as defined by TWDB [2021b, 2021f]), each with unique hydraulic conductivity values. Grid cells in the bottom layer (all set to a thickness of 250 meters) located in areas between the TWDB-defined extents of the major and minor aquifers—Carrizo, Gulf Coast, Nacatoch, Queen City, Sparta, Trinity, and Woodbine aquifers—were assigned an average hydraulic conductivity value based on the lithology of those areas.

The surface of the model was developed to represent the land surface based on an approximately 30-meter digital elevation model from the USGS National Elevation Dataset (USGS 2020), which was resampled to the 500-meter model cell size. The base of the TRAA was delineated by using Railroad Commission of Texas geophysical logs (Railroad Commission of Texas 2021), TWDB groundwater database geophysical logs (TWDB 2021c), TWDB Brackish Resources Aquifer Characterization System geophysical logs (TWDB 2021d), and TWDB drillers' reports (TWDB 2021e) from wells and boreholes within the boundaries of the Quaternary alluvium and terrace deposits. Keywords used to select drillers' reports containing the alluvium included "alluvium," "alluvial," "sand," "silt," "clay," and "gravel." Reports with these keywords, along with the geophysical logs, were used to make picks on the base of the aquifer from underlying units. The base of wells that were labeled as completed in the alluvium were selected as the aquifer base, as well formations above which sand, gravel, silt, and clay were found. Aquifer thickness values ranged from a minimum of 5 meters (set manually to avoid convergence issues with thin cells) to a maximum of slightly less than 44 meters, based on values provided by the Brazos River alluvium aquifer conceptual model (Ewing et al. 2016). The thickness of the Brazos River alluvium aquifer is likely similar to that of the TRAA because their depositional histories are similar and the formations that contain the aquifers are of similar age, size, and lithology. Because there were little available data to characterize the thickness of the TRAA throughout its extent, the uncertainty associated with the assigned thickness was large, and it is likely that the alluvium is thinner than depicted in parts of the model.

MODFLOW-NWT packages used in the TRAA numerical groundwater-flow model include discretization, basic, upstream weighting, drain, general-head boundary, well, head-observation, output control, and recharge. Detailed descriptions of these packages are presented in the MODFLOW-NWT documentation (Niswonger et al. 2011). All these packages, except for recharge and well, are held constant across all simulated scenarios. The discretization package is used to specify model settings such as layers, rows, columns, cell sizes, and time discretization. The basic package is also used to specify model settings, which include defining active and inactive cells and the starting hydraulic heads for all model cells. The upstream weighting package is used to define storage properties, such as specific storage and specific yield, and flow properties, such as horizontal and vertical hydraulic conductivity. The well package is used to define locations, volumes, and times for groundwater pumpage, or withdrawals. The drain package is used to simulate groundwater flowing out of the aquifer as outflows contributing to surface water. The drain package only accommodates surface-water outflow; it does not allow water to return to the aquifer. In contrast to the drain package, the river package accommodates flow both into and out of the aquifer. Streamflow gain-loss data are commonly used for assessing flows into and out of the aquifer. Because streamflow gain-loss data that could be used to assess groundwater–surface water exchanges between the alluvium aquifer and the Trinity River were not available, the drain package was used instead of the river package. The general-head boundary package is also used to simulate head-dependent flux boundaries. In this case, it was used to handle low-elevation areas with convergence issues near the seaward extent of the model north of Trinity Bay. The head-observation package is used to specify observations of hydraulic head so observed groundwater levels in wells can be compared with the simulated values. Finally, the recharge package is used to input a specified flux distributed across the top layer of the model, in units of meters per day (m/day).

Model Values

To simplify the model, uniform values were used for both specific storage (the volume of groundwater released from one unit volume of the aquifer under one unit decline in hydraulic head) and specific yield (the ratio of the volume of water that a saturated aquifer will yield by gravity relative to the total volume of the aquifer [Johnson 1967]) for both layers. Similarly, to model-thickness values, the specific storage and specific yield values used in the Brazos River Alluvium aquifer conceptual model (Ewing et al. 2016) were also used to guide decisions for these model values. Specific storage was set to 0.0001 inverse meters for the top layer and 1.0x10-7 inverse meters for the bottom layer, whereas specific yield was set to 0.15 for the top layer and 0.01 for the bottom layer. Hydraulic conductivity, a coefficient describing the capacity of a rock to transmit water (Fetter 1994), was set in units of meters per day. The value used for much of the top layer (including Quaternary alluvium and Quaternary terrace geologic units) was 100 m/day, whereas the bottom layer varied 8.4–40 m/day, with a value of 27.4 m/day for the non-aquifer areas. The value of horizontal hydraulic conductivity for all lakes in the top layer of the model was 1,500 m/day—a high value to allow water to pass through the lake cells because of the complex nature of inter-basin transfer and regulation in the TRB. Vertical hydraulic conductivity for both layers was set to 1% of horizontal hydraulic conductivity, ranging 1–15 m/day for the top layer and 0.08–0.4 m/day for the bottom layer.

Primary Model Control: Recharge

The main control on water going into the groundwater model is recharge, which affects the output to surface water from aquifer storage. Recharge was calculated using the USGS Soil-Water-Balance (SWB) code (Westenbroek et al. 2010) for the historical model recharge calculation and SWB code version 2.0 (Westenbroek et al. 2018) for all climate scenario recharge calculations. SWB 2.0 was used for the climate scenarios because it has been refactored to allow use of Network Common Data Form (NetCDF) version 4 input files, which is the native format of the climate data sets used (LLNL 2021).

SWB uses a modified Thornthwaite and Mather (1957) soil-water-balance method on a gridded data structure to compute the daily volume of net infiltration; net infiltration is assumed to take place any time the soil-moisture value exceeds the total available water for the cell. Inputs for SWB are daily climate data (precipitation, minimum air temperature, and maximum air temperature), elevation, flow direction (generated from the elevation grid), land cover, and soil type. Climate data for the historical model run were acquired from the National Oceanic and Atmospheric Administration's historical daily dataset (NOAA 2021), and climate data for the future scenarios was acquired from Lawrence Livermore National Laboratory (LLNL; LLNL 2021). Land-cover types from the National Land Cover Database (MRLC 2016) were used to assign runoff curve numbers and plant root-zone depths, values that respectively control the surface-water runoff and rate of infiltration through the soil (Westenbroek et al. 2010). Four Gridded Soil Survey Geographic Database (gSSURGO) hydrologic soil groups, categorized from A (high infiltration, low overland flow) to D (low infiltration, high overland flow; NRCS 2021), were used to characterize cells by available water content. All inputs were resampled to fit the 500-meter model grid cells. SWB results were filtered to remove the fifth percentile outliers from each annual result for all scenarios and otherwise left as-is, without an automated calibration process. Annual recharge values across all scenarios range from about 8,000 acre-feet/year (0.03 inches/year) to about 2,400,000 acre-feet/year (8.55 inches/year) with a mean value of about 620,000 acre-feet/year (2.21 inches/year).

Uncertainty and Sensitivity

Uncertainty in groundwater modeling is assessed in a variety of ways. In this study, hydraulic head values measured in wells were compared to simulated hydraulic head values at the same time (for the historical period) and location in the model. Both observed and simulated values of hydraulic head were plotted and compared to a 1:1 line that represents a perfect fit (Figure 3) to evaluate the overall simulation-to-observation performance. The figure shows that the simulated values tend to be less than the observed values and, on average, the simulated hydraulic heads are 5.01 meters (6.3%) lower than the observed hydraulic heads (which average just under 80 meters). Over 80% of all simulated hydraulic heads were between 10 meters lower and 5 meters higher than the observed hydraulic heads. Additionally, the differences between the GCMs and the historical model run were compared to understand variance and the range of the simulated values. In contrast to a traditional calibration approach, the outputs of both SWB and MODFLOW were used to bound the uncertainty through the modeling process.

Varying specific yield ratio in the top model layer was also used to assess model sensitivity—understanding how this parameter affects water-budget components is important in understanding model sensitivity. Specific yield values were adjusted from low (0.1) to high (0.2) and compared to what was used in the base model (0.15). When adjusted to low specific yield, the average annual volumetric rate of water leaving to drains of the GCM ensemble mean(the annual mean of the 30 GCMs) increased from about 596,000 acre-feet to about 598,000 acre-feet, an increase of about 0.3%. In contrast, the average annual volume of water going to storage in the aquifer decreased from about 7,000 acre-feet to about 5,000 acre-feet,

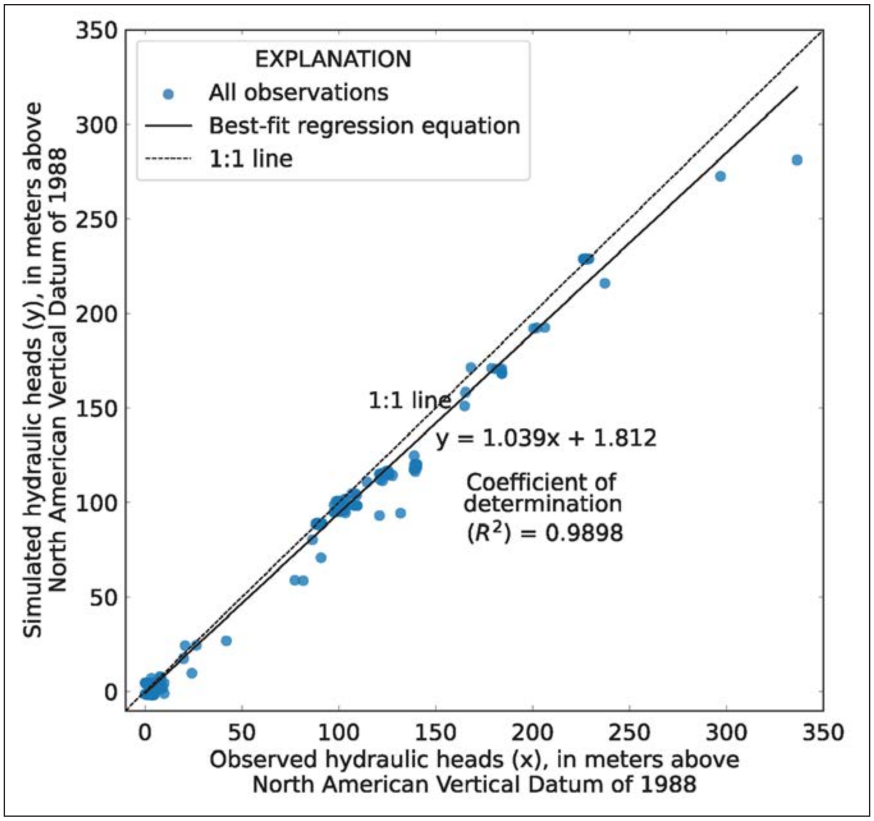

Figure 3. One-to-one plot comparing observed and simulated hydraulic heads.

a decrease of about 29%. The change of simulated hydraulic heads when adjusted to low specific yield was a negligible increase (less than a hundredth of a percent). When adjusted to high specific yield, the average annual volumetric rate of water leaving to drains of the GCM ensemble mean also decreased by about 2,000 acre-feet/year, whereas the average annual volumetric rate of water going to storage in the aquifer increased by about 2,000 acre-feet/year. The change of simulated hydraulic heads when adjusted to high specific yield was a negligible decrease (less than a hundredth of a percent).

Model Scenarios

The groundwater model runs consist of 32 scenarios for the period from 2018 to 2087 (Table 2) in addition to the historical base run. The scenarios are 30 downscaled LOCA GCMs (LLNL 2021), one forward run using climate data from 1949 through 2017 (TRAA-fwd), and one trend run applying historical long-term trends from Harwell et al. (2020) to TRAA-fwd climate data (TRAA-trend). The TRAA-fwd scenario was generated by repeating historical climate data (NOAA 2021) starting in 2018 until the year 2087. To develop the TRAA-trend scenario, local historical climate data (NOAA 2021) were averaged over the period of record from 1949 to 2017 and extrapolated out for future data use starting in 2018 after applying an upward linear rate of change of 0.06 inches/year from Harwell et al. (2020). Additionally, historical air temperature trends of 0.02 °F per year from Harwell et al. (2020) for both daily minimum air temperature and daily maximum air temperature were applied to account for projecting rates of change in the future.

Global Climate Model Scenarios

Thirty LOCA GCM scenarios (LLNL 2021) were selected to evaluate possible future basin conditions as climate inputs to the surface-water and groundwater models developed for this study. Fifteen unique LOCA GCMs were used, each with representative concentration pathways (RCPs) of 4.5 and 8.5 (Table 2). An RCP of 4.5 simulates a scenario that represents moderate global emissions, whereas an RCP of 8.5 simulates a scenario that represents high global emissions. Where the temperature data for each RCP differed, once factored into the models, the variance was minimal because precipitation was the primary driver of model outputs. The USGS Geo Data Portal (Blodgett et al. 2011) was the source of the surface-water model GCM data, and the LLNL (LLNL 2021) was the source for the groundwater model GCM data. Climate data from

Table 2. List of Trinity River Basin (TRB) model scenarios used for both the surface-water model and the Trinity River alluvium aquifer (TRAA) groundwater model. A representative concentration pathway (RCP) of 4.5 simulates a scenario that represents moderate global emissions, whereas an RCP of 8.5 simulates a scenario that represents high global emissions. The climate data for all scenarios with an RCP value were acquired from the Lawrence Livermore National Laboratory's downscaled climate projections dataset (LLNL 2021).

Scenario name	RCP	Short name	Scenario details	TRB surface-water model	TRAA groundwater model
TRB forward	--	TRB-fwd	Forward run of historical data (1980–2016) for the PRMS model	X	--
TRB forward trend	--	TRB-trend	Trends from Harwell et al. 2020 applied to PRMS-fwd	X	--
TRAA forward	--	TRAA-fwd	Forward run of historical data (1949–2017) for the TRAA model	--	X
TRAA forward trend	--	TRAA-trend	Trends from Harwell et al. 2020 applied to TRAA-fwd-base	--	X
BCC-CSM1.1-M	4.5	GCM1	Beijing Climate Center, Climate System Model, moderate resolution, version 1.1	X	X
BCC-CSM1.1-M	8.5	GCM2		X	X
CanESM2	4.5	GCM3	Second Generation Canadian Earth System Model	X	X
CanEMS2	8.5	GCM4		X	X
CCSM4	4.5	GCM5	Community Climate System Model, Version 4	X	X
CCSM4	8.5	GCM6		X	X
FGOALS-G2	4.5	GCM7	Flexible Global Ocean-Atmosphere-Land System Model Grid-Point, version 2	X	X
FGOALS-G2	8.5	GCM8		X	X
GFDL-CM3	4.5	GCM9	Geophysical Fluid Dynamics Laboratory Climate Model, version 3	X	X
GFDL-CM3	8.5	GCM10		X	X
GFDL-ESM2G	4.5	GCM11	Geophysical Fluid Dynamics Laboratory Earth System Model with Generalized Ocean Layer Dynamics (GOLD) component	X	X
GFDL-ESM2G	8.5	GCM12		X	X
GFDL-ESM2M	4.5	GCM13	Geophysical Fluid Dynamics Laboratory Earth System Model with Modular Ocean Model 4 (MOM4) component	X	X
GFDL-ESM2M	8.5	GCM14		X	X
GISS-E2-R	4.5	GCM15	Goddard Institute for Space Studies Model E2, coupled with the Russell Ocean model	X	X
GISS-E2-R	8.5	GCM16		X	X
IPSL-CM5A-LR	4.5	GCM17	L'Institut Pierre-Simon Laplace Coupled Model, version 5A, coupled with Nucleus for European Modeling of the Ocean (NEMO), low resolution	X	X
IPSL-CM5A-LR	8.5	GCM18		X	X
IPSL-CM5A-MR	4.5	GCM19	L'Institut Pierre-Simon Laplace Coupled Model, version 5A, coupled with NEMO, mid resolution	X	X
IPSL-CM5A-MR	8.5	GCM20		X	X
MIROC5	4.5	GCM21	Model for Interdisciplinary Research on Climate, version 5	X	X
MIROC5	8.5	GCM22		X	X
MIROC-ESM	4.5	GCM23	Model for Interdisciplinary Research on Climate, Earth System Model	X	X
MIROC-ESM	8.5	GCM24		X	X
MPI-ESM-LR	4.5	GCM25	Max Planck Institute Earth System Model, low resolution	X	X
MPI-ESM-LR	8.5	GCM26		X	X
MRI-CGCM3	4.5	GCM27	Meteorological Research Institute Couple Atmosphere-Ocean General Circulation Model, version 3	X	X
MRI-CGCM3	8.5	GCM28		X	X
NorESM1-M	4.5	GCM29	Norwegian Earth System Model, version 1 (intermediate resolution)	X	X
NorESM1-M	8.5	GCM30		X	X

RCP: Representative Concentration Pathway; TRB: Trinity River Basin; TRAA: Trinity River alluvium aquifer; PRMS: Precipitation-Runoff Modeling System; GCM: Global Climate Model;

the GCM scenarios that were used as inputs in both the surface-water model and the TRAA groundwater model include daily precipitation, minimum air temperature, and maximum air temperature. A majority of the GCM data extend to the year 2099; therefore the choice was made to run the surface-water model scenarios to the year 2099. The simulation period for the TRAA groundwater model extends to 2087 to allow for roughly equivalent time periods for both historical data and future projections.

To minimize the number of GCMs in this study and use the most suitable climate data, GCMs were selected based on Venkataraman et al. (2016), which evaluated how well GCM historical data fit the different Texas climate divisions. Metrics used to evaluate the GCMs include mean absolute error, normalized standard deviation, and Kendall's *tau*. Additionally, because of the variability of the GCM climate data, the model outputs in this study are reported using the annual mean of the 30 GCMs, referred to as GCM ensemble mean. The GCM ensemble mean is used because it reduces the dispersion of the results as compared to individual GCM scenarios.

RESULTS

Historical long-term trends, surface-water model results, and groundwater model results were analyzed using Kendall's *tau*, Theil slopes, and Mann-Whitney rank-sum tests. When possible, comparisons were made with projected water availability estimates in the 2016 RWPG water plan (Freese and Nichols, Inc. et al. 2015; Region H Water Planning Group et al. 2015).

Historical Long-term Trend Analysis

From the results of previous work by Harwell et al. (2020), precipitation trend analyses on an annual time step in the TRB indicated upward trends in most sections (Figure 2). Data from eight of the 36 stations selected in Harwell et al. (2020, p. 4) and analyzed for annual streamflow trends indicated upward trends, and all eight stations are in the upper sections (sections 4 and 5) of the study area. None of the data from stations in the lower sections indicated trends in annual streamflow. Data from 16 of the 36 stations indicated upward trends in annual minimum streamflow. All the trends in annual peak streamflow were in the sections that include the Dallas-Fort Worth metropolitan area. Data from two monitoring stations—one USGS streamgage and one U.S. Army Corps of Engineers (USACE) simulated-inflow station—indicated upward trends in annual peak streamflow, and data from one other USGS streamgage indicated a downward trend in annual peak streamflow. Simulated-inflow stations are reservoir stations with inflow data calculated as a mass balance over a 24-hour period. These data were provided by USACE for analyses in Harwell et al. (2020). Refer to Harwell et al. (2020) for the mass balance equation used by USACE to simulate reservoir inflow.

Of the different river basins included in Harwell et al. (2020), the TRB has the second largest potential flood storage volume at 8,947,349 acre-feet available in the numerous reservoirs built between 1890 and 2013. Potential flood storage volume is defined as the difference between maximum storage volume and normal storage volume. A positive association between potential flood storage volume and annual streamflow was detected at 11 monitoring stations in the TRB, indicating that annual streamflow increases as potential flood storage increases. Data from seven of the 11 monitoring stations also indicated upward trends in annual streamflow. The ratio of streamflow volume to precipitation volume (percent of total water that falls on a watershed that results in streamflow) from analysis in Harwell et al. (2020) was used to estimate the amount of runoff volume to reservoirs in response to upward trends in precipitation in the historical record. Precipitation data in Harwell et al. (2020) included the period from 1900 through 2017. Streamflow volume data included variable time periods ranging from 1869 through 2017, and periods of record for each station are included in Harwell et al. (2020). The purpose of this analysis was to determine how much additional surface water might be available in reservoirs within Region C (Figure 1) in the future if the upward trends in precipitation reported in Harwell et al. (2020) were to continue. For this study, the Theil slope estimate was calculated for all years and seasons in sections 3, 4, and 5 with statistically significant upward trends in precipitation. The mean annual slope was 0.06 inches/year, and the mean seasonal slope was 0.02 inches/year for each of the three seasons.

Figure 4 shows the annual increase in volume by season to the 14 reservoirs analyzed in Harwell et al. (2020) within Region C using the aforementioned ratios of streamflow volume to precipitation volume. Harwell et al. (2020) defined three seasons for the purpose of analysis: season 1 (November, December, January, and February), season 2 (March, April, May, and June), and season 3 (July, August, September, and October). All 14 reservoirs are expected to increase in volume during season 1, with a total annual increase in volume of 3,440 acre-feet/year (Figure 4). Five of the 14 reservoirs are expected to increase in volume during season 2, with a total annual increase in volume of 1,338 acre-feet/year. Lastly, three of the 14 reservoirs are expected to increase in volume during season 3, with a total annual increase in volume of 708 acre-feet/year. Therefore, the estimated total annual increase in volume to the 14 reservoirs from upward trends in precipitation is 5,486 acre-feet, or 0.12% of the projected water availability in 2070 of 4,444,916 acre-feet/year in regions C and H (Table 3). Projected water availability in 2070 is calculated from the values in Table 3 as the sum of the total volumes including

Table 3. Current and estimated future water supply availability (acre-feet/year) as reported in the 2016 regional water planning group water plans (Freese and Nichols, Inc. et al. 2015; Region H Water Planning Group et al. 2015).

	2020	2030	2040	2050	2060	2070
Region C totals (including groundwater)	2,316,273	2,279,349	2,275,427	2,282,147	2,281,830	2,270,143
Region C groundwater totals	146,178	146,190	146,188	146,135	146,132	146,096
Region H totals (including groundwater)	3,053,250	2,986,351	2,988,846	2,991,555	2,993,812	2,995,590
Region H groundwater totals	742,067	672,561	673,289	674,231	674,721	674,721

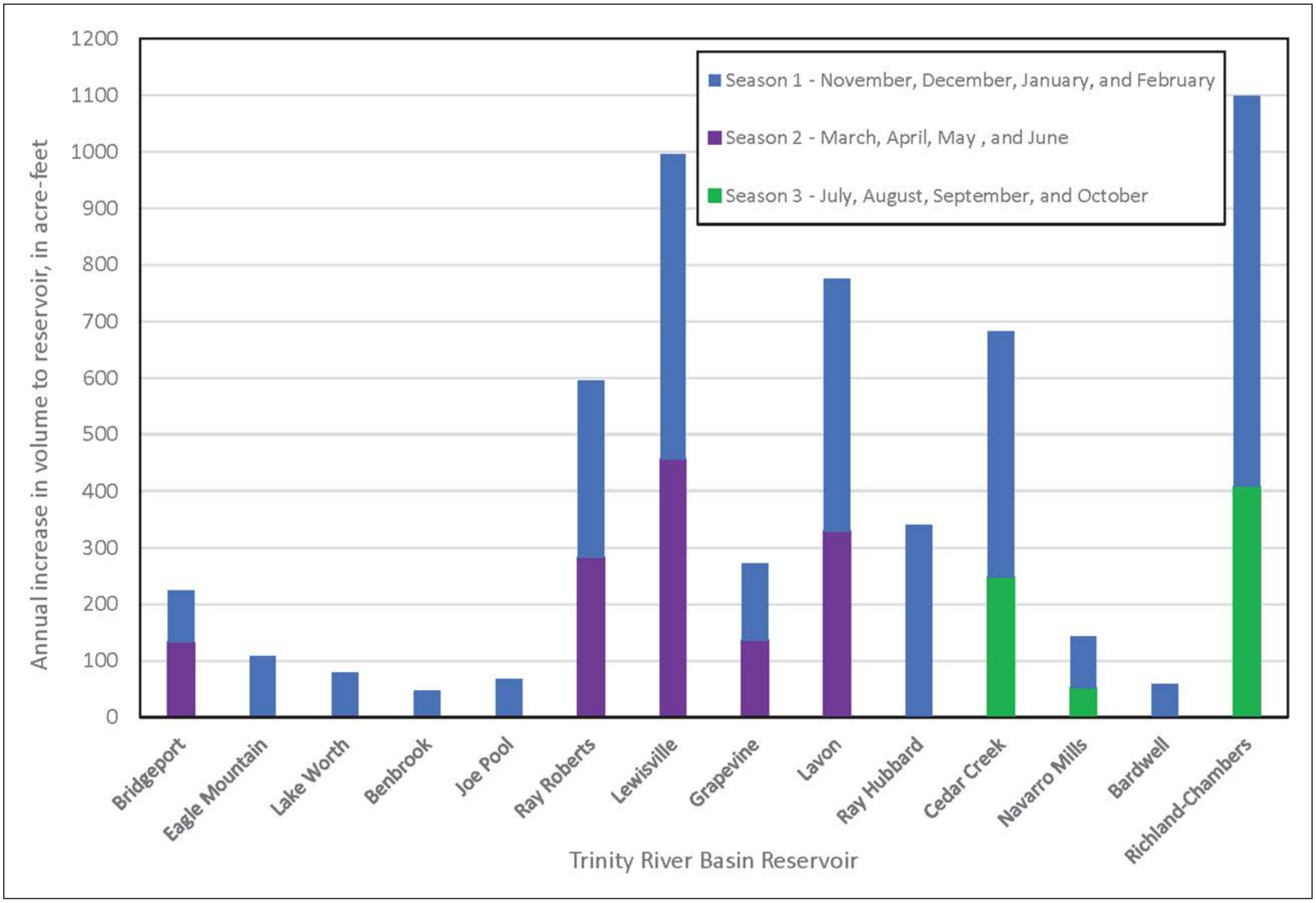

Figure 4. Annual increase in volume by seasons to reservoirs in Region C based on projected annual increases in precipitation in the Trinity River Basin from Harwell et al. (2020).

Table 4. Summary statistics of the simulated annual water budget (2018–2099) from the Precipitation-Runoff Modeling System (PRMS) surface-water model within the Trinity River Basin (TRB).

		TRB-fwd	TRB-trend	TRB global climate model ensemble mean
Precipitation (inches/year)	Mean	42.11	43.74	38.21
	Min	25.33	26.29	34.08
	Max	68.77	70.54	41.21
	Kendall's *tau*	−0.0620	−0.0063	−0.2980
	p-value	0.4116	0.9330	< 0.001
	Theil slope	−0.0307	−0.0052	−0.0314
Actual evapotranspiration (inches/year)	Mean	27.94	28.9	27.88
	Min	20.63	21.37	25.38
	Max	33.58	34.76	29.82
	Kendall's *tau*	−0.0533	0.0120	−0.2314
	p-value	0.4784	0.8727	0.0021
	Theil slope	−0.0088	0.0023	−0.0127
Hortonian runoff (inches/year)	Mean	1.86	1.94	1.53
	Min	0.83	0.86	1.34
	Max	3.88	4.11	1.69
	Kendall's *tau*	−0.0757	−0.0187	−0.2096
	p-value	0.3184	0.8039	0.0061
	Theil slope	−0.0021	−0.0008	−0.0013
Recharge (inches/year)	Mean	5.03	5.2	3.64
	Min	1.73	1.88	2.87
	Max	10.81	10.91	4.28
	Kendall's *tau*	−0.0534	−0.0087	−0.4263
	p-value	0.4784	0.9075	< 0.001
	Theil slope	−0.0038	−0.001	−0.0092

groundwater in regions C and H and subtracting the sum of the groundwater volumes in both regions.

PRMS Surface-water Model

The surface-water model results for the scenarios include water budget variables of precipitation as an input and actual evapotranspiration, Hortonian runoff, and recharge as outputs. Figure 5 shows annual means of the water budget variables from 2018 to 2099 for all the model scenarios: the 30 GCMs, TRB-fwd, TRB-trend, and the GCM ensemble mean, which is the annual mean of all the GCM scenarios. Precipitation is a large driver for model outputs, as seen in the Figure 5. As precipitation increases, Hortonian runoff and recharge values increase.

From 2018 to 2099, TRB-fwd and TRB-trend mean annual precipitation values were 42.11 and 43.74 inches/year, respectively, a difference of 1.63 inches/year (Table 4). Neither the TRB-fwd nor the TRB-trend mean annual precipitation values indicate statistically significant upward or downward trends. For the 2018–2099 period, the GCM ensemble mean yielded a mean annual precipitation value of 38.21 inches/year. The time trend of the GCM ensemble mean data is statistically significant with a Kendall's *tau* value of –0.2980 (p-value ≤ 0.01), indicating a downward trend in precipitation. The computed Theil slope estimate for the period from 2018 to 2099 is –0.0314, which corresponds to a downward trend in precipitation of about 0.03 inches/year.

Mean annual actual evapotranspiration for the TRB-fwd scenario was 27.94 inches/year and 28.90 inches/year for the TRB-trend scenario, a difference of 0.96 inches/year. Neither the TRB-fwd nor the TRB-trend mean annual actual evapotranspiration values indicate statistically significant time trends. The GCM ensemble mean had a mean annual actual evapotranspiration value of 27.88 inches/year. The time trend of the GCM ensemble mean data is statistically significant with

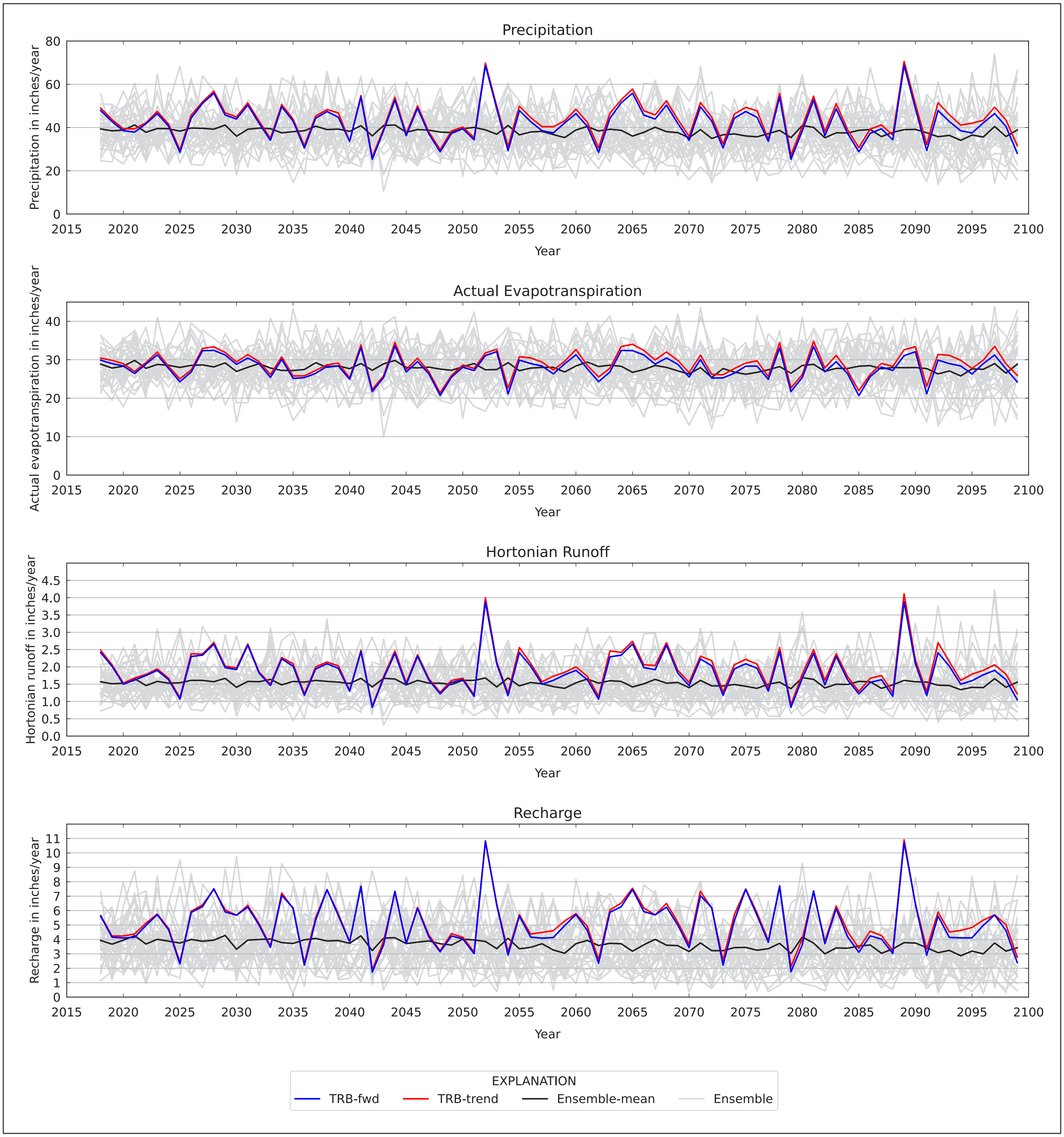

Figure 5. Annual increase in volume by seasons to reservoirs in Region C based on projected annual increases in precipitation in the Trinity River Basin from Harwell et al. (2020).

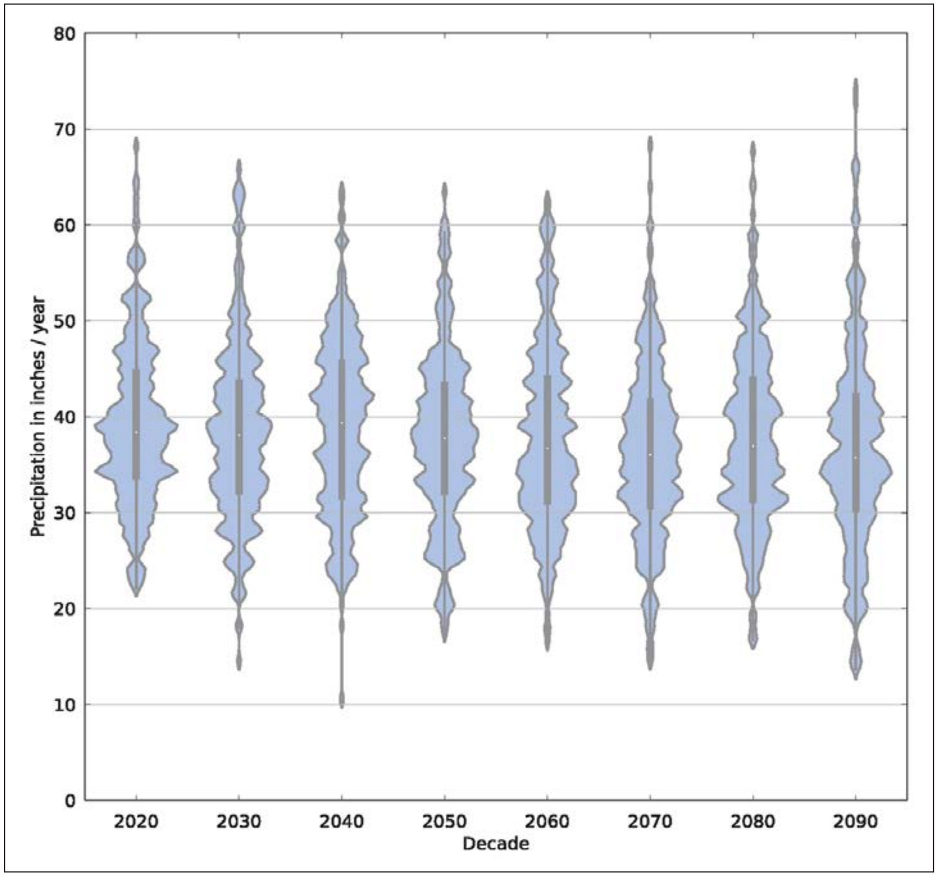

Figure 6. Violin plots showing the distributions, median values, and quartiles of the precipitation component of the Trinity River Basin surface-water model budget by decade. Blue indicates the distribution of data, white dots indicate the median, the gray box indicates the interquartile range, and the vertical gray lines indicate the extent of the range of values, with outliers excluded.

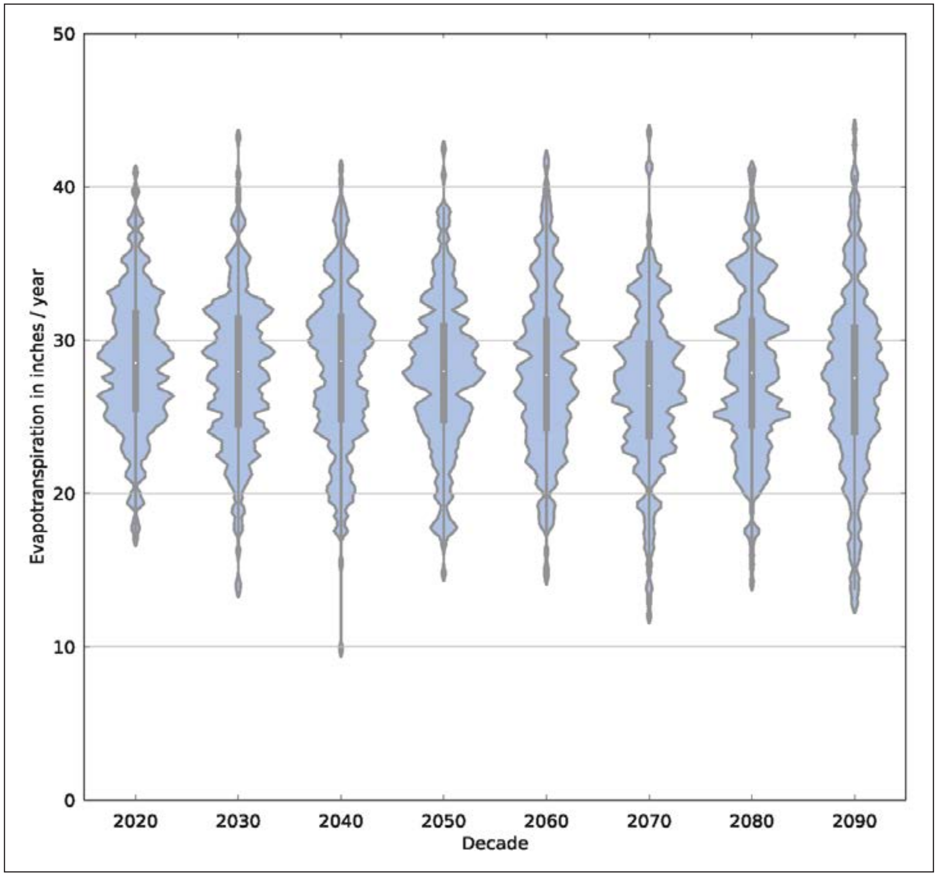

Figure 7. Violin plots showing the distributions, median values, and quartiles of the evapotranspiration component of the Trinity River Basin surface-water model budget by decade. Blue indicates the distribution of data, white dots indicate the median, the gray box indicates the interquartile range, and the vertical gray lines indicate the extent of the range of values, with outliers excluded.

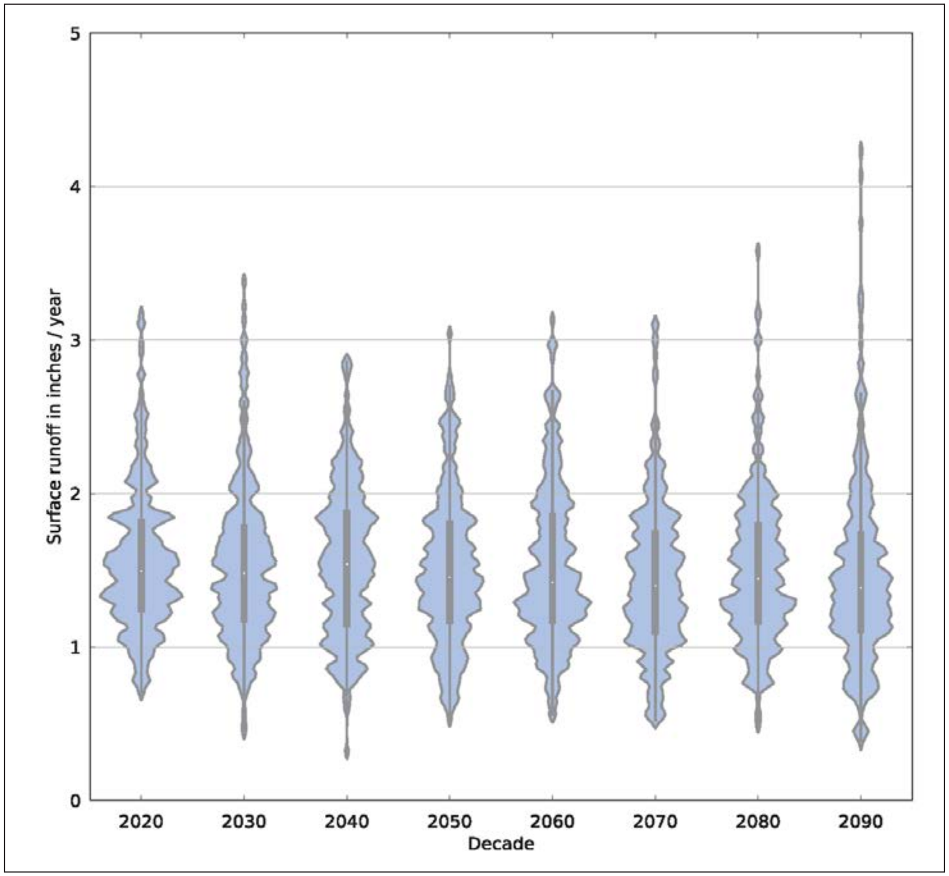

Figure 8. Violin plots showing the distributions, median values, and quartiles of the Hortonian runoff component of the Trinity River Basin surface-water model budget by decade. Blue indicates the distribution of data, white dots indicate the median, the gray box indicates the interquartile range, and the vertical gray lines indicate the extent of the range of values, with outliers excluded.

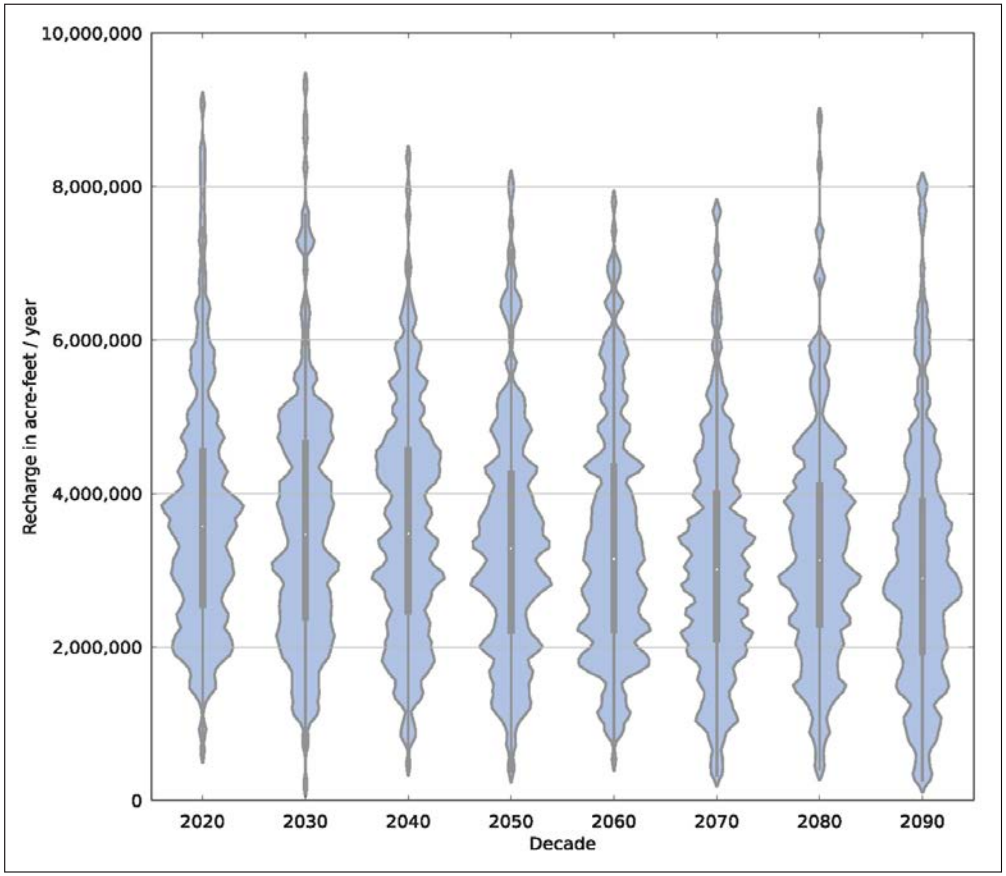

Figure 9. Violin plots showing the distributions, median values, and quartiles of the recharge component of the Trinity River Basin surface-water model budget by decade. Blue indicates the distribution of data, white dots indicate the median, the gray box indicates the interquartile range, and the vertical gray lines indicate the extent of the range of values, with outliers excluded.

a Kendall's *tau* value of –0.2314 (p-value ≤ 0.01), indicating a downward trend in actual evapotranspiration. The computed Theil slope estimate for the period from 2018 to 2099 is –0.0127, which equates to a downward trend in actual evapotranspiration of about 0.01 inches/year. This is likely a result of less water input to the system as precipitation, resulting in less surface water available for evapotranspiration.

From 2018 to 2099, TRB-fwd and TRB-trend mean Hortonian runoff values were 1.86 inches/year and 1.94 inches/year, respectively, a difference of 0.08 inches/year. Neither the TRB-fwd nor the TRB-trend mean annual Hortonian runoff values indicate statistically significant time trends. The GCM ensemble mean had a mean annual Hortonian runoff value of 1.53 inches/year. The time trend of the GCM ensemble mean data is statistically significant with a Kendall's *tau* value of –0.2096 (p-value ≤ 0.01), indicating a downward trend in Hortonian runoff. The computed Theil slope estimate for the period from 2018 to 2099 is –0.0013, which equates to a downward trend in Hortonian runoff of about 0.0013 inches/year.

TRB-fwd and TRB-trend mean annual recharge values were 5.03 inches/year and 5.2 inches/year, respectively, a difference of 0.17 inches/year. Neither the TRB-fwd nor the TRB-trend mean annual recharge values indicate statistically significant time trends. The GCM ensemble mean for 2018 to 2099 yielded a mean annual recharge value of 3.64 inches/year. The time trend obtained from the surface-water model for the GCM ensemble mean is statistically significant with a Kendall's *tau* value of –0.4263 (p-value ≤ 0.01), indicating a downward trend in recharge. The computed Theil slope estimate for the period from 2018 to 2099 is –0.0092, so the downward trend in recharge is about 0.0092 inches/year.

Decadal plots of the GCM ensemble data are included to show the distributions and the variability in the GCM data by decade (Figures 6–9). The violin plots (Hintze and Nelson 1998) were constructed to visualize the distribution and probability density of the GCM ensemble data (Figures 6–9) and include 300 data points per decade, representing 10 years of annual variable data for each of the 30 GCM scenarios. Variables plotted include precipitation (Figure 6), actual evapotranspiration (Figure 7), Hortonian runoff (Figure 8), and recharge (Figure 9). According to results of the Mann-Whitney rank-sum test (p-value ≤ 0.05), the 2090 decadal precipitation data are not equivalent to the 2020, 2030, and 2040 decadal precipitation data. As expected from the downward precipitation trend of the GCM mean annual precipitation data previously discussed, the 2090 decadal precipitation data are significantly less than the 2020, 2030, and 2040 decadal precipitation data (Figure 6). The differences between the 2090 decadal precipitation data and the 2050, 2060, 2070, and 2080 decadal precipitation data are not statistically significant.

Decadal differences for evapotranspiration, Hortonian runoff, and recharge are similar to those of precipitation. Mann-Whitney test results indicate that the 2090 decadal values are significantly less than the earlier decades of 2020, 2030, and 2040 for the other components of the water budget, except for evapotranspiration. For evapotranspiration, there is no difference between the 2090 and 2030 data. However, 2090 evapotranspiration values are less than 2020 and 2040 values. These results are expected given the downward trends in the ensemble means for all water budget components.

Numerical Groundwater Model Inflows, Outflows, and Storage

The simulated output of the numerical groundwater model for the TRAA-forward, TRAA-trend, and GCM scenario runs includes volumetric water budget components in acre-feet/year for the inputs and outputs of the model (Figure 10). These water budget components are recharge, drains, storage change, cumulative storage change, head-dependent boundaries, and wells. Except for groundwater storage change, positive values indicate groundwater going into the model (groundwater inflows), whereas negative values indicate groundwater flowing out of the model (groundwater outflows).

Recharge to the aquifer—the primary inflow to the MODFLOW model—is largely controlled by precipitation but is also dependent on other variables, such as land cover and soil type. Groundwater storage change represents the change in groundwater being stored in the aquifer at any given time. When groundwater storage change is negative, net groundwater is entering the aquifer, and when groundwater storage change is positive, net groundwater is leaving the aquifer. Cumulative groundwater storage change is simply the cumulative change in aquifer storage by year, representing the change in simulated volume of groundwater stored in the aquifer in any given year. For reference, at the end of the base model transient period, the model estimates there are about 4.3 million acre-feet in storage for the TRAA. Drains signify the volume of water flowing out of the aquifer and include all simulated reaches of rivers and streams. Head-dependent boundaries show groundwater flowing out of the aquifer (and sometimes entering the system) at the seaward extent of the model near Trinity Bay, and wells show groundwater being pumped out of the system.

Because of the many different approaches and objectives when creating the GCMs (Table 2), the GCM input data exhibit a high level of variance, which is reflected in the output of the various GCM scenarios and is why the GCM ensemble mean is analyzed. Annual simulated values for recharge from all GCM scenarios range from about 8,000 acre-feet to about 2,385,000 acre-feet, whereas the GCM ensemble mean ranges from about 377,000 acre-feet/year to about 743,000 acre-feet/year (Table 5). The time trend of the GCM ensemble mean recharge data is statistically significant with a Kendall's *tau* value of –0.3998 (p-value ≤ 0.05), indicating a downward trend

Table 5. Summary statistics of the simulated annual water budget (2018–2087) from the groundwater model in the Trinity River alluvium aquifer (TRAA) within the Trinity River Basin.

		TRAA-fwd	TRAA-trend	TRAA global climate model ensemble mean
Recharge (acre-feet / year)	Mean	637,713	968,917	607,644
	Min	116,723	797,750	376,876
	Max	1,981,320	1,147,434	742,647
	Kendall's *tau*	0.1688	1.0	−0.3998
	p-value	0.04	< 0.001	< 0.001
	Theil slope	4,054	5,141	−2,376
Drains (acre-feet / year)	Mean	634,298	941,728	604,051
	Min	335,892	696,359	485,036
	Max	1,195,479	1,118,890	701,611
	Kendall's *tau*	−0.2481	−1.0	0.4834
	p-value	0.0026	< 0.001	< 0.001
	Theil slope	−3,015	−5,118	1,878
Storage change (acre-feet / year)	Mean	1,923	−17,230	−2,186
	Min	−782,919	−93,348	−126,506
	Max	364,225	−11,988	108,676
	Kendall's *tau*	−0.0307	−0.2089	0.1390
	p-value	0.709	0.011	0.091
	Theil slope	−494	−45	472
Cumulative Storage Change (acre-feet / year)	Mean	238,009	−678,744	−269,746
	Min	−214,616	−1,188,868	−424,124
	Max	791,989	−93,348	−21,513
	Kendall's *tau*	−0.3222	−1.0	0.4510
	p-value	< 0.001	< 0.001	< 0.001
	Theil slope	−5,407	−14,152	3,650

in recharge. The computed Theil slope estimate of recharge for the period from 2019 to 2087 indicates a downward trend of −2,376 acre-feet/year. From 2019 to 2087, TRAA-fwd and TRAA-trend mean annual recharge values were about 638,000 and 969,000 acre-feet/year, respectively, a difference of 331,000 acre-feet/year. The TRAA-fwd recharge values indicate a statistically significant upward trend with a Kendall's *tau* value of 0.1688 (p-value ≤ 0.05).

The time trend of the GCM ensemble mean drain data is statistically significant with a Kendall's *tau* value of 0.4834 (p-value ≤ 0.05), indicating an upward trend (decrease in groundwater flowing out of the aquifer). The computed Theil slope estimate for the period from 2019 to 2087 indicates an upward trend of 1,878 acre-feet/year, or a decrease in the amount of groundwater flowing out of the aquifer. From 2019 to 2087, TRAA-fwd and TRAA-trend mean annual drain values were about 634,000 and 942,000 acre-feet/year, respectively, a difference of 308,000 acre-feet/year. The TRAA-fwd drain values indicate a statistically significant downward trend with a Kendall's *tau* of −0.2481 (p-value ≤ 0.05).

The trend of the GCM ensemble mean storage change data for the period from 2019 to 2087 is not statistically significant, so the Theil slope estimate was not calculated. From 2019 to 2087, TRAA-fwd and TRAA-trend mean annual groundwater storage change values were about 2,000 and 17,000 acre-feet/year stored in the aquifer, respectively, a difference of 15,000 acre-feet/year.

The time trend of the GCM ensemble mean cumulative groundwater storage change data is statistically significant with a Kendall's *tau* value of 0.4510 (p-value ≤ 0.05), indicating an upward trend in groundwater consistently flowing out of the aquifer to rivers and streams. The computed Theil slope estimate of cumulative storage change for the period from 2019 to 2087 indicates an upward trend of 3,650 acre-feet/year, or a decrease in the amount of groundwater in storage over time. From 2019 to 2087, TRAA-fwd and TRAA-trend mean annu-

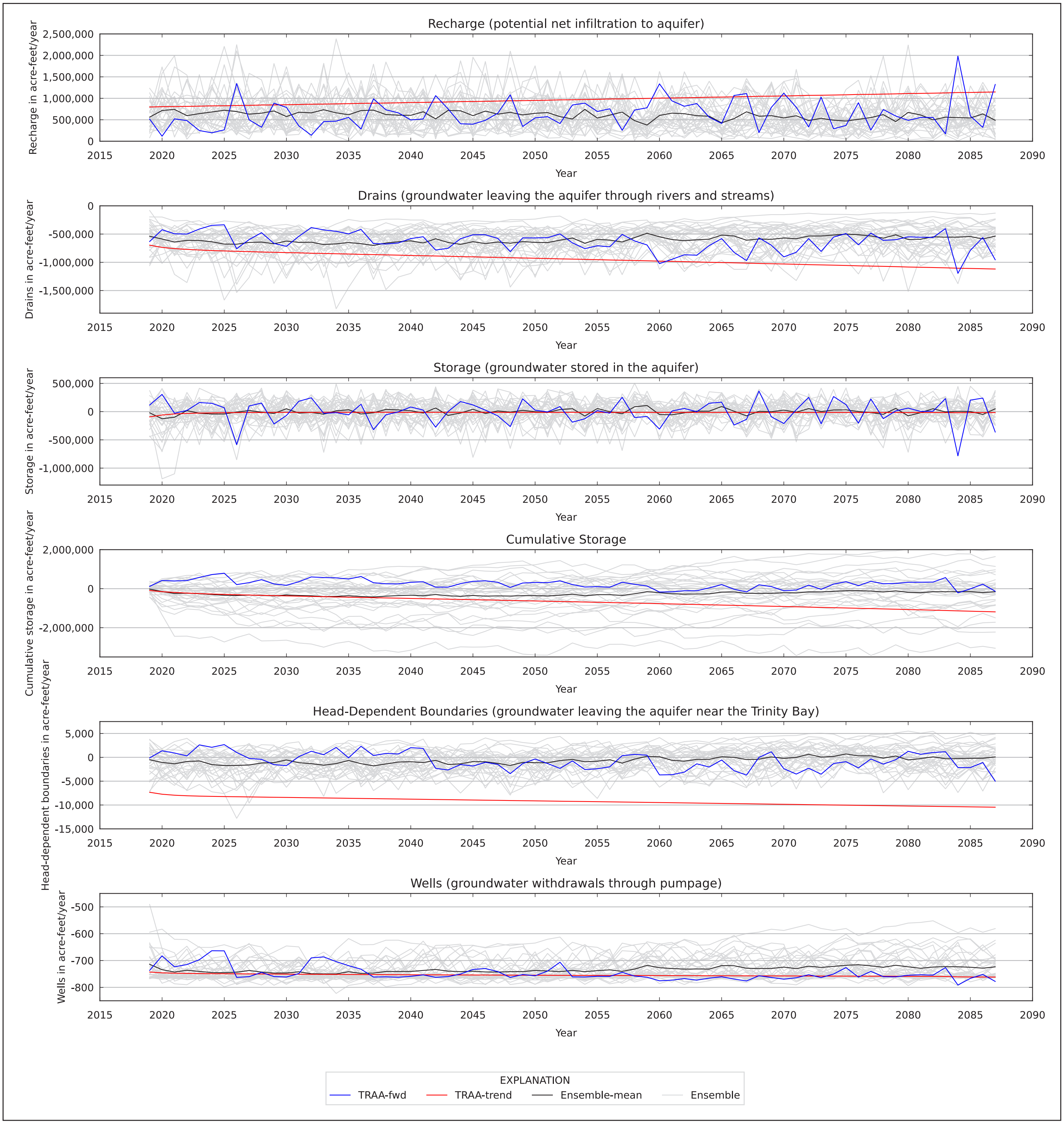

Figure 10. Annual simulated numerical groundwater-model water budget components (recharge, drains, storage change, cumulative storage change, head-dependent boundaries, and wells) from 2019 through 2087 for the Trinity River alluvium aquifer-fwd scenario (blue), the Trinity River alluvium aquifer-trend scenario (red), the global climate model ensemble mean (black), and global climate models (light gray).

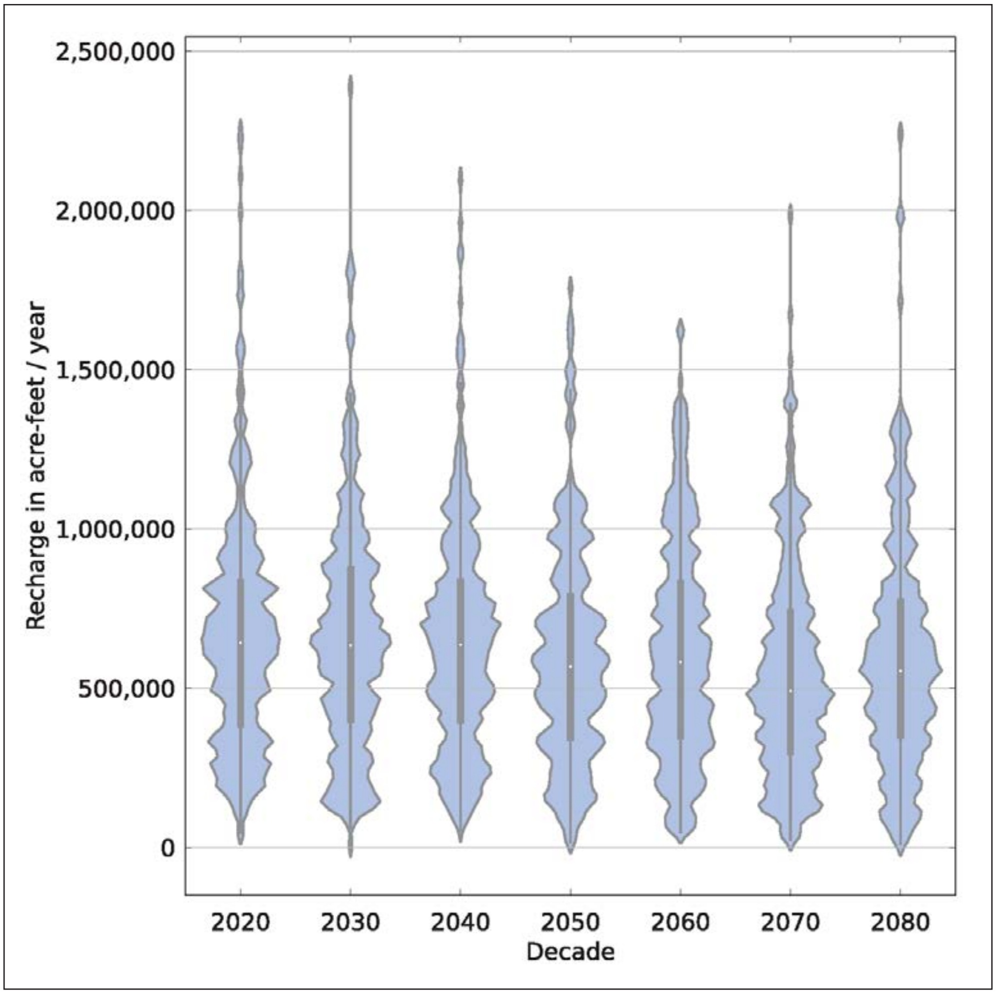

Figure 11. Violin plots showing the distributions, median values, and quartiles of the recharge component of the groundwater budget by decade. Blue indicates the distribution of data, white dots indicate the median, the gray box indicates the interquartile, and the vertical gray lines indicate the extent of the range of values, with outliers excluded. There are 300 values per decade for each violin plot, except for the 2080 decade, which includes 240 values.

al cumulative groundwater storage change values were about 238,000 acre-feet/year flowing out of the aquifer and about 679,000 acre-feet/year being stored in the aquifer, respectively, a difference of 917,000 acre-feet/year. The TRAA-fwd annual cumulative groundwater storage change indicates a statistically significant downward trend with a Kendall's *tau* of −0.3222 (p-value ≤ 0.05).

The GCM ensemble mean, TRAA-fwd run, and TRAA-trend run water budget components are compared in Figure 10. Because of the linear nature of the trend extrapolation for the trend run (which was based on the 1900–2017 period of record), it is likely a high estimate of the range of possible outcomes. Conversely, the GCM ensemble mean indicates that the overall water availability for the future will likely be within the upper and lower bounds of water availability determined in the historical simulation period (1949–2018).

Decadal analysis of the water budget also provides insight into future groundwater conditions in the TRB. Violin plots of the primary water budget components (recharge, drains, and storage change) were created to better understand the distribution of values across decades (Figures 11–13). Figure 11 shows the recharge component of the groundwater model water budget by decade, including every year in each decade for all 30 GCM scenarios. Because recharge is the main control on volume of groundwater in the model, more recharge to the model means more groundwater is available to leave the model via drains or to be stored in the aquifer. Simulated median annual recharge (Figure 11) ranges from about 632,000 acre-feet/year in the 2020 decade to about 462,000 acre-feet/year in the 2070 decade. Simulated median annual drain values (Figure 12) range from about 633,000 acre-feet/year out of the system in the 2040 decade to about 517,000 acre-feet/year out of the system in the 2070 decade. Simulated median annual

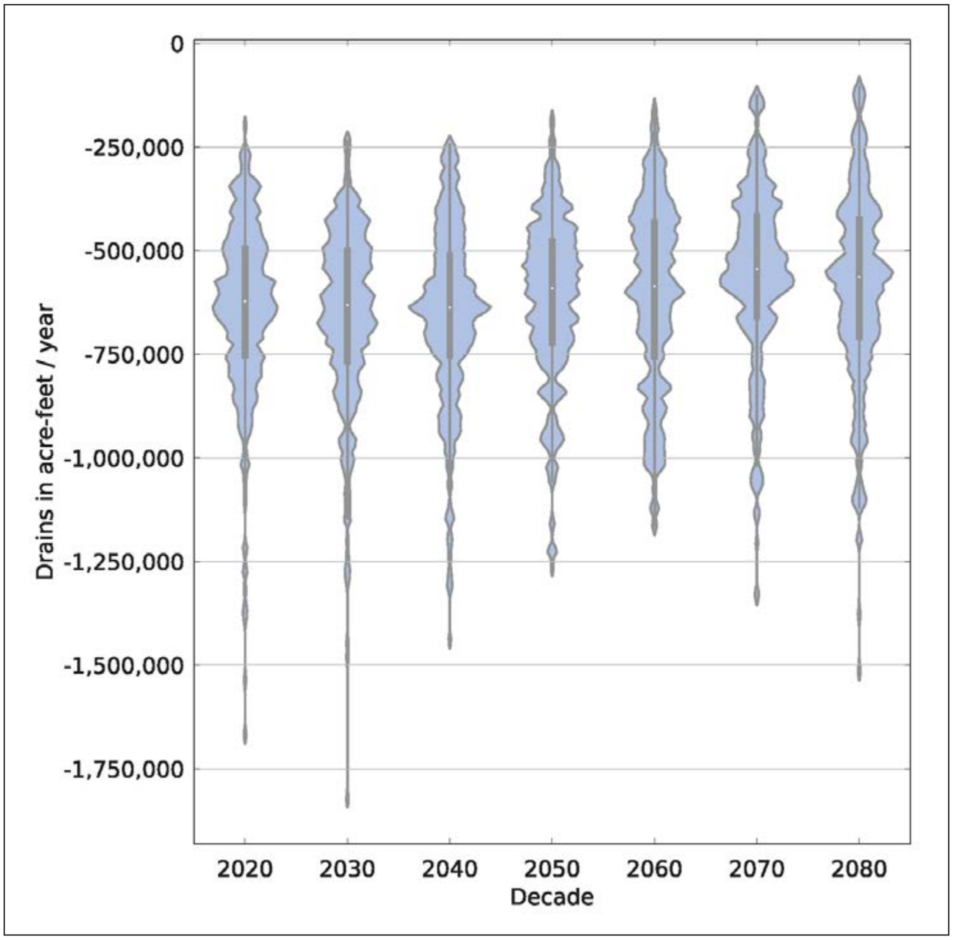

Figure 12. Violin plots showing the distributions, median values, and quartiles of the drain component of the groundwater budget by decade. Blue indicates the distribution of data, white dots indicate the median, the gray box indicates the interquartile, and the vertical gray lines indicate the extent of the range of values, with outliers excluded. There are 300 values per decade for each violin plot, except for the 2080 decade, which includes 240 values.

storage change (Figure 13), while highly variable, ranges from about 16,000 acre-feet/year being added to aquifer storage in the 2020 decade to about 40,000 acre-feet/year flowing out of the aquifer in the 2050 decade.

Negative cumulative storage change values mean that water is going into the aquifer—an increase in groundwater storage in the alluvial aquifer. There is a high degree of variability across different climate scenarios, as some scenarios show groundwater will be increasing in the aquifer whereas others show groundwater will be decreasing. Typically, when there is more recharge to the aquifer for a given scenario and year, cumulative storage change values will be more negative, representing an increase in groundwater storage and vice versa. Figure 14 shows that the GCM ensemble mean has an initial increase of groundwater available (negative values) in the alluvial aquifer, followed by a gradual decrease over the rest of the projected time period.

Limitations

All water budgets, including the results of this study, have uncertainties associated with them because of simplifying assumptions within the models. Uncertainties for the results of this study stem from measurement and modeling errors, as well as natural variability in precipitation patterns, evapotranspiration, soil and vegetation properties, and diurnal, seasonal, and long-term climate trends (Healy et al. 2007). Model limitations associated with PRMS include the following four factors: (1) groundwater or reservoir withdrawals are not simulated, (2) interbasin transfers are not simulated, (3) land use changes are not simulated, and (4) the effect of frozen ground on runoff is not simulated (Bjerklie et al. 2015). Additional uncertainties exist specifically for the TRAA. Because the TRAA is not formally classified as an aquifer, few data have been collected to characterize its geologic or hydraulic properties, and no gain-loss studies have been done to assess groundwater–surface water

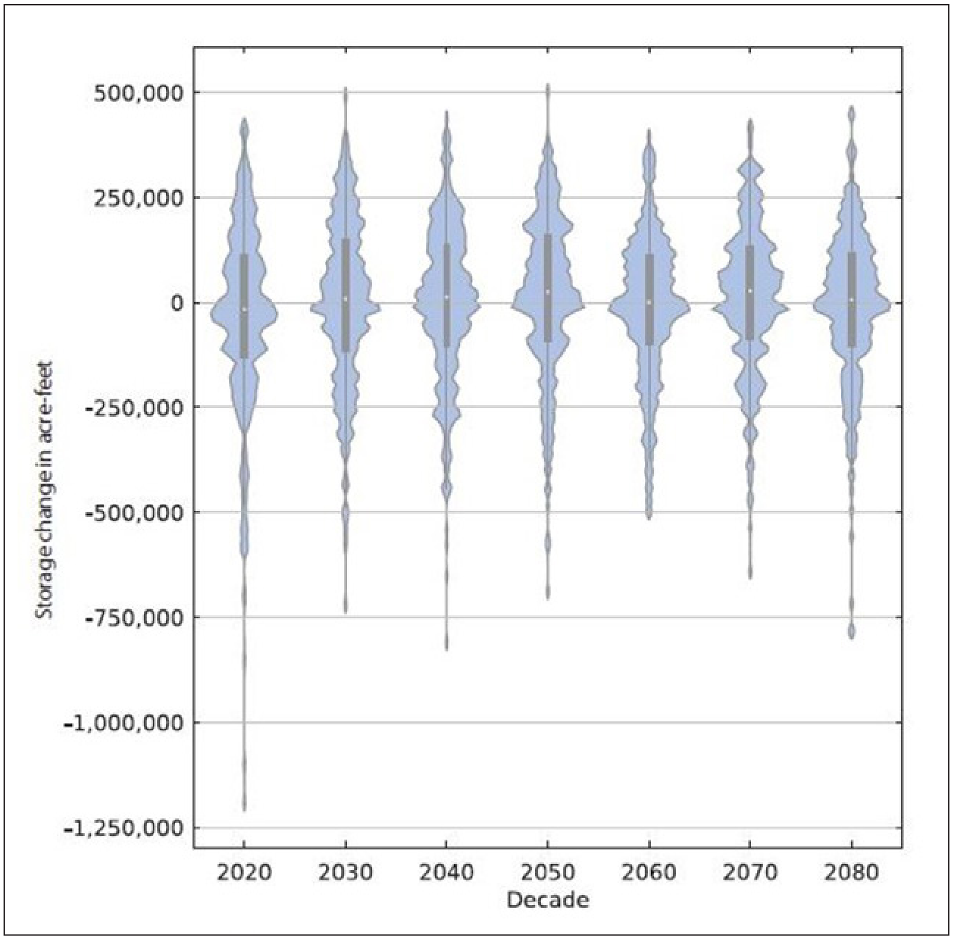

Figure 13. Violin plots showing the distributions, median values, and quartiles of the storage change component of the groundwater budget by decade. Holding with MODFLOW convention, gain of groundwater storage is shown as an aquifer outflow (negative). Blue indicates the distribution of data, white dots indicate the median, the gray box indicates the interquartile, and the vertical gray lines indicate the extent of the range of values, with outliers excluded. There are 300 values per decade for each violin plot, except for the 2080 decade, which includes 240 values.

exchanges between the alluvium aquifer and the Trinity River. As such, this groundwater model should be used for basin-wide water budget assessments and not localized regions within the TRB. Population growth, land-use changes, and other likely anthropogenic effects that could appreciably reduce water availability in the future were not considered in the simulations described herein.

Application and interpretation of outputs from GCM simulations require an understanding of some basic considerations and limitations of the results as summarized by Taylor et al. (2012). These include unforced variability, bias correction, downscaling, and multi-model ensemble (Krinner et al. 2020; Soriano et at. 2019). GCMs typically have grid cells that are approximately 100 kilometers by 100 kilometers. Climate change models are being tasked to provide climate change effects on increasingly smaller spatial scales. To accomplish this task, downscaling techniques have been developed to take GCM output and provide meaningful information at scales smaller than the size of the GCM's grid cells (Taylor et al. 2012). LOCA is a statistical downscaling technique that uses history to add improved fine-scale detail to GCMs (Pierce et al. 2014). LOCA errors tend to pattern those of random variability in sampling as opposed to errors showing spatial pattern biases. However, like all statistical models, LOCA is based on historical data and thus assumes that spatial relationships and local and average climate fields will not change for future climate scenarios.

Research has shown that the use of multi-model ensemble means and the ensemble range (spread of minimum and maximum across many GCMs) will provide better projections of future changes in climate and represent the most conservative approach given the challenges of predicting complicated systems like climate (Venkataraman et al. 2016). Therefore, long-term climate trends from an ensemble mean of many GCMs

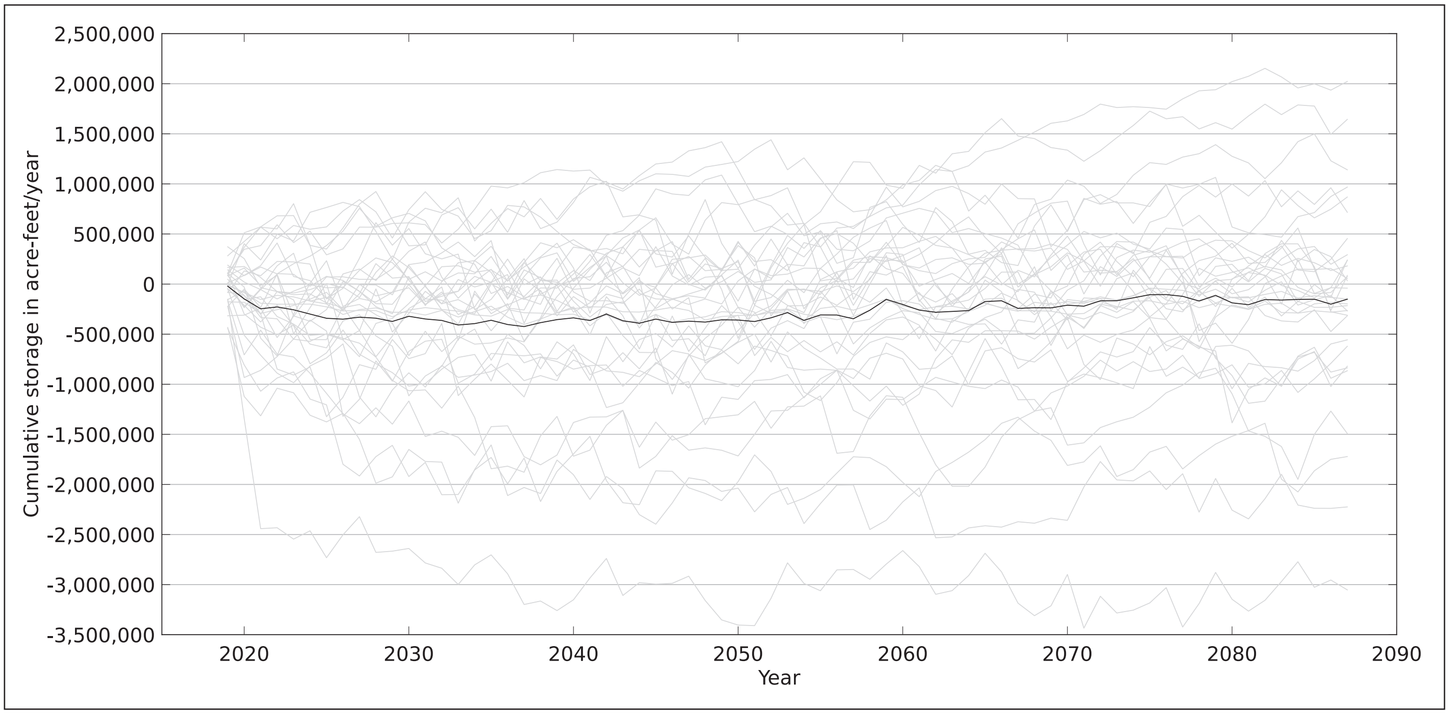

Figure 14. Plot showing cumulative groundwater storage change over time for all global climate model scenarios, with the ensemble mean plotted in black and each global climate model scenario plotted in gray. Negative values represent an increase in groundwater storage.

will provide a broad representation of future climate conditions, not an accurate description of the timing and magnitude of individual future events (Venkataraman et al. 2016).

DISCUSSION

The TRB is predominately within two regions of the TWDB RWPGs: Region C is in the upstream part of the TRB, and Region H is in the downstream part of the TRB (Figure 1). Both RWPGs inform stakeholders of the water supply and demand by providing and updating a water plan every 5 years. Although water plans for these two regions are available for 2021 (Freese and Nichols, Inc. et al. 2020; Region H Water Planning Group et al. 2020), for the purpose of this study, values provided in the 2016 water plans were used (Freese and Nichols, Inc. et al. 2015; Region H Water Planning Group et al. 2015). Using land use change projections and predicted population changes in the area, TWDB and the RWPGs produce water supply availability values for the regions for the next 50 years in decadal increments. Local entities use the information provided in the RWPG water plans to make management decisions regarding water use. Although the RWPGs' water plans are thorough and comprehensive, one limitation is that they do not consider future climate change as part of their projected water budget. This study aimed to provide an initial framework for stakeholders to evaluate the vulnerability of the TRB to a changing climate through the use of GCMs. However, the scope of this study is limited by simplified models that do not account for the complex regulation in the upper part of the TRB or the TRB's projected anthropogenic changes, which include substantial population growth and land-use changes, particularly in and near the Dallas-Fort Worth and Houston metropolitan areas. As such, the results of this study and the findings of the RWPG water plans cannot be compared directly but could be studied in conjunction to better understand TRB water availability.

The mean annual increase in precipitation to Region C reservoirs from historical data (1900–2017) is 0.06 inches/year, and the mean seasonal increase is 0.02 inches/year for each of the three seasons. The estimated total annual volume increase from upward precipitation trends reported in Harwell et al. (2020) to 14 Region C reservoirs is 5,486 acre-feet/year (2018–2070) inches/year, or 0.12% of regions C and H's projected water availability in 2070 of 4,444,916 acre-feet/year (Table 3). Projected water availability in 2070 is calculated from the values in Table 3 as the sum of the total volumes including groundwater in regions C and H and subtracting the sum of the groundwater volumes in both regions.

However, according to the surface-water model analysis, the GCM ensemble mean annual precipitation indicates a downward trend in precipitation of about 0.03 inches/year (2018–2099), resulting in a downward trend in Hortonian runoff. The surface-water model GCM ensemble mean indicates a downward trend in Hortonian runoff of about 0.0013 inches/year.

Simulated results of the surface-water model GCM ensemble mean indicate a downward trend in actual evapotranspiration of about 0.01 inches/year, likely a result of less water input to the system as precipitation and therefore less surface water available for evapotranspiration. Lastly, the surface-water model GCM ensemble mean indicates a downward trend in recharge of −0.0092 inches/year or approximately 8,764 acre-feet/year to the TRB.

Similar to the surface-water model results, the TRAA groundwater model analysis of the GCM ensemble mean indicates a downward trend of about 2,376 acre-feet/year of recharge to the TRAA, or 0.30% of the projected 2070 groundwater availability in regions C and H (Table 3). The downward trend in recharge is a result of the downward trend in precipitation from the GCM ensemble mean. The TRAA groundwater model GCM ensemble mean indicates an upward trend in the amount of groundwater flowing out of the aquifer to rivers and streams at a rate of about 1,877 acre-feet/year. The TRAA model GCM ensemble mean also indicates an upward trend of 3,655 acre-feet/year in cumulative storage change, and the amount of groundwater in the aquifer is decreasing despite an initial increase in groundwater storage, as depicted by the annual GCM ensemble mean data in figure 14.

The GCM ensemble mean and trend scenario results show long-term stability in the water budget for both surface water and groundwater for the study period. The estimated total annual increase in volume to 14 Region C reservoirs from upward trends in precipitation is 5,486 acre-feet/year (2018–2070). However, the surface-water model GCM ensemble mean annual precipitation indicates a downward trend in precipitation of about 0.03 inches/year (2018–2099), resulting in a downward trend in Hortonian runoff of approximately 0.0013 inches/year. The GCM ensemble mean for the surface-water model (11,471,544 acres) indicates a downward trend in recharge of about 8,764 acre-feet/year. The GCM ensemble mean for the TRAA groundwater model (3,369,961 acres) also indicates an upward trend (decrease of groundwater storage) of 3,655 acre-feet/year in cumulative storage change, and the amount of groundwater in the aquifer is decreasing despite an initial increase in groundwater storage. The results of this analysis show that the overall change in future water availability attributable to climate change is small, assuming the average of the ensembles is the best predictor of the future. The scientific consensus is that water availability in the future will be more variable compared to the past because of the likelihood of longer and more severe droughts punctuated by more intense storms (Nielsen-Gammon et al. 2021).

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Frac Sand Facilities and Their Potential Effects on the Groundwater Resources of the Monahans-Mescalero Sand Ecosystem, Permian Basin, Texas

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Abstract: Up until the end of the oil and gas boom in 2014, much of the sand used in the Permian Basin for hydraulic fracturing was sourced from upper Midwest of the United States. Because of substantial cost savings, producers in the Permian Basin began using local sand resources in 2015, creating an associated boom in local frac sand mining in the Monahans-Mescalero Shinnery Sands. By December 2018, 17 frac sand operations had registered with the Texas Commission on Environmental Quality with a cumulative annual capacity of 56.8 million tons and a self-reported 2,927 acres of disturbed land. We identified 230 production wells for the 16 facilities with depths ranging from 80 to 1,199 feet. Most were completed in the Pecos Valley Alluvium and/or Dockum aquifers. Estimated frac sand facility water use (10,000–40,000 acre-feet per year, based on 60–250 gallons of water consumed per ton of produced sand) rivals or exceeds that of water used in the four counties (Crane, Ector, Ward, and Winkler counties) with active frac sand facilities (23,500 acre-feet per year). Modeling suggests that long-term pumping of the unconfined Pecos Valley Aquifer may be a challenge requiring additional wells over time or the use of alternative water supplies. For the confined Dockum Aquifer, simulations suggest that pumping might completely deplete artesian pressure at the well field after 10 years.

Keywords: frac sand, groundwater, Permian Basin, fracking

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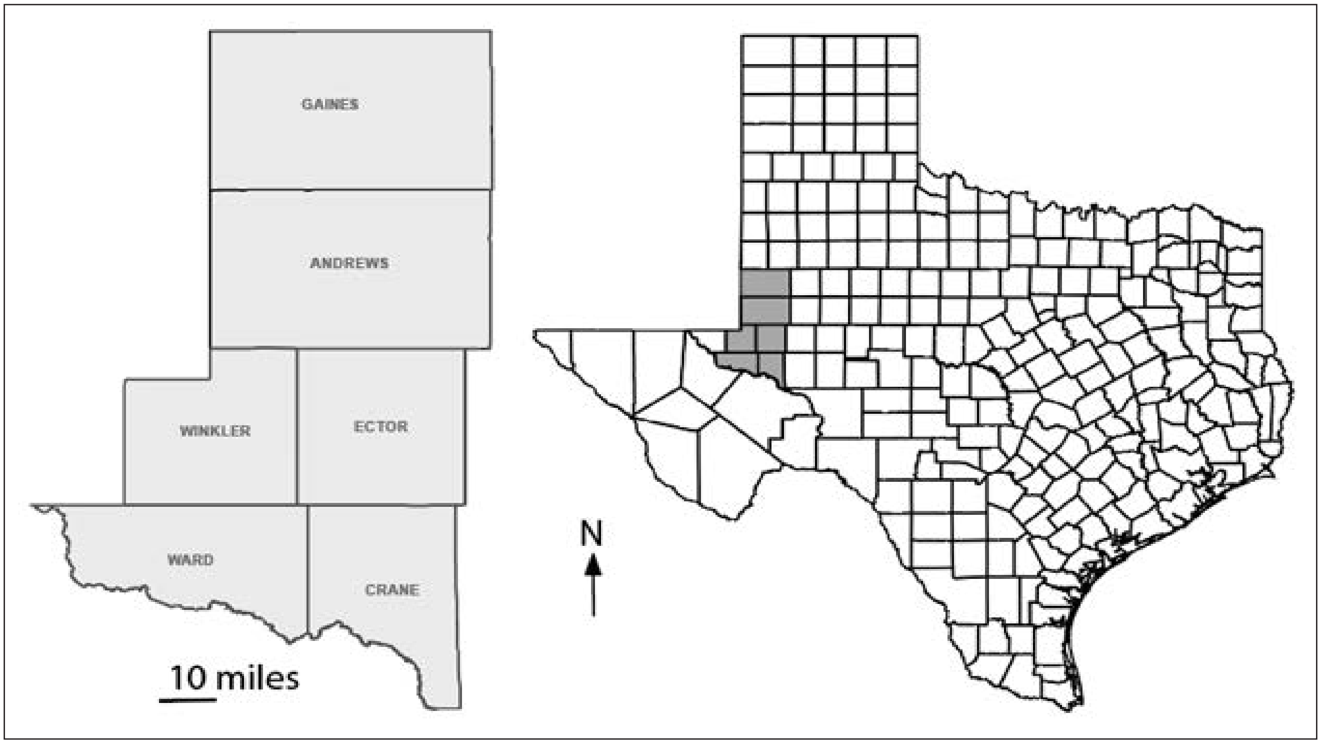

Figure 1. Study area is located in Andrews, Crane, Ector, Loving, Ward, and Winkler counties.

INTRODUCTION

There are many aspects to successfully hydraulic fracturing a well, but there are no raw ingredients more critical than sand and water. Water is needed to overpressure the formation to its breaking point and carry sand into the resulting array of fractures, and sand is necessary to prop those fractures open once the overpressure is released. Water and sand work together to create passageways for oil and gas to flow to a producing well.

The ideal sand used for fracking (frac sand) is uniform in size and shape (WDNR 2012) and can withstand lithostatic pressure, temperature, and dissolution (Bleiwas 2015). Traditionally, frac sand was sourced from the Northern White or Ottawa White in the upper Midwest (Benson and Wilson 2015). However, the cost of transportation, which is generally by rail and truck, can double to triple the price of sand sourced from the upper Midwest and delivered to the Permian Basin (based on numbers provided by Bleiwas 2015; McEwen 2017).

After a downturn in oil prices in 2015, engineers in the Permian Basin began experimenting with local sand from the Monahans-Mescalero Shinnery Sands and found them passable (McEwen 2017; Mentz 2018; Zdunczyk 2018). By reducing transportation costs through using local sources, cost savings can be $45 per ton of sand (Zdunczyk 2018). Triepke (2018a) estimated that 20 local frac sand facilities could save the oil and gas industry in the Permian Basin $3.5 billion per year.

As with any mining and processing activity, frac sand facilities have their potential environmental impacts, including air quality degradation, land damage, surface-water and groundwater contamination, and groundwater depletion (Orr and Krumenacher 2015), as well as increased noise and traffic (Maslowski 2012 as cited in Benson and Wilson 2015) and deleterious impacts to wildlife habitat (e.g., Kline and Osterberg 2014).

The purpose of this study was to investigate the potential effects of frac sand facilities on groundwater resources in the Monahans-Mescalero Shinnery Sands, home to the dunes sagebrush lizard (Zdunczyk 2018), a species proposed for listing under the Endangered Species Act. We did this by describing the physiography, hydrogeology, groundwater management, and frac sand production in the area; estimating water usage; and modeling potential effects groundwater production may have—short-term and long-term—on water levels in the area.

STUDY AREA

The study area includes Andrews, Crane, Ector, Gaines, Ward, and Winkler counties in West Texas (Figure 1). These counties are part of the Southern High Plains physiographic province, which is characterized by its flatness, playa lakes, and local dune fields (Wermund 1996). Average annual precipitation is about 15 inches and is unimodal, with most precipitation falling between May and October (TWDB 2012). Aver-

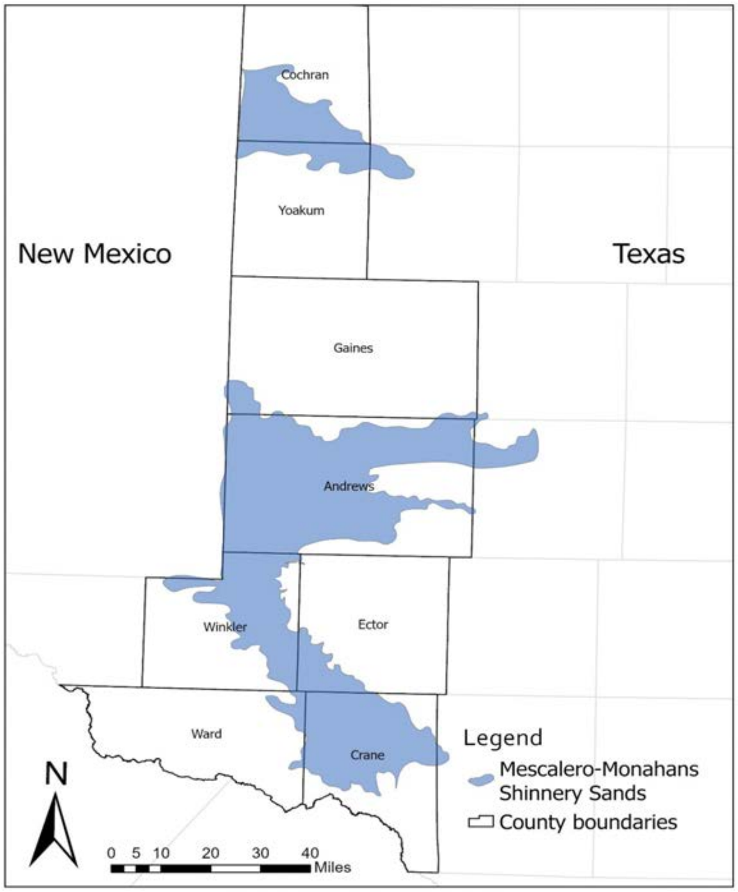

Figure 2. Approximate extent of the Monahans-Mescalero Shinnery Sands in Texas.

age annual gross lake evaporation is about 70–75 inches per year, and average annual temperature is about 58–60 degrees Fahrenheit (TWDB 2012 p. 149). All six counties of the study area include parts of the Monahans-Mescalero Shinnery Sands (Figure 2). Havard Shin Oak, Havard Shin Oak-Mesquite, and Mesquite-Lotebush brush communities exist in the dune area (TPWD 1984).

The study area has three major aquifers—Edwards-Trinity (Plateau), Ogallala, and Pecos Valley—and four minor aquifers—Capitan Reef Complex, Dockum, Edwards-Trinity (High Plains), and Rustler—as defined by the Texas Water Development Board (Figure 3; George et al. 2011). The two aquifers locally used for frac sand production in the study area are the Pecos Valley and Dockum aquifers; therefore, we will only present hydrologic information on these two.

The Pecos Valley Aquifer consists of alluvial and windblown sediments in the Pecos River Valley (George et al. 2011) and underlies all of Ward County, most of Crane and Winkler counties, and parts of Andrews and Ector counties (Figure 3a). The Dockum Aquifer consists of gravel, sandstone, siltstone, mudstone, shale, and conglomerate, with the highest yields from the middle and base of the aquifer, generally from the Santa Rosa Formation (George et al. 2011). The lower, productive part of the Dockum Aquifer is often referred to locally and on well logs as the Santa Rosa Aquifer. The Dockum Aquifer underlies most of the study area, including all or almost all of Andrews, Ector, and Winkler counties and most of Crane, Gaines, and Ward counties (Figure 3b). Before oil and gas activities in the area, most aquifer production from the Pecos Valley and Dockum aquifers in the study area was for municipal purposes, with some agricultural use in Ward County (Table 1). Jones (2004) noted that minor amounts of saline groundwater flow from the deeper Permian sediments into the Pecos Valley Aquifer.

There are historical and contemporary reports of long-term standing water among the Monahans-Mescalero Shinnery Sands. Many Indian artifacts have been found among the dunes, indicating that humans were drawn to the area (Justice and Leffler 2016). In 1848, Captain R.B. Marcy of the Corps of Topographical Engineers traveled through the dunes and noted "…several large, deep pools of pure water the very last place on earth where one would ever think of looking for it";

Table 1. Groundwater pumping in acre-feet in the study area in 2016 for the Ogallala and Dockum aquifers (data from TWDB 2018c).

County	Aquifer	Municipal	Manufacturing	Mining	Electric	Irrigation	Livestock	Total
Andrews	Dockum	-	-	8	-	-	2	10
	Pecos Valley	110	-	-	-	-	28	138
Crane	Dockum	154	-	-	-	-	21	175
	Pecos Valley	1,014	-	-	-	-	41	1,055
Ector	Dockum	61	4	-	-	-	2	67
	Pecos Valley	-	-	-	-	-	-	-
Gaines	Dockum	17	-	-	-	-	-	17
Ward	Dockum	6	-	-	-	21	8	35
	Pecos Valley	5,273	-	-	16	1,650	50	6,989
Winkler	Dockum	1,438	29	-	-	-	6	1,473

The Mining category includes water pumped for oil and gas as well as for frac sand facilities; however, for the study area, these pumping estimates do not include frac sand facilities because the estimates pre-date frac sand activities.

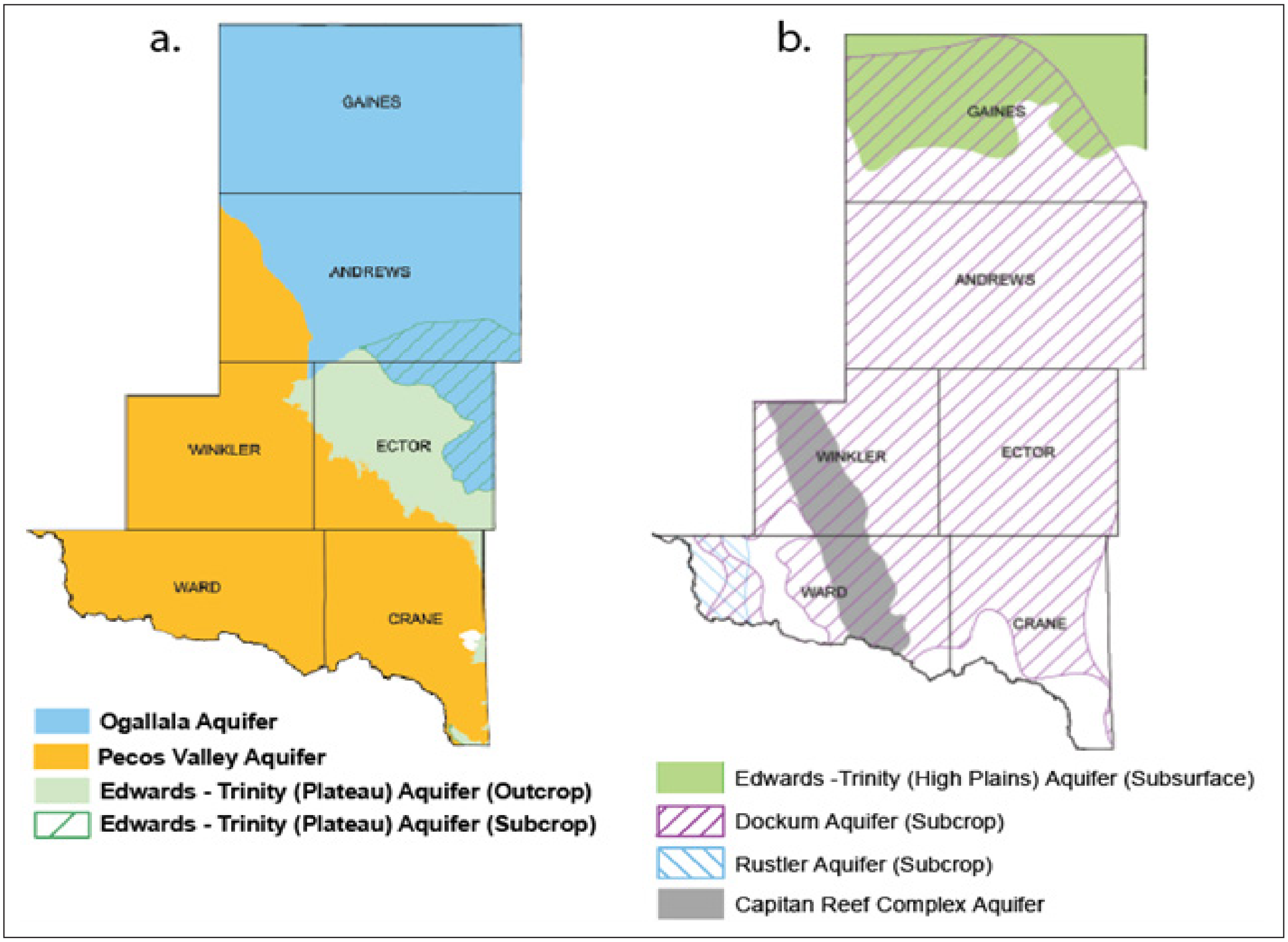

Figure 3. Major and minor aquifers in the study area (modified from TWDB 2018a).

Table 2. Modeled available groundwater and 2016 groundwater production for the relevant aquifers in the counties of the study area.

County	Aquifer(s)	Modeled available groundwater in 2020 (acre-feet/year)	Pumping in 2016[a] (acre-feet)
Andrews	Pecos Valley Alluvium	-	138
	Dockum	1,319	10
Crane	Edwards-Trinity (Plateau) and Pecos Valley[a]	4,991	-
	Dockum	94	1,055
Ector	Edwards-Trinity (Plateau), Pecos Valley, and Trinity[b]	5,542	2,463
	Dockum	-	67
Gaines	Dockum	0	17
Ward	Edwards-Trinity (Plateau) and Pecos Valley[c]	49,976	6,989
	Dockum	2,150	35
Winkler	Edwards-Trinity (Plateau) and Pecos Valley[d]	49,949	9,366
	Dockum	6,000	1,473

[a] 1,055 acre-feet for the Pecos Valley Aquifer and 0 acre-feet for the Edwards-Trinity (Plateau) Aquifer for pumping

[b] 2,453 acre-feet for the Edwards-Trinity (Plateau) Aquifer, 10 acre-feet for the Trinity Aquifer, and 0 acre-feet for the Pecos Valley Aquifer for pumping

[c] 6,989 acre-feet for the Pecos Valley Aquifer and 0 acre-feet for the Edwards-Trinity (Plateau) Aquifer for pumping

[d] 9,364 acre-feet for the Pecos Valley Aquifer and 2 acre-feet for the Edwards-Trinity (Plateau) Aquifer for pumping

Data for modeled available groundwater are from TWDB (2018d, e, f), and numbers for pumping are from TWDB (2018c).

his guide told him that the water was always there, even during dry seasons (Marcy 1850, Mace 2006). Machenberg (1982, 1984) mentioned "interdunal ponds" at Monahans Sandhills State Park and includes photographs of them. Machenberg (1982) noted that unvegetated dunes immediately absorb rainfall (there is no surface drainage in the dune field) and can store large amounts of rainfall and that the surficial sand is a locally important aquifer. She also noted that perched water tables form where underlying caliche is sufficiently thick. If these dune pools source from perched aquifers—as they appear to be—then pumping from the Pecos Valley Aquifer beneath would have no impact on the pools or vegetation communities associated with dunes sagebrush lizard habitat. However, removing contributing dunes or pumping or potential pumping from the pools, as described by Triepke (2018c, 2018d), would likely impact these perched aquifers.

The study area has one groundwater conservation district: the Llano Estacado Underground Water Conservation District in Gaines County. This district requires well registration, a production limit of 10 gallons per minute per contiguous acre not to exceed 16.13 acre-feet per acre per year, and setbacks from property lines and other wells (LEUWCD 2018). There is no regulatory authority for groundwater use in the rest of the study area beyond state requirements on well construction and submitting a driller's report with the Texas Department of Licensing and Regulation.

Groundwater conservation districts are required to establish desired future conditions for relevant groundwater resources in their groundwater management area every 5 years (with 2016 being the most recent year). A desired future condition—the management goal for a particular aquifer through the state water planning period of 50 years—is then used by the Texas Water Development Board to estimate the modeled available groundwater, or the amount of water that can be pumped to achieve the desired future conditions. State law requires regional water planning groups to use modeled available groundwater numbers in their planning exercises regardless of the existence of a district. Although planning groups do not have regulatory authority, modeled available groundwater numbers may disallow the use of state funds or state financing for a groundwater project. Alternative (such as private) funding could still be used to implement the groundwater project.

Modeled available groundwater for the Pecos Valley and Dockum aquifers is about 50,000 acre-feet per year in Ward and Winkler counties, with most in the Pecos Valley Aquifer (96% in Ward County and 89% in Winkler County; Table 2). Except for the Dockum Aquifer in Gaines County, estimated pumping is below modeled available groundwater for 2016 (Table 2).

If groundwater conservation districts were formed in any of the five counties in the study area without a district, they would inherit the existing desired future conditions and modeled available groundwater and would be required to manage toward the desired future condition. Any new districts would participate in subsequent 5-year revisions of desired future conditions.

Table 3. Registered frac sand facilities in the study area as of January 21, 2019.

County	Operator/facility name	Initial permit	Disturbed[a] acres	Registration #	Tonnage[b]
Crane	Unimin Corporation[c]/Covia Crane Facility	5/9/2018	228	AP0002685	3
	U.S. Silica/Crane County Plant	12/1/2017	188	AP0002546	4
Ector	Preferred Sands of Monahans	10/23/2017	100	AP0002853	3.3
Gaines	U.S. Silica/Seagraves Sand Plant	5/23/2017	33	Idled	0.5
Ward	Wisconsin Proppants/E Ranch Facility	5/24/2018	213	AP0002697	3
	Black Mountain Sand/Sealy Smith Facility	9/21/2018	150	AP0002792	1
Winkler	Hi-Crush Permian Sand/Hi-Crush	4/4/2017	70	AP0002202	3
	Black Mountain Sand/Vest Facility	12/11/2017	348	AP0002552	6
	High Roller Sand Operating[d]/Kermit Plant	12/21/2017	134	AP0002560	4
	Lonestar Prospects[e]/West Texas Sand Plant	1/19/2018	250	AP0002587	3
	FML Sand[c]/FML Kermit	3/26/2018	250	AP0002645	3
		10/16/2018	300	AP0002849	
	Black Mountain Sand/El Dorado Facility	4/27/2018	247	AP0002673	6
	Alpine Silica/Alpine Silica	5/4/2018	60	AP0002679	3
	Badger Mining Corporation/Kermit Plant	5/4/2018	125	AP0002680	3
	Atlas Sand Company/Atlas North	6/8/2018	83	AP0002721	4
	Atlas Sand Company/Atlas South	8/29/2018	88	AP0002804	4
	Hi-Crush Permian Sand/Kermit Plant North	12/14/2018	60	AP0002879	3
	Smart Sand[f]	-	-	-	-

[a] The Texas Commission on Environmental Quality requires operators to report projected acreage of excavation for the year. Acreage is added annually and reported as the cumulative size of the excavation. Additional surface disturbances, including facilities and supporting infrastructure, are not included in the calculation.

[b] Registrations do not report annual tonnage capacity; we found these numbers from facility sites, press releases, or media reports.

[c] Unimin and FML Sand merged to form Covia.

[d] Now owned by Wisconsin Proppants

[e] Lonestar Prospects is a subsidiary of Vista Proppants.

[f] Smart Sand has not registered with the state but is drilling water wells in the area; we include this as a potential future frac sand facility.

FRAC SAND FACILITIES

In Texas, the state considers frac sand facilities as aggregate production operations, which must be registered with the water quality program at the Texas Commission on Environmental Quality (30 Texas Administrative Code §342.25[a]) with an annual renewal. There is also a requirement to obtain air permits from the Texas Commission on Environmental Quality, generally for bulk sand handling; boilers, heaters, and other combustion devices; and wet sand and gravel production. We used an online database of these registrations to identify frac sand facilities in the study area (TCEQ 2018). As of December 26, 2018, 17 frac sand facilities had been registered, with all the actively registered facilities clustered along the dunes between southeast of Monahans and northeast of Kermit in a 20-mile by 40-mile area (Table 3, Figure 4). Disturbed acres reported by operators in annual state registration paperwork for frac sand facilities in the study area range from 5 to 300 acres for a total of 2,927 acres for the 17 facilities (Table 3).

Based on operator-reported or press reports of annual production amounts, the 17 facilities had a combined 56.8 million tons of annual capacity (Table 3). Not including an idled plant, the 16 frac sand facilities average about 3.6 million tons of annual capacity per facility. More frac sand facilities—in addition to Smart Sand listed in Table 3—may be in development. Triepke (2018e) identified more than 30 potential facilities for the area. Current frac sand capacity is meeting about 40% of total demand and is expected to grow to 50% by 2023 (Rock Products News 2018).

Figure 4. Location of actively registered frac sand facilities in the study area (base map from Google Maps). Not shown is U.S. Silica's idled Seagraves Sand Plant located near the town of Seagraves in Gaines County.

WATER USE FOR FRAC SAND FACILITIES

The production of frac sand may require water for mining, transport, sorting, dust control, and on-site potable water needs. Depending on the type of mining, water may be used or encountered (WDNR 2012) for hydraulic mining and slurry transporting sand (Orr and Krumenacher 2015) or for dewatering if mining encounters a shallow water table. Mining in the study area, at least at present, does not appear to require much if any water for the extraction or transporting of sand.

Frac sand needs to have uniform shape and size. To achieve the desired shape and size, mined sand is washed, dried, sorted, and stored (WDNR 2012). Washing, which removes the fine particles, can be done in multiple ways. Water can either be sprayed on sand on a vibrating screen or be sprayed through an up-flow clarifier, where the sand is fully immersed in wash-water and the sand falls to the bottom (WDNR 2012) while the fine particles are carried away by the up-flow (MEQB 2013; Orr and Krumenacher 2015). The washed sand may then be drained with a dewatering screen before subsequent processing

(Kelley 2012). The wash-water may be treated with flocculants to remove the fines and then used again (MEQB 2013). The slurry of fines may then be plate pressed to recycle as much of the water it holds as possible (e.g., Triepke 2017a; Triepke 2018b). Wet fines are then generally used for partial reclamation of the mine.

Washed sand is then taken to a surge pile, where water adhering to the grains of the sand either evaporates out of the pile or drains down out of the pile (WDNR 2012). One operator, Hi-Crush (2018), claimed to deliver sand to the surge pile with less than 12% moisture. Water that drains downward out of the pile may be collected and reused (e.g., Triepke 2017). A drainage system beneath these piles can reduce moisture content to 2–4% (Hi-Crush 2018). Sand from the surge pile is then collected, dried, and screened into specific particle sizes (WDNR 2012).

Water may also be used on the site to meet potable needs and for dust control (WDNR 2012). Dust control is a significant environmental concern because breathing silica dust can cause silicosis; spraying water at the mine and plant is effective in mitigating airborne particles (Orr and Krumenacher 2015; Zdunczyk 2018; Mathews 2017). Mathews (2017) estimated that operators would need about 57 inches of water per year under average conditions to stay even with evaporation for dust control. Mathews (2017) also noted several alternatives to using water, such as creating greater paved areas, road cleaning, using dust control chemicals, limiting exposure, minimizing wind exposure, and using stabilized berms.

It is important to note the difference between water use and water consumption. Water use is the total amount of water needed to achieve a certain task. Consumption refers to the amount of water lost during the process, perhaps from evaporation, leaks, or incorporation into a product. Use and consumption can be equal, but with water recycling, consumption will be less than use. Unfortunately, use and consume are employed interchangeably in reference to water in frac sand operations, making it difficult to determine what is used and what is consumed. Furthermore, it can be challenging to identify what processes are included in use and efficiency estimates.

Facilities commonly recycle water used to wash mined sand (Orr and Krumenacher 2015). WDNR (2016) notes that for Wisconsin frac sand facilities, water use efficiency is generally high because many operators use closed-loop systems where evaporation and incorporation are the only processes in which water is lost during processing. Furthermore, newer plants are more efficient and therefore require less water than older plants (WDNR 2016).

Closed-loop systems that recycle 90% of their water can consume as little as 6.6 million gallons per year as compared to open-loop systems that can use as much as 730 million gallons per year (Orr and Krumenacher 2015; values not normalized to sand production). Facilities that recycle can consume 6.6 million–91 million gallons per day (Orr and Krumenacher 2015; values not normalized to sand production).

An average industrial sand facility in Wisconsin can withdraw 657 million gallons per year from aquifers or streams and rivers (WDNR 2016). However, this number is for a range of facility sizes and efficiencies and is not normalized to sand production (and the use of the word "can" by the authors of WDNR 2016 suggests permitted amounts, not actual produced amounts). Orr and Krumenacher (2015) noted that facilities might need 250–500 gallons per minute of make-up water per million tons of sand production (130–260 gallons of water consumed per ton of sand produced) for closed-loop systems that recycle 90% of their water.

We were unable to find published numbers for water consumption for frac sand facilities in Texas; however, we were able to access limited information and compare it to Orr and Krumenacher's (2015) numbers. We list the estimates below from largest to smallest. Note that only one of the estimates (U.S. Silica) was explicitly normalized to tons of sand produced. For many of the other estimates, we assumed that reported (or contracted) water use is associated with plant capacity, which may not be accurate, especially if a facility is ramping up production. We first present the data in the units they were reported in and then end each bullet with a summary in gallons per ton of sand (gallons of water consumed per ton of sand produced).

- Preferred Sands of Monahans has a take-or-pay contract with the Colorado River Municipal Water District for 2,000 gallons per minute of supply for 4.2 million tons per year of possible production (Triepke 2018b), resulting in a high-end water consumption of 250 gallons per ton of sand.
- Based on estimated well yields reported in water well drillers reports, Atlas Sand South may be able to produce 1,870 gallons per minute for its 4-million-tons-of-sand-per-year plant, which results in a high-end water consumption of 246 gallons per ton of sand.
- For a frac sand facility in Cooke County, Texas, the operator, EOG, estimated its consumptive water use at 370 gallons per minute (Osborne 2013) to produce 1 million tons of sand a year (Russell 2011). That amounts to a possible water consumption of 194 gallons per ton of sand.
- Triepke (2018a) estimated that the addition of 20 potential frac sand facilities with 56 million tons per year of production would add about 10 billion gallons of annual freshwater demand to the Permian Basin. That amounts to an average water consumption per facility of about 180 gallons per ton of sand.
- A local driller noted that frac sand companies were generally seeking 400–600 gallons per minute (210 million–315 million gallons per year) of supply. If this range applies for an average frac sand operation that produces

3.6 million tons per year, that amounts to a possible water consumption of about 60–90 gallons per ton of sand.

- U.S. Silica reported that its water consumption is 70 gallons per ton of sand (Wes Penn, U.S. Silica, personal communication).

Atlas Sand, which can produce 4 million tons of sand per year, claimed that its total consumption was 500 barrels per day (Hunter Wallace, Atlas Sand, personal communication). That results in the consumption of 1.9 gallons per ton of sand, a number that is too low to operate a frac sand operation. At a minimum, the water lost to capillary forces before sand is dried is about 11 gallons of water per ton, and this does not account for water lost through adhesion to the fine particulates and other processes (Mace 2019).

Based on these estimates, reported or inferred consumptive water use ranges from 60 to 250 gallons of water consumed per ton of sand in the Permian Basin as compared with Orr and Krumenacher's (2015) 130–260 gallons per ton.

With the study area's dry climate and lack of available surface-water resources, local frac sand operations almost exclusively use groundwater. Local aquifers provide most of the water for frac sand production in the Permian Basin (Campbell 2018); municipal and private suppliers are also sources or future sources of water.

To assess water sources for frac sand facilities in the study area, we used the Texas Water Development Board's Groundwater Data Viewer (TWDB 2018b) to inspect submitted drillers reports. Drillers reports include information on location, borehole size and depth, lithology, and casing. The reports also request information on water quality, water level, and well tests, but drillers generally do not collect or report data in these categories.

Drillers may submit reports electronically or in paper form. Forms submitted electronically are instantly available online, but papers forms may take more than a year to be entered by Texas Water Development Board staff. For example, for Lonestar Prospects' West Texas Sand Plant, four well reports submitted in paper form in October 2017 were not entered into the database until late December 2018. Therefore, if a driller submitted paper forms for the wells it drilled, the wells may not be reflected in this study.

We identified a total of 230 production wells for the 16 sites that had production wells drilled at their locations. Drillers identified most production wells as industrial; however, drillers marked a few as irrigation wells (perhaps because they were intended for dust suppression). Because we did not see any agricultural irrigation associated with these wells from aerial photography, we included irrigation wells as production wells for the facilities. Several facilities also had test and monitor wells, which we did not include in the analysis. Test wells were generally plugged after boring, and monitor wells generally had small diameters consistent with monitoring rather than production purposes. Two sites did not have any wells in the state database, suggesting an off-site source of water or delay in reporting drillers reports.

Based on the depth of wells, which ranged from 80 to 1,199 feet deep (Table 4), and geologic structure (Meyer et al. 2012; Ewing et al. 2008; Mace 2019), supply wells at the facilities are completed in the Pecos Valley Aquifer (103 wells), the Dockum Aquifer (71 wells), both the Pecos Valley and Dockum aquifers (32 wells), and, at one facility, the Pecos Valley and Dockum aquifers and the upper part of the Permian Basin (14 wells). The drillers for 10 wells did not report completion information, but given their depths, they are either completed in the Dockum Aquifer or both the Dockum and Pecos Valley aquifers. Seven facilities have wells completed in both aquifers either explicitly (screened in both) or non-explicitly (screened in the Dockum Aquifer but with the borehole annulus packed with gravel or sand across both formations).

The number of wells at individual facilities ranged from four to 29 (Table 4). For facilities solely reliant on the Pecos Valley Aquifer, the number of wells per facility ranges from eight to 14, whereas for facilities reliant exclusively on the Dockum Aquifer, the number of wells per facility ranges from four to 27 (Table 4). Nine—possibly 10—facilities have wells completed in both aquifers. Our results agree with Campbell (2018), who found that facilities have 10–15 wells pumping water from Pecos Valley and Dockum aquifers, and wells can be screened in both aquifers.

The relatively large number of wells drilled at these facilities suggests that the aquifers in this area are not highly productive, a conclusion supported by the thin saturated thickness of the Pecos Valley Aquifer and the low hydraulic conductivities of the Dockum Aquifer. Facility operators have to drill and string together wells until they meet their water needs, presumably with several additional back-up wells to provide supplies when other wells are down for maintenance.

POTENTIAL IMPACTS FROM GROUNDWATER PRODUCTION

The Minnesota Environmental Quality Board (MEQB 2013), writing about the effects of frac sand facilities in Minnesota, noted that the cumulative effects on water quantity of multiple silica sand mines in proximity are not well understood and recommended requiring monitoring wells at frac sand facilities to measure water levels, flow directions, and water quality. Rock Products News (2018), quoting IHS Markit, noted that regional Texas sands have challenges related to water availability. Campbell (2018), referring to the Permian Basin, indicated that "…increasing stresses on the aquifer will provide the 'opportunity' to test the sustainability of the supply and the success of the collective efforts to plan and provide for future demand."

Table 4. Number of production wells drilled at the facilities.

County	Facility name	Latitude, longitude	# Wells	Depth (feet)	Aquifer
Crane	Covia Crane Facility	31.480, -102.704	8	123–153	Pecos Valley
	Crane County Plant[a]	31.602, -102.690	2	150	Pecos Valley
			8	485–705	Dockum
			16	190–320	Both (upper)[b]
			1	550	Both (lower)[b]
Ector	Preferred Sands of Monahans[c]	31.658, -102.775	14	581–1,199	Both + Permian
Gaines	Seagraves Sand Plant	32.924, -102.568	0	-	-
Ward	E Ranch Facility	31.610, -102.792	13	120–155	Pecos Valley
	Sealy Smith Facility	31.618, -102.897	0	-	-
Winkler	Hi-Crush	31.965, -102.973	5	910–944	Dockum
			2	910–940	Both
			4	900	Unknown
	Vest Facility	31.861, -102.915	10	129–161	Pecos Valley
			1	721	Dockum
			2	720–769	Both
	Kermit Plant	31.996, -103.036	28	80–230	Pecos Valley
			1	910	Dockum
	West Texas Sand Plant	31.764, -102.869	26	520–640	Dockum
			1	600	unknown
	FML Kermit	31.932, -102.983	9	917–938	Dockum
	El Dorado Facility	31.840, -102.966	9	120–185	Pecos Valley
			3	702–725	Dockum
	Alpine Silica	32.055, -103.049	9	840–906	Dockum
	BMC-Kermit Plant	31.962, -103.108	4	496¬–515	Dockum
	Atlas North	31.967, -103.009	14	140–240	Pecos Valley
	Atlas South	31.659, -102.877	19	100–120	Pecos Valley
			3	330–380	Both
	Kermit Plant North	31.967, -102.972	5	200–220	Dockum
			2	200–210	Both
			5	900	Unknown
	Smart Sand	31.770, -103.035	6	360–512	Both

[a] Listed owner of wells drilled in area is Barr Engineering; we assumed these wells were all drilled for Unimin.

[b] "Upper" refers to wells completed in the shallower part of the Dockum Aquifer on-site and "lower" refers to the lower part. All other references to Dockum Aquifer in this table refer to the lower part.

[c] Listed owner of wells drilled in area is Hydro Logics; we assumed these wells were all drilled for Preferred Sands.

It was too soon at the time of our study to see possible impacts from pumping beneath frac sand facilities with available data collection. Because there are no groundwater districts in the area measuring water levels, the only available data is collected by the Texas Water Development Board and entered into its online database (TWDB 2018b). In areas without groundwater conservation districts or in districts that do not measure water levels, the Texas Water Development Board measures water levels annually during the winter months when irrigation and other seasonal uses are at a minimum. Because most of the frac sand facilities went into operation during 2018, many of those measurements were not available at the time of our work. However, even with the Texas Water Development Board's measurements, the monitor wells may not be in the right place to accurately assess effects.

COMPARISON TO OTHER WATER USES

Other pumping may make it difficult to assess the effects of frac sand facilities without purpose-built monitoring. With at least 53.8 million tons per year of production capacity possibly needing 60–250 gallons of water per ton of sand production, frac sand facilities may be pumping 10,000–40,000 acre-feet per year of water. This use may be less than half or almost twice the 23,500 acre-feet of water currently produced for other uses in Crane, Ector, Ward, and Winkler counties, the counties that include active frac sand facilities.

Municipal suppliers also source their water from area aquifers. Besides the local communities, the City of Midland, the Midland County Freshwater Supply District #1, and the Colorado River Municipal Water District have well fields in the area. Many of the larger communities, including Monahans, seek water from the Monument Draw Trough of the Pecos Valley Aquifer west of the frac sand facilities. The City of Crane has a well field about 7 miles southeast of Monahans in the Pecos Valley Aquifer. The City of Kermit has water supply wells in the Pecos Valley and Dockum aquifers in and near the city. There are also numerous household and stock wells across the area, as well as supply wells for the oil and gas industry.

Because the Monahans-Mescalero Shinnery Sands rest in the middle of the Central Basin Platform between the Midland and Delaware basins (sub-basins of the Permian Basin), most of the local drilling is for conventional oil and gas accessed through vertical, unfracked wells, which require "low water volumes" (Scanlon et al. 2017). In the Central Basin Platform, 96–152 non-conventional (fracking) horizontal wells were drilled per year in 2012–2015, as compared to 1,256 wells drilled in the Midland Basin (Scanlon et al. 2017 Table S3b). With an average of about 80 acre-feet of water used to frac an oil well in the Permian Basin (Kondash et al. 2018), 100 fracked wells in the Central Basin Platform would use about 8,000 acre-feet of water per year.

A total of 1,557 conventional wells were drilled in the Permian Basin outside of the Midland and Delaware basins in 2015, down from 2,967 in 2014 (Scanlon et al. 2017 Table S3a). If half of those were drilled in the Central Basin Platform—and assuming water use of 300,000–600,000 gallons per well for drilling (Mielke et al. 2010)—water use for conventional drilling could range from 1,400 to 5,500 acre-feet per year. Note that these water estimates for oil and gas activities in the Central Basin Platform are over a much larger area than where frac sand facilities in the study area are currently focused. Furthermore, drilling intensity in the Central Basin Platform has generally been away from the Monahans-Mescalero Shinnery Sands (Scanlon et al. 2017 Figure 1).

Summing the above pumping estimates results in a range of 42,900–77,000 acre-feet of water possibly being pumped in Crane, Ector, Ward, and Winkler counties. Groundwater availability for the Pecos Valley and Dockum aquifers for the four counties (the modeled available groundwater in Table 2) sums to 118,702 acre-feet per year. Therefore, the combined four counties' uses—including those for frac sand facilities—are below the estimated groundwater availability with the ability to accommodate additional pumping.

WATER-LEVEL TRENDS

Some published information is available on water-level impacts for the study area. Wight (2018), a landowner near the dunes and frac sand facilities, noted that "there is an inevitable conflict between the people who need water and the folks who have it. Even though the nascent sand industry is not the largest water user in the sandhills, we are starting to see some dramatic effects on the supply of water since they arrived." Wight (2018) noted that he had seen some small decreases in the water table and had one well with a water-level decline of over 70 feet in the previous year. Using measurements made by the Texas Water Development Board as part of its annual water-level monitoring activities, Mace (2019) did not find any declines associated with frac sand mining; however, the wells were too distant from the mines to detect any changes as of December 2018.

CROSS-FORMATIONAL FLOW THROUGH MULTI-SCREENED WELLS

A total of 32 wells were screened in both the Pecos Valley and Dockum aquifers, and one well was screened in the Pecos Valley Aquifer, Dockum Aquifer, and upper part of the Permian rocks. Given the greater hydraulic head in the Pecos Valley Aquifer compared to the Dockum Aquifer, there is the potential for cross-formational flow from the Pecos Valley Aquifer to the Dockum Aquifer. While a well with multiple completions will produce from multiple formations during production (as

Table 5. Simulated water-level declines in the Pecos Valley and Dockum aquifers for single wells and hypothetical well fields.

Years of pumping	Water-level decline at well site (feet)	Radius of influence to 5-foot water-level decline (feet)	Radius of influence to 1-foot water-level decline (feet)
Scenario 1: *Single well pumping 40 gallons per minute in the Pecos Valley Aquifer*			
1	18	100	1,000
10	20	300	3,000
Scenario 2: *Twelve wells pumping 40 gallons per minute in the Pecos Valley Aquifer*			
1	25	550	2,100
10	47	4,000	9,000
Scenario 3: *Single well pumping 70 gallons per minute in the Dockum Aquifer*			
1	124	16,000	23,000
10	136	51,000	74,000
Scenario 4: *Seven wells pumping 70 gallons per minute in the Dockum Aquifer*			
1	272	40,000	65,000
10	360	130,000	-

long as the production head is lower than the head in any of the screened formations), once the well is no longer producing, groundwater will flow into the borehole from formation with higher heads into formations with lower heads. In the case of the dual completed wells, groundwater from the Pecos Valley Aquifer will flow through the borehole to the Dockum Aquifer. Such well completions should be discouraged because these wells are likely to affect water resources for remaining users as long as the well connection exists.

PROJECTIONS OF WELL-SITE WATER-LEVEL DECLINES

We developed two simple, interpretive groundwater models to project water-level declines in well clusters completed in the Pecos Valley and Dockum aquifers. Water-level declines due to pumping can be estimated given information on the aquifer (saturated thickness, hydraulic heads, hydraulic conductivity, storativity) and the pumping well (pumping rate, duration of pumping, well radius). Because we lacked specifics on the facilities, we investigated two type cases that are representative of the hydrogeology beneath frac sand facilities in the study area, one for the Pecos Valley Aquifer and one for the Dockum Aquifer. These type cases are intended to provide a general sense of how area aquifers might respond to pumping. An assessment of specific impacts at specific sites requires site-specific information that was not publicly available.

Based on the hydrogeologic data for the study area (Mace 2019), the type case for the Pecos Valley Aquifer had a saturated thickness of 70 feet, a hydraulic conductivity of 10 feet per day, and a storativity of 0.2. This type case facility for the Pecos Valley Aquifer produced 3.6 million tons of sand per year and had 12 wells with 8-inch diameters spaced 1,000 feet apart pumping 70 gallons of water per ton of sand, which amounts to about 40 gallons per minute per well. We chose 70 gallons of water per ton of sand, which is on the low end of the range we reported earlier, both because this rate was reported by U.S. Silica and because this type case would not support much higher amounts of pumping over 10 years.

The type case for the Dockum Aquifer included a saturated thickness of 200 feet, a hydraulic conductivity of 1.0 feet per day, a confined storativity of 2.5×10-4, an unconfined storativity of 0.15, and 300 feet of artesian pressure above the top of the aquifer. This type case facility for the Dockum Aquifer had seven wells with 8-inch diameters spaced 2,000 feet apart pumping 70 gallons per minute per well (again assuming a facility that produced 3.6 million tons per year pumping 70 gallons of water per ton of sand).

To model these type cases, we first used the Theis (1935) non-equilibrium equation for unsteady radial flow (with Jacob's [1963] correction for unconfined aquifers for the Pecos Valley Aquifer) to investigate water-level declines around a single well. We then then developed simple numerical groundwater flow models using MODFLOW-2000 (Harbaugh et al. 2000) through Groundwater Vistas (Rumbaugh and Rumbaugh 2017) with lateral boundaries placed distantly enough to have no impact on drawdowns caused by the well fields. To verify the numerical groundwater model, we compared its results for a single well to the results from Theis (1935). For the numerical groundwater flow model, we allowed transmissivity to vary with saturated thickness for the Pecos Valley Aquifer and allowed the Dockum Aquifer to convert from a confined to an unconfined aquifer when water levels fell below the top of the aquifer.

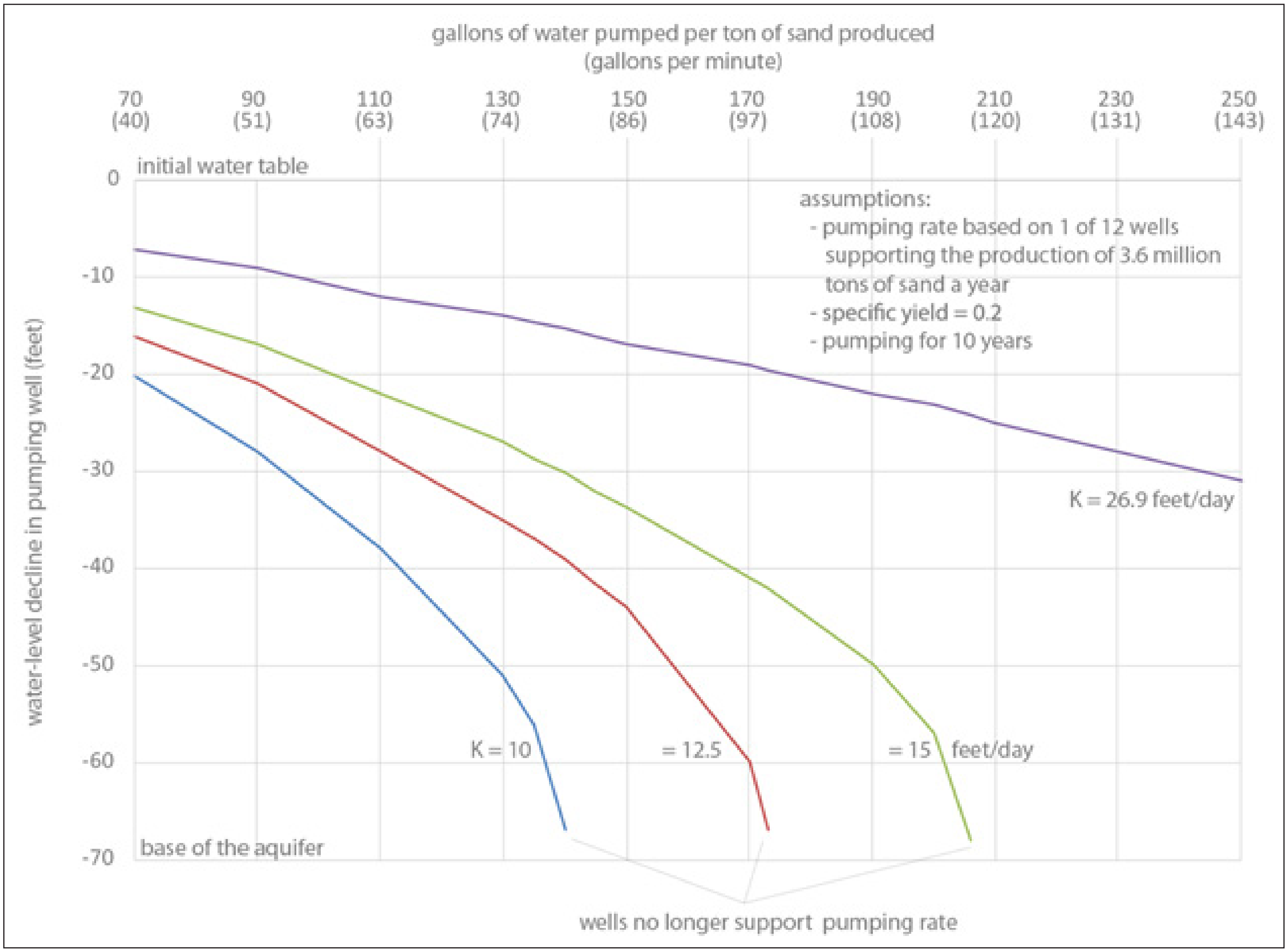

Figure 5. Sensitivity analysis of pumping rate and hydraulic conductivity on water-level declines in a single well in the Pecos Valley Aquifer after pumping 10 years.

For the modeling results presented below, we first discuss water-level declines around a single well pumping 40 gallons per minute in the Pecos Valley Aquifer and 70 gallons per minute in the Dockum Aquifer after pumping for 1 year and 10 years (Table 5). We then present a sensitivity analysis on a single well pumping for 10 years, where we plot water-level declines at the well for different pumping rates and hydraulic conductivities. We present these single well analyses to demonstrate how the unconfined Pecos Valley Aquifer responds differently to pumping than the confined Dockum Aquifer and how a single well responds to different levels of pumping and hydraulic conductivity. In the case of the Pecos Valley Aquifer, this analysis helps establish a physical bound on how much water can be pumped from the aquifer and thus how much water may be being pumped for frac sand facilities.

After that, we present results from the numerical model where all the wells are included, 12 for the Pecos Valley Aquifer and seven for the Dockum Aquifer, first for 1 year of pumping and then for 10 years of pumping (Table 5). These are the simulations that show the water-level declines around the frac sand facility type cases. As a sensitivity analysis on the numerical model, we increased the pumping rate until the aquifer could no longer support the pumping (in modeling parlance, cells in the model go dry when the simulated water-level falls below the base of the aquifer). We did this for both the 1-year and 10-years simulation periods.

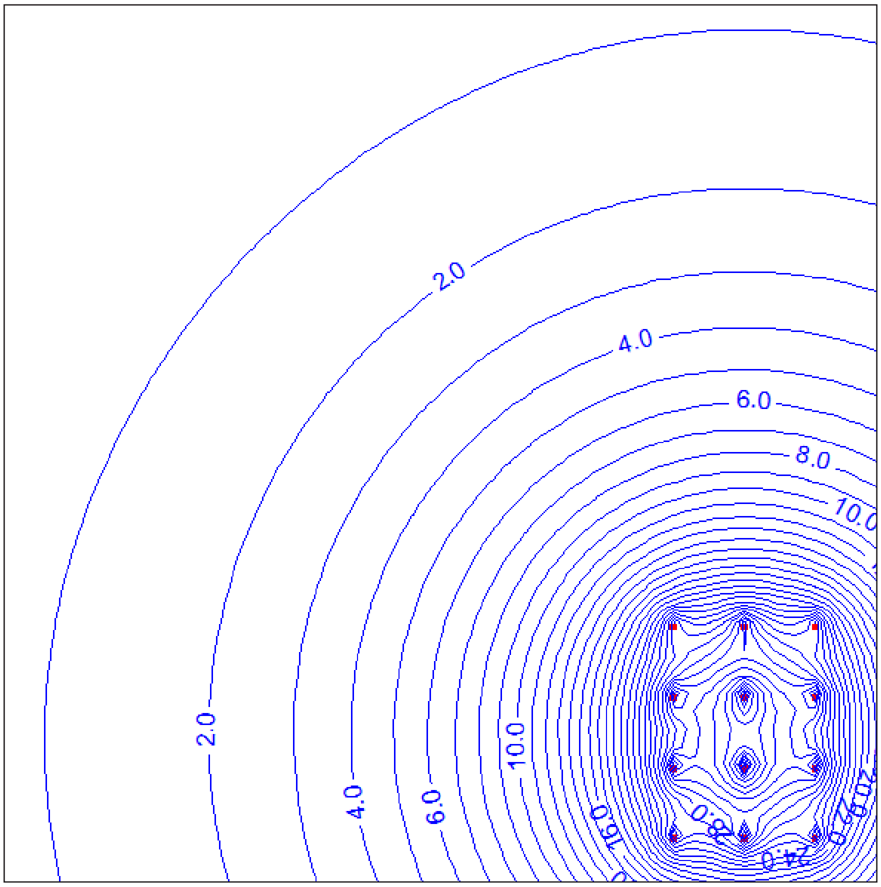

Figure 6. Water-level declines at a 1-foot interval around a hypothetical well field in the Pecos Valley Aquifer after pumping for 10 years. The wells (red squares) are spaced 1,000 feet apart.

MODELING RESULTS FOR THE PECOS VALLEY AQUIFER

For a single well pumping 40 gallons per minute in the Pecos Valley Aquifer, there would be about 18 feet of water-level decline after 1 year of pumping and 20 feet after 10 years of pumping (Table 5). After 10 years of pumping, the distances to the 5-foot and 1-foot water-level declines are 300 feet and 3,000 feet, respectively (Table 5).

A single well in the Pecos Valley Aquifer with a hydraulic conductivity of 10 feet per day can support up to 80 gallons per minute of pumping for 10 years before going dry (Figure 5). If the hydraulic conductivity is 15 feet per day, a single well can support upwards of 115 gallons per minute of pumping for 10 years before going dry (Figure 5). At the highest reported hydraulic conductivity of 26.9 feet per day (Anaya and Jones 2009), a single well could support more than 140 gallons per minute of pumping without depleting more than half of the saturated thickness at the well (Figure 5).

For a well field of 12 wells arranged in a three-by-four pattern (Figure 6) in the Pecos Valley Aquifer with each well pumping 40 gallons per minute, there would be about 25 feet of water-level decline after 1 year of pumping and 47 feet after 10 years of pumping in the center of the well field (Table 5). After 10 years of pumping the well field, the distances to the 5-foot and 1-foot water-level declines were 4,000 feet and 9,000 feet, respectively (Table 5).

We increased the pumping rate for all of the wells in the well field to identify when the type case would no longer support pumping after one year. According to the model, the well field could support increased pumping until it reached about 101 gallons per minute per well, which equates to 177 gallons of water consumed per ton of sand produced. We also increased the pumping rate to identify when the type case of the aquifer would no longer support pumping after 10 years. The well field could support increased pumping until it reached about 45 gallons per minute per well. This simulation and the reported use by U.S. Silica are why we used 70 gallons of water consumed per ton of sand produced for the Pecos Valley Aquifer type case.

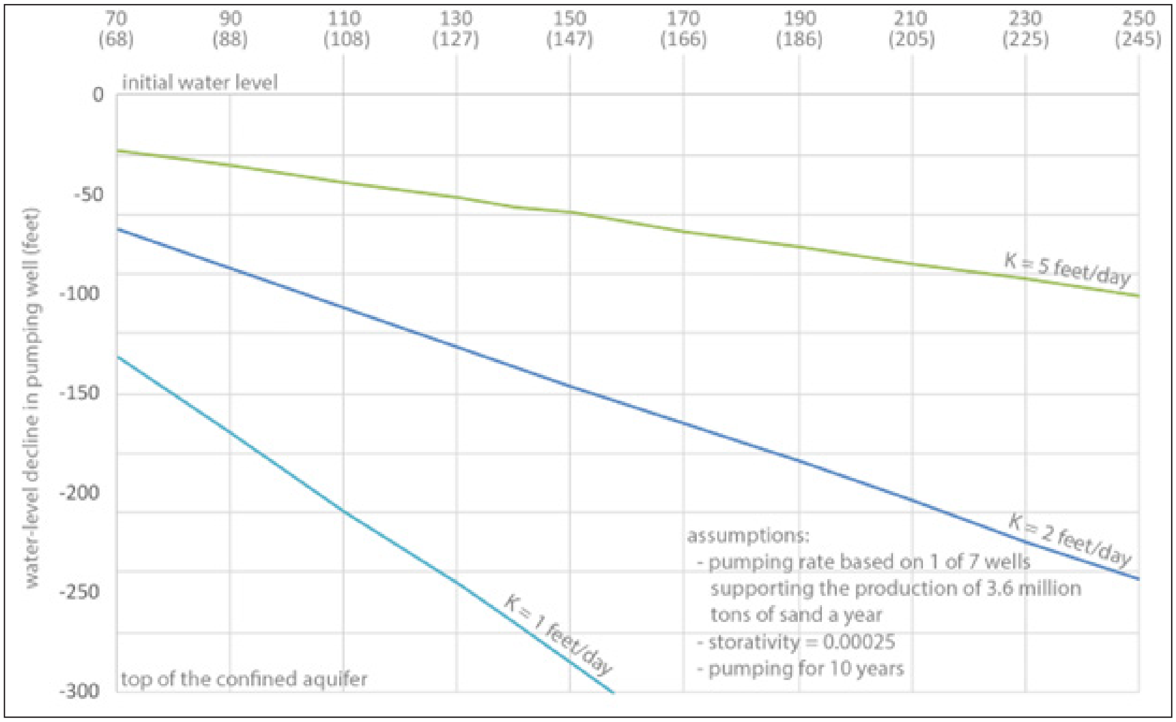

Figure 7. Sensitivity analysis of pumping rate and hydraulic conductivity on water-level declines in a single well in the Dockum Aquifer after pumping 10 years.

MODELING RESULTS FOR THE DOCKUM AQUIFER

For a single well pumping 70 gallons per minute in the lower part of the Dockum Aquifer, there would be about 136 feet of water-level decline after 10 years of pumping (Table 5). A single well in the Dockum Aquifer with a hydraulic conductivity of 1 foot per day can support up to 150 gallons per minute of pumping for 10 years before drawing water levels below the top of the aquifer (Figure 7). If the hydraulic conductivity is 2 feet per day, a single well can support more than 250 gallons per minute of pumping (Figure 7). At the highest reported hydraulic conductivity of 5 feet per day, a single well could support considerably more than 250 gallons per minute of pumping while depleting about a third of the artesian pressure head (Figure 7).

With a well field of seven wells arranged in a two-by-three pattern with a single well on top, each pumping 70 gallons per minute in the Dockum Aquifer, the distance from an outer well in the well field to the 5-foot water-level decline contour after one year of pumping is about 40,000 feet (7.5 miles; Table 5, Figure 8). Using superposition and the Theis (1935) equation, a well in the center of the drawdown would have about 272 feet of drawdown after the well field has been pumped for 1 year.

After pumping for 10 years, the distance from an outer well in the well field to the 5-foot water-level decline line is about 130,000 feet (24.6 miles; Table 5). A pumping well in the center of the well field would have about 360 feet of drawdown after pumping the well field for 10 years. For the Dockum Aquifer, this simulation suggests that pumping might completely deplete the artesian pressure in the well field after 10 years of operation.

Using the MODFLOW model, we increased the pumping rate to identify when the type case of the aquifer would no longer support pumping after 10 years. The well field could support increased pumping until it reached about 115 gallons per minute per well.

While the modeling provides an indication of what might happen around a well and at a well field, it does have its limitations. This is especially true in the case of the Dockum Aquifer, once available artesian head is exhausted, and the aquifer at the well transitions to unconfined conditions. Once this condition is reached, well yields could be severely impacted in the

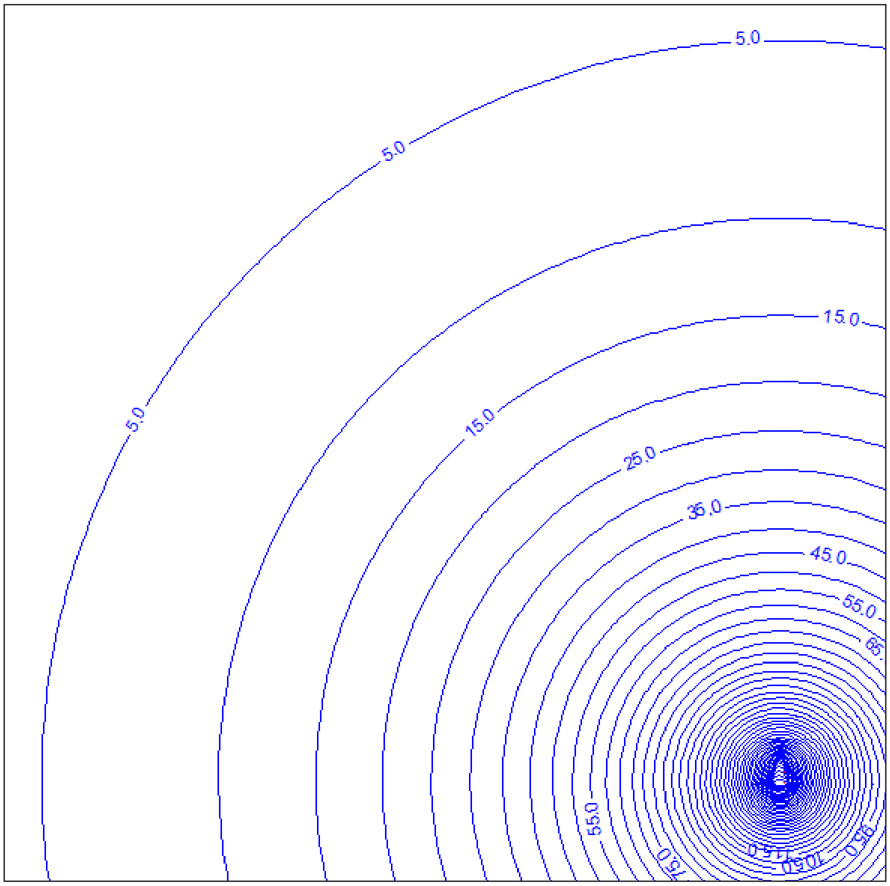

Figure 8. Water-level declines at a 5-foot interval around a hypothetical well field in the Dockum Aquifer after pumping for 10 years. The distance from the 5-foot contour to the well field in the lower right is about 130,000 feet (about 25 miles).

Dockum Aquifer due to decreasing saturated thickness and air impingement. In the unconfined Pecos Valley Aquifer, well yields will also decline as the saturated thickness decreases. At some point, the economics of drilling more wells to replace declining well yields will become prohibitive. When saturated thicknesses decline significantly, the numerical model will overpredict well yields.

RECOMMENDATIONS

We recommend following ongoing activity in the area by all pumpers and, if possible, expanding water-level monitoring to gain a better understanding of how additional pumping is affecting the aquifers. This study suffered from a lack of site-specific information on water use and produced sand tonnage in the public domain. If the State of Texas wishes to have a better understanding of potential effects of pumping at these facilities, then requiring the reporting of this information is critical. Finally, well completions across different aquifers should be discouraged. Even when pumping at these wells stop, aquifers with higher water-level elevations—such as the Pecos Valley Aquifer—will continue to drain into deeper, depleted formations, thus affecting the water resources for remaining users as long as the well connection exists.

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Discrete Streamflow Measurements and Waterborne Self-Potential Logging of a 43-Kilometer-Long Reach of the Elm Fork Trinity River Upstream from Dallas, Texas

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Abstract: Continuous and discrete streamflow data were combined with waterborne self-potential, surface-water temperature, and surface-water conductivity surveys obtained along an approximately 43-kilometer (26.7 mile) surveyed reach of the Elm Fork Trinity River (hereinafter referred to as "Elm Fork") upstream from Dallas, Texas, to investigate areas of gaining and losing streamflow under various streamflow and seasonal climatic conditions. Discrete streamflow measurements were made at 17 locations on October 12, 2021, and January 25, 2022, at 19 locations on May 17, 2022, and at 18 locations on August 9, 2022. Waterborne self-potential data were measured from a kayak in January 2022 during a period of base flow along three individually surveyed reaches between the Lake Lewisville Dam and Frasier Dam on the Elm Fork. Together, these data indicated different parts of the Elm Fork functioned as either a gaining or losing stream depending on streamflow and seasonal climatic conditions. Overall, there were estimated net gains in streamflow during the first two discrete-measurement events of about 107 and 2 cubic feet per second in October 2021 and January 2022, respectively, and estimated net losses in streamflow in May 2022 and August 2022 of about 24 and 18 cubic feet per second, respectively.
Keywords: Gain, Loss, Trinity River, Elm Fork, Dallas

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Terms used in paper

Acronym / Initialism	Descriptive Name
°C	degrees Celsius
ADCP	acoustic Doppler current profilers
ADV	acoustic doppler velocimeters
C/m^3	cubic meters
C/m^3	coulombs per cubic meter
CST	Central Standard Time
DWU	Dallas Water Utilities
ft^3/s	cubic feet per second
GW	groundwater
Hz	hertz
km	kilometer
m	meters
m/m	meters per meter
m/s	meters per second
m^2	square meters
mv	millivolts
mV/m	millivolts per meter
NWIS	National Water Information System
ohm-m	ohm meters
s	seconds
SP	spontaneous potential
SW	surface water
TRAA	Trinity River alluvium aquifer
TWDB	Texas Water Development Board
USGS	U.S. Geological Survey
WaSP	waterborne self-potential
WTP	water treatment plant
µS/cm	microsiemens per centimeter

INTRODUCTION

Dallas Water Utilities (DWU) is a primary supplier of water to more than 2.5 million people in north Texas (Dallas Water Utilities, 2019). To meet the increasing water demands of a growing population, DWU has developed a water-conservation plan to reduce consumptive losses and increase water reuse within their service area (Dallas Water Utilities, 2019). Additionally, DWU has constructed reservoirs and infrastructure to procure and manage water resources and to augment surface-water (SW) diversions from the Elm Fork Trinity River (hereinafter referred to as "Elm Fork"). A better understanding of streamflow gains and losses in the Elm Fork would help to inform DWU's water conservation plan. Hence, the U.S. Geological Survey (USGS) in cooperation with DWU characterized possible gaining and losing reaches of the Elm Fork during different streamflow conditions between October 2021 and August 2022.

SW and groundwater (GW) are typically managed separately as disconnected resources even though they are indeed a single resource with respect to streams that are hydraulically connected to alluvial aquifers (Winter and others, 1999; Fuchs and others, 2019). Braun and Grzyb (2015, p. 1) explain "in the absence of appreciable tributary inflows or diversions of flow out of the channel, the question of whether a given reach gains or loses streamflow depends largely on groundwater/surface-water interactions." Transfers of water between streams and the Trinity River alluvium aquifer (TRAA), referred to herein as SW-GW exchanges, occur throughout the Trinity River basin and vary spatially and temporally depending on the amount of streamflow (Slade and others, 2002). During drought periods, streamflows in the Elm Fork are primarily sustained by reservoir releases or base flows from the TRAA. During peak-streamflow periods, recharge to the TRAA occurs as SW flows into the aquifer from the stream. At a given moment, SW gains can occur at one location in the stream, or in a net sense along an arbitrary reach, while SW losses are simultaneously occurring at another location, or in a net sense along a different reach (McCallum and others, 2013). Quantifying the rates of SW-GW exchange in the Elm Fork is, therefore, challenging because the spatial and temporal dynamics governing SW gains and losses are often unknown and variable (Sophocleous, 2002; Kalbus and others, 2006).

Traditional hydrologic methods such as discrete streamflow measurements provide low spatial and temporal resolution of the SW-GW exchanges that they seek to quantify and generally only indicate the net gain or loss along a given reach for practical purposes. In contrast, continuous streamflow data computed at USGS streamgages provide better temporal resolution of streamflow variability at specific stream locations but provide limited spatial resolution because they can only indicate net quantities of SW gain or loss between streamgages. Alternatively, waterborne self-potential (WaSP) surveys enable mapping of SW-GW exchanges over stream reaches that vary in length from a few meters (m) to hundreds of kilometers or more. WaSP surveys have been used to identify distributed reach-scale and hyporheic-scale exchanges (Ikard and others, 2018; Ikard and others, 2021b), as well as focused exchanges in specific sections of a reach (Ikard and others, 2021a); however, as with any geophysical method, WaSP surveys require auxiliary geophysical, geochemical, or hydraulic data to infer locations and quantities of gain or loss. Combining continuous streamflow data and discrete streamflow measurements with WaSP surveys provides an enhanced methodology to better understand SW-GW exchanges distributed over long stream reaches and the relative magnitudes of the exchange rates between locations where continuous and discrete streamflow measurements are acquired.

This article describes gaining and losing reaches of the Elm Fork that were assessed between Lake Lewisville Dam and Frasier Dam, upstream from Dallas, Texas (Figure 1). During the study, continuous streamflow and discrete streamflow measurements were obtained at five continuous USGS streamgages and 14 discrete streamflow measurement sites. Three of the streamgages were on the main stem of the Elm Fork and two were on tributaries to the Elm Fork. Streamflow data were combined with WaSP survey data obtained along a 43-kilometer (km) long (26.7 mile) surveyed reach of the Elm Fork between Lake Lewisville Dam and Frasier Dam. Streamflow measurements were made multiple times between October 2021 and August 2022 and supplemented by the WaSP survey in January 2022.

DESCRIPTION OF THE STUDY AREA

The Elm Fork is one of four main tributaries that form the Trinity River (Figure 1). The Trinity River flows from its headwaters in north-central Texas north of the Dallas-Fort Worth metropolitan area southeastward for approximately 885 km (550 miles) before emptying into the Gulf of Mexico east of Houston, Texas (Texas Water Development Board, 2019). Four main tributaries (Clear Fork, East Fork, Elm Fork, and West Fork Trinity River) converge in the Dallas-Fort Worth metropolitan area to form the main stem of the Trinity River (Trinity River Authority, 2021). The main stem of the Trinity River conveys the third largest average annual streamflow volume of all major rivers in Texas; the average annual streamflow estimated by the Texas Water Development Board (TWDB) is about 5,727,000 acre-feet per year (Texas Water Development Board, 2019). The Trinity River currently (2023) provides water to an estimated 14 million people—slightly less than half of the entire Texas population of about 30 million in 2022 (U.S. Census Bureau, 2023)—and the number of people that will rely on Trinity River water is projected to increase to 25.7 million by 2070 (Trinity River Authority, 2021).

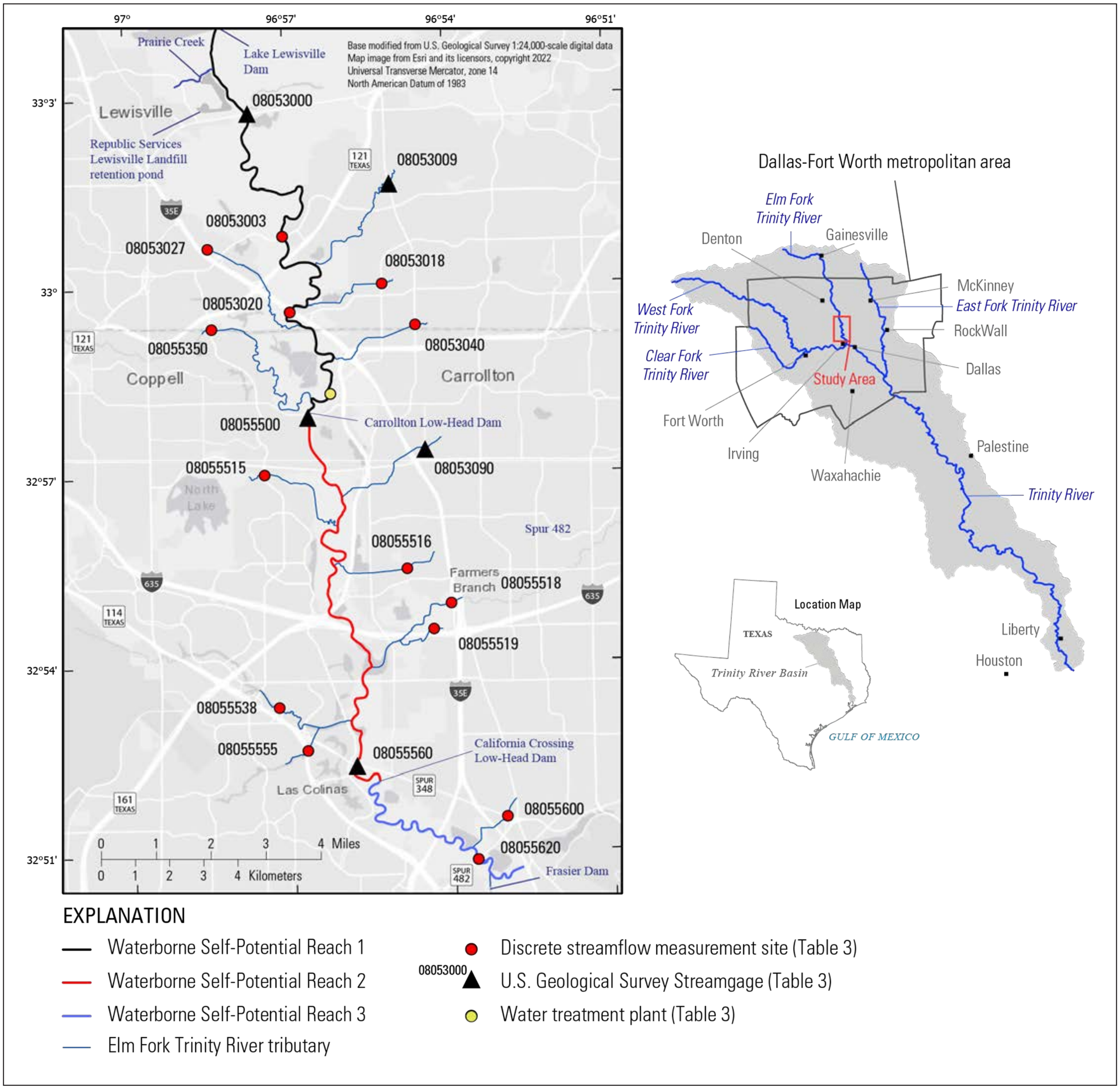

Figure 1. Location map showing discrete streamflow measurement sites, continuous streamgages, waterborne self-potential reaches, and a water treatment plant (WTP) in the study area of the Elm Fork Trinity River between Lake Lewisville Dam and Frasier Dam in the Dallas-Fort Worth metropolitan area.

The Trinity River has carved its main floodplain into the underlying sediments. Carved out fluvial valleys are now infilled by five terraced alluvial units, distinguishable according to their elevation above the streambed (Allen and Flanigan, 1986). The lithology of the terraces varies from sand and gravel to sandy loams to scattered pebbles and cobbles of quartzite at the highest elevations above the floodplain (Allen and Flanigan, 1986). The TWDB does not recognize the Trinity River alluvium aquifer as a major or minor aquifer of Texas, although Groundwater Management Area 14, the Region H Water Planning Group, and Bluebonnet Groundwater Conservation District all recognize the TRAA as a viable aquifer (Williams, 2010; Groundwater Management Area 14, 2016; Region H Water Planning Group, 2021). According to the Bluebonnet Groundwater Conservation District's GW management plan, there is little published information on the composition and hydraulic properties of the aquifer, although it is likely to have similar composition and texture as the Brazos River alluvial aquifer and is described generally as alluvium and broad fluvial terrace deposits of silts and fine-grained sands and gravels of Quaternary age (Coffman and others, 2011; U.S. Geological Survey, 2014). The TRAA was formed by incision of the Trinity River and its tributaries as a result of increased rainfall and streamflow within the basin during the Pleistocene (Stern, 2019). Allen and Flanigan (1986) describe the alluvium of the present-day floodplains and terraces as varying between silty clays, impervious to semi-pervious clays, clayey sands, and gravel lenses, and indicate that the thickness of the TRAA varies from 1.5–4.6 m on small tributaries to 17–27 m on the major streams and main stem (Allen and Flanigan, 1986). An analysis from more than 1,000 geotechnical driller's logs has identified that at least four levels of terraced deposits are present in the downtown Dallas central business district ranging in thickness from 3.1–10.7 m and are primarily composed of silty clays, clays, and silty sands with interspersed sand and gravel lenses (Allen and Flanigan, 1986). These alluvium and terrace geologic units are hydraulically connected to the present-day Trinity River and its tributaries.

Within the Dallas Fort Worth metropolitan area, the humid subtropical climate is characterized by hot summers and wide annual temperature ranges; sporadic large thunderstorms are common (National Weather Service, 2023a). Likewise, precipitation varies considerably, where annual values range from less than 20 inches to more than 50 inches and is unevenly distributed throughout the year, typically favoring a bimodal distribution of wet spring/fall and dry summer/winter (National Weather Service, 2023a).

METHODS

Because the spatial and temporal dynamics governing SW gains and losses in the reach of the Elm Fork between Lake Lewisville Dam and Frasier Dam are not well understood, a combination of methods were used to improve the understanding of the complex nature of SW and GW interactions in this reach. The objective was to better understand streamflow gains and losses by (1) assessing existing continuous streamflow data from select USGS streamgages, (2) collecting discrete streamflow measurements at select streamgages over four discrete-measurement events, and (3) measuring and logging continuous surveys of WaSP, SW temperature, and specific conductance along each WaSP reach of the Elm Fork.

Streamflow Measurements

This study combined continuous streamflow data from USGS streamgages, discrete streamflow measurements on the main stem of the Elm Fork and its tributaries, and a WaSP survey of streamflow gains and losses in three reaches on the main stem of the Elm Fork (Figure 1). Discrete streamflow measurements were made at 17 locations on October 12, 2021 and January 25, 2022, at 19 locations on May 17, 2022, and at 18 locations on August 9, 2022. Each streamflow measurement location is shown on Figure 1. In total, 65 discrete streamflow measurements were made consisting of 23 acoustic Doppler current profilers (ADCP) streamflow measurements and 42 acoustic doppler velocimeters (ADV) streamflow measurements; there were also six observations of no flow. The methods used to measure streamflow are described in Turnipseed and Sauer (2010) and Mueller and others (2013). Each discrete streamflow measurement was assigned a measurement rating by a hydrographer (excellent, good, fair, or poor) representing different estimated uncertainty ranges; the uncertainty ranges are assigned using both quantitative and qualitative guidelines as described in Turnipseed and Sauer (2010) and Mueller and others (2013). For this study, the assigned uncertainty for a given measurement ranged from 5 percent for a measurement rated as good to 10 percent for a measurement rated as poor and provides context as to how precise additional computations using these values may be considered (Turnipseed and Sauer, 2010). All discrete streamflow measurements for this study are available from the U.S. Geological Survey National Water Information System (NWIS) (U.S. Geological Survey, 2023).

Streamflow measurements were completed during a wide range of streamflow conditions, where the inflow at the uppermost site (USGS streamgage 08053000 Elm Fork Trinity River near Lewisville, Texas [hereinafter referred to as "streamgage 08053000"]) varied from 207 to 1,610 ft^3/s. In addition to streamgage 08053000, continuous streamflow data were evaluated at two additional USGS streamgages: USGS streamgage 08055500 Elm Fork Trinity River near Carrollton, Texas (hereinafter referred to as "streamgage 08055500"), and USGS streamgage 08055560 Elm Fork Trinity River at

Table 1. Summary of U.S. Geological Survey streamgages and Elm Fork Water Treatment Plant withdrawals in cubic feet per second (ft^3/s) on the Elm Fork Trinity River between Lake Lewisville Dam and Frasier Dam. Statistics include streamflow data for the date of discrete measurements (gray rows) and from 12:00 am Central Standard Time (CST) two days prior to and including the date of the discrete measurements (white rows).

Date range	Streamflow statistic	USGS streamgage 08053000 Elm Fork Trinity River near Lewisville, Texas	Elm Fork Water Treatment Plant withdrawals	USGS streamgage 08055500 Elm Fork Trinity River near Carrollton, Texas	USGS streamgage 08055560 Elm Fork Trinity River at Spur 348, Irving, Texas
	Elm Fork Trinity River near Carrollton, Texas				
October 10–12, 2021	Minimum	298	221	124	142
	Maximum	429	237	851	993
	Mean	320	229	302	406
October 12, 2021	Mean	310	221	210	312
January 23–25, 2022	Minimum	204	182	59.0	68.0
	Maximum	214	231	130	112
	Mean	209	204	93.2	86.7
January 25, 2022	Mean	207	182	107	91.8
May 15–17, 2022	Minimum	1,610	253	1,400	1,460
	Maximum	1,670	310	1,630	1,770
	Mean	1,630	281	1,530	1,580
May 17, 2022	Mean	1,610	310	1,450	1,510
August 7–9, 2022	Minimum	478	351	139	142
	Maximum	519	382	231	186
	Mean	494	366	173	163
August 9, 2022	Mean	502	363	182	155

Spur 348, Irving, Texas (hereinafter referred to as "streamgage 08055560") and are summarized in Table 1 for both the day of and two days prior to each discrete-measurement event. The streamgages are depicted in downstream order (Figure 1). Streamflow hydrographs measured at each streamgage from September 1, 2021 to September 30, 2022, and during the survey are shown in Figure 2 beginning at 12:00 am Central Standard Time (CST) two days prior to the discrete-measurement events and ending five days later.

For this article, streamflow gains or losses were estimated by measuring the difference in streamflow at the upstream and downstream extent of each reach while accounting for other sources of gains and losses such as tributary inflow and water supply withdrawals. Gains and losses were calculated as a whole and were not broken out into spring or seep inflow, unidentified return flows, or evaporative losses. Estimates of gains or losses for each reach (between main stem streamflow measurements) were estimated using Equation 1.

$$G = (QD+W) - (QU + T) \qquad (1)$$

Estimated gains or losses *(G)* represent a gaining streamflow reach when positive and a losing streamflow reach when negative. For each reach, the upstream streamflow measurement was used for *QU* and the next downstream main stem streamflow measurement was used for *QD*. The water-use withdrawal value *(W)* is representative of the total withdrawals in a reach; however, the only appreciable withdrawal rates relative to the Elm Fork streamflow were made at a water treatment plant (WTP) (Figure 1). Tributary inflow *(T)* was calculated by the sum of all measured tributary inflows to the Elm Fork between *QU* and *QD.*

Waterborne Self-potential Survey

WaSP surveys utilize the physical relation between the electric field (E; millivolts per meter [mV/m]) and the electric-potential gradient. An electric field exists in a region of space around an electrically charged object or surface-area such as a streambed (Blakely, 1996; Griffiths, 1999). The electric field is a vector-field whose direction is defined to be the direction of electromotive force exerted on a positive electric charge placed at an arbitrary point within the electric field. The electric field

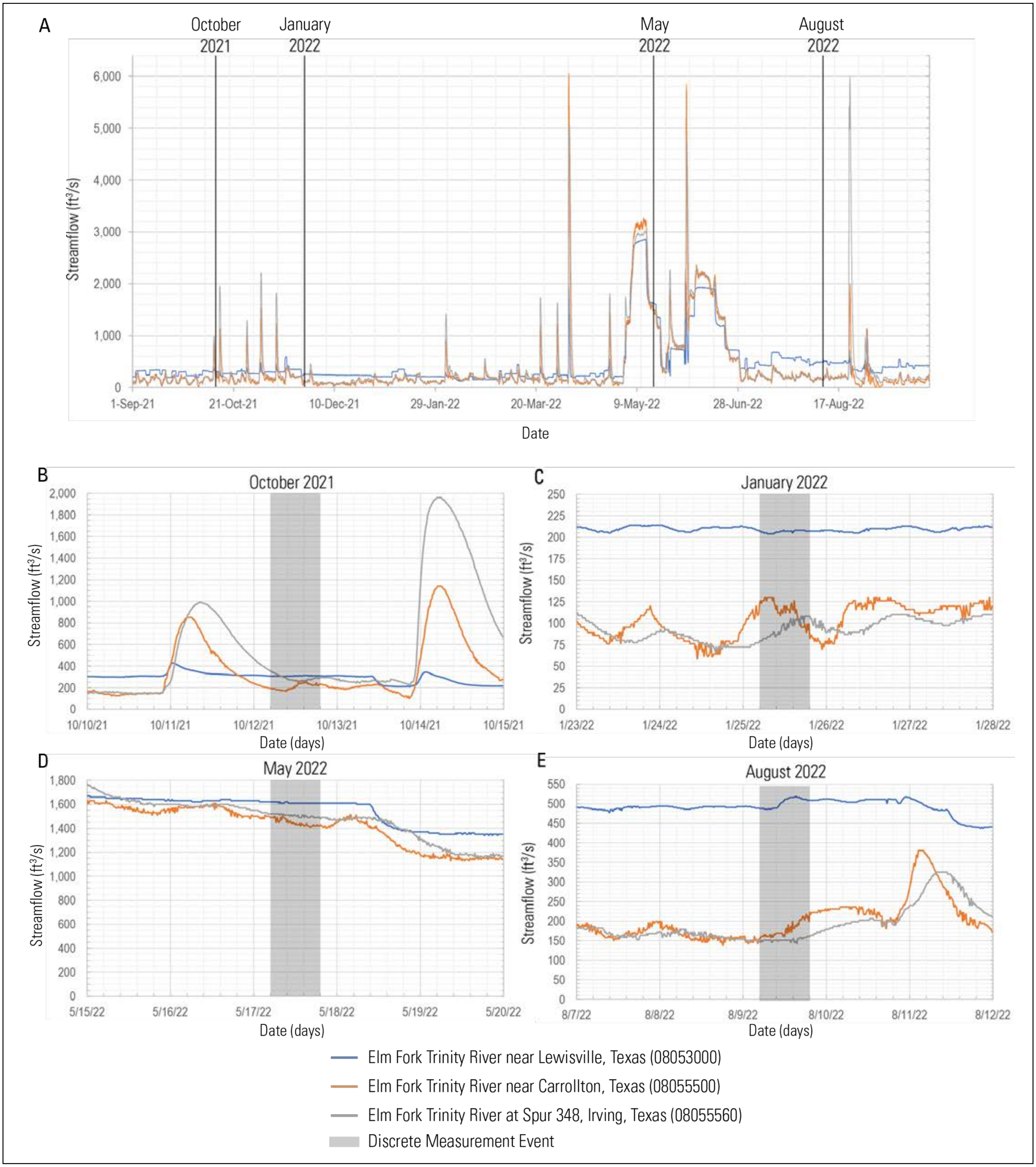

Figure 2. Streamflow in cubic feet per second (ft³/s) in the Elm Fork Trinity River at U.S. Geological Survey streamgages from (A) September 1, 2021 to September 30, 2022 and (B–E) from 12:00 am Central Standard Time (CST) two days prior to and through two days after the date of the discrete-measurement events in (B) October 2021, (C) January 2022, (D) May 2022, and (E) August 2022 between Lake Lewisville Dam and Frasier Dam.

can be derived from the electric potential gradient ($-\nabla\varphi$; mV/m) by Equation 2 where $\mathbf{x}$ (m), $\mathbf{y}$ (m), and $\mathbf{z}$ (m) are unit vectors in the x-, y-, and z-coordinate directions, respectively, and $\partial\varphi/\partial x$, $\partial\varphi/\partial y$ and $\partial\varphi/\partial z$ are partial derivatives of the electric-potential gradient in the x, y, and z directions (Blakely, 1996; Griffiths, 1999).

$$E = -\nabla\varphi = -\frac{\partial\varphi}{\partial x}\mathbf{x} - \frac{\partial\varphi}{\partial y}\mathbf{y} - \frac{\partial\varphi}{\partial z}\mathbf{z} \qquad (2)$$

The vector magnitude of the electric field intensity decreases from regions of high electric potential (φ; mV) toward regions of low electric potential. Assessing the electric field in one-dimension, the x-coordinate direction (defined herein as the streamflow direction), the partial derivatives in Equation 2 in the y- and z-coordinate directions are neglected and the partial derivative in the x-coordinate direction is expressed as $-\partial\varphi/\partial x=(-\Delta\varphi)/\Delta x$, as shown in Equation 3 where φ_2 and φ_1 are electric potentials at locations x_2 and x_1, respectively, $\Delta\varphi=(\varphi_2-\varphi_1)$ (mV) is the potential difference of the two electric potentials, and $\Delta x=(x_2-x_1)$ (m) is the distance between x_2 and x_1. Equation 3 indicates that the electric field intensity is calculated as the difference in electric potential between two arbitrary points divided by the distance between the points (Blakely, 1996; Griffiths, 1999).

$$E = -\frac{\Delta\varphi}{\Delta x} = -\frac{(\varphi_2-\varphi_1)}{(x_2-x_1)} \qquad (3)$$

Electric potential is a measure of energy per unit charge, such that the potential difference between two points is the change in potential energy of an electric charge as it accelerates from position x_2 to position x_1 within the surrounding electric field (Blakely, 1996; Griffiths, 1999). The electric-potential between locations x_2 and x_1 is calculated with Equation 4 as the integral summation of the electric field intensity, where $\varphi(x)$ is the electric potential in the x-coordinate direction between locations x_1 and x_2 (Blakely, 1996; Griffiths, 1999).

$$\varphi(x) = -\int_{x_1}^{x_2} E(x)dx \qquad (4)$$

The basic premise of a WaSP survey is that an electric potential in a SW body is calculated from voltage differences that are measured by an electric dipole composed of two non-polarizing electrodes as the dipole traverses the reach. The voltage differences between the positive and negative electrodes of the dipole are measured continuously and logged at a 1-hertz (Hz) frequency as the dipole floats in a downstream x-coordinate direction in the SW with the positive electrode positioned at x_2 downstream from the negative electrode at x_1, such that the measured voltage difference at each location along the profile is $\Delta\varphi=(\varphi_2-\varphi_1)$. The locations x_2 and x_1 are updated with each successive measurement, and the distance between them remains constant for every measurement such that Δx is equal to the dipole length. The measured voltage differences are corrected for transient electrode-drift and topographic effects (Table 2; Figures 3–4) when present (Ernston and Scherer, 1986; Ikard and others, 2021a), converted into electric field intensity with Equation 5, partitioned into low spatial-frequency (L) and high spatial-frequency (H) data components through digital signal processing (Oppenheim and Schafer, 2010; Ikard and others, 2018; Ikard and others, 2021b), and subsequently numerically integrated into corresponding L and H electric-potential components. The electric-potential profile is then interpreted to identify apparent gaining and losing stream reaches over different spatial scales by the changes in polarity of the electric potential (Valois and others, 2017; Ikard and others, 2018). In the case of SW-GW exchange, the attributed causes of the electric-potential changes in polarity (gains represented by positive electric-potential values) are streaming-currents generated on the streambed and submerged streambanks by streamflow gains from GW or SW losses into the porous streambed and flood-plain sediments (Ikard and others, 2021b). The data-processing scripts that produce the electric-potential values were published as part of the companion data release (Ikard and others, 2022).

Figures 3B–D show plots of the voltage differences versus the topographic elevation at the location of each measurement. Minor topographic effects are present in WaSP reach 1, shown by the small positive slope of the ordinary least-squares linear regression line fitted to the point cloud of elevation-voltage data in the corresponding scatterplot (Table 2; Figure 3B). There is negligible topographic effect in WaSP reaches 2 and 3, indicated by the approximately horizontal regression lines fitted to the data (Table 2; Figures 3C and D). The topographic effects are described by the slope *(m)* and y-intercept *(b)* coefficients of the regression lines that are summarized in Table 2.

$$\Delta V_Z = mz + b \qquad (5)$$

$$\Delta V_C = \Delta V - \Delta V_Z \qquad (6)$$

Terrain corrections are commonly applied to self-potential data when topographic effects are present. Topographic effects are typically attributed to the downward percolation of GW along hill slopes in areas with topographic relief (Ernstson and Scherer, 1986; Barde-Cabusson and others, 2021) and in that sense are expected to produce a topographic effect characterized by linear increases in measured voltage differences with decreasing elevation (Ernstson and Scherer, 1986). Ikard and others, (2021c) observed the opposite topographic effect where the measured voltage differences increased with increasing elevation. A topographic terrain correction was applied to the measured voltage data obtained from each reach of the Elm Fork by computing a terrain voltage (ΔV_Z; mV) for each

Table 2. Summary of Equation 5 coefficients of ordinary least-squares linear regression lines used to make terrain corrections to each waterborne self-potential reach data measured in the Elm Fork Trinity River.

Survey Reach	Eqn. 5 slope coefficient (m; millivolts/meter)	Eqn. 5 intercept coefficient (b; meter)	Coefficient of determination (unitless)
1	0.0817	-9.49	0.0668
2	-0.0278	4.602	0.0038
3	-0.0322	2.987	0.0042

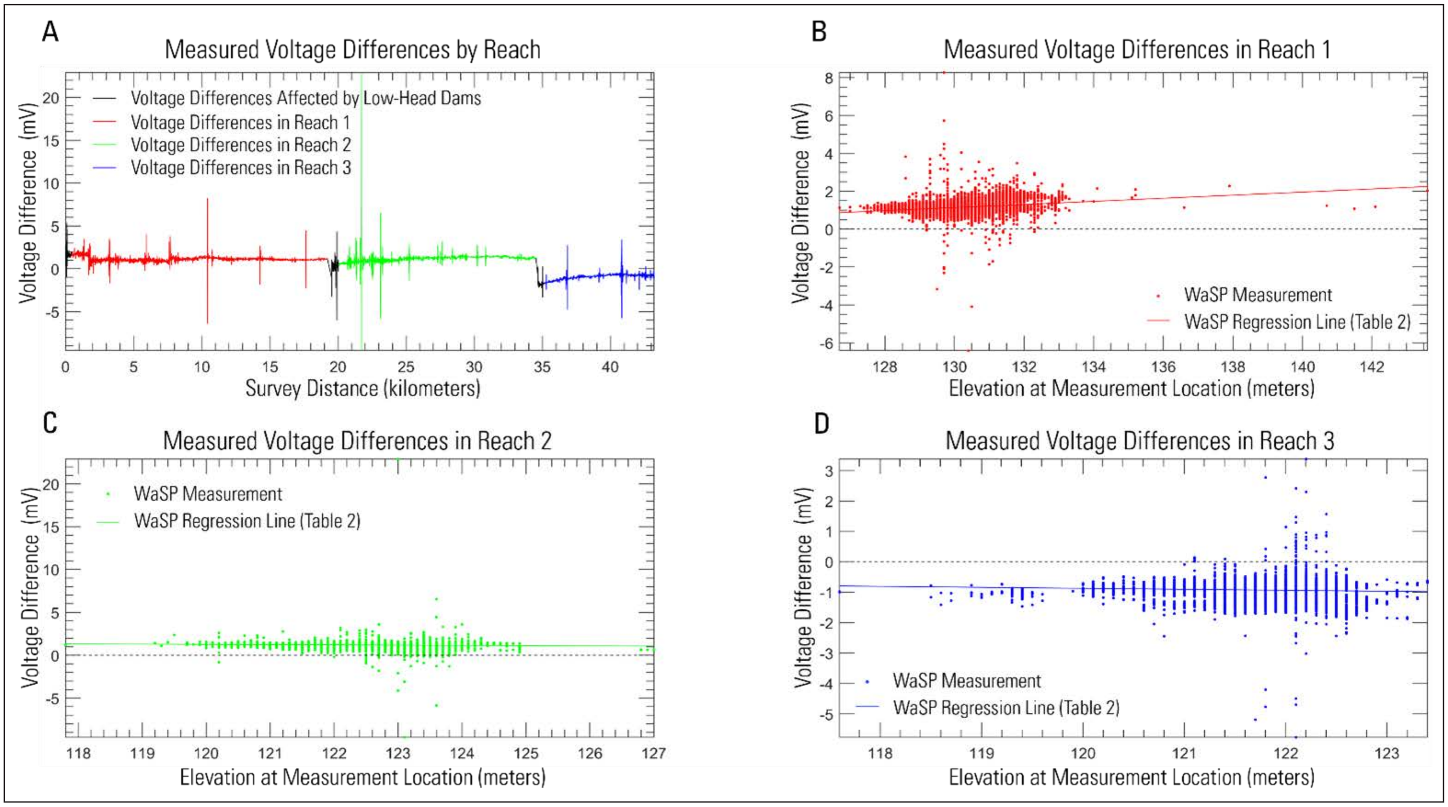

Figure 3. Graph in panel A shows the voltage differences in millivolts (mV) measured along three waterborne self-potential (WaSP) reaches of the Elm Fork Trinity River. Graphs in panels B, C, and D plot voltage differences (mV) versus elevation (meters) along each WaSP reach. In panel A, voltage differences are depicted in black for areas affected by low-head dams and subsequently removed from further consideration (Figure 1).

measurement using Equation 5 and the coefficients in Table 2. Equation 6 is then used to subtract the terrain voltages from the measured voltages to calculate the corrected voltage (ΔV_c; mV). The effects of the terrain corrections on the measured voltage differences are shown in Figure 4 for each survey reach. After applying terrain corrections, the corrected voltage differences were centered around 0 mV. The corrected voltage differences were then processed into electric potential by the signal processing approach described by Ikard and others (2018) and Ikard and others (2021a, 2021b), and the electric-potential data for each WaSP reach were combined into a continuous profile shown in Figure 4D.

The underlying physical mechanisms of streaming-current generation are generally well understood (Onsager, 1931a; Onsager, 1931b; Overbeek, 1952; Ishido and Mizutani, 1981; Sill, 1983; Ishido, 1989; Revil and others, 1999a; Revil and others, 1999b; Nyquist and Corry, 2002; Boléve and others, 2007; Sheffer and Oldenburg, 2007; Crespy and others, 2008; Haas and Revil, 2009; Cerepi and others, 2017; Revil and others, 2017). Streaming-current sources and sinks are attributed to GW flow through porous sediments and advection of counterions in a diffuse band of the electrical double layer that lines the pore-surfaces of the streambed sediments (Ikard and others, 2021b). During steady-state

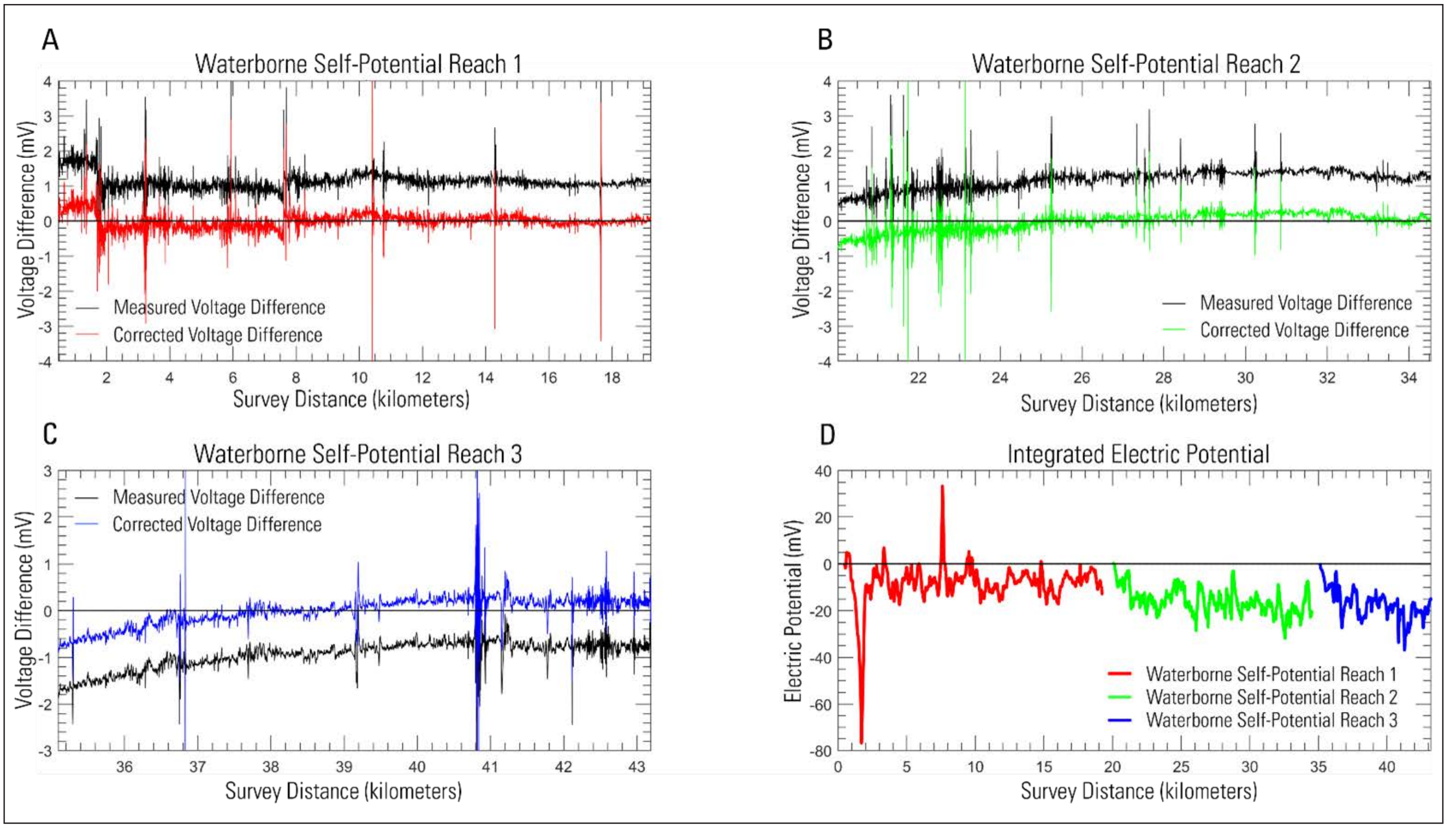

Figure 4. Graphs in panels A–C show the effects of applying terrain corrections to the measured voltage differences for (A) reach 1, (B) reach 2, and (C) reach 3. Graph in panel D shows the integrated electric potential profiles that were processed from the corrected voltages differences following the processing methods described by Ikard and others (2018) and Ikard and others (2021a, 2021b).

hydraulic conditions, GW flow is described by Equation 7 (Fetter, 2001; Anderson and others, 2015), where $\mathbf{u}$ (m/s) is the Darcy velocity, $\nabla\cdot\mathbf{u}$ (1/s) is the divergence of Darcy velocity, and Q_s (1/s) represents a GW source (i.e. SW flow into the porous streambed sediments) when greater than zero and a GW sink (GW flow out of the streambed into the SW) when less than zero.

$$\nabla\cdot\mathbf{u} = \pm Q_s \tag{7}$$

The Darcy velocity is related to the hydraulic properties of the streambed sediments and the hydraulic-head distribution within the streambed and the aquifer by Equation 8, where K_s (m/s) is the saturated hydraulic conductivity, H (m) is the hydraulic head, and ∇H (m/m) is the hydraulic gradient. The hydraulic gradient is a vector whose direction is oriented from high to low hydraulic potential and controls the nature of SW-GW exchange between the stream and aquifer. Streams gain streamflow when the direction of the hydraulic gradient is from the aquifer toward the stream and lose streamflow when the direction of the hydraulic gradient is from the stream toward the aquifer (Anderson and others, 2015).

$$\mathbf{u} = -K_S \nabla H \tag{8}$$

On the streambed and submerged streambanks, GW flow into or out of the porous sediments generates streaming-current ($\mathbf{j}_s$; A/m²) by advection of the excess volumetric charge density $(\widehat{Q_v})$ in the electric double layer coating the pore spaces in the streambed sediments. The intensities of the streaming currents generated by GW flow into or out of the streambed are described by the petrophysical relation in Equation 9 between streaming-current and Darcy velocity (Boléve and others, 2007), where $\widehat{Q_v}$ in coulombs per cubic meter (C/m³) is expressed in terms of permeability (k; m²) as shown in Equation 10 (Jardani and others, 2007; Jardani and others, 2008; Jardani and others, 2009; Cerepi and others, 2017).

$$\mathbf{j}_s = \widehat{Q_v}\mathbf{u} \tag{9}$$

$$\log_{10}\widehat{Q_v} = -9.2 - 0.82 * \log_{10} k \tag{10}$$

SW flow into the streambed (losing stream locations) creates streaming-current sinks and produces negative electric-potential anomalies on the streambed surface and saturated banks. Conversely, GW flow out of the streambed (gaining stream locations) creates streaming-current sources and produces positive streaming-potential anomalies on the streambed surface and saturated banks (Ernstson and Scherer, 1986; Ikard and others, 2021c). The streaming-potential field on the streambed and saturated banks attributed to the distribution and intensities of streaming-current sources and sinks at the streambed surface is described by the electrostatic equation shown in Equation 11, where ρ (ohm-m) is the resistivity of the streambed sediments.

$$\nabla\cdot(\rho^{-1}\,\nabla\varphi)=\nabla\cdot\mathbf{j}_S \tag{11}$$

The wetted perimeter of the stream channel defines a closed surface with respect to streaming-current generation (streaming currents are only generated by GW flow through porous geologic materials and therefore are not generated in SW); however, the electric-potential field is continuous from the porous sediments into the SW. Therefore, the electric-potential of the streambed and the submerged banks is electrically conducted from the streambed sediments, across the streambed surface, and into the SW where it can be measured by a WaSP survey if the signal-to-noise ratio is sufficiently large (Ikard and others, 2021b).

In addition to electric-potential data, SW temperature and conductivity data were collected during the WaSP survey in January 2022 (Ikard and others 2022). SW temperature and conductivity data were continuously logged at a period of 2 seconds per sample with an Onset HOBO (Onset, Cape Cod, Massachusetts, https://www.onsetcomp.com) conductivity and temperature logger. Because heat travels through stationary and moving water, temperature measurements are well suited for water-exchange investigations (Constantz, 2008). Water-quality data such as conductivity measurements are valuable for assessing SW-GW exchanges and determining various sources of water based on differences in water-quality properties. For example, Baldys and Schalla (2016) discuss using the correlation of specific conductance and dissolved oxygen to evaluate water sources and streamflow gains and losses. Due to the complexity of heat transport related to diurnal and seasonal temperature variation temporally, it is important to evaluate diurnal patterns when assessing surface-water temperature changes regarding gaining and losing reaches of a stream (Ren and others, 2018). For this study, diurnal patterns were evaluated and only temperature gradients greater than the diurnal patterns were assessed as possible indicators of locations of GW-SW interaction. During the WaSP survey, the air temperature in the metropolitan area (as measured at Dallas Fort Worth International Airport) ranged from 37–60°F, 27–50°F, and 37-51°F on January 25, 26, and 27, respectively (National Weather Service, 2023b). SW temperature and conductivity data with spatial and time-stamp information are available in Ikard and others (2022).

RESULTS AND DISCUSSION

The four discrete-measurement events were completed under a wide range of streamflow conditions; for example, streamflow at the farthest upstream site (streamgage 08053000) ranged from 207 to 1,610 ft^3/s (Tables 3–7). Streamflow measurements indicate that the approximately 43-km-long (26.72 mile) surveyed reach of the Elm Fork was primarily gaining streamflow in the upper reaches and losing streamflow in the lower reaches during the study. Key locations of measured gains and losses are discussed in the "Conclusions" section of this report.

Streamflow Conditions of the Elm Fork Trinity River

During three of the four discrete measurement events, the average monthly rainfall totals were below the long-term average (1900 to 2022) for the metropolitan area at 0.4, 1.3, and 1.8 inches below average in October 2021, January 2022, and May 2022, respectively (National Weather Service, 2023c). Alternatively, during the May 2022 discrete measurement event, the monthly average was 8.3 inches above the long-term average at 10.7 in (National Weather Service, 2023c). Precipitation totals were also reviewed for seven days prior to each measurement event and the only measurable precipitation during those periods was for the October 2021 discrete measurement event, at 0.77 in on October 11, 2021 (National Weather Service, 2023b). Except for the October measurement event, the elevated (above base streamflow conditions) were due to releases from Lake Lewisville upstream of the survey reach (Figure 2).

Streamflow at streamgage 08053000 downstream from Lake Lewisville Dam was about 304, 207, 1,610, and 509 ft^3/s during the October 2021, January 2022, May 2022, and August 2022 measurement events, respectively; farther downstream the streamflow at streamgage 08055500 near Carrollton Dam was about 220, 107, 1,490, and 170 ft^3/s during the same discrete-measurement events (Tables 4–7, Figure 2). This appreciable decrease in streamflow is primarily the result of withdrawals at the Elm Fork WTP between the two streamgages. Withdrawal rates for a WTP for each discrete discrete-measurement event were not publicly available at the time of publication from Dallas Water Utilities. Withdrawal volumes were provided directly from Dallas Water Utilities in units of million gallons per day for this study. A constant withdrawal rate per day was then used to calculate average daily withdrawal rates for this study in ft^3/s. Average daily withdrawal rates during the four discrete-measurement events were about

Table 3. Summary of discrete streamflow-measurement sites and water treatment plant (WTP) in the Elm Fork Trinity River between Lake Lewisville Dam and Frasier Dam. Discrete measurements made on the main stem are indicated in bold font and reaches are grouped by horizontal dashed lines. River distances were calculated from U.S. Geological Survey (USGS) streamgage 08053000 to the main-stem measurement location or confluence of the measured tributary.

USGS streamgage number or site identifier	USGS streamgage or WTP	River distance from USGS streamgage 08053000 (km)	Latitude	Longitude	Description
08053000	**Elm Fork Trinity River near Lewisville, Texas**	**0.0**	**-96.961**	**33.046**	**Main Stem**
08053003	**Elm Fork Trinity River at Hebron Parkway near Lewisville, Texas**	**6.5**	**-96.951**	**33.013**	**Main Stem**
08053009	Indian Creek at FM 2281 Carrollton, Texas	8.7	-96.917	33.028	Tributary
08053018	Dudley Branch at Rosemeade Parkway near Carrollton, Texas	10.6	-96.920	33.000	Tributary
08053020	**Elm Fork Trinity River at IH-35E near Lewisville, Texas**	**11.3**	**-96.949**	**32.993**	**Main Stem**
08053027	Timber Creek at Waters Ridge Drive near Lewisville, Texas	11.9	-96.974	33.010	Tributary
08053040	Furneaux Creek at Old Denton Road near Carrollton, Texas	13.6	-96.910	32.990	Tributary
WTP	Water Treatment Plant Withdrawal	15.1	--	--	Withdrawal
08055350	Denton Creek at N. MacArthur Boulevard near Coppell, Texas	15.8	-96.974	32.989	Tributary
08055500	**Elm Fork Trinity River near Carrollton, Texas**	**16.4**	**-96.945**	**32.966**	**Main Stem**
08053090	Hutton Branch at N. Denton Drive at Carrollton, Texas	19.3	-96.907	32.957	Tributary
08055515	Grapevine Creek at N. MacArthur Boulevard near Irving, Texas	20.2	-96.958	32.950	Tributary
08055516	Cooks Branch at Hutton Drive near Dallas, Texas	22.8	-96.914	32.925	Tributary
08055518	Farmers Branch at N. Stemmons Freeway near Dallas, Texas	26.3	-96.900	32.916	Tributary
08055519	Farmers Branch Tributary at IH 635 Service Road near Dallas, Texas	26.3	-96.906	32.909	Tributary
08055538	Hackberry Creek at Love Drive at Irving, Texas	28.7	-96.954	32.889	Tributary
08055555	Cottonwood Branch at John Carpenter Freeway near Irving, Texas	28.7	-96.946	32.877	Tributary
08055560	**Elm Fork Trinity River at Spur 348, Irving, Texas**	**30.1**	**-96.931**	**32.874**	**Main Stem**
08055600	Joes Creek at Dallas, Texas	37.7	-96.884	32.859	Tributary
08055620	**Elm Fork Trinity River at Spur 482 near Irving, Texas**	**38.2**	**-96.893**	**32.848**	**Main Stem**

[--; not available, USGS; U.S. Geological Survey, km; kilometers, WTP; water treatment plant]

221 ft³/s on October 12, 2021, 182 ft³/s on January 25, 2022, 310 ft³/s on May 17, 2022, and 363 ft³/s on August 9, 2022 (Tables 4–7). Additional permitted Elm Fork withdrawal volumes were also provided by DWU but were negligible relative to streamflow during the four discrete-measurement events. After accounting for WTP withdrawals in the reach between streamgages 08053000 and 08055500, gains were measured in three of the four discrete-measurement events (Figures 5 and 6); however, the estimated gain in May 2022 was less than the combined measurement uncertainty. The slight loss of approximately 8 ft³/s in that reach was measured during the August 2022 measurement event but was also less than the combined measurement uncertainty (Table 7). Streamflow in the lower reach of the study area showed both gains and losses during various streamflow and seasonal climatic conditions relative to the upstream streamgage and was time-lagged relative to minimums and peaks in streamflow upstream at streamgage 08055500. Downstream from streamgage 08055500 streamflow losses of about 13.6, 95.4, and 9.6 ft³/s were observed during the January, May, and August 2022 discrete-measure-

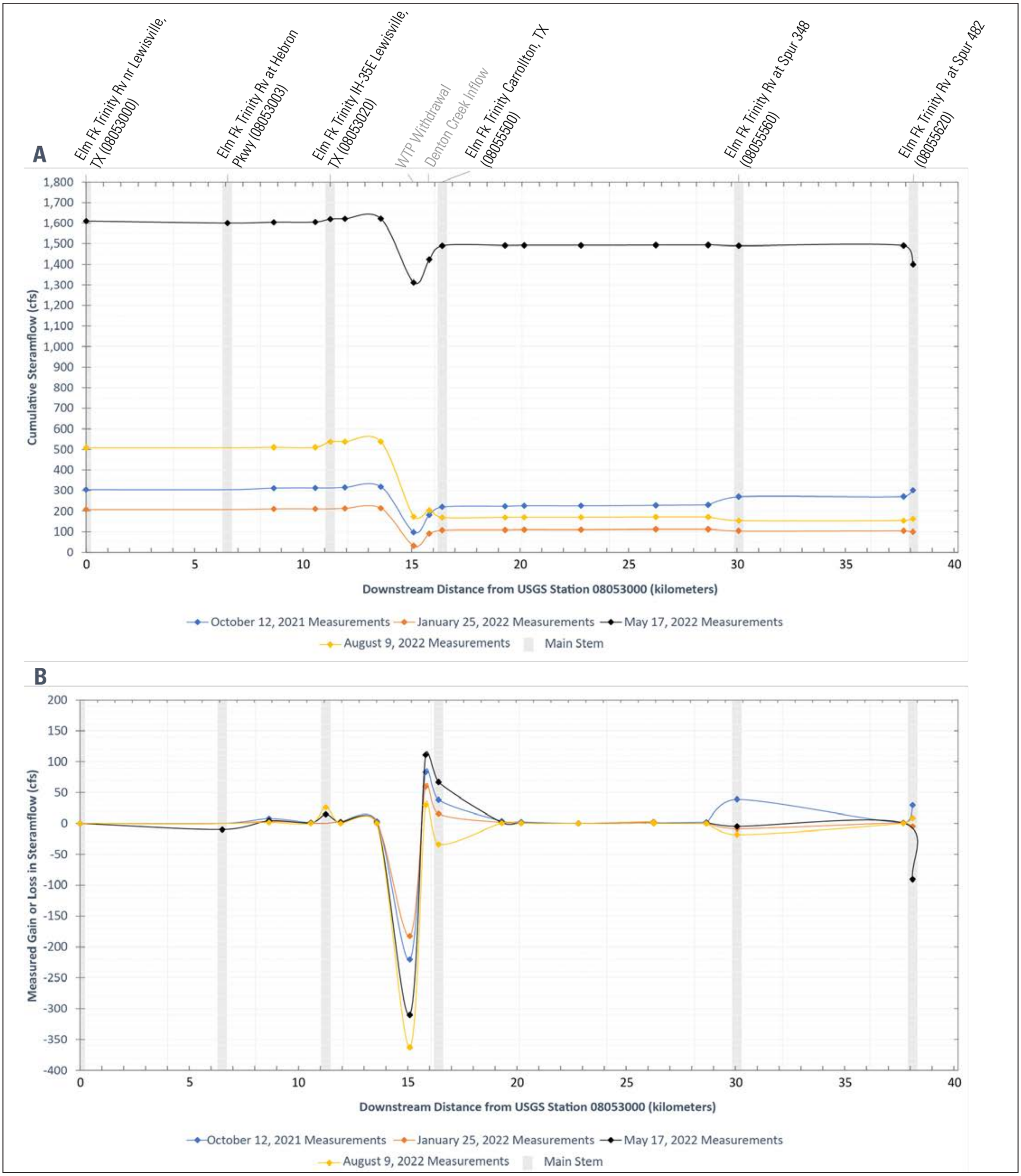

Figure 5. Graph showing cumulative streamflow gaining and losing reaches in cubic feet per second (f[t3]/s) during the four discrete-measurement events in October 2021, and January, May, and August 2022 along the Elm Fork Trinity River between Lake Lewisville Dam and Frasier Dam. Shaded tan columns show locations of main-stem Elm Fork Trinity River discrete measurements. Between main-stem measurements, streamflow gains are highlighted in blue and losses in red when the gain or loss exceeds the total measurement uncertainty and gray when less than the uncertainty.

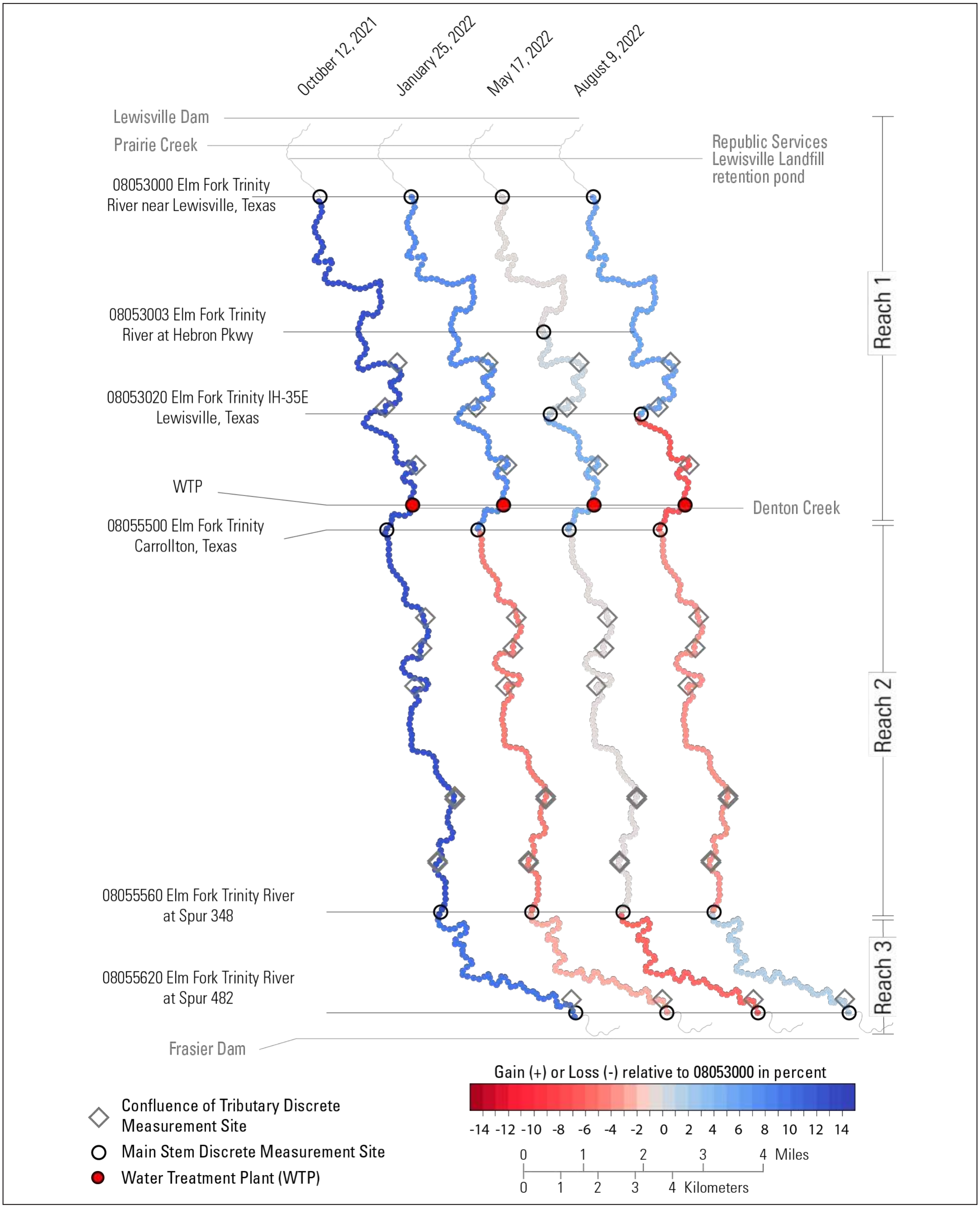

Figure 6. Graph showing gains and losses in percent of streamflow relative to the streamflow at U.S. Geological Survey streamgage 08053000 during the four discrete-measurement events in October 2021, and January, May, and August 2022 along the Elm Fork Trinity River between Lake Lewisville Dam and Frasier Dam.

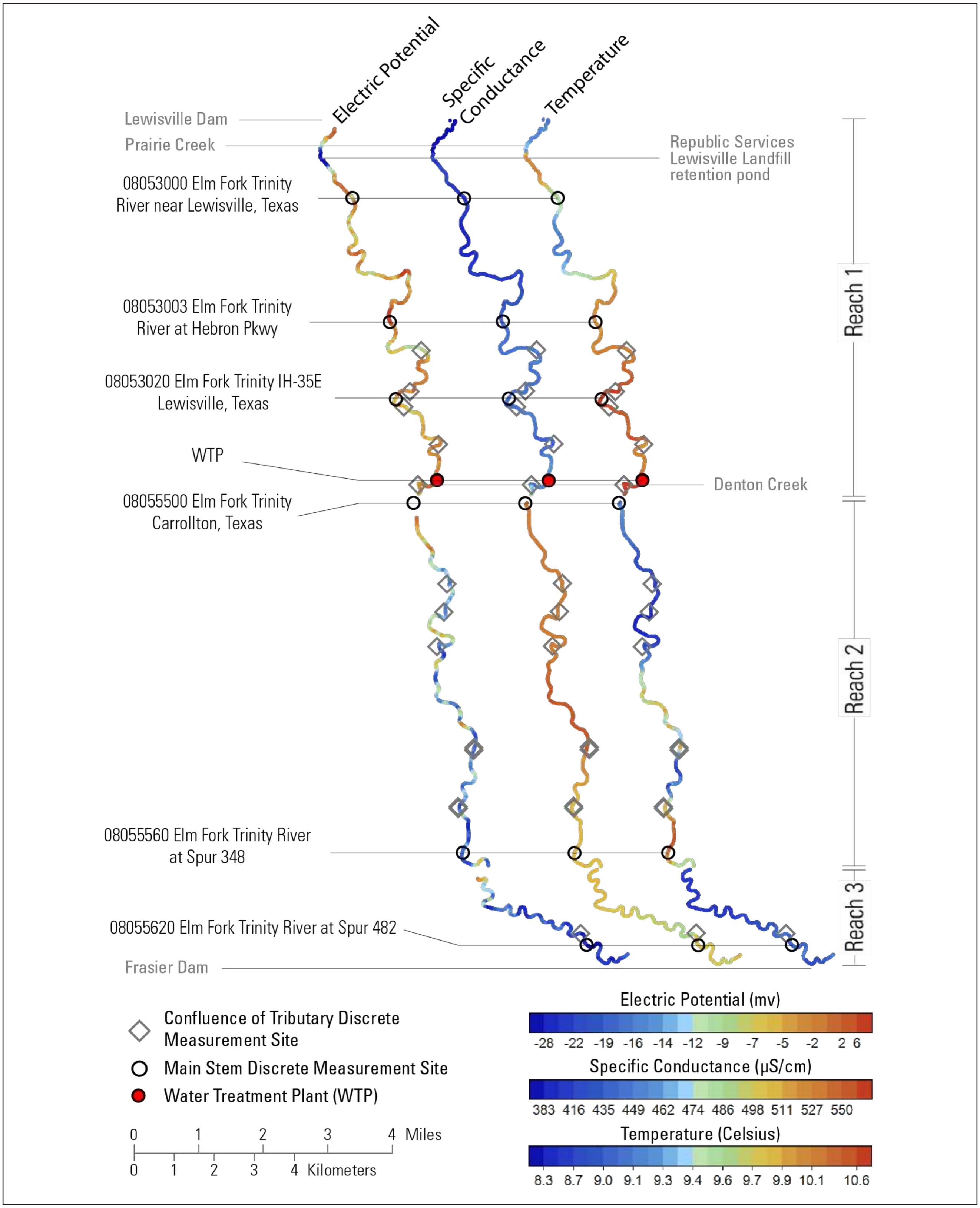

Figure 7. Map surface-water electric potential in millivolts (mV), specific conductance in microsiemens per centimeter at 25 degrees Celsius (µS/cm), and temperature in degrees Celsius (°C) from the waterborne self-potential (WaSP) survey in January 2022 along the Elm Fork Trinity River between Lake Lewisville Dam and Frasier Dam.

Table 4. Summary of discrete streamflow measurements and water treatment plant (WTP) withdrawals in the Elm Fork Trinity River between Lake Lewisville Dam and Frasier Dam on October 12, 2021. Discrete measurements made on the main stem are indicated in bold font and reaches are grouped by horizontal dashed lines. Between main-stem measurements, streamflow gains are highlighted in blue when the gain exceeds the total measurement uncertainty. Streamflow data from U.S. Geological Survey (2023).

USGS streamgage number or site identifier	Measured streamflow (ft^3/s)	Measurement uncertainty (ft^3/s)	Cumulative streamflow in the main stem (ft^3/s)	Total measurement uncertainty for a given reach (ft^3/s)	Streamflow gain (+) or loss (-) per reach (ft^3/s)	Gain or loss relative to USGS streamgage 08053000 (%)
08053000	**304**	**6.08**	**304**			
08053009	7.86	0.157	312			
08053018	0.89	0.089	313			
08053027	2.71	0.054	315			
08053040	3.39	0.170	319			
WTP	-221		98.3			
08055350	83.3	4.17	182	15.1	+38.4	12.6
08055500	**220**	**4.40**	**220**			
08053090	3.79	0.379	224			
08055515	2.27	0.114	226			
08055516	0.00	0.000	226			
08055518	2.04	0.204	228			
08055519	0.38	0.038	228			
08055538	1.96	0.196	230			
08055555	0.47	0.047	231	18.9	+39.1	12.9
08055560	**270**	**13.5**	**270**			
08055600	1.06	0.106	271	28.7	+29.9	9.8
08055620	**301**	**15.1**	**301**			
Gain or Loss over full reach					*+107.4*	*35.3*

ment events, respectively (Tables 4–7). A gain in streamflow of about 69 ft^3/s was observed during the October 2021 discrete-measurement event. A more in-depth evaluation of these gaining and losing reaches is provided in the "Conclusions" section of this report.

Waterborne Self-potential, Surface-Water Temperature, and Surface-Water Conductivity

The largest electric-potential anomaly occurs along WaSP reach 1 (approximately 1 mile downstream from the start of the WaSP reach 1; Figure 7). Electric-potential results processed from the measured voltage data indicate that streamflow losses may occur at a focused location in the northern part of WaSP reach 1 and losses and gains may be more distributed along WaSP reaches 2–3. A notable change in both the measured voltage differences and in the processed electric potential occurs near the inflow of Prairie Creek and adjacent Republic Services Lewisville Landfill retention pond. This effect is shown in the WaSP reach 1 data in Figure 4D and in the electric potential in Figure 7 and further discussed in the "Conclusions" section of this report.

The electric-potential profile data support the qualitative interpretation that the individual WaSP reaches generally represented distributed losing conditions. In general, the electric-potential profile data along the full WaSP reach depict observable decreases at the downstream ends of the reaches and relative increases in electric potential at the upstream ends of the reaches, which reflects the localized reductions in hydraulic gradient attributed to low-head dams positioned at these locations that produce localized losing conditions on the upstream sides and localized gaining conditions on the downstream sides of the low-head dams. The electric-potential data further indicate that some short, interspersed stream reaches may be characterized by discrete gains or losses of varying magnitudes, and these discrete gains or losses appear to occur over spatial scales

Table 5. Summary of discrete streamflow measurements and water treatment plant (WTP) withdrawals in the Elm Fork Trinity River between Lake Lewisville Dam and Frasier Dam on January 25, 2022, during the waterborne self-potential logging survey. Discrete measurements made on the main stem are indicated in bold font and reaches are grouped by horizontal dashed lines. Between main-stem measurements, streamflow gains are highlighted in blue and losses in red when the gain or loss exceeds the total measurement uncertainty. Streamflow data from U.S. Geological Survey (2023).

USGS streamgage number or site identifier	Measured streamflow (ft^3/s)	Measurement uncertainty (ft^3/s)	Cumulative streamflow in the main stem (ft^3/s)	Total measurement uncertainty for a given reach (ft^3/s)	Streamflow gain (+) or loss (-) per reach (ft^3/s)	Gain or loss relative to USGS streamgage 08053000 (%)
08053000	**207**	**4.14**	**207**			
08053009	3.33	0.33	210			
08053018	0.18	0.02	211			
08053027	2.22	0.04	213			
08053040	1.02	0.10	214			
WTP	-182		31.4			
08055350	59.9	1.20	91.3	7.98	+15.7	7.6
08055500	**107**	**2.14**	**107**			
08053090	1.54	0.15	109			
08055515	0.98	0.02	110			
08055516	0.01	0.00	110			
08055518	2.69	0.27	112			
08055519	0.13	0.01	112			
08055538	0.36	0.01	113			
08055555	0.00	0.00	113	4.68	-8.71	-4.2
08055560	**104**	**2.08**	**104**			
08055600	0.93	0.09	105	4.17	-4.93	-2.4
08055620	**301**	**15.1**	**301**			
Gain or Loss over full reach					*+2.04*	*1.0*

ranging from a few hundred meters to about 2–2.5 km along reach 1. For example, polarity reversals from negative to positive electric-potential occur at locations along survey reach 1 between survey profile distances of about 0.6–0.9, 3–3.5, 7.5–8, and 9.4–9.8 km downstream from the survey starting point. These locations correspond to positive electric-potential anomalies characterized by magnitudes of about 5, 7, 33, and 6 mV, respectively. Relatively discrete losses are indicated along reach 1 between survey distances of about 1 km and 3.5 km downstream from the survey start point. The conspicuous reduction in electric-potential over this reach length corresponds to a negative electric-potential anomaly with a magnitude that decreases to less than -70 mV adjacent to a retention pond on the west flood-plain of the Elm Fork. The electric-potential profiles along WaSP reaches 2 and 3 each displayed predominantly negative electric-potential values and negative slopes in the profile data whereby increasing downstream distance corresponds to decreasing electric potential in the stream. The negative slope of the electric-potential data increases along WaSP reach 2 relative to the slope of the profile data along WaSP reach 1, and increases again along WaSP reach 3 relative to the electric-potential profile data along WaSP reach 2. Spatial patterns in the electric-potential data along WaSP reaches 2 and 3 (relative increases and decreases in the electric-potential data along the profile) appear to vary over a kilometric scale, predominantly between about 1–3 km.

Specific conductance data in microsiemens per centimeter at 25 degrees Celsius (µS/cm) were calculated from the SW temperature in degrees Celsius (°C) and SW conductivity data (µS/cm) (U.S. Geological Survey, 2019) (Figure 8C). A general pattern in the relation between SW temperature and specific conductance was observed for each WaSP reach, and perhaps multiple different patterns along each individual WaSP reach (Figure 8D). Higher temperatures and lower specific conductance values were recorded in WaSP reach 1 compared to WaSP reaches 2–3.

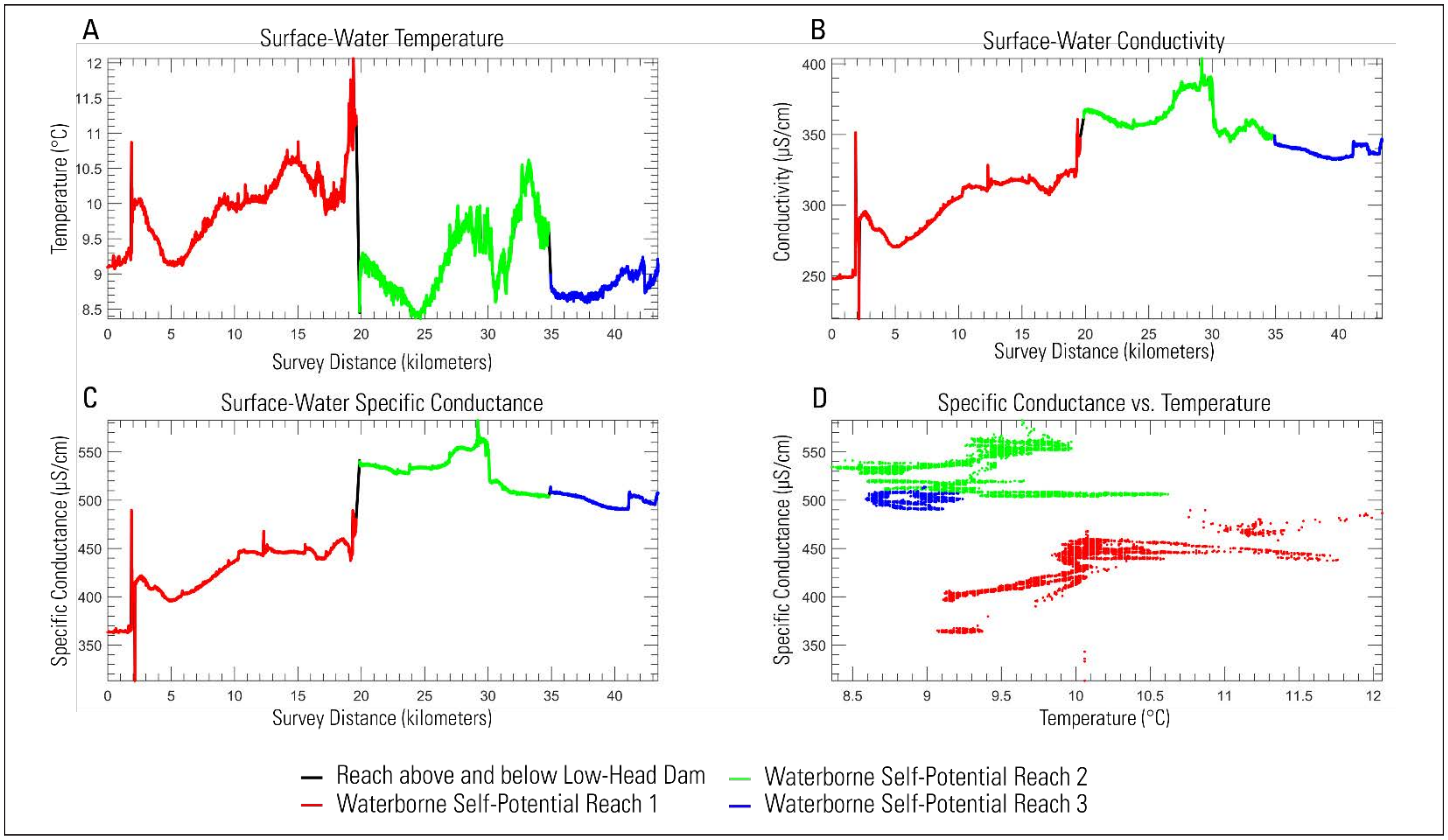

Figure 8. (A) Surface-water temperature in degrees Celsius (°C) and (B) conductivity in microsiemens per centimeter (µS/cm) data measured along each waterborne self-potential (WaSP) survey reach of the Elm Fork Trinity River between Lake Lewisville Dam and Frasier Dam. (C) Calculated surface-water specific conductance in µS/cm at 25 degrees Celsius from the measured surface-water temperature and conductivity along each WaSP survey reach. (D) Scatterplot of temperature and specific conductance for each WaSP reach. Reaches are depicted in black for areas directly upstream or downstream of low-head dams, where surface-water temperature and conductivity were not collected (Figure 1).

CONCLUSIONS

Overall, the measurements in the Elm Fork reach between Lake Lewisville Dam and Frasier Dam indicated both gains and losses in streamflow during this study over a wide range of streamflow conditions (207 to 1,610 ft^3/s at USGS streamgage 08053000 Elm Fork Trinity River near Lewisville, Texas (streamgage 08053000) after accounting for inflows from measured tributaries and withdrawals at a WTP. Average WTP withdrawal rates ranged from a minimum of about 182 ft^3/s on January 25, 2022, to a maximum of about 363 ft^3/s on August 9, 2022, during discrete-measurement events. The only discrete measurement event with a calculated gain over the full reach greater than the measurement uncertainty, was during the October 2021 measurement event that followed 0.77 in of precipitation the day prior. The largest loss for the full reach was observed during the August measurement event, where approximately 3 percent of the streamflow from streamgage 0853000 was estimated to be lost but was less than the measurement uncertainty. Accounting for measured tributary inflows to the Elm Fork in this reach, streamflow gains and losses were primarily observed in three locations: between Lake Lewisville Dam and streamgage 08053000, between USGS streamgages 08053020 Elm Fork Trinity River at IH-35E near Lewisville, Texas and 08055500 Elm Fork Trinity River near Carrolton, Texas, and between USGS streamgages 08055560 Elm Fork Trinity River at Spur 348, Irving, Texas and 08055620 Elm Fork Trinity River at Spur 482 near Irving, Texas.

SW temperature and specific-conductance profile data show some spatial changes collocated with electric-potential anomalies along WaSP reach 1, and otherwise show spatial patterns that vary on a predominantly kilometric scale. GW temperatures generally are more stable than SW temperatures and are therefore well suited for identifying SW-GW interactions (Winter and others, 1999). The negative electric-potential anomaly observed along WaSP reach 1 at survey distance of 1 to 3 km is collocated with a notable increase in SW temperature and SW specific-conductance data that appears initially as a discrete increase over a short segment of the profile followed by a more gradual decrease to about 5 km downstream from

Table 6. Summary of discrete streamflow measurements and water treatment plant (WTP) withdrawals in the Elm Fork Trinity River between Lake Lewisville Dam and Frasier Dam on May 17, 2022. Discrete measurements made on the main stem are indicated in bold font and reaches are grouped by horizontal dashed lines. Between main-stem measurements, streamflow losses are highlighted in red when the loss exceeds the total measurement uncertainty. No streamflow gains exceeded the total measurement uncertainty. Streamflow data from U.S. Geological Survey (2023).

USGS streamgage number or site identifier	Measured streamflow (ft^3/s)	Measurement uncertainty (ft^3/s)	Cumulative streamflow in the main stem (ft^3/s)	Reach uncertainty (ft^3/s)	Streamflow gain (+) or loss (-) per reach (ft^3/s)	Gain or loss relative to USGS streamgage 08053000 (%)
08053000	**1,610**	**32.2**	**1,610**	**64.2**	-10.0	-0.6
08053003	**1,600**	**32.0**	**1,600**			
08053009	4.27	0.43	1,604			
08053018	1.02	0.10	1,605	64.9	+14.7	0.9
08053020	**1,620**	**32.4**	**1,620**			
08053027	1.70	0.17	1,622			
08053040	0.48	0.05	1,622			
WTP	-310		1,312			
08055350	111	11.10	1,423	118	+67.1	4.2
08055500	**1,490**	**74.5**	**1,490**			
08053090	1.55	0.08	1,492			
08055515	0.68	0.01	1,492			
08055516	0.00	0.00	1,492			
08055518	0.89	0.09	1,493			
08055519	0.54	0.05	1,494			
08055538	0.07	0.01	1,494	105	-4.8	-0.3
08055560	**1,490**	**29.8**	**1,490**			
08055600	0.62	0.06	1,491	57.9	-90.6	-5.6
08055620	**1,400**	**28.0**	**1,400**			
Gain or Loss over full reach					*-23.6*	*-1.5*

the start point, and then a general increase over another 9–10 km in a downstream direction. In general, the SW temperature profile showed the largest gradients at locations of mixing SW sources. Along WaSP reach 1 the SW temperature profile showed downstream warming SW conditions throughout the collection period with anomalies larger than the diurnal patter near the confluence of Prairie Creek and the Republic Services Lewisville Landfill retention pond, a WTP, and inflow from Timber Creek. Specific-conductance values in WaSP reach 1 were relatively stable to the confluence of Denton Creek, where higher values were measured downstream. The SW temperature profile data along reach 2 showed two primary deflections, with cooler SW below Farmer Branch tributary and warmer SW below the confluence of Hackberry Creek and Cottonwood Branch. SW temperatures in the WaSP reach 3 were relatively constant. Relative to WaSP reach 1, elevated specific-conductance values were measured in WaSP reach 2. Specific conductance along reach 2 slightly decreased below the confluence of Farmers Branch and remained relatively constant downstream.

Whereas the uppermost streamflow measurement was made at the Elm Fork River near Lewisville streamgage 08053000, the WaSP survey completed in January 2022 started below Lake Lewisville Dam. The large negative spontaneous potential (SP) anomaly and shift in SW temperature observed just downstream from Lake Lewisville Dam, is spatially aligned with the outflow to Prairie Creek and a retention pond associated with a waste-disposal site (Figure 1). Two possible hypotheses for these results are: (1) a hydraulic gradient exists from the Elm Fork to the retention pond causing the Elm Fork to lose water to the retention pond, or (2) a subsurface redox plume associated with the presence of the waste-disposal site is producing the negative SP anomaly. The first hypothesis has been shown to be capable of producing a negative SP anomaly by

Table 7. Summary of discrete streamflow measurements and water treatment plant (WTP) withdrawals in the Elm Fork Trinity River between Lake Lewisville Dam and Frasier Dam on August 9, 2022. Discrete measurements made on the main stem are indicated in bold font and reaches are grouped by horizontal dashed lines. Between main-stem measurements, streamflow losses are highlighted in red when the loss exceeds the total measurement uncertainty. No streamflow gains exceeded the total measurement uncertainty. Streamflow data from U.S. Geological Survey (2023).

USGS streamgage number or site identifier	Measured streamflow (ft^3/s)	Measurement uncertainty (ft^3/s)	Cumulative streamflow in the main stem (ft^3/s)	Reach uncertainty (ft^3/s)	Streamflow gain (+) or loss (-) per reach (ft^3/s)	Gain or loss relative to USGS streamgage 08053000 (%)
08053000	**509**	**25.5**	**509**			
08053009	1.72	0.03	511			
08053018	0.16	0.02	511	36.2	+26.1	5.1
08053020	**537**	**10.7**	**537**			
08053027	0.00	0.00	537			
08053040	0.16	0.02	537			
WTP	-363	0.00	174			
08055350	29.8	0.60	204	14.8	-34.1	-6.7
08055500	**170**	**3.40**	**170**			
08053090	0.47	0.05	170			
08055515	0.54	0.05	171			
08055516	0	0.00	171			
08055518	1.13	0.11	172			
08055519	0.05	0.01	172			
08055538	0.2	0.02	172			
08055555	0.00	0.00	172	6.72	-18.4	-3.6
08055560	**154**	**3.08**	**154**			
08055600	0.19	0.02	154	11.2	+8.81	1.7
08055620	**163**	**8.15**	**163**			
Gain or Loss over full reach					*-17.6*	*-3.4*

Ikard and others (2018), Valois and others (2017), Ikard and others (2021a), and Ikard and others (2021b), whereas the second hypothesis has been shown to be capable of producing a negative SP anomaly by Hämmann and others (1997), Timm and Möller (2001), Nyquist and Corry (2002), and Naudet and others (2003).

Between streamgage 08053000 and streamgage 08055500, the largest inflows and withdrawals occur. The only major source of withdrawals on this reach of the Elm Fork was for a WTP; these withdrawals were responsible of the largest changes in streamflow during the study period. During each discrete-measurement event, the inflow from Denton Creek was the largest inflow from any tributary. Inflow from Denton Creek during the discrete-measurement events was about 83 ft^3/s on October 12, 2021, 60 ft^3/s on January 25, 2022, 111 ft^3/s on May 17, 2022, and 30 ft^3/s on August 9, 2022. After accounting for the WTP withdrawals and inflows from measured tributaries, streamflow gains were measured during three of the four discrete-measurement events; however, the streamflow gain in May 2022 was less than the measurement uncertainty for that reach. These gains in October 2021 and January 2022 ranged from about 16 ft^3/s to 38 ft^3/s, respectively. During the final discrete-measurement event on August 9, 2022, a loss of about 8 ft^3/s was measured between streamgages 08053000 and 08055500 but was within the uncertainty of the measurements for that reach. This potential loss is likely the result of measurement uncertainty or drier and hotter conditions during the August 2022measurement event relative to the others. The downstream reach between streamgages 08055500 and 08055560 also had the only loss of more than 10 ft^3/s during the August 2022 discrete-measurement event and was nearly three times larger than the measurement uncertainty, this loss is likely a result of extremely dry and hot conditions that prevailed during this measurement event.

Both gains and losses were observed in the reach between the Elm Fork Trinity River at Spur 348 (08055560) and Elm Fork Trinity River at Spur 482 (08055620) streamgages, depending on streamflow conditions. During the discrete measurements in January and August 2022, streamflow was relatively stable with a loss of about 5 ft^3/s and a gain of about 9 ft^3/s, respectively but the gain in August 2022 was within the measurement uncertainty. A 0.77 precipitation event was recorded on October 11, 2021 and corresponded to a peak computed streamflow of 993 ft^3/s obtained from the continuous streamgage at Spur 348 (08055560) that showed elevated streamflow, compared to the conditions found during the discrete streamflow measurement of 270 ft^3/s on October 12, 2021. A gain of about 30 ft^3/s was observed during the October 2021 discrete-measurement event in this reach and is likely a result of runoff from the precipitation event and drainage of SW from low lying areas adjacent to the Elm Fork that were inundated by streamflow the day prior. The upstream reach between streamgages 08055500 and 08055560 also had the only gaining discrete-measurement event during October 2021 likely due to the same conditions. Conversely, during the highest streamflow measured in this study (about 1,610 ft^3/s at 08053000), a loss of about 91 ft^3/s was measured in this reach during the August 2022 discrete event and is likely due to increases in SW storage of low-lying areas.

Due to the complex nature of gaining and losing conditions over the relatively long reach assessed during this study, there are likely still additional studies needed to fully understand these conditions under all hydrologic and seasonal climatic conditions. Additional rounds of discrete measurements, coupled with continuous streamflow information, would build on results of this study, and overall improve the spatial and temporal understanding of gaining and losing conditions in the reach. The results from this study, completed over a wide range of streamflow, and seasonal conditions, provide Dallas Water Utilities and other water resource managers vital synoptic results to inform their water management strategies. This information will enable water resource managers information to evaluate gaining and losing impacts under similar conditions that were observed during this study to help maximize water resources.

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Commentary: 88th Texas State Legislature: Summaries of Water-Related Legislative Action

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Editor-in-Chief 's Note: September 1 of every odd-numbered year is the date when most new legislation from the most recent session of the Texas Legislature typically goes into effect. With this in mind, the Texas Water Journal invited seven 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 2023 session. The opinions expressed in these summaries are the opinions of the individual organizations and not the opinions of the Texas Water Journal, the Texas Water Resources Institute, or the Bureau of Economic Geology.

Organizations:

- Texas Water Conservation Association
- Texas Alliance of Groundwater Districts
- Texas Water Foundation
- Sierra Club, Lone Star Chapter
- Texas Water Infrastructure Network
- Environmental Defense Fund
- Texas 2036

[1] Texas Water Conservation Association
[2] Texas Alliance of Groundwater Districts
[3] Texas Water Foundation
[4] Sierra Club, Lone Star Chapter
[5] Texas Water Infrastructure Network
[6] Environmental Defense
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Terms used in paper

Acronym / Initialism	Descriptive Name
AG	Attorney General
ASR	Aquifer Storage and Recovery
CEO	Chief Executive Officer
Ch	Chapter
CCN	Certificate of Convenience and Necessity
D	Democrat
DFC	Desired Future Condition
EDAP	Economically Distressed Areas Program
EDF	Environmental Defense Fund
EFAG	Environmental Flows Advisory Group
ETJ	Extraterritorial Jurisdiction
GCD	Groundwater Conservation District
GMA	Groundwater Management Area
HB	House Bill
IIJA	Infrastructure Investment and Jobs Act
LLC	Limited Liability Corporation
PUC	Public Utility Commission of Texas
R	Republican
RWPG	Regional Water Planning Group
SB	Senate Bill
SJR	Senate Joint Resolution
SOAH	State Office Administrative Hearings
SWIRFT	State Water Implementation Revenue Fund for Texas
SWIFT	State Water Implementation Fund for Texas
SWQS	Surface Water Quality Standards
TAGD	Texas Alliance of Groundwater Districts
TCEQ	Texas Commission on Environmental Quality
TEC	Texas Ethics Commission
TPDES	Texas Pollutant Discharge Elimination System
TPWD	Texas Parks and Wildlife Department
TWCA	Texas Water Conservation Association
TWDB	Texas Water Development Board
TXPWC	Texas Produced Water Coalition
TXWIN	Texas Water Infrastructure Network
US	United States
WAM	Water Availability Model
WSTF	Water Supply for Texas Fund

TEXAS WATER CONSERVATION ASSOCIATION SUMMARY OF THE 88TH LEGISLATIVE SESSION

By Sarah R. Kirkle, Director of Policy and Legislative Affairs

The Texas Water Conservation Association *(TWCA) is a non-profit association of water professionals and organizations working to promote sound water policy in Texas. TWCA's members provide water and/or wastewater services to a great majority of the state and include river authorities, cities, groundwater conservation districts, flood/irrigation/drainage/water districts, industries, consultants, and others interested in Texas water policy and development.*

After a fast and furious 140 days, the 88th Texas Legislature adjourned *sine die.* Governor Abbott has already called the Legislature Back for two special sessions, with more expected over the interim. The Legislature headed into the 88th regular session with a nearly $33 billion surplus, making the budget the most significant topic on the legislative docket, followed by various social issues. Issues that surrounded the budget included property tax reform and funding for retired teachers, state employees, higher education, parks, broadband, electric generation, and water.

Legislators filed 8,345 bills and joint resolutions, about 14% more than in the 87th session. Only 1,256 of those bills passed both chambers by *sine die,* providing for a 15% percent bill passage rate and resulting in the 88th session having the highest number of bills filed and lowest passage rate in recent memory (Telicon 2023). Governor Abbott vetoed 76 bills (nine of which TWCA tracked), second only to Rick Perry in 2001 (Legislative Reference Library 2023). In many cases, the Governor's veto proclamation noted the importance of the vetoed bill and invited the Legislature to reconsider the bill after the passage of legislation addressing property tax or education reform.

On the waterfront, this session marked the formation of the first-ever House Water Caucus, chaired by Rep. Tracy O. King. The goals of the caucus include educating legislative members and staff on water issues, elevating water issues as a priority within the Legislature, and cultivating the next generation of water champions. Seventy-three of the 150 members of the Texas House joined the Water Caucus, demonstrating the importance of water issues across the state (Texas Water Foundation 2023).

As in past sessions, TWCA closely followed bills that could impact its members, tracking 754 bills and designating 61 of those bills as a high priority. One hundred nineteen, or about 16% of our tracked bills, made it to the finish line, with 16 of those being a high priority. The most significant bills that may interest water professionals are summarized below.

Water infrastructure

After an interim filled with discussions about infrastructure woes, such as line breaks and boil water notices due to extreme weather events, the Legislature passed Senate Bill (SB) 28 and Senate Joint Resolution (SJR) 75 (Perry/T. King) to create the Texas Water Fund. This umbrella fund allows the Texas Water Development Board (TWDB) to disburse money to other funds and programs it administers, such as the State Water Implementation Fund for Texas and the Rural Water Assistance Fund. The bill also creates the New Water Supply for Texas Fund and includes a goal for TWDB to fund 7 million acre-feet of new water supplies by 2033 through eligible projects such as desalination, aquifer storage and recovery, and use of produced water outside the oil and gas arena. SB 28 requires a portion of the Texas Water Fund to be used for water infrastructure projects for rural political subdivisions and municipalities with a population under 150,000; projects for which all permitting is complete; a statewide water public awareness program; water conservation strategies; and water loss mitigation projects. The bill requires all recipients of financial assistance to submit a water conservation plan. TWDB must also establish a technical assistance program to assist retail public utilities with water loss audits and post certain water loss information on its website (SB 28 2023).

SJR 75, which amends the Texas Constitution to create the Texas Water Fund, must be approved by Texas voters this November before funding may be accessed. The resolution provides that not less than 25% of the initial $1 billion appropriation to the Texas Water Fund be used for eligible projects in the New Water Supply for Texas Fund (SJR 75 2023).

Beyond SB 28/SJR 75, the Legislature funded other water infrastructure priorities through the state budget and supplemental appropriations bill (HB 1 and SB 30 – Bonnen/Huffman). Most significantly, this included $625 million to the Flood Infrastructure Fund, $550 million toward the coastal spine, and $125 million in match funds for the State Revolving Funds. SB 469 (Springer/T. King) also updated the definition of "rural political subdivision" to access TWDB programs (SB 469 2023).

Advocacy for investment in water infrastructure also brought about unprecedented collaboration within and beyond the water community. TWCA partnered with other key water associations to form a water infrastructure coalition to help advocate for water, wastewater, and flood infrastructure investment. Despite very different water needs and priorities, the coalition of 24 associations and 47 individual districts, organizations, and firms share a common goal of ensuring our water future. The water community is thankful for the leadership of our chairmen – Senator Charles Perry and Representative Tracy O. King – in passing and securing an appropriation for SB 28/SJR 75, and all realize the conversation around water infrastructure and funding needs is just beginning.

Sunset review of water agencies

All of the key water-related agencies – TCEQ, TWDB, and PUC – underwent review by the Sunset Advisory Commission leading into this session. Sunset review is a comprehensive review process identifying key management and statutory changes intended to make the agencies operate more efficiently and effectively. Complete summaries of the Sunset bills and adopted management recommendations for each of these agencies are available on the Sunset website, and a synopsis of relevant water-related provisions in each Sunset bill is below

- **TCEQ Sunset: SB 1397 (Schwertner/K. Bell)** requires periodic review of environmental flow standards by the Environmental Flows Advisory Group (EFAG), specifies the criteria for those reviews, and requires a biennial statewide work plan to prioritize and standardize review of environmental flow standards. The bill requires TCEQ to submit a biennial report to the EFAG and removes the abolishment date for EFAG & the Science Advisory Committee. The bill expands various public notice and outreach requirements related to permits, requires additional specificity in calculating compliance history, and increases administrative penalty authority from $25,000 to $40,000 for certain violations. The bill requires an enforcement diversion program for small businesses and local governments. The bill also requires notice of the proposed creation of a new water district to each representative and senator representing an area in the proposed district boundaries (SB 1397 2023).
- **TWDB Sunset: HB 1565 (Canales/Perry)** requires each regional water planning group to include in its regional plan certain information (expenditures of sponsor money, status of permit applications, and status of phases of construction) for large projects, including reservoirs, interstate water transfers, innovative technology projects, desalination, and other large projects as determined by TWDB. The bill allows a regional water planning group to plan for a drought worse than the drought of record and allows TWDB to adopt a risk-based review of plans and specifications if a professional engineer makes specific findings (HB 1565 2023).
- **PUC Sunset: HB 1500 (Holland/Schwertner)** clarifies that a temporary manager of a water utility is one year, and the term may be renewed for another year or a reasonable time if the utility is undergoing sale or transfer (HB 1500 2023).

Surface and groundwater

TWCA's Surface Water Committee and Groundwater Committee, which each have more than 150 members representing all facets of the water community, met in advance of the 88th session and considered a wide range of issues, applying a 90% consensus requirement for all proposals. The committees ultimately recommended that TWCA offer specific legislation related to surface water availability models and support nine other initiatives in the groundwater space. House Bill (HB) 2460 (T. King/Perry) requires TCEQ to update WAMs for five river basins (HB 2460 2023). TWCA has consistently supported WAM updates and hopes to eventually obtain funding to update all the WAMs. Some WAMs are more than 30 years out-of-date and do not reflect potential new droughts of record. Unfortunately, while the bill passed the Legislature, the budget did not include funding for updates, so TCEQ is not required to initiate updates.

Other notable water-related bills that passed include:

- **HB 692 (Rogers/Springer)** allows authorization by rule for land application of dairy waste and disposal of dairy waste from a concentrated animal feeding operation into a control or retention facility (HB 692 2023).
- **HB 1971 (Ashby/Springer)** provides that for a GCD board with 10 or more directors, a concurrence of a majority of directors eligible to vote is sufficient to take action on a groundwater permit application or amendment. The bill prohibits a director who files a conflict-of-interest affidavit from voting on or attending a closed meeting unless a majority of the directors are also required to file an affidavit. HB 1971 provides that a GCD's final permit decision must be in writing and adopted within 180 days after receipt of a proposal for decision. If the GCD has not finalized its decision by then, the recommendations of the administrative law judge are deemed adopted by the GCD and are not appealable or subject to a motion for rehearing. The bill prohibits continuances from exceeding time limits for issuing a final decision; provides for timelines and consolidation of motions for rehearing; and provides procedures for appealing a decision (HB 1971 2023).
- **HB 2443 (Harris/Perry)** allows a person with a real property interest in groundwater to petition a GCD where the property interest is located to adopt or modify a rule. The bill requires a GCD to prescribe the form for a petition and procedures for submission, consideration, and disposition. The bill provides a 90-day timeline for a GCD to deny the petition or engage in rulemaking (HB 2443 2023). (TWCA-supported bill)

- **HB 2815 (Jetton/Creighton)** changes TCEQ approval, petition processes, and confirmation elections for district creation and initial directors. The bill changes authorization thresholds for assessments, taxes, fees, or bonds and changes the per diem of directors from $150 per day to not exceed the legislative per diem, which is currently $221. HB 2815 provides that a special law authority may not set the annual limit on fees for a director at an amount greater than would be produced by 60 days of service per year at the maximum daily rate. The bill allows the use of a county website for online meeting notices and excludes the personal email of a director from public information. The bill makes various changes to bond election requirements and TCEQ review of the economic feasibility of bonds. HB 2815 amends requirements for dividing or consolidating a district and adds notice requirements for property sold or conveyed within a district. The bill adds requirements to allocation agreements, amends the qualifications of directors, and repeals certain provisions regarding the conversion of a municipal utility district, vacancies, and solid waste (HB 2815 2023).
- **HB 3059 (T. King/Perry)** increases the export fee cap for tax- and fee-based GCDs to 20 cents per thousand gallons exported and provides that the cap on the export fee or existing 50% surcharge increases at 3% per year. The bill allows a special law district to charge an export fee or surcharge in accordance with either special law or Ch. 36, Water Code. The bill requires any new export fee or increase in an existing export fee or surcharge to be approved by a GCD board after a public hearing. HB 3059 authorizes a GCD to use fees to maintain the operability of wells significantly affected by groundwater development, among other purposes. The bill provides that funds obtained from the increase in an export fee on or after January 1, 2024. These funds may only be used to maintain the operability of wells significantly affected by groundwater development, to develop and distribute alternative water supplies, or to conduct aquifer monitoring, data collection, or science (HB 3059 2023).
- **HB 3232 (Rogers/Perry)** provides that if a retail public utility service is integrated into a regional service, TCEQ may enter into a compliance agreement with the regional provider and not initiate an enforcement action for existing or anticipated violations resulting from the operation due to service integration (HB 3232 2023).
- **HB 3278 (Price/Blanco)** requires GCDs to submit supporting materials, including new or revised model run results, to the GCD representatives in the GMA and be made publicly available on a website on behalf of the GMA. The bill requires information to be posted for at least 30 days before GCDs may reconvene for a joint planning meeting to receive comments and adopt a final DFC. The bill requires that the explanatory report include reasons why the GMA did not incorporate into the DFC comments offered during the public comment period or joint planning meeting (HB 3278 2023). (TWCA-supported bill)
- **HB 3810 (Landgraf/Perry)** requires a nonindustrial public water supply system providing water for public or private use to notify TCEQ of an unplanned condition that has caused an outage or issuance of a do-not-use, do-not-consume, or boil water notice. The bill allows TCEQ to partner with the Texas Department of Emergency Management in administering the notification requirement. The bill does not require a person in charge of a nonindustrial public water supply system to provide notice of a weather or emergency alert, warning, or watch issued by specific state or federal agencies (HB 3810 2023).
- **HB 4256 (Murr/Blanco)** requires TCEQ to administer a grant program for plugging certain wells in Pecos County. The bill sets out program eligibility and requires funds to be awarded to a contractor or subcontractor on a list of approved well pluggers maintained by the Railroad Commission (HB 4256 2023).
- **SB 1289 (Perry/T. King)** provides that a wastewater treatment facility that treats domestic wastewater for reuse may dispose of treated wastewater without a permit if the facility disposes through a collection system and has the consent of the operator of the system and treatment facility. The bill clarifies that the owner of a reclaimed water production facility may not be required to own a wastewater treatment facility permitted by TCEQ and requires TCEQ to adopt rules (SB 1289 2023). (TWCA-supported bill)
- **SB 2440 (Perry/Burrows)** requires a plat application to attach a statement certifying adequate groundwater availability for a proposed subdivision. The bill allows a municipality or county to waive this requirement if the authority determines there is sufficient groundwater in the vicinity of the proposed subdivision and the entire tract is supplied by groundwater from certain aquifers, or if the proposed subdivision divides the tract into not more than 10 parts. A municipality or county can require the certification of groundwater if it determines the proposed subdivision is part of a series of subdivisions from an original tract that collectively includes more than 10 parts (SB 2440 2023).

Transparency and government operations

The Legislature passed several bills related to public information and transparency:

- **HB 3033 (Landgraf/Zaffirini)** defines business day for purposes of the public information law. Allows the AG to require training of a public official if the governmental body has failed to comply with legal requirements. The bill provides that some exceptions to public disclosure do not apply if related to specific elections and adds an exception for attorney general settlement negotiations. HB 3033 provides limitations on a requestor of public information who has exceeded certain limitations and allows a governmental body to request photo identification from a requestor. The bill requires requests to the AG to be submitted electronically and lists exceptions. The bill adds requirements for notifying a requestor of the status of a request. The bill also requires the AG to make available on its website a searchable database of each request and decision on public information law (HB 3033 2023).

- **HB 3440 (Canales/Hinojosa)** requires municipalities, counties, and various special districts - including conservation districts - to post the agenda for an open meeting on their website and in the location where the notice is posted (HB 3440 2023).
- **SB 943 (Kolkhorst/Hunter)** requires that a newspaper that publishes a notice shall, at no additional cost to a government entity, place the notice on the newspaper's website (if it has a website) in an area clearly designed for notices at no cost to the public. The bill also requires the Texas Press Association to publish notices on its website if it has a statewide repository of notices and provides details on such a repository (SB 943 2023).

Other key bills that impact the operations of government entities include:

- **HB 1845 (Metcalf/Perry)** requires TCEQ to establish a provisional certification program for a Class D water/wastewater operator for people who do not hold a high school diploma or equivalency if the operator has satisfied specific training and exams and acts under the direct supervision of a license holder (HB 1845 2023).
- **HB 3437 (Holland/Nichols)** increases the cap for change order approvals that can be delegated from a board to staff from $50,000 to $150,000 (HB 3437 2023).
- **HB 3507 (Holland/Nichols)** increases from $75,000 to $150,000, the minimum dollar amount of contracts requiring advertisement in newspapers. The bill requires competitive bidding for contracts between $25,000 and $150,000, up from the current $75,000 cap (HB 3507 2023).
- **SB 29 (Birdwell/Lozano)** prohibits a governmental entity from mandating face coverings, vaccines, or business or school closures due to COVID-19 (SB 29 2023).
- **SB 1893 (Birdwell/Anderson)** requires governmental entities to adopt a policy prohibiting the installation or use of TikTok on a device owned or leased by the entity, requires the removal of TikTok, and lists exceptions to the prohibition. The bill allows the Governor to identify other social media apps that pose similar risks to the security of governmental entity information and requires the Department of Information Resources and the Department of Public Safety to develop a model policy (SB 1893 2023).

Looking ahead

The next significant event in the water space will be the November 7th election to see if voters approve Proposition 6, which creates the Texas Water Fund. Voter approval of this measure will trigger an appropriation of $1 billion to the Fund for distribution through loans and grants to local water and wastewater providers to improve and expand their infrastructure (SJR 75 2023).

The full Legislature has a lot of activity on its horizon. Given the Governor's promises for special sessions and the impeachment trial of the Attorney General, there may not be much of an interim before the 89th Legislature convenes in January 2025.

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TEXAS ALLIANCE OF GROUNDWATER DISTRICTS SUMMARY OF THE 88TH LEGISLATIVE SESSION

By Leah K. Martinsson, Executive Director

Texas Alliance of Groundwater Districts (TAGD) is a 501(c)3 nonprofit membership organization created in 1988 to provide a centralized means for groundwater conservation districts to engage and stay current on the quickly evolving world of groundwater science, policy, and management. TAGD currently has 92 groundwater conservation district members and 39 associate members.

The 88th Texas Legislature adjourned sine die on May 29, 2023 after a hectic legislative session. The session saw 8,046 bills filed— the highest ever. However, just because legislators filed a lot of bills does not mean many of them actually passed. A relatively low 1,246 bills passed both chambers; of those, the Governor subsequently vetoed 76 bills. Committee leadership for the House Natural Resources Committee and Senate Water, Agriculture, and Rural Affairs Committee – most relevant to groundwater conservation districts (GCDs) and groundwater stakeholders – remained the same as last session. Representative Tracy King (D-Uvalde) remained chair of the Natural Resources Committee. On the Senate side, Senator Charles Perry (R-Lubbock) was reappointed to chair the Water, Agriculture, and Rural Affairs Committee for the fifth time.

For the first time in years, the session could fairly be described as a "water session." Attention on water began early with House Natural Resources Chairman Rep. Tracy King forming the first-ever House Water Caucus, which attracted the participation of 73 House members committed to ensuring a secure water future for Texas. A $33 billion surplus made the budget and spending priorities a central focus of the session. Leading up to the session, momentum had been building for a generational investment in Texas's water infrastructure. The water community rallied together to support such an investment. Both Chairmen led on this critical issue, which ultimately resulted in the passage of SB 28/SJR 75 (Perry/T. King). This bill creates the Texas Water Fund and the Legislature appropriated $1 billion for the fund, subject to voter approval. This umbrella fund will allow the Texas Water Development Board (TWDB) to disburse funds to other water funds and programs it administers. The bill also creates the New Water Supply Fund, which aims to fund projects (including desalination, aquifer storage and recovery, and use of produced water) that will generate 7 million acre-feet of new water supplies by 2033. (SB 28 2023).

Groundwater bills that passed

Throughout the 88th Legislative Session, TAGD tracked legislation that could impact GCDs and groundwater management. TAGD has a Legislative Committee that follows pending legislation and determines if a bill warrants action. Participation on the Legislative Committee is open to all TAGD members. This committee will then vote on relevant bills (only GCD members may vote) and needs 75% consensus to take a position. Positions are then subject to confirmation by TAGD's Executive Committee.

Unlike the 87th Legislative Session, this session saw a high volume of groundwater bills filed, several of which became law. TAGD identified 25 bills that either sought to make substantive changes to Chapter 36 of the Texas Water Code or otherwise implicated groundwater management and classified these as potentially actionable groundwater bills. In total, six of those bills crossed the finish line. Each of these is discussed below.

distinct sections, this nevertheless represented fewer Chapter 36-related bills than in prior legislative sessions (15 bills in the 86th, 25 in the 85th, and 23 in the 84th). There were also several other bills filed that implicated groundwater policy and GCD operations. In total, TAGD identified 10 statewide priority groundwater bills for tracking during the legislative session. Of those 10 bills, none crossed the finish line.

- **HB 1971 (Ashby/Springer)** This bill makes several changes to various provisions of Chapter 36 of the Texas Water Code:
    - In a contested case hearing on a permit application or permit amendment for which the GCD has contracted with the State Office of Administrative Hearings (SOAH), the GCD board must issue its final decision in writing no later than 180 days after receipt of SOAH's proposal for decision. Failure to do so will result in the final SOAH proposal for decision becoming the board's final order. This final order is then immediately appealable and not subject to a request for rehearing.
    - In a proceeding for permit application or amendment where the GCD has contracted with SOAH for a contested case hearing, the board may not continue a matter in excess of the time limits for issuing a final decision.
    - A board must consolidate all motions for rehearing in a contested case hearing. It must issue its final decision by 90 days after the original decision date.

  - **o** For a GCD board with 10 or more directors, a concurrence of the majority of directors eligible to vote is sufficient to take action on a permit application or amendment.
  - **o** A director required to file a conflict-of-interest affidavit on a matter is prohibited from voting or attending a closed meeting on that matter unless a majority of the directors are also required to file conflict-of-interest affidavits on that matter. (HB 1971 2023).

The concepts in this bill originated from a river authority that sought certain changes to Chapter 36 to bolster the finality of GCD decisions in the context of contested cases after it had gone through a lengthy contested case hearing process with one GCD. Representative Ashby spearheaded extensive stakeholder discussions during the session in which TAGD participated, resulting in a committee substitute for the filed version of HB 1971. TAGD supported the changes incorporated into the committee substitute and ultimately is the version that became law.

- **HB 2443 (Harris/Perry)** This bill adds a new Section 36.1025 to the Texas Water Code, which allows a person with a real property interest in groundwater to petition their GCD to adopt or modify a district rule. It includes notice and hearing requirements and requires a GCD to issue an explanation for the reasoning if a rulemaking petition is not granted. GCDs must adopt rules governing the form and procedure for such petitions by December 1, 2023. (HB 2443 2023). TAGD previously prepared a template that districts may use to include such a petition process in their rules. This TAGD-supported bill was a refile from the last two sessions.
- **HB 3059 (T. King/Perry)** This bill makes the following changes to Sections 36.122 and 36.207 of the Texas Water Code:
  - **o** Increases the export fee cap for both tax- and fee-based districts to 20 cents per thousand gallons of water exported;
  - **o** Beginning January 1, 2024, allows for a 3% annual increase to the maximum allowable export fee rate that a district may impose;
  - **o** Provides that increases to export fees are not valid unless there is a public hearing prior to GCD board approval;
  - **o** Allows for a district governed by a special law with provisions regarding export fees to continue to charge fees in accordance with that special law;
  - **o** Restricts a district's use of export fees collected from the authorized 3% annual increase only to costs related to assessing and addressing impacts associated with groundwater development; and
  - **o** Clarifies that a district may use funds obtained from fees to maintain the operability of wells significantly affected by groundwater development to allow for the highest practicable level of groundwater production while achieving the desired future conditions. (HB 3059 2023).

Over the interim, both the House Natural Resources Committee and the Senate Water, Agriculture, and Rural Affairs Committees held hearings focused on the impacts of large-scale groundwater production and export projects. There was broad acknowledgement that current district funding levels are often insufficient to support the science and monitoring needed to assess impacts or to implement potential programs to address local impacts from those export projects. The export fee caps and structure had remained unchanged since their adoption in 2001. This set the stage for the passage of HB 3059, which TAGD supported.

- **HB 3278 (Price/Blanco)** This bill makes changes to Section 36.108 and the steps required for final adoption of desired future conditions (DFCs) by a groundwater management area (GMA). Specifically, if a GCD receives supporting materials (including new or revised model run results) during the district's public comment period on draft DFCs, then that GCD is required to provide those materials to the other GCD representatives in the GMA and to post those materials on a publicly available website for 30 days. After these 30 days, the GMA may reconvene for a joint planning meeting at which it shall take additional public comment and may adopt a final DFC. The bill further requires that the explanatory report include the reasons for including or excluding comments provided during the public comment period or GMA meeting. (HB 3278 2023)
- **SB 1746 (Perry/Bell)** This bill creates a new exemption in Section 36. 117(b)(4) of the Texas Water Code to cover the use of a water well as a temporary water supply for drilling a permitted groundwater production well. It provides that this exemption may not exceed 180 days unless a district grants an extension not to exceed the time it takes to complete the groundwater production well. It also clarifies that a district may cancel this exemption if the temporary well is no longer used solely for the exempted purpose. (SB 1746 2023)
- **SB 2440 (Perry/Burrows)** This bill modifies the Local Government Code to mandate that cities and counties require groundwater availability certifications as a part of plat applications. Previously, Local Government Code Sections 212.0101 and 232.0032 allowed (but did not require) cities and counties, respectively, to require a person filing a plat application to certify adequate groundwater availability for that subdivision. The bill allows a city

or county to issue a waiver from this new groundwater availability certification requirement if the municipality or county determines, based on credible evidence, that there is sufficient groundwater available and will continue to be available and either: (1) the entire tract will be supplied with water from the Gulf Coast Aquifer or the Carrizo Wilcox aquifer, or (2) the proposed subdivision will divide the tract into not more than 10 lots. The requirements of this bill apply to plat applications filed on or after the bill's effective date of January 1, 2024. (SB 2440 2023). The Texas Commission on Environmental Quality (TCEQ) is responsible for establishing the form and content of groundwater availability certifications and will undergo a rulemaking to implement the bill. This bill arose in the context of continued rapid growth in Texas as many developers identify groundwater as the source of water to supply planned homes. In some cases, however, those homes are constructed and sold and groundwater availability is subsequently inadequate to serve those homes. TAGD supported this bill.

While not directly affecting Chapter 36 of the Texas Water Code, there are a few other bills relevant to groundwater:

- **HB 2759 (Thompson/Perry)** The bill provides specific statutory authority for the TWDB as the lead agency to coordinate the TexMesonet through station ownership and partnerships and codifies associated duties. (HB 2759 2023). The TexMesonet is a hydrometeorological network that provides statewide data on hydrological and meteorological conditions collected from earth observation stations. Many GCDs partner with TWDB to locate and maintain TexMesonet stations. TAGD supported this bill.
- **SB 1047 (Perry/Tepper)** This bill directs the Texas Produced Water Consortium (created in 2021 through SB 601) to select and implement a pilot project on the beneficial use of produced water and submit a report to the Legislature on that project. (SB 1047 2023). The Legislature appropriated $5 million to fund this effort. TAGD supported this bill.
- **HB 4256 (Murr/Blanco)** This bill establishes a fund and associated grant program for plugging certain wells that will be administered by TCEQ. The bill requires RRC to establish and maintain a list of approved well pluggers that may plug wells through the grant program. The bill defines various program requirements and narrowly defines eligibility in a manner that effectively limits the program to Pecos County in far West Texas. Several particularly problematic deteriorated and abandoned wells are bringing contaminated water, hydrogen sulfide, and radioactive materials to the surface in Pecos County. (HB 4256 2023). The Legislature allocated $10 million to this fund. Because TAGD does not take positions on local bills, it did not have an official position on this bill. However, the organization broadly supports addressing orphaned, abandoned, and deteriorated wells.

Select groundwater bills that did not pass

Because groundwater bills that are not successful in one session have a habit of returning in future sessions, it is worth briefly mentioning a few other key groundwater bills that did not pass during the 88th legislative session. These included:

- **SB 156 (Perry)** This omnibus groundwater bill was a refile from the 87th session. The bill included four distinct parts. First, it would have changed the mandatory award of attorney's fees to GCDs when a district prevails under Section 36.066(g) of the Texas Water Code to be discretionary. Second, it would have clarified which DFC should be used in a GCD's management plan if a petition is filed that the adopted DFC is unreasonable under the provisions of Chapter 36. Third, it included the same petition for rulemaking process contained in the successful HB 2443 (Harris), discussed above. Finally, SB 156 would have added a new section to Chapter 36 to require an applicant for a well permit application or amendment to provide notice to each person with a real property interest in groundwater beneath the land within the space prescribed by the district's spacing rules for the proposed or existing well, with certain exceptions. (SB 156 2023). TAGD supported three of the four components of SB 156—all except the proposed change to the attorney's fees provision. Bills to modify the attorney's fees provisions of Chapter 36 have been filed in several prior legislative sessions and have consistently reflected a point of disagreement among stakeholders. SB 156 passed the Senate with the attorney's fees provision intact. As the end of the session neared, the House Natural Resources Committee approved a committee substitute to SB 156 that removed the attorney's fees change and added the provisions contained in several other Chapter 36 bills that passed the House but did not receive a committee hearing in the Senate. Those added to CSSB 156 included HB 4444, HB 4532, HB 5052, and HB 5302 (all discussed below), as well as HB 3059 (which did pass, discussed above). (CSSB 156 2023). While CSSB 156 was placed on the House calendar, the clock ran out before it could receive a vote by the full House.
- **HB 4532 (Kacal)** This bill would have required TWDB to calculate the modeled sustained groundwater pumping of the state's aquifers in order to provide context for the calculated total estimated recoverable storage number that is required to be considered by GCDs in the DFC adoption process. (HB 4532 2023). This bill was a refile from earlier legislative sessions, and, like prior sessions, TAGD

supported this bill. The House approved this bill, but did not receive a hearing in the Senate Water, Agriculture, and Rural Affairs Committee.

- **HB 5052 (Gerdes)** This bill would have added registered exempt wells to the list of factors that a GCD considers in reviewing a permit application. (HB 5052 2023). Similar versions of this TAGD-supported bill have been filed in prior legislative sessions. While the House approved this bill, it did not receive a hearing in the Senate Water, Agriculture, and Rural Affairs Committee.
- **HB 2735 (T. King)** This bill sought to add a bonding requirement for petitioners other than the applicant in a contested case hearing to cover both the GCD's and the applicant's attorney's fees. (HB 2735 2023). TAGD took no position on this bill. This bill was voted favorably by the House Natural Resources Committee but did not receive a vote by the House.
- **HB 4444 (T. King)** This bill sought to make certain changes to the definitions section of Chapter 36. These included: updating the antiquated definition of "waste;" clarifying that "use for a beneficial purpose" must not be wasteful; and adding a definition of "conservation." It would have also cleaned up some obsolete provisions regarding wells contained in Chapter 11 of the Texas Water Code. (HB 4444 2023). TAGD supported the engrossed version of this bill. This bill was approved by the House but did not receive a hearing in the Senate Water, Agriculture and Rural Affairs Committee.
- **HB 5302 (Kacal)** This bill sought to improve certain aspects of the petition for inquiry review process, which is a GCD oversight mechanism contained in Section 36.3011 of the Texas Water Code. Changes would have included: clarifying TCEQ's responsibility for compliance with any open government requirements associated with a review panel; providing that the Office of Public Interest Counsel shall provide legal support to the review panel; establishing a process for both the review panel and TCEQ to obtain technical support from TWDB; and providing for compensation of actual expenses of review panel members. (HB 5302 2023). The basis for these clarifications arose from TCEQ's and the review panel's experience in 2019, the first time a petition for inquiry was granted and a review panel appointed. TAGD supported this bill. This bill was approved by the House but did not receive a hearing in the Senate Water, Agriculture and Rural Affairs Committee.

Finally, after allocating $1 billion to water infrastructure and new water supply, smaller budgetary requests related to groundwater were less successful. TWDB had sought funding for several exceptional items to bolster its groundwater monitoring, TexMesonet, and Texas water data programs. They also sought to replenish the Agricultural Water Conservation Fund (which will run out of funding at the end of the next biennium) for an additional ten years. A number of GCDs and other entities have utilized this effective program over the years, generating significant water savings by Texas irrigators. By and large, however, these items were not funded – or were funded at a small portion of the requested amounts – in the adopted budget.

Government bills that passed

There were several bills affecting government operations that became law and are relevant to GCDs:

- **HB 3440 (Canales/Hinojosa)** This bill requires that certain governmental entities, including GCDs, post the agenda for an open meeting on the government website and also post the agenda in the same location where the meeting notice is posted. (HB 3440 2023).
- **SB 232 (Hinojosa/Geren)** This bill provides for the automatic removal of any person holding elected or appointed office with a political subdivision if that person commits certain enumerated criminal offenses. (SB 232 2023).
- **SB 271 (Johnson/Shaheen)** This bill requires a local government (including GCDs) that holds computerized data with sensitive personal information to report a security incident. A "security incident" is defined to include a breach or suspected breach of system security and the introduction of ransomware. (SB 271 2023)
- **SB 1893 (Birdwell/Anderson)** This bill prohibits the installation or use of certain social media, including TikTok, on any device owned or leased by a governmental entity and requires a governmental entity to adopt a model policy to implement the prohibition. The Department of Information Resources and Department of Public Safety is required to develop the model policy. (SB 1893 2023).
- **HB 3033 (Landgraf/Zaffirini)** This bill makes various changes to the public information law. Key provisions include:
  - o defining a "business day" as any day other than a Saturday or Sunday, national holiday, state holiday, or days specifically designated by the government body;
  - o clarifying the exceptions to disclosure requirements as they relate to election information;
  - o imposing certain limitations on repeat requestors and allowing for photo identification requirements;
  - o requiring prompt release of basic responsive information, even if the government body is seeking an Attorney General decision on whether other information is subject to the request;
  - o adding requirements to notify a requestor of the status of a request; and

- **o** authorizing the Attorney General to require training of a public official of a government body if the government body fails to comply with a requirement of the public information law. (HB 3033 2023).

A look ahead

The interim looks like it will be an interesting one around the Capitol. At the time of this writing, Governor Abbott has already called two special sessions to address property tax relief. In addition, the Senate is poised to hold the impeachment trial of Attorney General Ken Paxton in September.

With respect to water, in November we will see the SJR 75 on the ballot. Voter approval of this measure is necessary to create the new Texas Water Fund and trigger the associated $1 billion appropriation to that fund. And sometime in the late fall or early winter, Speaker of the House Dade Phelan and Lieutenant Governor Dan Patrick will issue their interim charges. Those charges often drive policy discussions over the interim and set the tone for the upcoming session.

To further TAGD's mission to promote and support sound groundwater management based on local conditions and good science, TAGD will continue to engage in groundwater-related interim charges and associated policy discussions. TAGD will also assist its members in adjusting management and operations in accordance with legislation enacted during the 88th Legislative Session.

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A CRUCIAL AND HISTORIC DROP IN THE BUCKET

By Sarah Rountree Schlessinger, Texas Water Foundation, Chief Executive Officer

Texas Water Foundation (TWF) is a nonpartisan 501(c)(3) nonprofit that equips decision makers with tools to lead Texas into a sustainable water future.

From a national perspective, Texas' water policy has always carried the designation of being unique. In many cases, Texas has confronted water policy challenges ahead of national trends and invested significant funds to create sophisticated water planning and funding mechanisms. Texas water policy has also tended to be largely reactive, spurred by a history of disastrous droughts or catastrophic floods. This year, Texas' water agenda took a markedly more proactive tone and tracked unusually parallel to national ones.

The momentum around water infrastructure during this legislative session was predictable. Water infrastructure nationwide was funded mainly by a wave of federal investments fifty years ago. Much of that is aging beyond its useful lifespan and deteriorating faster than local utilities can maintain, replace, or expand. The passage of the Bipartisan Infrastructure Investment and Jobs Act at the end of 2021 signaled a significant course correction for decades of missing federal investment in critical infrastructure. It offered an opportunity for individual states to draw down funding for water.

Over the past two years, evidence of that aging infrastructure was present in Texas. Between statewide water system failures during Winter Storm Uri, the emergence of water loss data amidst staggering water supply projections, and a year of more boil water notices than any other state, it was inevitable that the state of Texas' water infrastructure would come into stark focus.

Water infrastructure, however, is much more technical and nuanced than previous water policy agendas. It has as much to do with built infrastructure nature-based infrastructure, complex funding mechanisms, technical assistance, workforce, and considerations of affordability and access. Compounding that complexity, Texas' existing and successful water infrastructure funding mechanisms, such as the State Water Infrastructure Fund for Texas (SWIFT), were reportedly oversubscribed or struggling to meet growing demands. Again, Texas' headline water agenda tracked with national debates on building, funding, and maintaining critical infrastructure.

In addition to the focus on water infrastructure, there were three other factors that we knew would influence how water would fare during the 88th Texas Legislature:

The first was, unsurprisingly, the weather. Texas continues to endure prolonged and devastating droughts, heat waves, water shortages, and more frequent and significant freeze events. As a result, Texans and our legislators have become increasingly aware of the inextricable link between power, food, and water. While the need for resilience drove policy discussions focused on energy production, it also spilled over appropriately to water.

The second factor was that all three key state agencies impacting water planning, financing, and regulation were undergoing sunset review. Sunset, the process by which a state agency is reviewed to determine whether it is meeting its statutory obligations, offered opportunities for the Texas Water Development Board (TWDB), the Texas Commission on Environmental Quality (TCEQ), and the Public Utility Commission (PUC) to be carefully assessed and produce legislation that would serve as vehicles for Texas water policy to make significant strides.

The third and arguably more significant factor was that the Texas Comptroller ended 2022 with the forecast that Texas would enter the 88th Legislative Session with a historic budget surplus of $32.7 billion. Incidentally, Texas Comptroller Glenn Hegar completed his Good for Texas tour shortly before that announcement, which included a timely focus on water as a cornerstone of our Texas economy. Weeks before the end of the interim, the budget surplus signaled a significant opportunity for water to be meaningfully addressed. It also, however, turned up the competition against countless other statewide priorities for water to retain the attention of our legislators.

Getting legislators' attention to the critical state of Texas water appeared not to be the challenge. In a historic move, Representative Tracy O. King formed the first Texas House Water Caucus, a bipartisan effort to provide educational resources, develop a new generation of water champions, and support the prioritization of water. The Texas House Water Caucus was established in February 2023 with a starting roster of 38 legislators. Within one month, that roster grew 92% to include 73 members from the Texas House of Representatives, making it the largest bipartisan caucus in the Texas Legislature. Either by the visible water challenges each legislator's district faced or the refreshingly nonpartisan nature of water, the caucus' rapid popularity signaled water had their attention.

However, keeping their attention and ensuring that water was prioritized required an unusual but successful streamlining of water agendas, terminology, and priorities. That focus was very clearly on water infrastructure and supply. Between January 1 and May 22, "water infrastructure" was mentioned 759 times in media outlets and 875 times on Twitter. "Water Supply" was mentioned 1,386 times in media outlets, and "underserved communities" was mentioned in the context of water 664 times. As a result of that coverage or the issues themselves, it was unsurprising that member engagement, or total authors, co-authors, and sponsors on water bills, grew 63% during the 88th Legislative Session compared to previous sessions.

As with all past significant water sessions, it took dedicated water champions to prioritize water. Senator Charles Perry, author of the 88th session's headline water bill SB 28 and its companion SJR 75, led the charge on addressing Texas' water supply and infrastructure challenges. Following considerable efforts by legislators, advocates, and agency staff, SB 28 was passed almost unanimously in both the House and Senate to create a new constitutionally protected fund for water. The Governor signed SB 28 and SJR 75 with a $1 billion appropriation and a constitutional amendment to be approved by Texas voters on the November ballot.

While SB 28's $1 billion was not the only funding allocated for water during the 88th Legislative Session, it was the most significant and was received with mixed emotions. On the one hand, it resonated with some as a deflated win, a drop in the bucket relative to Texas' staggering water infrastructure funding needs and available surplus budget. On the other hand, it represents a crucial triumph in a legislative session where state priorities could have easily eliminated the opportunity. In addition to SB 28 representing the most significant investment Texas has made in water since 2013, it is significant in its proactive acknowledgment of the technical and complex state of Texas water infrastructure. Most importantly, it creates the infrastructure, pun intended, for future investments.

The 88th Legislative Session made some other essential investments in water. Texas approved $125 million in match funds to draw down on the $750 million federal Infrastructure Investment and Jobs Act funding. It also dedicated $625 million for flood mitigation projects, $550 million to match federal funding for coastal projects and $1.5 million towards Texas water data.

Between sunset bills, local bills, and the usual array of groundwater, planning, and regulatory reform, the 88th Texas Legislature saw almost 200 water-related bills filed. Of those, 29 were enacted. Meaningful regulatory reform was advanced for water utilities and Groundwater Conservation Districts, and considerations of mitigation funding, climate change, and the importance of water data even made headway.

Beyond the success of water infrastructure funding, there was another less obvious triumph for water during the 88th Legislature. It came in the form of tireless coordination and the development of deeper trust amongst Texas' water associations, nonprofits, and advocates. Whereas past sessions may have been marked by each industry segment advocating in their lane, there was an evident recognition that the prioritization of water would require a Texas-sized effort. For that, Texas water champions should be commended.

The success of this coordination may continue to provide Texas with benefits beyond the 88th Legislative Session. As record temperatures and increasing water demands put unprecedented strain on our infrastructure, workforce, reservoirs, rivers, and aquifers, working together will be paramount to advancing water security for Texas.

DEFINITELY A "WATER SESSION" — BUT FOR WHOM? AND WHAT'S AROUND THE RIVERBEND?

By Alex R. Ortiz, Water Resources Specialist, Sierra Club Lone Star Chapter

The Lone Star Chapter of the Sierra Club is the state-level arm of the national grassroots environmental organization. Organized in 1965, the Lone Star Chapter represents over 29,000 Texans committed to the protection and enjoyment of the state's natural resources. The Lone Star Chapter has been actively lobbying the Texas Legislature on water and other issues for over 50 years.

The 88th Regular Texas Legislative Session has come and gone; and it has already been hailed as a "water session" with the passage of Senate Bill 28 and Senate Joint Resolution 75. SB 28 creates the Texas Water Fund and New Water Supply for Texas Fund while SJR 75 authorizes an appropriation of $1 billion to the Texas Water Fund pending a constitutional amendment and reserves $250 million for the New Water Supply Fund. This level of investment in Texas's water future through infrastructure is big, bold, and needed. What remains unclear is the future of these mechanisms. The Texas Water Development Board (TWDB) will likely need to undergo rulemaking in order to interpret terms like "new water supplies" and "new water sources."[1]

Of course, more happened in the legislature than just the creation of these two new bold funds, including the continuation of the two agencies with primary authority over Texas's water resources and infrastructure: the Texas Commission on Environmental Quality (TCEQ) and the Texas Water Development Board (TWDB). Moreover, this is all to speak aside from the abundance of beneficial (and harmful) water legislation that did not make it to the Governor's desk.

Taking a look at SB 28 and SJR 75 with a focus on equity and community needs across the state

There was broad support for SB 28 and SJR 75 across the water community. For transparency: the Lone Star Chapter remained neutral on the bill. The intended result and priorities of SB 28 are quite clear: bolster water infrastructure across Texas, with a particular focus on communities that are either a "rural political subdivision" or "municipalities with a population of less than 150,000".[2] Unfortunately — this methodology perpetuates a clear issue of environmental justice by minimizing the needs of areas in the state that have faced historic disinvestment, predominantly in communities of color. For example, the most recent census data for Brownsville shows a population of 186,738 as of 2020, with Cameron County's whole population of 421,017, which means that the surrounding communities are highly unlikely to be able to take advantage of the prioritization scheme drawn out in the Texas Water Fund. Similarly, we see Corpus Christi's population of 317,863, with Nueces County's total population of 353,178. Corpus Christi as a community will imminently face water supply issues due to increased petrochemical development and yet is unlikely to benefit from specific prioritization outside of (perhaps) the New Water Supply Fund.[3]

An amendment on the House floor by Representative Ana-Maria Ramos would have extended the prioritization scheme to include "economically distressed areas" as priority areas.[4] While it was easily amended onto the House version of SB 28, largely due to it being acceptable to House sponsor Chairman Tracy King, the amendment did not survive the conference committee.

SB 28 begins the path of addressing water loss and water conservation

Two of the intended Texas Water Fund recipients include: the statewide water public awareness program (which previously focused on water conservation exclusively, but has been expanded to encompass water issues comprehensively) as well as projects that mitigate water loss. Water loss mitigation has been shown by our partners at the Texas Living Waters Project to be a genuine concern resulting in the loss of 572,000 acre-feet of water annually.[5] Both water loss and water conservation strategies are integral to meeting the needs of our ever-growing state. Additionally, water loss mitigation and water conservation strategies could potentially be eligible for funding from the New Water Supply for Texas Fund depending on the results of rulemaking at TWDB interpreting terms related to that fund.

[1] Senate Bill 28, enrolled text. Sec. 15.453 USE OF FUND.

[2] Senate Bill 28, enrolled text. "Rural Political Subdivision" is defined in Texas Water Code §15.992(4) as "(A) a nonprofit water supply or sewer service corporation, district, or municipality with a service area of 10,000 or less in population or that otherwise qualifies for financing from a federal agency; or (B) a county in which no urban area exceeds 50,000 in population."

[3] See The Corpus Christi Water Wars, *Rolling Stone*, Reed Dunlea, May 3, 2021 (https://www.rollingstone.com/politics/politics-features/corpus-christi-exxon-sabic-water-supply-problem-1163453/).

[4] Texas House of Representatives Journal, 88th Legislature, 64th Day, p. 4361. Amendment No. 3 by Representative Ramos (http://journals.house.texas.gov/hjrnl/88r/pdf/88RDAY64FINAL.PDF#page=33).

[5] Hidden Reservoirs: Addressing Water Loss in Texas, Texas Living Waters Project (https://texaslivingwaters.org/deeper-dive/water-loss/#:~:text=Texas%20water%20systems%20lose%20at,It's%20a%20lot%20of%20water).

"New" water supplies gain traction as an answer to water supply concerns

SB 28 also creates the New Water Supply for Texas Fund which is dedicated to addressing Texas's water supply needs by financing of projects "that will lead to seven million acre-feet of new water supplies by December 31, 2023." The bill describes projects intended to be funded, including desalination projects, produced water treatment projects (other than projects only for oil and gas exploration), aquifer storage and recovery projects, and infrastructure to transport water from a new source. Crucial environmental and human health concerns remain unaddressed in these sources, especially for the use of produced water and desalination.

1. Produced water continues to be discussed as an opportunity despite lack of meaningful progress on standards and risk assessment.

Produced water has become a more frequent topic of conversation since the 87th regular session and the creation of the Texas Produced Water Consortium (TXPWC). This session, SB 1047 provided some next steps for the TXPWC, including the development of pilot projects which must be selected by October 1, 2023, as well as requiring the consortium to produce another report to the legislature by October 1, 2024, describing the status of pilot projects and suggested policy changes.

The TXPWC provided a preliminary report to the legislature in 2022, which included recommendations to establish a fund for pilot project testing, among others. What continues to go underexamined is the need for risk assessment and the development of novel standards before the widespread use of produced water as a supplemental water source. Texas has no standards for treatment and discharge or reuse as a potable water supply developed specifically with produced water in mind. Because these have never been developed, treating produced water to protect existing surface water quality standards (SWQS) or drinking water standards would wholly miss the point of risk assessment, which is to establish what would sufficiently protect human health and the environment.

2. Desalination as a new water supply faces regulatory uncertainty and TCEQ must address coastal resilience rapidly.

For more than a decade, the legislature and private entities have continued to analyze and pursue the feasibility of marine desalination to supplement our water supplies. With the Gulf of Mexico being the largest body of water available to the state, it would be sensible to imagine this source as being optimal and high priority. However, despite the state's desires, marine desalination projects still face substantial pushback at the local level. The primary concern for communities is the disposal of the highly concentrated saline brine.

Texas bay and estuarine systems are a hub for biodiversity due to their delicately balanced salinity, making them invaluable economic resources as they support major tourist and recreational fishing economies along our coast. However, despite this, there has been little movement on regulatory protections of coastal salinity gradients. In fact, in the entire time that TCEQ has had regulatory authority over Clean Water Act NPDES permitting, there has been no attempt to bolster protections for these sensitive ecosystems through surface water quality standards. Instead, the protections for these areas rely on vague narrative criteria such as "Salinity gradients in estuaries must be maintained to support attainable estuarine-dependent aquatic life uses." [6] Two decades worth of data is more than enough to establish more comprehensive standards, especially in light of increasing pressures on coastal environments due to climate change-induced sea level rise, additional coastal development, decreased freshwater inflows, and more frequent drought and flooding.

Our neighboring state of Louisiana describes salinity standards for waters of varying salinity

content by describing the presence of specific salinity-dependent species. These standards maintain of a narrative rather than numeric criteria but tie salinity content to affected species. Degraded salinity gradients are a present concern in Texas, as evidenced by changes in saline-sensitive aquatic life. This degradation affects wildlife and risks increased coastal land loss attributed to the feedback loop of saltwater intrusion. The vague narrative criteria create significant regulatory uncertainty at TCEQ, making permitting these projects more difficult and risking increased likelihood of contested case hearings and lawsuits.

Finally, the eligibility for desalination projects under the New Water Supply Fund may hinge on how the TWDB defines terms like "new source" and "new water supply." If these terms exclude projects currently within the state water plan or regional water plans, then certain areas of the state would be categorically excluded from funding some projects. If the projects exist in the state or regional water plans, then funds from the State Water Implementation Fund for Texas (SWIFT) would be the more appropriate vehicle for those projects.

Additional major legislative shortfalls on water equity: HB 3522, HB 3523, and SB 1823

As noted in the discussion about SB 28, there was lack of priority for economically distressed areas. These areas are predominantly communities of color that have faced historic disin-

[6] TAC §307.4(g)(3). The provision continues: "Numerical salinity criteria for Texas estuaries have not been established because of the high natural variability of salinity in estuarine systems and because long-term studies by state agencies to assess estuarine salinities are still ongoing." This provision has been in effect for over two decades, since the 1997 SWQS.

vestment and, unfortunately, appear to continue doing so. HB 3522 and HB 3523 (M. Gonzalez) directly dealt with increasing access to the Economically Distressed Areas Program (EDAP) by expanding the amount available to be spent in grants from 70% to 90% of funds (HB 3522) as well as expanding the ability of TWDB to spend $100 million in EDAP funding (up from the present $25 million) in one fiscal year (HB 3523). Both bills passed the House with overwhelmingly bipartisan support but failed to get a hearing in the Senate Committee on Water, Agriculture, and Rural Affairs.

Relatedly, Senator Nathan Johnson filed SB 1823, which would have broadened the scope of EDAP-eligible projects to include drainage. Many EDAP-eligible communities suffer from the impacts of flooding due to inadequate drainage, and this bill would have included these projects as eligible in addition to water and wastewater projects. Unfortunately, the bill was not heard in Senate Water, Agriculture, and Rural Affairs, and without a House companion, went nowhere.

The story told by these three bills and the Ramos amendment to SB 28 is quite clear. Senator Charles Perry brought none of these three bills for hearing despite the good they would do. He moved SB 28 into a conference committee to "remove EDAP," despite the program never directly benefitting from the bill. While expanding our water supply is a priority, and access to water is a large concern in rural parts of the state, marginalized communities will continue to suffer disinvestment — or at the very least, lack of prioritization in such investment.

Both TCEQ and TWDB Sunset Reviews make needed changes at the agencies

The review of both TCEQ and TWDB resulted in the continuation of the agencies with essential reforms. HB 1565 (Canales) codified in statute good guidance from TWDB to the regional water planning groups, permitting the regional groups to plan for a drought worse than the drought of record. With drought expected to become more frequent and prolonged due to climate change, this is an important step in recognizing that state water planning must be climate resilient.

SB 1397 (Schwertner) provided for additional permit notice requirements. Permitting notice and transparency were critical issues identified by the Sunset Advisory Commission; additional community outreach and required electronic posting of permit applications are major steps forward in resolving public distrust of the agency. Moreover, there was a renewed commitment by the legislature to address the needed review of environmental flow standards. Unfortunately, there was a missed opportunity to correct a major environmental misstep from a floor amendment to TCEQ's previous sunset legislation (HB 2694, 82nd Texas Legislature). The floor amendment prohibited any state agency, notably affecting Texas Parks and Wildlife Department (TPWD), from contesting a TCEQ permit. Legislation to correct this issue was filed as a standalone bill in the 87th Texas Legislature (HB 2716 by T. King) as well as during this session (SB 2293 by Zaffirini) to attempt to return this authority. Unfortunately, SB 2293 was not heard in committee, resulting in TPWD and other agencies being barred from contested case hearings.

Pre-Production Plastics Continue to Linger in Texas Waters

HB 4144 (Zwiener) would have empowered TCEQ to analyze pre-production plastic pollution (including nurdles) through its existing authority under the federal Clean Water Act. While the legislation may not have been necessary for TCEQ to do so, the agency claimed to be unsure about its statutory authority during its most recent triennial review of the surface water quality standards, likely caving to industry pressure. Rather than quibble over details, the bill would have simply instructed TCEQ to consider pre-production plastic pollution and its potential harms in monitoring, assessing, and developing surface water quality standards.

There is significant scientific evidence to show that nurdles wreak environmental havoc on habitats and wildlife and have the potential to cause harm up the food chain through bioaccumulation and biomagnification, including to humans. The sole registered opposition to the bill came from the Texas Chemical Council, which also sought to remove the first-ever attempt to prohibit nurdle pollution during the last review of the standards.[7] Unfortunately, the bill did not make it out of the House Committee on Environmental Regulations.

Conclusion

Our retrospective on this session reminds us that there is still a long path downstream. There is little doubt that with the passage of SB 28 and SJR 75, the 88th Texas Legislature will be remembered as a "water session," with meaningful investment in water. However, despite these far-reaching additions to statewide water funding, there is substantial work left to be done by the State to implement these new mechanisms and ensure they are implemented in a way that supports all Texans. It is also abundantly clear that there is a substantial disconnect between our state's emphasis on water quality and our state's focus on water quantity. In order for water to continue to support our great state and all its life, it must be both abundant and clean.

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[7] TCEQ Agenda Item Request with response to comments regarding Rulemaking Adoption of TAC Chapter 307, Texas Surface Water Quality Standards, Rule Project No. 2020-014-307-OW (https://www.tceq.texas.gov/downloads/agency/decisions/agendas/backup/2021/2021-0310-rul-ado.pdf)

TEXAS WATER INFRASTRUCTURE SUMMARY OF WATER-RELATED LEGISLATION IN THE 88TH LEGISLATIVE SESSION

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

Texas Water Infrastructure Network (TXWIN) is a 501 C6 non-profit association founded in 2013 by a group of like-minded Texas construction companies who agreed that there was a need to create a statewide organization specifically focused on construction-related legislative and regulatory issues in the Texas water infrastructure construction market. TXWIN members are building the infrastructure that keeps the Texas economy moving while securing our water future.

The TXWIN membership includes the most respected and capable construction companies in the water sector in Texas. TXWIN members specialize in the construction of water treatment plants, pipelines, flood control, and other projects for municipal and regional water utilities, industrial and commercial clients. TXWIN strives to partner with other key industry groups, engaging in advocacy on funding, procurement regulatory, and other market related issues behalf our membership with the Texas State Legislature, local, state and federal government entities. TXWIN members have put billions of dollars of construction projects in place in Texas and across the nation. On behalf of our membership, we appreciate the opportunity to share the construction industry's viewpoint on key developments in the 88th Regular Session, and the opportunity participate in the *Texas Water Journal's* legislative report for the fifth consecutive time since 2015.

88th regular session background

Leading up to the 88th Regular Session, drought, high-profile water infrastructure failures, pandemic-related project challenges related to supply, and inflation were top issues facing the Texas water and water infrastructure construction industry. Many of the key issues and trends driving the needs for water infrastructure investment were identified in the 2022 Texas Water Capital Needs Survey conducted by TXWIN with the assistance of the water stakeholder community and Water Opinions, LLC.[1]

Similarly, interim Committee Reports from House and Senate Committees of jurisdiction provided insights into what would manifest into legislative proposals, including the need for additional state funding for water infrastructure funding.[2] Other water relate legislative issues were identified and included Sunset legislation to address key policy areas and operational issues identified by Sunset Advisory Commission staff, legislators and stakeholders which could ultimately end up in reauthorization legislation for the Texas Water Development Board and the Texas Commission on Environmental Quality.[3]

The 2023 88th Regular Session of the Texas Legislature also began with speculation about the use of a significant budget surplus estimated by the Comptroller and major policy issues competing for the attention of lawmakers. Infrastructure was among top the priorities identified by the Governor, Lieutenant Governor, and Speaker of the House, which prominently included addressing water issues, securing the electric grid, property taxes, provision, and proliferation of broadband to connect Texas. A new bipartisan Water Caucus was also formed which would eventually be comprised of 70 members of the Texas House.[4]

All these factors combined to set the stage for an unprecedented focus on water and related policies especially as they related to the further development and enhancement of state resources to fund and administer programs related to water policy to ensure the health and safety of the Texas public and the Texas economy. The most significant developments in Texas water this Session was the passage of new programs and funding to enhance the capacity of the Texas Water Development Board (SB 28 & SJR 75) to provide additional significant funding for water, wastewater, and flood control infrastructure.

While TXWIN and others advocated for more significant funding, the progress achieved, the increased coordination of advocacy efforts by water interests, and the momentum generally around Texas water issues cannot be understated. The 88th Session was foundational in many ways, with unprecedented support and focus on water. TXWIN was honored to play a role in the creation of a broad-based coalition comprised of over 60 organizations, including 20 statewide membership-based trade associations and non-governmental organizations representing the water, construction, engineering, agriculture, business, municipal government, the energy sector, and numerous other

[1] Texas Water Capital Needs Survey, https://www.txwin.org/texas-water-needs-survey-2022,

[2] Texas Senate Committee on Water, Agriculture & Rural Affairs Interim Report to the 88th Legislature, https://senate.texas.gov/cmtes/87/c700/c700_InterimReport_2022.pdf.

[3] Texas Water Development Board Sunset Report, https://www.sunset.texas.gov/reviews-and-reports/agencies/texas-water-development-board; Texas Commission on Environmental Quality Sunset Report, https://www.sunset.texas.gov/reviews-and-reports/agencies/texas-commission-environmental-quality.

[4] The Texas Tribune, A new bipartisan group of Texas lawmakers wants to highlight the state's fragile water infrastructure, https://www.texastribune.org/2023/01/13/texas-legislature-water-infrastrucutre-boil-water-notices/.

partners to support funding for water infrastructure, flood control projects. We are particularly grateful for the efforts of our coalition partners, the leadership of Chairmen Charles Perry and Chairman Tracy King, House and Senate Leadership, and the support of all the members of the Texas Legislature and legislative staff for their active engagement on water issues and strong support water funding this Session.

The following legislation represents the most significant developments related to water infrastructure policy in the contracting, procurement, liability, and general government administration areas with the potential to impact Texas water projects, construction and related legal issues.

FUNDING

SB 28: Relating to financial assistance provided and programs administered by the Texas Water Development Board

This legislation creates new Water Supply for Texas Fun, which allows money transfers from any source to create an additional seven million acre-feet of water supplies by 2033. Provides financial assistance to political subdivisions to create new water supplies, including desalination (i.e., seawater or brackish), produced water (not applicable for oil and gas exploration), aquifer storage and recovery projects (ASR), and development of infrastructure to transport water. The legislation also allows transfers of WSTF to SWIFT and other specific TWDB funding programs at the Board's discretion.

It is noteworthy to mention that TXWIN strongly advocated for provisions allowing the use of the new water supply fund for ASR, water transport infrastructure, and water reuse projects. Unfortunately reuse provisions supported by TXWIN were removed in the final version of the bill, in addition to provisions allowing/promoting water acquisition from other states.

Other key provisions in the bill specifically allow the new fund to be used with political subdivisions as part of Public-Private Partnerships under processes defined in Texas Government Code § 2267, with additional provisions prohibiting use of funds for operations and maintenance of facilities developed under this type of arrangement.

The Texas Water Development Board will be required to adopt administrative rules to enact the Water Supply Fund for Texas considering the criteria which including:

- Intended end users of the water supply, needs of the area to be served by the project, and expected benefit of the project to the area.
- Relationship of the project to the water supply needs of this state overall, the relationship of the project to the state water plan, and the amount of water expected to be produced by the project.
- The availability of money or revenue to the political subdivision from all sources for the ultimate repayment and cost of the project, including all interest.

The legislation allows transfers of the fund to State Water Implementation Fund for Texas (SWIFT), State Water Implementation Revenue Fund for Texas (SWIRFT), the Water Supply for Texas Fund, WSTF, a potential new revolving water fund (as yet to be defined), the Rural Water Assistance Fund, Texas Water Development Fund (D-Fund), and the State Participation Fund.

Portions of the fund are to be allocated to rural political subdivisions, municipalities with populations under 150,000, projects with state and federal permitting "substantially complete" to be determined by the Board, and a new statewide water awareness program, water conservation strategies, technical assistance for water utilities and water loss mitigation strategies. The new water fund and associated programs will have oversight from the SWIFT Advisory Commission.

HB 1: General Appropriations Bill & SB 30: Relating to supplemental appropriations and reductions in appropriations and giving direction and adjustment authority regarding appropriations

Water-related budget highlights include:

Texas Water Development Board

- Texas Water Fund: $1,000,000,000 (contingent on passage of the Constitutional amendment authorized by SJR 75).
- Flood Mitigation Funding (FIF): $624,949,080
- Clean Water State Revolving Fund Match: $51,132,249
- Drinking Water State Revolving Fund Match: $73,918,671
- SRF matching funds unlock $2.9 billion in federally assisted program funds allocated to Texas to through existing EPA State Revolving Fund programs and funding provided through the ``Infrastructure Investment and Jobs Act of 2021" (IIJA).
- Funding to enable the Economically Distressed Areas Program (EDAP) to allocate approximately $100,000,000 over the biennium.
- TWDB also received funding for most exceptional items requested in its budget, including essential workforce development and retention efforts.

General Land Office

- Gulf Coast Protection District "Coastal Management": $591.7M
- Disaster Recovery Infrastructure Projects: $906.96 M

SJR 75: Proposing a constitutional amendment creating the Texas water fund to assist in financing water projects in this state

This is the Constitutional amendment to enact programs created under SB 28 and create the constitutionally protected funds therein.

- Twenty-five percent of the allocated funds will go to the New Water Supply for Texas Fund.
- SJR 75 will require approval by voters in the 2023 Constitutional Amendment ballot on November 7, 2023.

CONTRACTING AND PROCUREMENT

HB 679: Relating to limitations on the use of workers' compensation insurance experience modifier values in soliciting and awarding public and private construction contracts

Prohibits using or specifying an Experience Modifier which is numerical system that insurance companies use to set workers' compensation premiums as a numerical condition to measure or score safety records in the award or acceptance of a contract.

HB 1440: Relating to the authority to approve change orders for certain municipal contracts.

Amends local government code population threshold to assign change order authority of $100,000 or less to staff rather than the governing body of political subdivisions from 300,000 to 240,000 persons.

HB 3507: Relating to contracts for the construction, repair, and renovation of certain conservation and reclamation district facilities.

Amends the Water Code to increase flexibility for purchases of $150,000 or less and waives notice requirements to advertise solicitations and award certain contracts under the $150,000 threshold for water districts and water authorities.

HB 3437: Relating to the authority to approve change orders for certain contracts for the construction, repair, and renovation of water district facilities.

Amends the Water Code to allow delegation of change order authority to staff for change orders of $150,000 or less.

HB 3485: Relating to a contractor's or subcontractor's right to elect not to proceed with additional work under a contract.

Amends the public Prompt Pay Act in Texas Government Code § 2215 & Chapter 28 of the Texas Property Code to allow a contractor to elect not to proceed with additional work directed by a governmental entity if the contractor has not received a fully executed change order for the additional work. This applies if the aggregate or anticipated value of the additional work plus any other outstanding additional work requests exceed 10% of the original contract amount, or there is an unsigned change order. The bill also establishes that a contractor or subcontractor who elects not to proceed with additional work as provided by these conditions is not responsible for damages associated with the election not to proceed with work under a change order that is not agreed to by all parties.

HB 1817: Relating to the validity of a contract for which a disclosure of interested parties is required.

HB 1817 addresses a loophole in Texas Ethics Commission (TEC) 1295 conflict of interest reporting requirements, which previously allowed the nullification of contract awards for failure to submit required conflict of interest disclosures. The new law requires a governmental entity to provide notice of failure to submit required conflict-of-interest affidavit, allowing the contractor "a right to cure" the oversight and file the appropriate forms to TEC within ten days.

HB 2334: Relating to an exemption from the plumbing licensing law for plumbing work performed on certain private property.

Provides that a person is not required to be a licensed plumber under the Texas Occupations Code Chapter 1301in order to perform work consisting of installing, servicing, or repairing service mains or service lines that provide water, sewer, or storm drainage services on private property in an area that extends from a public right-of-way or public easement to not less than five feet from a building or structure. This exemption only applies to "public works" construction and does not apply to plumbing work performed on private property designated for use as a one-family or two-family dwelling.

SB 2440: Relating to requiring certain plats for the subdivision of land to include proof of groundwater supply.

This legislation is intended to ensure that new housing developments have sufficient water resources when groundwater is the intended water supply. SB 2440 requires subdivision developers to provide evidence of sufficient available groundwater for residential housing developments and receive permits from governing municipalities. There are some exceptions in the bill for areas in the Gulf Coast and Carrizo Wilcox Aquifers.

GENERAL GOVERNMENT & LIABILITY

HB 5: Relating to agreements to create jobs and to generate state and local tax revenue for this state.

This legislation reauthorizes Texas Tax Code Chapter 313 tax incentive legislation. Chapter 313, goals and incentives include the ability to provide tax credits based on types of businesses, jobs created, money invested in communities which includes projects that create new "high-paying" permanent jobs and construction jobs, encourage energy and water infrastructure development including:

- New and expanded dispatchable electric generation.
- Manufacturing
- Facilities related to construction, expansion, and development of natural resources which is undefined and could include water.

HB 2127**: Relating to state preemption of certain municipal and county regulations.**

Preemption legislation, referred to as the "Death Star" bill, effectively states that local governments cannot pass ordinances or laws not explicitly delegated to them by the state. Gives standing to companies, individuals, and trade associations to bring legal action for violations and allows for recovery of attorney's fees.

SB 29: Relating to prohibited governmental entity implementation or enforcement of a vaccine mandate, mask requirement, or private business or school closure to prevent the spread of COVID-19.

Prohibits mask mandates, business closures, and mandatory vaccinations with the exception of state assisted living facilities, facilities operated by the Texas Department of Criminal Justice or the Texas Juvenile Justice Department, and government owned healthcare facilities.

HB 2007: Relating to a certificate of merit in certain actions against certain licensed or registered professionals.

Provides that a third-party plaintiff that is a design-build firm or a design-build team, or an architect, engineer, or other members of a design-build firm or design-build team, is not required to file a certificate of merit (relating to requiring a claimant to be required to file with a complaint for damages an affidavit of a third-party licensed architect, licensed professional engineer, registered landscape architect, or registered professional land surveyor) in connection with filing a third-party claim or cross-claim against a licensed or registered professional. This applies under the circumstances where the action or arbitration proceeding arises out of a design-build project in which a governmental entity contracts with a single entity or integrated design and construction company, as opposed to a joint-venture or design-build team, to provide both design and construction services. This applies to the construction, expansion, extension, rehabilitation, alteration, or repair of a facility, a building or associated structure, a civil works project (which could include water facilities), or a highway project.

HB 2965**: Relating to certain construction liability claims concerning public buildings and public works.**

This legislation concerns construction defect notices and the "right to cure "said defects without engaging in litigation. In its original form, the legislation removed exemptions to civil works projects defined in Gov. Code 2269 which would have created a fundamental standard of fairness for public works construction projects. The legislation also stated that this notice cannot be waived. TXWIN supported the legislation in its original form. While this legislation was moving through the House, certain entities sought exemptions which would have established unreasonable legal distinction between various types of infrastructure, specifically for certain water authorities. The bill was ultimately narrowed to only include the "no waiver" provision. This legislation should be reintroduced to include water infrastructure in the future to ensure fair risk allocation and efficient project administration.

SB 2038**: Relating to the release of an area of a municipality's extraterritorial jurisdiction by petition or election.**

Allows for the release of property from the extraterritorial jurisdiction (ETJ) of a municipality under certain circumstances. This legislation could have implications for the ability to execute construction projects and the utilization of eminent domain, right of way and other legal authorities used in conjunction with the development of infrastructure.

Overall, the 88th Regular Session of the Texas State Legislature should be regarded by even the most casual observer as a significant and meaningful benchmark for the future, especially in terms of the intense focus and prioritization of water issues by lawmakers, and an unprecedented collaboration on water issues by key stakeholders. From the standpoint of TXWIN and many of our other partners in Texas water, what was accomplished this session was foundational especially in terms of a greater interest and engagement in water policy and funding. Fortunately, this phenomenon coincides with a very real and timely need for Texas and Texans to focus and commit more significant effort and resources to secure our shared water future. Public engagement and continued focus on water issues is essential to accomplish this task.

Prior to the 88th Regular session the fundamentals of Texas water were strong. As a state we have far surpassed our national peers in terms of planning and funding, but to ensure adequate investment in our water future, we need to acknowledge the real and growing cost of water infrastructure. Texas must implement intelligent water strategies aligned in sound science to accompany and drive the construction of pipes, water treatment plants, flood control projects, and the development of new and additional water supplies. Fair contracting law, efficient use of limited funds and construction policy is an important part of the future of Texas water.

In the near-term we can all support Proposition 6 (SJR 75) on the Constitutional Amendment ballot in November 2023. Passing Prop 6 which will unleash the promise of SB 28 which will be a strong addition to our "toolkit" allowing more affordable options to invest in our current and future Texas water needs. There is still much work to be done and TXWIN members look forward to the opportunity to build the future of Texas Water!

THE MOST CONSEQUENTIAL LEGISLATIVE SESSION FOR WATER IN A DECADE HAD A CRUCIAL BLIND SPOT: GROUNDWATER PLANNING AND MANAGEMENT

By Vanessa Puig-Williams, Director, Climate Resilient Water Systems, Texas, Environmental Defense Fund

Environmental Defense Fund (EDF) is a United States-based nonprofit environmental advocacy group. The group is known for its work on issues including global warming, ecosystem restoration, oceans, and human health, and advocates using sound science, economics and law to find environmental solutions that work.

While the 88th legislative Session was, on all accounts, a water session, Texas has more to do to ensure that we have safe and ample water for people, wildlife, and the environment in the future. Persistent drought, flooding, pollution, and infrastructure failures are water challenges that state leaders must continue to address. Indeed, the Legislature made significant investments in water during the most recent regular session, allocating roughly one billion to support flood infrastructure development and establishing a new billion-dollar water fund, which, if approved by voters this November, will finance the development of new water supply projects and badly needed water infrastructure improvements across the state. Importantly, the new water fund prioritizes water infrastructure improvements in rural Texas, where water infrastructure is often in disrepair and resources to fix problems are limited. However, these investments, while substantial and important, overlook a critical component of water security – the sustainability of Texas' water resources, particularly groundwater resources – and the data and modeling water managers and planners need to proactively manage them.

Water in underground aquifers is one of Texas' most vital natural resources. It provides over half of the water used in the state, from agriculture to industry to cities. Outflows from aquifers sustain flows in springs, streams and rivers that support additional water uses, fish and wildlife, and recreation. Aquifers are, indeed, a critical component of Texas' water infrastructure, just as much as reservoirs, drinking water systems and treatment plants. Yet, Texas is underinvesting in the management of aquifers.

Despite a $30 billion historic budget surplus, the Legislature did not approve the Texas Water Development Board's (TWDB) request for approximately $8 million to support water data enhancements. The Legislature allocated half of what TWDB requested to support statewide groundwater modeling (reducing TWDB's request from $1,044,075 to a mere $522,038) and half of what TWDB requested to support the Water Data Hub, an online platform that will house a variety of water data accessible to the public (reducing TWDB's request from $2,651,936 to $1,325,968). Additionally, the Legislature failed to provide additional funding for the Texas Mesonet Program, a network of weather stations that collect weather data to help officials understand and respond to changing weather conditions across the state. To summarize, compared to the billions the Legislature allocated for developing new water supplies, water infrastructure improvements, and flood preparedness, the Legislature appropriated just under $2 million to support water science this session.[1]

This lack of investment in groundwater science is particularly concerning. The Texas Water Development Board's entire 2022 budget for Technical Assistance and Modeling Programs (which includes both surface water and groundwater) was only about $ 2.6 million in 2022 (reduced from about $ 4.5 million/year in the 2010/2011 budget), out of a total budget of about $260 million.[2] This compares with about $ 10 million per year for "water planning," and with billions spent every year to build and repair water infrastructure throughout the state.[3]

Moreover, the legislature has provided little in the way of financial or technical assistance to groundwater conservation districts, which are the preferred method of managing Texas groundwater. The lack of an investment in groundwater is an oversight that state leaders must address next session.

In addition, this session the Legislature ignored opportunities to update and enhance groundwater and surface water modeling, to increase groundwater and surface water data, and to provide groundwater managers with data related to the sustainability of aquifers. HB 3990 (Kacal) required TWDB to identify areas of the state with significant groundwater and surface water interaction and that lack adequate data and modeling and to prioritize these areas for study. The bill would have paved the way for more sophisticated, integrated watershed management in Texas, resulting in better protections for both groundwater and surface water resources in the future. Similarly, House Bill 4532 (Kacal/Blanco/Zaffirini) would have required TWDB to model the maximum sustained pumping volumes of aquifers in Texas and to provide this data to groundwater conservation districts to utilize when they adopt desired future conditions. The bill would have enabled groundwater conservation districts to make more informed planning and management decisions, particularly related to the long-term sustainability of aquifers and the conservation of groundwater.

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[1] This is based on exceptional item appropriations to the Texas Water Development Board in H.B. 1, General Appropriations Bill, 88th Legislature, Regular Session (Texas 2023).

[2] See S.B 1, 87th Legislature, Regular Session (Texas 2021).

[3] See, e.g., https://comptroller.texas.gov/economy/fiscal-notes/2019/apr/funding-water.php.

Both bills passed the House but did not receive a hearing in the Senate.

Aquifers are infrastructure. State leaders should view investments in groundwater science and sound, science-based groundwater management as critical to the state planning and water infrastructure financing picture.[4] Planning and financing of water projects may depend on assumptions about aquifer capacity, aquifer drawdown, and groundwater contributions to stream flow. Ensuring these assumptions are correct is a due diligence aspect of infrastructure planning and financing that requires continuous development of groundwater science.

The Legislature passed a few positive groundwater bills this session that should result in small, but necessary improvements to groundwater management, hopefully, precipitating support for more substantial policy advancements and investments in science next session. House Bill 3278 (Price/Blanco) creates more transparency in groundwater planning – the process by which groundwater conservation districts adopt long term management goals or desired future conditions (DFCs) for the aquifers they regulate. Under the new law, groundwater conservation districts must post documentation supporting a proposed DFC online. This change will enable greater public participation and enhance information access in what is an often obscure process that has real consequences for communities across Texas.

House Bill 3059 (King/Perry) provides groundwater conservation districts with additional tools and funding to address impacts to wells caused by large groundwater export projects – a growing challenge in rapidly developing parts of the state. The bill increases the fee rate that a groundwater conservation district can charge for the export of groundwater and, importantly, authorizes groundwater conservation districts to use export fees to mitigate impacts to wells, conduct groundwater monitoring and aquifer science, collect data, and develop alternative water supplies.

Senate Bill 2440 (Perry/Burrow) recognizes that there is insufficient groundwater in some areas of Texas to support new development. Cities and counties must now require developers to provide a certificate of groundwater availability before approving subdivisions where the water supply is groundwater. Previously, this was voluntary. The change is a prudent step that necessitates continued development of groundwater science and greater coordination between cities, counties, and groundwater conservation districts. While the legislation allows local governments to waive the requirement for small developments or developments over the Carrizo-Wilcox or Gulf Coast Aquifers, (where arguably there is more groundwater available) they must first determine sufficient groundwater available based on credible evidence of groundwater availability. As with the groundwater availability certification, waivers will require groundwater science to demonstrate availability.

Although it is not a groundwater bill, Senate Bill 1289 (Perry/King) could conserve rural groundwater resources by enabling buildings in urban areas to treat and reuse wastewater onsite. This will reduce the need for cities to import groundwater as their water supply demands increase. The bill amends Chapter 26 of the Water Code to remove a regulatory impediment that has made building scale wastewater reuse difficult in Texas and directs the Texas Commission on Environmental Quality (TCEQ) to amend its rules to implement the new changes to statute. Currently, to treat and reuse wastewater, the TCEQ requires an entity, referred to as a reclaimed water production facility, to obtain a Texas Pollutant Discharge Elimination System (TPDES) discharge permit as an alternate means of disposal in event the entity cannot reuse all the wastewater generated. Additionally, TCEQ rules require the entity to own the wastewater treatment facility associated with the discharge permit. These onerous requirements have made building scale reuse cost prohibitive for many entities in Texas desiring to construct innovate, water conservation-oriented buildings in urban areas. To address this issue, Senate Bill 1289 bill amends Chapter 26 of the Water Code to allow a reclaimed water production facility to treat and reuse wastewater onsite without the need to obtain a discharge permit from the TCEQ. To address instances where treated wastewater cannot be reused, the law requires the entity to have permission to dispose of treated wastewater into an existing wastewater collection system.

Finally, the formation of a bipartisan Water Caucus in the House of Representatives, comprised of nearly half of the members of the House, is another significant outcome of the 88th Legislative Session worth noting. Unlike other caucuses, which are often formed along party lines to support specific issues and legislation, the Water Caucus, chaired by Representative Tracy King, is bipartisan and purely educational, serving as a forum to educate members of the Legislature and to foster the leadership needed to solve Texas' pressing water challenges.

Texas wrapped up its most consequential legislative session for water policy in at least a decade, but the Legislature missed opportunities to further support groundwater planning and management. With Texas facing rapid population growth and persistent drought, it is imperative that the state take further action to ensure that groundwater conservation districts have the tools and resources they need to proactively manage groundwater. This session, state leaders prioritized funding for developing new water supply projects and infrastructure improvements. Next session, state leaders must focus on groundwater.

[4] In 2016, the California legislature enacted AB 2480, which recognizes the state's watersheds as "an integral component" of its water infrastructure. This statutory language opens the door to using traditional infrastructure financing approaches, such as bonds and other tools, for restoration and protection of watersheds and allows them to be valued as key assets in California's infrastructure inventory.

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THE NEEDLE MOVED FORWARD

By Jeremy B. Mazur, Senior Policy Advisor, Texas 2036

Texas 2036 is a nonprofit organization building long-term, data-driven strategies to secure Texas' continued prosperity for years to come. We engage Texans and their leaders in an honest conversation about our future, focusing on the big challenges. We offer non-partisan ideas and modern solutions grounded in research and data to break through the gridlock on issues that matter most to all Texans. Smart strategies and systematic changes are critical to prepare Texas for the future.

For the first time in ten years, water infrastructure was a priority for the Texas Legislature. The last big water infrastructure session of the Legislature occurred in 2013. Then, on the heels of the worst one-year drought of record in 2011, both the Legislature and Texas voters approved the creation of the $2 billion State Water Implementation Fund for Texas (SWIFT) for financing water supply projects. The SWIFT's creation was a significant deal at the time. After decades of talking about it, the state's water policy now included a financial strategy for delivering the water supply projects listed in the State Water Plan.

In the intervening decade, droughts ebbed and flowed, floods of near-biblical proportions came and went, and water and wastewater systems aged as building and maintenance costs escalated. Texas' water infrastructure problems still needed to be solved.

As fate or fortune would have it, a series of circumstances set up the 88th Session of the Texas Legislature to become the most comprehensive session focused on water infrastructure in a decade. These circumstances provided policymakers with a substantial window to move Texas' water policy needle forward - for the better.

For starters, the Sunset Commission reviewed the state's three key water agencies: the Texas Water Development Board, the Texas Commission on Environmental Quality, and the Public Utility Commission of Texas. Each review culminated in a Sunset bill for the applicable agency, legislation that carried tremendous implications for state water planning, regulation, and financial management.

Next, 2022 included several high-profile stories about water system failures. While the nation's most severe water system catastrophe unfolded in Jackson, Mississippi, several Texas towns, including Odessa, Laredo, and Zavalla, endured outages or extended boil water notices due to the poor condition of their water systems. In addition, millions of Texans living in Austin and Houston had to live with boil water notices due to system management issues.

Then there was drought. According to the *US Drought Monitor*, 2022 began with just over 50% of the state in the severe-to-worse drought category. By mid-August, drought conditions reached a fever pitch, with 87.5% of Texas in severe drought and nearly 30% of the state in the exceptional drought category. These dry conditions precipitated a series of calamities, including widespread wildfires, substantial crop and livestock losses, and diminishing water supplies. The water supply situation within the Lower Rio Grande Valley became so dire that planners anticipated having just days of water left. Fortunately, a well-placed low-pressure weather system in mid-August provided needed relief.

Lastly, there was money. In late 2021 Congress passed the U.S. Infrastructure Investment and Jobs Act, also known as IIJA. Aimed towards course-correcting decades of declining federal spending on water and wastewater infrastructure, IIJA appropriates $50 billion towards states' clean and drinking water revolving funds over a five-year window. Provided the Legislature appropriated required matching funds, IIJA would endow Texas' state revolving funds administered by the Texas Water Development Board (TWDB) with nearly $2.5 billion during that five-year window.

Beyond federal largesse, state coffers, unlike most west Texas reservoirs, were full and overflowing. High oil and gas prices, combined with robust economic activity, contributed to a historic, unprecedented budget surplus of $32.7 billion. This surplus spelled opportunity for Texas' long-term water infrastructure challenges, which include the need for more water supplies for a drought-prone state and the growing problem of aging, deteriorating water and wastewater systems.

Interestingly, voters were enthusiastic about the idea of greater state spending on water infrastructure. In September 2022, Texas 2036's Texas Voter Poll revealed that 82% of voters supported spending a portion of the surplus on developing new water supplies, while 84% favored using these funds to address the aging, deteriorating water infrastructure problem. Five months later, in February 2023, 89% of Texas voters supported using $5 billion, or about 15% of surplus funds, to help Texas communities fix aging water infrastructure. Of that cohort, 63% of Texas voters across all demographics, geography, and party affiliations strongly supported this proposal.

Texas 2036's poll also asked voters about other potential spending priorities, including parks, flood prevention, broadband, workforce development, and cybersecurity. All of these proposals received a majority of support. None of these spending proposals received a level of support as strong as that for water infrastructure, however. While voters did not specify why they supported water infrastructure funding, it is fair to postulate that stories about draining reservoirs and aquifers, incessant boil water notices, failing water systems, and the ever-present specter of drought informed voters' preferences. Regardless, in pure political parlance, water is a winner.

When the 88th Session began on January 12, the key ingredients were in place for a dynamic, historic water infrastructure session: water agency Sunset bills, high-profile water system failures, drought, and a landmark budget surplus. Moreover, Texas voters were interested in seeing the state take action toward addressing water infrastructure challenges. Back in January, water policy professionals and some legislators were optimistic that the 88th Legislature would dedicate renewed attention and resources to Texas' water challenges. One hundred and forty days later, the proverbial needle moved forward.

Texas 2036's water agenda

In 2022, Texas 2036 collaborated with the Water Finance Exchange and the Texas Water Foundation to host a series of stakeholder meetings to discuss the challenges facing Texas' water and wastewater infrastructure and the opportunities presented by the US Infrastructure Investment and Jobs Act. Over 40 organizations, including state agencies, water industry groups, nonprofits, and local water utilities, participated in these discussions. The salient issues highlighted throughout these discussions included the need for greater technical assistance capacity for facilitating small, rural, and disadvantaged communities' participation in state financial assistance programs, how regional solutions achieve economies of scale within the water sector, and the importance of a state financial strategy for both leveraging IIJA dollars and addressing the growing problem of aging, deteriorating water and wastewater infrastructure.

These stakeholder discussions informed Texas 2036's development of the Water Infrastructure Blueprint for the 88th Legislature. Released in January 2023, the Blueprint included five key findings. First, and based on available data, the state must address the aging, deteriorating water infrastructure problem. Second, the Legislature needed to maximize the state's leverage of IIJA dollars to better manage the water infrastructure problems endured by small, rural, and disadvantaged communities. Third, Texas must expand its technical assistance provider capacity to deliver financial assistance to small, rural, and disadvantaged communities more effectively. Fourth, state policy must encourage regional solutions to achieve better economies of scale regarding water, rate base, and workforce utilization. And lastly, Texas' water industry faces a shortage of qualified workers.

In light of these major findings, the Blueprint offered a series of recommendations developed by Texas 2036 of what the Legislature could do to address Texas' growing water infrastructure crisis. One of the Blueprint's salient recommendations was to create a new, constitutionally-dedicated fund that assists water and wastewater utilities that are either failing or at risk of failing. In addition to creating a new water fund, the Blueprint recommended that the Legislature appropriate the matching dollars necessary for maximizing the state's receipt of federal IIJA funds. Other recommendations included legislative actions to improve regional solutions among water utilities, expand the state's technical assistance capacity, and address the water workforce shortage. These recommendations guided Texas 2036's support for several measures during the 88th Regular Session, including SB 28, SJR 75, HB 3232, and HB 1845. The solutions enacted by these measures are described in greater detail in subsequent sections of this article.

In addition to the recommendations within the Water Infrastructure Blueprint, Texas 2036's legislative agenda for the 88th Session concentrated on five specific goals. These goals included: (1) funding solutions to address Texas' growing water needs; (2) supporting the Texas Water Development Board's Sunset bill; (3) developing accurate water planning data; (4) addressing the state's growing water workforce shortage; and (5) and establishing frameworks for the development of regional water markets that encourage the voluntary transfers of water.

The water infrastructure omnibus package

The headline water measures of the 88th Session were SB 28 (Perry/Tracy King) and SJR 75 (Perry/Tracy King). The initial bill, SB 28, creates two new funds, the New Water Supply for Texas Fund and the Texas Water Fund, to address Texas' water infrastructure challenges. Both funds are administered by the Texas Water Development Board. The first fund, the New Water Supply for Texas Fund, shall provide financial assistance to political subdivisions for water supply projects that create new water supplies. The operative focus here is on new water supplies, projects that expand the inventory of water molecules comprising the state's water supply portfolio. Eligible projects include seawater and brackish water desalination, produced water recycling, aquifer storage and recovery, and the development of transportation infrastructure to convey water from the aforementioned projects to where it is needed. SB 28 tasks TWDB with the ambitious goal of developing at least 7 million acre-feet of new water supplies over the next decade through the New Water Supply for Texas Fund.

In addition to the New Water Supply for Texas Fund, SB 28 creates the Texas Water Fund. This fund shall be used for water infrastructure projects for rural communities and small and mid-sized cities, prioritized according to risk or need. The Texas Water Fund may also provide financial assistance for water conservation strategies, water loss mitigation projects, and statewide public awareness programs regarding water.

Beyond expanding the state's financial strategy for addressing long-term water infrastructure challenges, SB 28 broadens technical assistance outreach to small and rural communities and those with significant water loss issues. The bill authorizes TWDB to use the Rural Water Assistance Fund for outreach, financial, planning, and technical assistance to assist rural political subdivisions in obtaining and using financing from the different financial assistance programs administered by the agency. Further, SB 28 requires that TWDB establish a program to provide technical assistance to retail public utilities in conducting water loss audits and applying for financial assistance from TWDB to mitigate water loss. TWDB shall prioritize the provision of technical assistance based on water loss audits, the population served by the utility, and the integrity of utility's system.

Senate Bill 28 was part of a larger water infrastructure package approved by the 88th Legislature that addressed Texas' water infrastructure challenges. Other measures in this package include SJR 75 (Perry/Tracy King) and SB 30 (Huffman/Bonnen). SJR 75 proposes to amend the Texas Constitution to create the Texas Water Fund administered by TWDB for providing financial assistance for water infrastructure projects. The proposed amendment authorizes TWDB to distribute money from the Fund to other funds or accounts administered by the agency without further legislative appropriation. These eligible funds and accounts, which SB 28 specifies, include the Water Assistance Fund, New Water Supply for Texas Fund, State Water Implementation Fund for Texas, State Water Implementation Revenue Fund for Texas, the state's clean and drinking water revolving funds, Rural Water Assistance Fund, Statewide Water Public Awareness Account, Texas Water Development Fund II, and the state participation account within the Texas Water Development Fund II.

Texas voters will decide on this new fund's creation during November's constitutional amendment election. If voters approve the constitutional amendment creating the Fund, then the contingency funding provision within SB 30 appropriates $1 billion to the Fund. Conversely, if voters reject the November's ballot proposition creating the Texas Water Fund, that $1 billion would remain in the state treasury. One of the provisions in SJR 75 states that a minimum of 25% of the initial appropriation to the Texas Water Fund shall be transferred to the New Water Supply for Texas Fund.

TWDB Sunset

While the water infrastructure package of SB 28, SJR 75, and SB 30 granted the 88th Regular Session with the imprimatur of a "water session," other essential bills, including the Texas Water Development Board's (TWDB) Sunset bill, contributed to this narrative. TWDB's Sunset review occurred during the legislative interim preceding the 88th Session. The Sunset Commission found TWDB a well-run agency and recommended that the Board be reviewed again in 12 years in 2035. This recommendation, and others made by Sunset staff, was incorporated in HB 1565 (Canales/Perry).

HB 1565 included a noteworthy provision relating to the regional water planning process for developing the State Water Plan. This new provision allows regional water planning groups (RWPGs) to use droughts worse than the Drought of Record of the 1950s as the basis for future water supply planning. While TWDB's existing rules allow RWPGs to use worse drought conditions, HB 1565 embeds an important recognition within the Texas Water Code that future droughts may be worse than the current planning baseline. This change was recommended by Texas 2036 during TWDB's Sunset review in 2022.

The Drought of Record of the 1950s was a severe, prolonged drought that had a lasting effect on the state's economy and subsequent development. Data from paleoclimatic records indicate that the 1950s drought was not the worst Texas ever endured, however. Moreover, data from a report on extreme weather trends prepared by Texas 2036 in collaboration with the Office of the State Climatologist at Texas A&M University reveals that future droughts may become more severe. Given these findings, Texas 2036 recommended that regional water planners be allowed to adjust the drought scenarios they use for planning purposes to account for the possibility of worsening conditions. Thanks to Representative Terry Canales' leadership, the recommendation that RWPGs be allowed to use drought conditions worse than the Drought of Record was included in HB 1565.

This represents a significant change in state water policy within the Texas Water Code. In addition to recognizing that future droughts may be more severe, the change made by HB 1565 provides legislative direction for the potential scaling of future water supply projects and strategies responsive to more extreme droughts. This critical change expands the state's resilience strategy for addressing future drought challenges.

Regulatory Reforms

The Legislature approved several important regulatory reforms for the water sector during the 88th Regular Session. These reforms affect differing aspects of state water policy, including regional solutions for water and wastewater systems, groundwater management, certificates of convenience and necessity (CCNs) for water and wastewater service, and water reuse. Texas 2036 supported several bills based on specific recommendations within the Water Infrastructure Blueprint or alignment with the goal of providing water for a growing state.

Regional Solutions

Despite the Legislature's articulated policy preference for regionalization found throughout the Texas Water Code, Texas still has over 10,000 public water systems and wastewater operators according to Texas Commission on Environmental Quality (TCEQ) data. Interestingly, before 2023, state regulatory policy partially worked to discourage regional solutions among water and wastewater systems, undermining the Legislature's preference for regionalization. Previously, if a water or wastewater utility other than a city or a county absorbed another system noncompliant with health, safety, or environmental protection requirements, those regulatory liabilities would transfer to the absorbing utility. This served as a regulatory disincentive for larger or well-run utilities to absorb distressed utilities with noncompliance challenges.

The Legislature approved HB 3232 (Rogers/Perry) to fix this problem. HB 3232 removes this regulatory disincentive by providing "safe harbor" protection to healthy water and wastewater utilities that absorb distressed systems as part of a regional solution. The bill authorizes TCEQ to enter into a compliance agreement with an absorbing utility where the Commission will not initiate an enforcement action against that utility for existing or anticipated violations accrued by the utility being absorbed, provided that there is a compliance agreement in place to address the problems contributing to noncompliance.

House Bill 3232 removes the existing regulatory disincentive for the regionalization of water and wastewater service, opening the door for the delivery of more efficient water and wastewater service through the development of regional solutions. Texas 2036 recommended this regulatory reform as part of its Water Infrastructure Blueprint for the 88th Regular Session.

Groundwater

The Environmental Defense Fund's Vanessa Puig-Williams has famously said, "aquifers are infrastructure." Like reservoirs and elevated storage tanks, aquifers are integral to the water supply to communities that rely on groundwater. More critically, this statement also meaningfully implies that aquifers, like other infrastructure resources, have limits concerning the demands they can sustain over time. In light of this, SB 2440 (Perry/Burrows) enacts a substantive change that carries significant implications for future groundwater development policy.

This bill requires that a developer submitting a plat for approval by a municipal or county authority for a new subdivision that will be supplied with groundwater include a statement prepared by a professional engineer or geoscientist that certifies that adequate groundwater is available for the subdivision. Previously, cities and counties were authorized to request these groundwater availability certifications; they were not required as a part of the development process. SB 2440 gives cities and counties the flexibility to waive the requirement for the certification of groundwater availability if they determine based on credible evidence that sufficient groundwater supplies exist for the subdivision and either the subject tract is supplied by the Gulf Coast or Carrizo-Wilcox aquifers or the proposed subdivisions divides the tract into no more than ten parts. The bill's requirements take effect on January 1, 2024.

Despite the limited exceptions, SB 2440 links the feasibility of future development dependent on groundwater to the availability of groundwater resources. In addition, the bill aligns the potential for future development growth with data on groundwater availability. This change recognizes that aquifers, especially for some areas of the state, are not limitless infrastructure resources: absent groundwater availability within a given aquifer, economic development – and perhaps human habitation – cannot be sustained.

CCNs for Water and Wastewater Service

During the last big water infrastructure legislative session in 2013, the Legislature transferred regulatory authority over water and wastewater utility rates and CCNs from TCEQ to the Public Utility Commission (PUC). This transfer substantively changed the administrative handling of utility rate amendments and CCNs: what was once a simple process at TCEQ required an administrative hearing for resolution before PUC. The Sunset Commission acknowledged this issue during its review of PUC before the 88th Regular Session. Given this finding, the Sunset Commission adopted a management action recommendation directing PUC to comprehensively review its water and wastewater rules, processes, and guidance documents to identify and address areas for improvement.

Separate from Sunset's recommendation, the Legislature also approved SB 893 (Zaffirini/Tracy King) authorizing PUC's executive director to correct a water or wastewater utility's CCN without going through the formal amendment procedure. SB 893 grants PUC's executive director the latitude to correct a typographical error, change the name of a CCN holder, rectify mapping errors, and resolve other non-substantive errors. These changes streamline the regulatory process for providing water and wastewater service to Texas communities, saving water and wastewater utilities time and money by allowing them to forgo the need for an administrative hearing to make these changes to their CCN.

Water Reuse

Another significant regulatory reform approved during the 88th Regular Session concerns water reuse. SB 1289 (Perry/Tracy King) allows developments with on-site wastewater treatment facilities to treat, recycle, and reuse wastewater for on-site disposal purposes without getting a separate permit from TCEQ for those disposal purposes. This change streamlines a regulatory hurdle for water reuse, encouraging innovative and efficient use of limited water resources. SB 1289 took effect on June 18, 2023.

Water Workforce

The success of any utility in meeting the needs of its customers, and of any state investment in local water and wastewater infrastructure, hinges on the availability of qualified personnel to operate those systems. Conversely, the absence of qualified personnel invites the perils of regulatory noncompliance, system mismanagement, and utility failure. Texas' water and wastewater utility operators are acutely aware of this problem. The 2022 Water Capital Needs Survey conducted by the Texas Water Infrastructure Network and Water Opinions LLC revealed that 82% of water utilities surveyed are worried about their current or future workforce. These findings were consistent with the previous year's survey results registering similar levels of concern.

In an effort to begin addressing this looming problem, the Legislature passed HB 1845 (Metcalf/Perry) requiring that TCEQ establish a provisional certification program for individuals without high school diplomas to serve as entry-level water or wastewater system operators. This provisional certification program would establish a pathway for Texans without a high school diploma – or those still in high school – to enter the state's water workforce. The pathway established by HB 1845 is a work-based learning opportunity where the individual is exposed to workplace culture and learns skills directly from practitioners. Moreover, the pathway aligns with the state's official workforce development strategy of expanding opportunities for work-based learning experiences. HB 1845 takes effect on September 1, 2023.

Better Data

Texas 2036's legislative agenda for the 88th Session included developing accurate water planning data. These data are essential for determining current and future water availability and assessing existing infrastructure's condition. Towards these ends, the Legislature approved three bills that enhance data collection on water availability and the condition of our state's drinking water infrastructure.

The first, HB 2759 (Ed Thompson/Perry), creates the TexMesonet Hydrometeorology Network within TWDB as a statewide resource for hydrometeorological data for weather forecasting, flood preparedness, drought monitoring, wildfire management, water resource planning, water conservation, agricultural readiness, industrial readiness, and related business readiness and productivity. The bill requires that the Network establish a series of stations across Texas to monitor hydrometeorological conditions, serve as a centralized repository for hydrometeorological data, and provide technical assistance for collecting these data.

HB 2759 codifies the TexMesonet Network already administered by TWDB and enacts a recommendation made by the Board for the 88th Session. Establishing TexMesonet within the Texas Water Code ensures the continued operation of this data collection network and repository, allowing for the maintenance of both contemporary and longitudinal water-related data sets.

Another water data bill approved by the Legislature was HB 2460 (Tracy King/Perry), which requires that TCEQ develop updated water availability models for the Guadalupe, Lavaca, Nueces, San Antonio, San Jacinto, and Trinity river basins. These data will provide state and regional water planners and TCEQ's surface water permitting program with a clearer understanding of the water volumes available in each basin.

Beyond meteorological and hydrological data collection, the Legislature also approved HB 3810 (Landgraf/Perry), improving the collection of data on the condition of drinking water systems. To be sure, HB 3810 does not explicitly contemplate the collection of systems' data. Instead, HB 3810 requires that a nonindustrial public water supply system maintain internal procedures to notify TCEQ of a condition that caused or could cause a public water supply outage or prompt the issuance of a boil water notice, do-not-use advisory, or a do-not-consume advisory. This change standardizes how drinking water utilities report water outages, boil water notices, or other advisories to TCEQ. Implementing this requirement will improve state data quality and give state regulators and the public a clearer picture of those utilities having problems delivering safe, clean drinking water.

Water Markets

Texas 2036's goals for the 88th Session included the development of regional water markets to facilitate the voluntary transfers of water. Data from two forthcoming case studies of functioning water markets in Texas – one for surface water in the Rio Grande Valley, the other for groundwater within the Edwards Aquifer – reveals that markets facilitate the efficient and effective allocation of water resources in a drought-prone state. In particular, the surface water market in the Rio Grande has allowed water to move from lower-valued crops to higher-valued crops that require less water, particularly during droughts. The Rio Grande market has also facilitated the supply of water towards growing municipal demands within the region. The Edwards Aquifer water market contributed to a decline in overall aquifer water use and a substantial reduction in per capita use, enabling the transfer of water rights from lower-value uses to those with a higher-value. It has also allowed for the creation of new tools to manage water during droughts. These findings, among others, will be described in greater detail in a report released by Texas 2036 later this year.

Given these preliminary research findings, Texas 2036 supported HB 4623 (Goldman), which proposed expanding the scope of the regional water planning process used to develop the state water plan to include the consideration of water markets. In particular, the bill allowed RWPGs to identify opportunities creating and establishing local or regional water markets. This change would enable regional water planning groups to consider how water markets could contribute to more effective water use, including less water use or the reallocation of water resources to other demands. Moreover, HB 4623 would have provided clear and concise legislative authorization for regional water planners to consider opportunities for water markets as a water management strategy. HB 4623 was unanimously approved by the House of Representatives but failed to move in the Senate in the closing weeks of the 88th Regular Session.

Postscript: Competing Priorities & the Road Ahead

For better or worse, water was one of many funding priorities for the 88th Legislature. Other compelling policy priorities that garnered appropriators' attention included property tax relief, broadband infrastructure, state park acquisition, electric generation reliability, and public-school safety. Throughout the legislative session, water advocates, including Texas 2036, recommended appropriating $3-5 billion as a meaningful down payment toward addressing the state's long-term water infrastructure challenges. Allied organizations put forth a yeoman's effort towards this funding goal.

Ultimately, the Legislature approved $1 billion for the new Texas Water Fund provided voters approve the Fund's creation in this November's constitutional amendment election. While this represents an essential initial down payment, Texas' long-term water needs require sustained investment. The 2022 State Water Plan forecasts that Texas will need to spend $80 billion over the next 50 years to develop and implement water supply projects and strategies to avoid water shortages during drought. Of that $80 billion, $47 billion in financial assistance will need to be provided by the State of Texas. (This amount may exceed the financial capacity of the State Water Implementation Fund for Texas established in 2013 to assist with the capital costs of water projects identified in the 2012 State Water Plan.) Looking beyond water supplies, the price tag for fixing aging drinking water and wastewater infrastructure exceeds $70 billion over the next 20 years according to federal cost estimates.

Should Texas voters ratify the fund in November, the $1 billion appropriation for the Texas Water Fund will help address these long-term water infrastructure challenges. As will the matching funds the Legislature appropriated for the state to maximize its receipt of available IIJA dollars. Still, the magnitude of Texas' water infrastructure challenges necessitate a sustained, consistent financial strategy. Towards that end, HJR 169 (Clardy) offered a bold – and needed – vision: a constitutionally-dedicated revenue stream for water infrastructure. This change would align the state's financial strategy for water infrastructure with those currently deployed for highways and parks. HJR 169 passed the House unanimously. While it did not receive Senate approval, its progress opens the door for a more extensive policy conversation leading into the 2025 legislative session.

Still, the water policy needle moved meaningfully forward in 2023. If voters approve the Texas Water Fund in November, the state's financial strategy will be enlarged for the first time since 2013 to address escalating water infrastructure challenges. In the meantime, TWDB received a clean bill of health through the Sunset review process, and regional water planners now have legislative encouragement to consider planning for worsening droughts. Moreover, the regulatory reforms and data collection measures approved during the 88th Session establish smart foundations for addressing other water policy matters. Lastly, the Legislature addressed the growing problem of needing a qualified water workforce. While the 88th Session will go down in the books as a historic "water session," the session adjourned *sine die* with the doors open to other critical policy discussions, including those relating to water markets and the need for a sustained financial strategy for addressing Texas' long-term infrastructure challenges.

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The State of Texas Wetlands: A Review of Current and Future Challenges

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Abstract: With roughly 3.9 million acres of wetlands, 2.3% of its total land area, Texas has the fifth largest wetland acreage in the United States. As of 1990, there was an estimated 52% reduction in the state's original wetland acreage, but there has been no recent assessment of statewide wetland loss or gain since then. Wetlands provide critical ecosystem services, including wildlife habitat, flood storage and control, aquifer recharge, water quality improvement, pollutant breakdown, and storage of greenhouse gases, as well as human recreational opportunities including boating, paddling, fishing, hunting, birdwatching, hiking, and nature photography. However, Texas wetlands face intensifying challenges in the coming decades. Forward-facing regulatory and legislative actions that anticipate effects of climate change, sea level rise, and urban expansion will likely aid in addressing ongoing and complex challenges. Incorporating new technologies will allow for more timely and cost-efficient large-scale monitoring of wetland loss and gain. The residents of Texas are largely in support of active management of the state's water resources, and we envision that the success of conservation initiatives will be strengthened when academic institutions, state and federal agencies, and conservation-minded private entities work together to ensure the wetlands of Texas persist for wildlife and generations to come.

Keywords: Texas, wetlands, climate, wildlife, regulatory

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Terms used in paper

Acronym / Initialism	Descriptive Name
C	carbon
CBBEP	Coastal Bend Bays and Estuaries Program
CH_4	methane
cm	centimeters
CMP	Texas Coastal Management Program
CO_2	carbon dioxide
CO_{2e}	carbon dioxide equivalent
CWA	Clean Water Act
CZMA	Coastal Zone Management Act
DDT	dichlorodiphenyltrichloroethane
E. coli	*Escherichia coli*
ESLR	eustatic sea level rise
EPA	U.S. Environmental Protection Agency
EWRA	Emergency Wetlands Resources Act
GAOA	Great American Outdoors Act
GCJV	Gulf Coast Joint Venture
GHG	greenhouse gas
GSLR	global sea level rise
in	inches
LMVJV	Lower Mississippi Valley Joint Venture
LWCF	Land and Water Conservation Fund
mm	millimeters
MSCI	Midcontinent Shorebird Conservation Initiative
N	nitrogen
N_2O	nitrous oxide
NAWMP	North American Waterfowl Management Plan

Acronym / Initialism	Descriptive Name
NEXRAD	Next Generation Weather Radar system
NH_3	ammonia
NO_3^--N	nitrate
NOAA	National Oceanic and Atmospheric Administration
NRCS	Natural Resources Conservation Service
NWI	National Wetlands Inventory
NWMAP	National Wetlands Mitigation Action Plan
NWPCP	National Wetlands Priority Conservation Plan
O_2	molecular oxygen
PET	potential evapotranspiration
RCP85	Representative Concentration Pathway scenario 8.5
RSLR	relative sea level rise
S	sulfur
SCOTUS	Supreme Court of the United States
SSP5	Shared Socioeconomic Pathways
SWCP	State Wetlands Conservation Plan
TORP	Texas Outdoor Recreation Plan
TPWD	Texas Parks and Wildlife Department
TRWD	Tarrant Regional Water District
TWDB	Texas Water Development Board
USACE	U.S. Army Corps of Engineers
USDA	U.S. Department of Agriculture
USFWS	U.S. Fish and Wildlife Service
WOTUS	Waters of the United States

INTRODUCTION

With roughly 3.9 million acres of wetlands, 2.3% of its total land area, Texas has the fifth largest wetland acreage in the United States. Only Alaska (174 million), Florida (11.4 million) Minnesota (10.6 million), and Louisiana (7.8 million) have more total wetland acres. Large-scale assessments (e.g., National Wetlands Inventory [NWI], National Land Cover Database) that aim to map and monitor changes in wetland extent and distribution are landscape- and continental-focused and fail to capture finer (state- or regional-scale) changes (Dewitz, 2021; U.S. Fish and Wildlife Service [USFWS], 2023a). As of 1990, there was an estimated 52% reduction in Texas' original wetland acreage, but there has been no recent assessment of statewide wetland loss or gain since then (Dahl & Stedman, 2013). We reviewed available literature related to wetlands and the challenges they face in Texas and present a synthesis of ecologically descriptive and timely issues. We also discuss relevant legislation and strategies currently in practice in Texas to protect and conserve wetlands.

Definition of Wetlands and Factors Contributing to Their Patterns

The formation of a wetland occurs in areas where there is a reliable water source at or close to the surface of the land (Mitsch & Gosselink, 2015). There are many different types of wetlands, each with its own plant communities and soil types. Wetland types found in Texas are described in detail in Appendix 1. There are, however, certain features that all wetlands have in common and that make them different from most other ecosystems. The most obvious feature is moisture, which leads to distinctive patterns of energy flow and storage. All living organisms (apart from some very specialized fungi and bacteria) require molecular oxygen (O_2) for respiration. Microbial respiration in the soil drives the decomposition of organic matter (e.g., dead plant materials, animal waste), and decomposition rates vary according to hydrology.

Water inhibits the availability of O_2. In environments where water flows quickly or is turbulent, dissolved O_2 may be considerably higher than in a setting in which water is standing and has little opportunity to interact with the air. The fast-flowing environment will have higher decomposition rates relative to the still water, leading to the development of different soil types. In systems that have little available dissolved O_2, anaerobic processes dominate and produce soils with low organic decomposition rates. Likewise, wetlands with high concentrations of dissolved O_2 are dominated by aerobic nutrient processes and are characterized by high organic decomposition rates. The dominant nutrient process in wetland soils ultimately determines the microbial, plant, invertebrate, and vertebrate communities it can support. It also influences the capacity of the wetland to store organic matter and dissolved gases.

The position and durability of the water supply are influenced by various factors, including climate, physiography, hydrology, and land/water use. Annual precipitation and runoff rates in Texas fluctuate each year and vary by location and season. In general, annual mean precipitation increases from west to east. January normal minimum temperatures increase from north to south. However, there is no July normal maximum temperature gradient along the same axis. Instead, the July normal maximum temperature increases moving west to east along the Rio Grande (Nielsen-Gammon, 2011; PRSIM Climate Group, 2023).

Potential evapotranspiration (PET) decreases from west to east across the state. In West Texas, annual lake evaporation surpasses annual precipitation by four to five times, while in East Texas, annual precipitation is almost equivalent to annual evaporation. The regions that experience the greatest yearly precipitation and the lowest PET are also the regions with the largest wetland coverage. East Texas accounts for over 50% of the total wetland acreage in the state (Fretwell et al., 1996).

Importance of Wetlands in Texas

Wetlands provide critical ecosystem services, including wildlife habitat, flood storage and control, aquifer recharge, water quality improvement, and pollutant breakdown and storage of carbon (C), methane (CH_4), sulfur (S), nitrogen (N), and other gases (Mitsch & Gosselink, 2000; Mitsch et al., 2013; Hiraishi et al., 2014). They provide crucial habitat for a diverse range of birds, mammals, reptiles, amphibians, fish, invertebrates, and plants. They also provide human recreational opportunities including boating, paddling, fishing, hunting, birdwatching, hiking, and nature photography. Thus, responsible wetland stewardship is essential for maintaining the health and resilience of both natural and human communities.

Wildlife

Texas sits in the middle of the Central Flyway, one of the four major flyways in North America, and sees up to 400 million migratory birds pass through each year (Gauthreaux & Belser, 1999; Russell, 2005). Of the 338 Nearctic-Neotropical migrant bird species occurring in North America, 98.5% have been recorded in Texas (Shackelford et al., 2005). Texas offers crucial stopover points for migratory birds; many follow marshes on the coast and playas in far North Texas as they take their annual roundtrip journey between their wintering and breeding grounds (Smith et al., 2004b; Shackelford et al., 2005; Contreras Walsh et al., 2017; Fern & Morrison, 2017). Birds are highly effective indicators of environmental well-being and overall ecosystem health (Burger & Gochfeld, 2004).

Capacity to monitor numerous bird species across extensive geographical areas surpasses that of any other animal category, which has allowed the implementation of multiple standardized bird-monitoring datasets in North America, some of which provide nearly five decades of population data (Rosenberg et al., 2019). A recent synthesis of range-wide population size estimates across 529 species and almost all biomes (e.g., boreal forest, arid lands, coasts, wetlands) reveals a net loss of approximately 2.9 billion birds, a 29% decline in North American since 1970 (Rosenberg et al., 2019). Abundance data from the Next Generation Weather Radar system (NEXRAD), a continent-wide weather radar network, indicate a similar decline in migrating birds within the Atlantic Flyway over the past decade (Dokter et al., 2019; Kranstauber et al., 2020; Rosenberg et al., 2019). Significant decline in abundance was seen in all breeding biomes except wetlands (Rosenberg et al., 2019). These data include only 95 of the 138 wetland-dependent species of continental breeding birds and not those that use wetlands for overwintering or migratory habitat. Approximately one-third of bird species in North America require wetlands to complete at least some of their life cycle (Chesser et al., 2021). A growing body of evidence suggests that wetlands are crucial to the survival of breeding, migratory, and overwintering birds, and continued wetland loss may accelerate extinction rates in North America (Gibbs & Kinkel, 1997; Golden et al., 2022; Niering et al., 1988; Şekercioğlu et al., 2004; Strassburg et al., 2020).

In addition to birds, many species of mammals in Texas are dependent on wetlands. Some species of bats (e.g., eastern red bat, *Lasiurus borealis;* big brown bat, *Eptesicus fuscus)* tend to roost near or in wetlands, likely due the concentration of prey (members of Lepidoptera and Hemiptera, among others) in these areas (Krusic & Neefus, 1996; Rydell et al., 1996). In East Texas, Rafinesque's big-eared bat *(Corynorhinus rafinesquii)* and federally endangered southeastern myotis *(Myotis septentrionalis)* commonly roost in hollow trees in bottomland hardwood forests near slow-moving rivers (Ammerman et al., 2012).

Texas is home to 231 species of reptiles and amphibians, many of which are wetland obligate (71 amphibian and 12 reptile species; David, 1975; Dixon, 2000; Whiting et al., 1997). Of the 12 wetland obligate reptile species in Texas, four are federally or state listed as either endangered or threatened: alligator snapping turtle *(Macrochelys temminckii)*, Brazos water snake *(Nerodia harteri)*, Chihuahuan mud turtle *(Kinosternon hirtipes murrayi)*, Cagle's map turtle *(Graptemys caglei;* Texas Parks and Wildlife Department [TPWD], 2023). Sixteen of the amphibian species in Texas are also federally or state listed as either endangered or threatened: Austin blind salamander *(Eurycea waterlooensis)*, Barton Springs salamander *(Eurycea sosorum)*, black-spotted newt *(Notophthalmus meridionalis)*, Blanco blind salamander *(Eurycea robusta)*, Cascade Caverns salamander *(Eurycea latitans)*, Comal blind salamander *(Eurycea tridentifera)*, Georgetown salamander *(Eurycea naufragia)*, Houston toad *(Anaxyrus houstonensis)*, Jollyville Plateau salamander *(Eurycea tonkawae),* Mexican burrowing toad *(Rhinophrynus dorsalis)*, Mexican treefrog *(Smilisca baudinii)*, Salado salamander *(Eurycea chisholmensis)*, San Marcos salamander *(Eurycea nana)*, sheep frog *(Hypopachus variolosus)*, South Texas siren (large form; *Siren* sp. 1), Texas blind salamander *(Eurycea rathbuni)*, and white-lipped frog *(Leptodactylus fragilis;* TPWD, 2023).

Many species of fish also rely on wetlands for their spawning, juvenile development, or life cycle. At present, over 170 and 180 freshwater and saltwater fish species, respectively, can be found in Texas. Many of these fish species are wetland obligate or rely on wetlands for some portion of their life cycle. Freshwater species like largemouth bass *(Micropterus salmoides salmoides)*, bluegill *(Lepomis* spp.), and catfish (members of Siluriformes) use wetlands for spawning and rearing of their young (Chumchal & Hambright, 2009). Likewise, saltwater species like red drum *(Sciaenops ocellatus)* and spotted seatrout *(Cynoscion nebulosus)* use wetlands as nursery areas during their juvenile stages. Some species are wetland-obligate and require wetland habitat for the entirety of their life cycle. Alligator gar *(Atractosteus spatula)* is the largest freshwater fish in Texas and one of the largest in North America (Buckmeier, 2008). This species is often found in the backwater swamps and flooded riparian zones in the southern and eastern portion of the state and requires both wetland types to complete its life cycle (Buckmeier, 2008; Lee & Wiley, 1980). Alligator gar are slow-growing, long-lived, and believed to be declining in numbers throughout their range (Cashner, 1995; Pflieger et al., 1975).

Socioeconomic

In addition to directly supporting fish and wildlife populations, wetlands also provide important ecosystem services that support the Texas economy and its people (Table 1).

These estimates of economic impact include both direct spending on fishing-related goods and services (e.g., fishing licenses and equipment) and indirect spending (e.g., lodging, guides, and other travel-related costs) from the multiplier effects of that spending. For private landowners, hunting lease income often exceeds agricultural income, and recreational use is the highest and best use of the land (Baen, 1997; Little & Berrens, 2008).

Wetlands act as natural sponges, absorbing and storing large amounts of water during times of heavy rainfall or flooding. This helps to reduce the risk of downstream flooding and damage to property (Antolini et al., 2020). Coastal wetlands act as a buffer to storm surges, slowing the water flow and providing habitat for soil-stabilizing plants, preventing erosion (Feagin et al., 2009; Maymandi et al., 2022). The

Table 1. Economic impacts of recreational waterfowl hunting, hunting (waterfowl excluded), and fresh and saltwater fishing in Texas.

Activity	Gross spending ($ billions)	Jobs supported
Waterfowl hunting [1]	1	14,000
Hunting [1, 2 +]	1.2	32,000
Freshwater fishing [1, 2, 3]	4.1	56,000
Saltwater fishing [1, 2, 3]	1.3	14,000
Non-consumptive recreation [1, 2 ++]	4.1	—— [+++]

[+] exclusive of waterfowl
[++] wildlife watching, outdoor physical recreation, and other non-resource consumptive activities.
[+++] number not available

[1] The state of outdoor tourism, recreation, and ecotourism, 2021
[2] Southwick Associates, Inc., 2007
[3] American Sportfishing Association, 2020

exact dollar amount of storm damages alleviated or prevented by wetlands in Texas can vary depending on the location and severity of storms. However, localized estimates indicate the economic value of these benefits is significant.

The Environmental Defense Fund (2023) estimated the wetlands in the Galveston Bay region of Texas provide storm protection benefits worth over $2 billion annually. Another study valued the storm protection benefits of the wetlands in the Sabine-Neches Lake estuary at up to $1.2 billion annually (Maymandi et al., 2022). The same study argues these wetlands can reduce the damage caused by storms by up to 70%. These estimates consider the value of the wetlands' ability to reduce flood heights and prevent property and infrastructure damages.

More recently, coastal wetlands were estimated to have reduced the amount of flooding during Hurricane Harvey by up to 80% in parts of the Houston area, protecting infrastructure and likely saving lives (Armitage et al., 2020). Natural coastal habitats in Texas annually protect approximately $2.4 billion worth of property and thousands of people, including many families living below the poverty line and other disadvantaged communities (Arkema et al., 2013). The Greater Houston Metropolitan Area has lost an estimated 3.7% of its tidal wetland acres over an 11-year period (2008–2019) and 5.5% of its natural freshwater (nontidal) coastal wetlands over an 18-year period (1992–2010; Al-Attabi et al., 2023; Jacob et al., 2014). However, concentrated loss in some areas has been substantially more severe. Harris County experienced the greatest loss of freshwater wetlands during that period (15,855 acres; 29%; Jacob et al., 2014). Hurricane Ike, making landfall as a Category 2 Hurricane in 2008, caused $7.27 billion in damages in the Galveston Bay area (Al-Attabi et al., 2023; Blake et al., 2011). Given the wetland loss since 2008, hydrological and economic models project a net increase of $2.52 billion if Hurricane Ike had made landfall in 2019 (Al-Attabi et al., 2023; Dotson, 2016).

Water Quality

Wetlands absorb and filter a variety of sediments, nutrients, and other natural and human-made pollutants that would otherwise degrade rivers, streams, and lakes (Fisher & Acreman, 2004; Nichols, 1983). The ability of wetlands, such as river floodplains and coastal areas, to hold these nutrients results in a high rate of primary productivity and provides nutrients for invertebrates such as shrimp, crabs, worms, and microfauna (Greenway, 2007; Nichols, 1983).

The nitrogen (N) cycle in wetlands is extremely complex (Nichols, 1983). N input is a primary driver in wetland biogeochemical processes through several pathways: denitrification (the uptake of nitrate [NO_3^--N] in anaerobic soils); N fixation (the fixing of atmospheric N into bioavailable forms); ammonia (NH_3) volatilization; nitrification; plant and microbial uptake; ammonification; nitrate-ammonification; anaerobic NH_3 oxidation; fragmentation; sorption; desorption; burial; and leaching (Nichols, 1983; Vymazal, 2007). In some studies, anerobic soils found in wetlands and lake bottoms had the capacity to capture as much as 90% of the added NO_3^--N within a few days (Wang et al., 2001). Constructed wetlands have the capacity to remove 40–50% of N from the water column (Vymazal, 2001, 2005; Vymazal et al., 2005). Constructed wetlands are engineered systems often created with the goal of restoration, imitating the biochemical cycles occurring in natural wetlands, or as a mitigation requirement satisfying the National Wetlands Mitigation Action Plan (NWMAP). In some cases, constructed wetlands can achieve up to 85–86% removal of phosphorous (P), rivaling the capacity of naturally occurring systems, specifically riparian wetlands (Doherty et al., 2015).

The George W. Shannon Wetlands project located at the Richland Creek Wildlife Management Area in Freestone County, Texas, is a 1,700-acre wetland complex constructed and managed by TPWD for the purpose of nutrient reduction in municipal wastewater. A series of 24 wetland units adjacent to the Trinity River filters 90 million gallons of water daily from the Tarrant Regional Water District (TRWD). The wetlands complex effectively removes 95% of suspended sediment as well as 77% of N and 45% of P from TRWD effluent. As of 2023, TRWD is constructing an additional water reuse project adjacent to Cedar Creek Reservoir. This 3,300-acre wetland complex will function similarly to the East Fork Water Reuse Project and the George W. Shannon Wetlands project and is expected to filter an average of 156 million gallons per day, delivering water to 1.1 million residents.

Climate

Wetlands act as important nutrient sinks, storing large amounts of C in their soils and vegetation (Mitra et al., 2003; Mitsch et al., 2013). Freshwater wetlands in Texas sequester an average of 115 grams of C per square meter per year (Hansen & Nestlerode, 2014). This is equivalent to 1.2 billion tons stored in inland (nontidal), freshwater wetlands in the state as of 2009.

Some studies have indicated that coastal (tidally influenced) wetlands sequester up to 10 times more C than freshwater wetlands (Nahlik & Fennessy, 2016; Taillardat et al., 2020). This is likely due to the anaerobic soils found in coastal wetlands that slow down the decomposition of organic matter, allowing more C to be stored in the soil. Additionally, coastal wetlands are often flooded with saltwater, which can kill microbes that would otherwise decompose organic matter, further slowing decomposition (Morris et al., 2012; Nahlik & Fennessy, 2016).

Wetlands can also sequester substantial amounts of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), three potent greenhouse gases (GHG; any gas that absorbs and emits infrared radiation) that contribute to atmospheric regulation and climate cycles (Mitra et al., 2003; Segers, 1998; Taillardat et al., 2020; Wahlen, 1993). The wetlands of the Texas Gulf Coast are estimated to sequester up to 2.8 million metric tons of CO_2 equivalent (CO_{2e}) annually, including both CH_4 and N_2O (Hansen & Nestlerode, 2014). Restored and constructed wetlands in Texas can sequester up to 2,444 and 77 kilograms of CH_4 and N_2O, respectively, per hectare annually (Hansen & Nestlerode, 2014).

Wetlands can serve as C sinks, meaning they absorb more C and CO_2 from the atmosphere than they release. However, they are also a significant source of CH_4, a more potent GHG (Wahlen, 1993). While CO_2 is more abundant in the atmosphere than CH_4 or N_2O, CH_4 has a global warming potential over a 100-year period that is 25 times greater than CO_2 (Forster et al., 2007). Several studies suggest the sudden rise in atmospheric CH_4 may be caused by wetlands (Dean et al., 2018; Zhang et al., 2014). Wetland CH_4 is produced by methanogens, microorganisms typically found in anaerobic environments. Until recently, CH_4 production has been considered to be at its highest level in permanently saturated, fully anoxic soils below the water column in which most organic carbon is stored (Dean et al., 2018). Recent evidence suggests that the highest CH_4 emissions from some wetland soils are produced in the near-surface, aerobic layers via reduction-oxidation cycles (redox oscillation; Angle et al., 2017; Yang et al., 2017). However, some compounds (e.g., polyphenols) have been observed acting as biogeochemical barriers to the creation of CO_2 via organic C degradation (i.e., carbon mineralization) in aerobic soils (Freeman et al., 2004). Thus, soils that experience drought cycles are likely to demonstrate decreased C storage and increased emissions of GHGs, particularly CH_4, during drought recovery (i.e., rewetting). Temporary exposures to oxygen (O_2) during dry periods may reduce the inhibitory effects of polyphenols on carbon mineralization (Fenner & Freeman, 2011).

CH_4 emissions can be increased by human activities such as draining, as well as natural flood-drought and freeze-thaw cycles (Le Mer & Roger, 2001; Megonigal et al., 2004; Metje & Frenzel, 2007). As the climate changes, the frequency and severity of flood-drought events are becoming more common and CH_4 emissions from wetlands may be accelerated, as they are repeatedly inundated and dried up (Cao et al., 1998; Morris et al., 2012).

CLIMATE CHANGE AND LAND CONVERSION IMPACTS ON TEXAS WETLANDS

Changes in Precipitation and Temperature Patterns

Precipitation patterns vary across Texas, as have their recent trends. In the eastern portion of the state, there has been a pronounced precipitation increase. Changes in precipitation, along with a warmer atmosphere, have intensified weather events (e.g., storms, droughts, flash flooding) and shifted rainfall to earlier or later in the year, disrupting wetland plant germination, water availability for migrating and resident wildlife, and salinity of coastal wetlands, as well as escalating erosion issues (Burris & Skagen, 2013; Hatfield & Prueger, 2004; Skendžić et al., 2021; Trenberth, 2011). Extreme oscillation between heavy rainfall and severe drought has led to drastic changes in hydrological regimes of Texas' wetlands. However, this pattern is most pronounced and arguably most impactful for the inland wetlands of East Texas, where precipitation has increased by an average of 3.8 centimeters (cm; 1.5 inches

[in]) per decade since 1950 (Nielson-Gammon, 2011; Vose et al., 2014). The historical average annual rainfall in East Texas is 119.4 cm (47 in), and it is expected to rise to 132.1 cm (52 in) by 2050, a 10% increase (PRISM Climate Group, 2023). More meaningful than average annual precipitation is the increasingly episodic nature of rainfall in the region, as evidenced in recent decades by several high-profile events. In 2017, Hurricane Harvey dumped up to 152.4 cm (60 in) of rain in some areas over the course of 10 days, causing significant flooding, billions of dollars in property damage, and the loss of 68 human lives (Frame et al., 2020; Jonkman et al., 2018). Extreme episodic flooding, exacerbated by the spread of impervious surfaces (i.e., concrete), has caused wetland loss through sedimentation, subsidence, and submergence (White & Tremblay, 1995). Approximately 63% of the original bottomland hardwood forests (inland forested wetlands) in East Texas has been lost (Frye, 1987; McWilliams, 1986). This estimate is based on data available in 1987, so an assumption of further deterioration and loss is appropriate given intensifying conditions known to be damaging to these systems (e.g., subsurface liquid withdrawal, urbanization, more frequent storm events). Increases in impervious surfaces from urbanization are associated with large pulses of stormwater runoff, reducing water quality of rivers and wetlands (e.g., increased turbidity, nutrient loading, increased heavy metal concentrations; Ehrenfeld, 2000). The Fourth National Climate Assessment, released in 2017 by the U.S. Global Change Research Program, projected an increase in the frequency and intensity of extreme weather events (e.g., droughts, floods, and heat waves) in the coming decades (Wuebbles et al., 2017).

In contrast to the challenges in East Texas, precipitation in West Texas has decreased by an average of 5.1 cm (2 in) per decade since 1950 (Vose et al., 2014). Water scarcity in other areas across the state and increasingly severe droughts have increased in recent years. The city of El Paso experienced its driest year on record in 2018, causing dangerous water shortages and emergency water conservation measures (PRISM Climate Group, 2023; Vose et al., 2014). To maintain their water supply during droughts, cities and water cooperatives often hold back more water in reservoirs, reducing the amount of water released downstream. This can have a negative impact on riparian wetlands, which rely on a steady flow of water to provide wildlife habitat and other ecosystem services characteristic of healthy wetlands (Mitchell et al., 2021; Mix et al., 2016; Samady, 2017). Sustained drought conditions can reduce freshwater discharge from rivers in coastal marshes, further compounding saltwater intrusion attributable to sea level rise (Silliman et al., 2005). Likewise, severe inland flooding can increase freshwater discharge into historically brackish or saline marshes, altering sensitive hydrological regimes to which some vegetation and wildlife are specially adapted (Falcini et al., 2012).

Data from the National Oceanic and Atmospheric Administration (NOAA) have demonstrated a gradual increase (0.8°C) in average temperature in Texas over the past century, with the warmest years occurring in recent decades (National Centers for Environmental Information [NCEI], 2023). In a report compiled by the Office of the Texas State Climatologist, the average Texas surface temperature in 2036 is projected to be 1.67°C (3.0°F) warmer than the 1950–1999 average and 1°C (1.8°F) warmer than the 1991–2020 average (Nielsen-Gammon et al., 2021). Severe and sustained heat waves have also become more frequent in the state, causing higher evaporation rates and increased water temperatures in rivers and wetlands (Nielsen-Gammon et al., 2021; Overpeck & Udall, 2010; Strzepek et al., 2010).The number of 38°C (100°F) days in Texas is expected to approximately double by 2036, with a higher frequency of 38°C (100°F) days in urban areas (Nielsen-Gammon et al., 2021).

Wetlands also play a critical role in mitigating impacts of microbial parthenogenic exposure to wildlife and human populations. Wetlands can reduce disease risk and exposure to dangerous pathogens (e.g., fecal coliforms, *Giardia* spp., *Cryptosporidium* spp.) through sediment trapping, nutrient transformation, plant uptake, adsorption, and microbial breakdown (Hsu et. al, 2017; Johengen & LaRock, 1993; Martin & Reddy, 1997; Vandegrift et. al., 2010). The effect of climate change on emerging infectious wildlife diseases in wetlands is threefold: (1) increasing frequency of extreme rainfall events can degrade water quality in wetlands through the sudden influx of nutrient-rich stormwater runoff, speeding up reproduction and proliferation of disease-causing organisms present in the water; (2) increasing temperatures can fuel harmful algal blooms by allowing for longer growing (i.e., reproductive) seasons (Refsnider et. al., 2021; Wells et. al., 2020; Wobeser, 1992); and (3) intensifying droughts can concentrate wildlife into smaller areas, increasing density and likelihood of disease outbreaks such as cholera and other water-borne diseases (Derne et al., 2015).

Fecal coliforms are the most common pollutant in waterways and wetlands (Geldreich, 1966). Even typical rainfall events cause increases in coliform concentration via nonpoint source pollution such as municipal treatment plants, storm water overflows, and agricultural runoff (Hill et. al., 2006; Kelsey et. al., 2004). Fecal coliform numbers and rainfall are so strongly correlated that rainfall can accurately predict coliform concentration, with some states using rainfall thresholds to regulate shellfish and game fish harvest due to public health concerns (Kelsey, 2006; Leight & Hood, 2018; Mallin et. al., 2001; Santiago-Rodriguez et. al., 2012). Pulses of nutrient-rich urban and agricultural runoff can also feed other harmful organisms such as cyanobacteria (often blue-green algae). While the cyanobacteria itself is not toxic, large pulses in reproduction (harmful algal blooms) trigger the production of hepatotoxin (Msagati et. al., 2006). The ingestion of hepatotoxin creates acute and chronic effects in wildlife and humans including liver damage, reproductive failure, intestinal damage, and, in some cases, death (Heil & Muni-Morgan, 2021; Young et. al., 2020). Cyanobacteria proliferate in warm, relatively still water—conditions characteristic of urban stormwater retention ponds, shallow drinking-water reservoirs, and wetlands—and are expected to become more common due to diminishing reservoir levels and increasing temperature (Patiño et. al., 2014; Wells et. al., 2020).

Wildlife species that inhabit wetlands, such as waterfowl, are natural reservoirs for zoonotic pathogens such as *Escherichia coli (E. coli)* and the H5N1 virus that causes highly pathogenic avian influenza (Hsu et. al, 2017; Samuel, et. al., 2005). Localized outbreaks of zoonotic disease among waterfowl are often density-dependent and can pose a serious threat to public health (Wobeser, 1992). Waterfowl tend to be more locally concentrated in wetlands during periods of drought due to the diminishing availability of freshwater, which often leads to disease outbreaks (e.g., avian cholera, avian influenza). These diseases can spread to humans as well as domestic birds, decimating some poultry farms (Capua & Marangon, 2006; Samy & Naguib, 2018). As the human population grows and urban areas expand, exposure to and contact with wildlife and these waters is expected to increase, leading to more potential disease spillover events.

Rising Sea Levels and Coastal Wetlands

Global sea level has been rising an estimated 0.2 millimeters (mm)/year (0.008 in/year) in recent millennia (pre-1900) and 1.8 mm/year (0.071 in/year) during the twentieth century (Gornitz & Lebedeff, 1987; Meehl et al., 2007). Recent data indicates a pronounced acceleration in the rate of global sea level rise (GSLR), currently estimated to be 3.0 mm (0.12 in) annually (Anderson et al., 2022). The effects of GSLR vary by location and are often measured at a more localized scale. Relative sea level rise (RSLR) is the change in ocean height relative to coastal land and is driven primarily by three processes: local variations in sea level (e.g., tides), relative land motion (e.g., land subsidence, coastal sediment transport), and eustatic sea level rise (ESLR; changes in mean ocean height as a result of increasing temperatures that cause thermal expansion and melting ice sheets; McKay et al., 2011). The impacts of RSLR on Texas wetlands are significant and multifaceted, with potential consequences for both the ecological and human communities that depend on these valuable ecosystems (Cahoon et al., 2006; Desmet et al., 2018; Feagin et al., 2009; Taha, 2007).

RSLR can lead to saltwater intrusion, an upstream movement of saltwater into historically freshwater wetlands and rivers, which may shift the composition of plant communities, thwart seed germination, and suppress photosynthetic efficacy via decreased plant respiration (Baldwin et al., 1996; Jackson & Drew, 1984; Pearlstine et al., 1993; Perry & Hershner, 1999; Peterson & Baldwin, 2004; Pezeshki et al., 1987; Schuyler et al., 1993). Increases in the soil salinity can stress plants (even those well-adapted to saline conditions) by inhibiting water uptake from the roots, damaging plant cells, and potentially leading to death (Pezeshki et al., 1989; Wilson et al., 2018). The reduction of freshwater availability can lead directly to vegetation loss and loss of wildlife habitat for resident and migratory species, crucial spawning grounds for commercially and recreationally valuable fishes and shellfishes, and freshwater for drinking and irrigation in vulnerable coastal communities (Anderson & Al-Thani, 2016; Grace & Ford, 1996; Tully et al., 2019; Wilson et al., 2018). The subsurface movement of seawater into coastal aquifers can also result in salinization of wetlands with a significant groundwater connection (Abdoulhalik & Ahmed, 2017). Fluctuating sea levels (e.g., tides) coupled with intensifying groundwater pumping (for municipal or industrial use) can disrupt the natural groundwater hydraulic gradient leading to land subsidence and amplifying the intrusion process (Hussain et al., 2019). Subsidence rates on the Texas coast range from less than 2 mm (0.08 in) per year to 7 mm (0.28 in) per year varying by land use practices and subsurface geology (Letetrel et al., 2015). Tidal marshes have historically kept pace and maintained relative equilibrium by building soil volume (i.e., accretion; Redfield, 1965; Pasternack, 2009). However, sudden or sustained increases in saltwater inundation can upset the balance between aerobic and anaerobic processes in the soil, which may reduce organic matter decomposition rates (Bridgham et al., 1998; Ponnamperuma, 1984). Because organic matter accumulation is the main driver of soil accretion in tidal freshwater marshes, reduced organic matter production can substantially impede the ability of these marshes to keep pace with RSLR (Neubauer, 2013; Spalding & Hester, 2007; Weston et al., 2011). The compounding effects of increasing subsidence rates and an accelerating ESLR are expected to result in substantial loss of historically freshwater wetlands on the Texas coast (Figure 1; NCEI, 2023).

Texas' coastal wetlands are also at risk of erosion due to RSLR and more intense and frequent storms. There have been a number of high-profile events in recent years in which Texas wetlands have been damaged or destroyed by degradation and loss attributable to RSLR (e.g., Hurricane Katrina in 2005 and Hurricane Laura in 2020; Cadigan et al., 2022; Stagg et al., 2021; Yao et al., 2020). Increased inundation and wave energy can cause the shoreline to erode, resulting in the loss of valuable wetland habitat and reduced water quality. Between 1950 and 1989, Galveston Bay lost an estimated 12% of saline marsh due to increased wave action and land subsidence associated with RSLR (White et al., 1993; White & Morton, 1997). Sediment from eroded soil can also contain nutrients and pollutants that are released into the water column, leading to

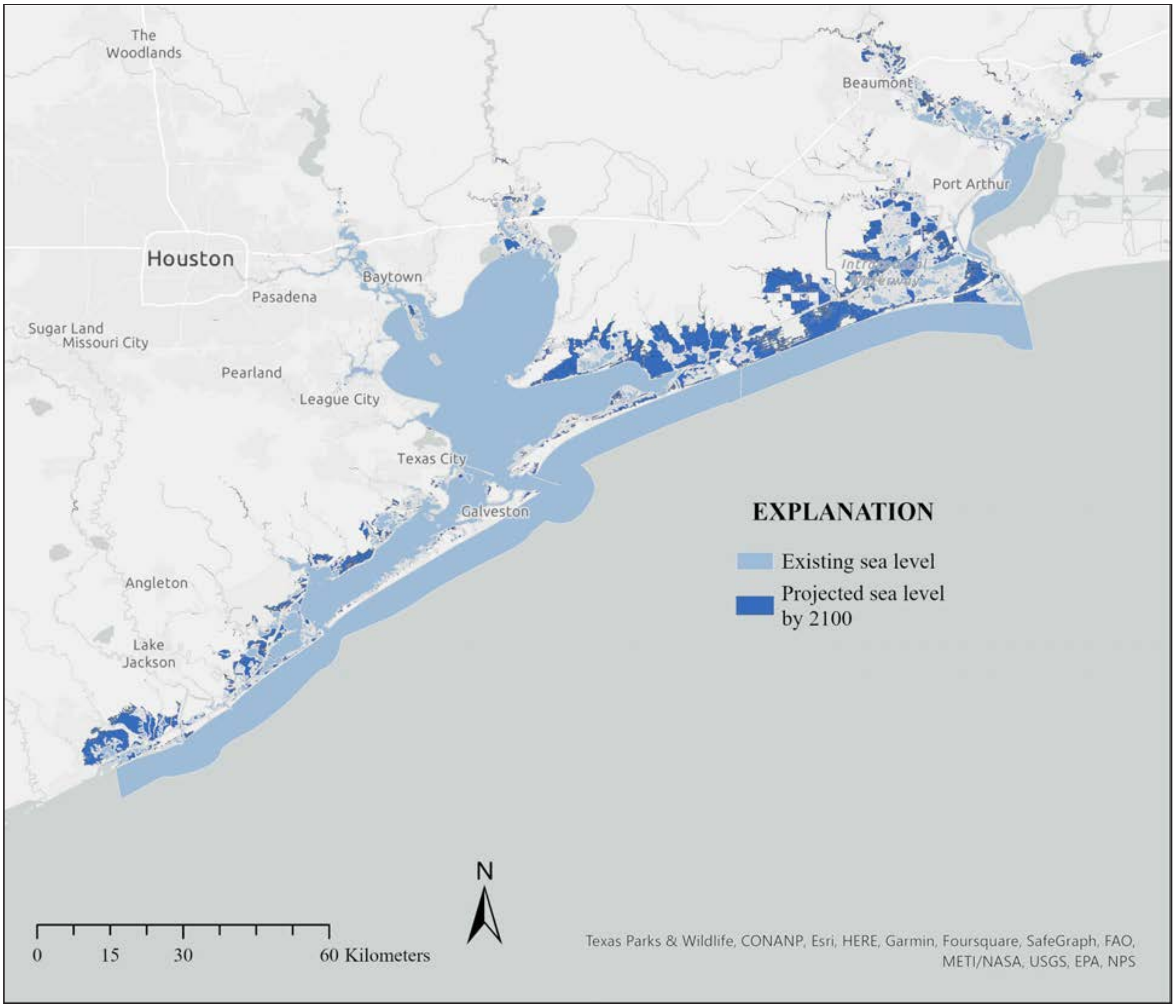

Figure 1. Representation of current and projected sea level rise of 1 foot by 2100 on the upper Texas coast.

reduced water quality and harmful algal blooms (Terhaar et al., 2021). Erosion-caused wetland degradation can create a negative feedback loop: As sea levels rise, wetlands are inundated more frequently and exposed to more wave energy. This process can lead to vegetation loss and soil erosion, which reduces the wetlands' ability to buffer storm surge. As a result, storm events can be even more damaging to the wetlands and the sensitive wildlife communities that rely on them (Farber, 1987; Morton & Barras, 2011; Ravens et al., 2009; Truong et al., 2015; White & Tremblay, 1995).

The rising sea level and compounding effects of erosion, saltwater intrusion, and changing precipitation patterns are causing—and will continue to cause at an increasing pace—a migration of freshwater wetlands inland (Van Dolah et al., 2020; Wuebbles et al., 2017). However, significant loss of fresh and intermittently flooded marsh will likely occur as sea levels rise, and few opportunities are available for marsh zones to migrate inland. This phenomenon, known as coastal squeeze, occurs when intertidal habitats are lost due to the highwater mark being fixed by a defense or structure and the low water mark migrating landward in response to sea level rise (Pontee, 2013). Shifts in the distribution of wetlands along the Texas coast pose severe challenges to the approximate 6.8 million people (22.7% of the state's population) who live in this zone (U.S. Census Bureau, 2020).

State and federal agencies may need to anticipate a rapid modification of coastal conservation priorities as shoreline fortification and the resulting urban development inland will likely cause more loss of sensitive wetland systems and wildlife habitat.

Land Conversion

Dams in the United States disrupt river discharges at a much higher degree than any hydrological shifts anticipated from climate change (Graf, 1999; Tonitto & Riha, 2016). Some projections estimate hydrological impacts of climate-induced reduction (15–20%) of annual water yield and sharp increases in flood magnitude and frequency (Tegart et al., 1990; Waggoner, 1990; Watson & Adams, 2010). However, many dams in the United States have storage capacities greater than the annual runoff generated by their watersheds and reduce downstream flow by almost 100% (Baker et al., 1990; Graf, 1999). Texas has the greatest number of dams in the United States (7,381) and achieved its storage capacity exceeding mean annual runoff (exceedance) in 1962. While many states are removing dams over growing concerns regarding hazard mitigation, river restoration, and health of downstream wetlands, Texas has not yet removed any dams for primarily ecological reasons (Grabowski et al., 2018; Graf, 1999; Dascher & Meitzen, 2020).

The Texas Water Development Board (TWDB) has included the installation of 22 new reservoirs (14 to be functional by 2030 and the remaining eight to be functional by 2050) in its most recent state water plan (TWDB, 2022). TWDB has also identified 24 "unique reservoir sites" that present a unique value for growing water needs in the state (TWDB, 2022). While reservoirs can create additional fisheries habitat and increase the number of lacustrine wetlands, significant adverse impact can occur to existing palustrine wetlands. Wetlands are lost through direct inundation, modification of vegetation communities, construction of dam and spillways, and altered downstream hydrology from proposed reservoirs. Over 1.5 million acres of natural vegetation, including over 600,000 acres of bottomland hardwoods, are estimated to have been lost from reservoirs already constructed as of 1995 (TPWD, 1995). Total losses of bottomland hardwoods from reservoirs already built or proposed is estimated to exceed 860,000 acres (TPWD, 1995; TWDB, 2022). These losses are not spread evenly over remaining riparian vegetation but rather are concentrated principally within the East Texas river systems.

In addition to reservoir development, more changes are expected in riparian systems from ongoing timber harvest operations (Murphy, 1976; Texas Forest Service, 1992). These operations are sustained by a demand for hardwood products and a continuing desire from timber owners to market timber from locations that are difficult to access. Such timber operations have and will include conversion of hardwood forests to pine plantations, mixed pine-hardwood stands, or younger stands of hardwood timber (Larson et al., 1981; Parajuli et al., 2017).

Rice fields can provide habitat for wetland-dependent taxa, but historic and current rice management practices are driven foremost by agricultural economic decisions and may result in a spectrum of conservation value. Most rice rotation lands in Texas exist in the former coastal prairie footprint, where mosaics of grasslands and pothole wetlands once existed. Rice in Texas is typically cultivated on a 2- or 3-year rotation, such that a year of cultivation is followed by 1–2 years of other crops or fallow conditions. Consequently, the geographic footprint of rice rotation lands is two to three times the 185,000 acres cultivated annually in recent years (U.S. Department of Agriculture [USDA], 2023). However, total harvested rice acreage is only approximately one-third of the historical planted acreage. Factors influencing the reduction in rice cultivation acreage include expanding urban developments and simultaneous declines in available water during the growing season. Rice production practices have historically included a shallow water flooding regime after planting, and producers therefore need sufficient access to available water throughout the growing season (approximately March–October). Rice grown in Texas occurs within the historic Gulf Coastal Plain, and water availability occurs largely through either surface water diversion from the Colorado River or localized groundwater pumping. Within the last two decades, Colorado River surface water availability has decreased and become less reliable, resulting from drought, increased urban municipal demand, and overallocation for agricultural consumption. As a result, annual rice production has steadily declined, and remaining acreage is heavily dependent on access to local groundwater pumping. When considering rice's current conservation value, the declining footprint on the landscape is biologically significant and can in part explain regional distribution shifts of migratory waterfowl that have historically utilized flooded rice fields within the Gulf Coastal Plain in winter (Jefferies et al., 2004; Moore et al., 2023).

Total rice acreage planted in Texas has experienced long-term declines since the 1960s, owing to shifting agricultural demands and diminishing freshwater availability (Figure 2). Changing agricultural technologies may have cascading effects on the conservation value of rice. Wetland-dependent birds have historically capitalized on the inefficiencies of agricultural production such as "waste rice" (residual rice not harvested by agricultural equipment) or the presence of agricultural weeds that provide energetic value. Late-winter flooded rice fields can also be extremely important for aquatic invertebrate production that yield high sources of protein (Foley, 2015). Yet evolving technologies that increase production efficiency may simultaneously decrease value for wetland-dependent wildlife. For example, the advent of herbicide-resistant strains of rice seed has allowed producers to transition away from cultural practices to mitigate weed control and instead increase chemical control of weeds. The predominant form of rice planting has shifted away from aerial seeding (historically used to control against competitive weeds) to drill-seeding of herbicide-resistant rice varieties. As a result, the timing and extent of water applied to rice fields has shifted and may disproportionately affect bird species that use rice fields during spring migration or breeding (Hohman et al., 1994). Another evolving technology is the use of seed- and soil-treated pesticides to mitigate effects of target pests, such as the rice-water weevil *(Lissorhop-*

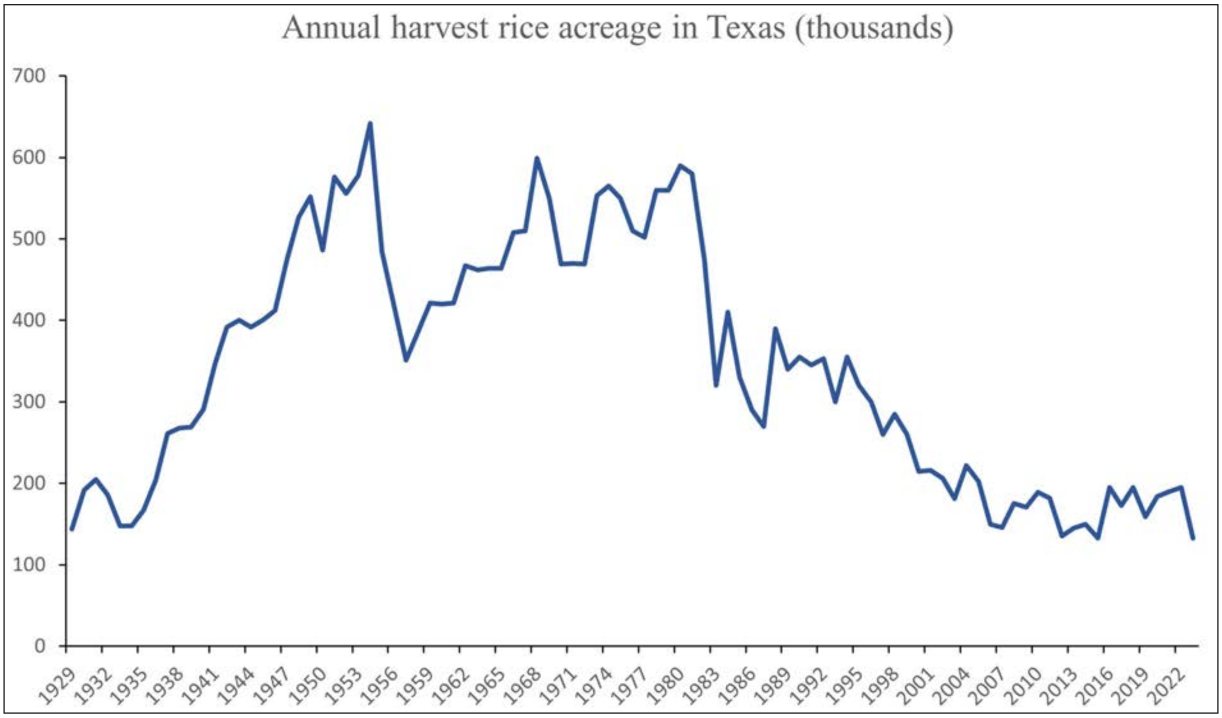

Figure 2. Graph reporting the declines in total harvest rice acreage in Texas 1929–2022 (United States Department of Agriculture [USDA], 2023).

trus oryzophilus Kuschel). These pesticides are highly effective at reducing target taxa and are used widely across cropping systems because their application is usually associated with higher economic returns (Wilson & Tisdell, 2001). However, many chemicals used are highly mobile in soil and water and have been found at high concentrations in wetland systems adjacent to treated crops (Krupke & Tooker, 2020; Main et al., 2014). While little research has evaluated the effects of seed-treated pesticides on aquatic invertebrates in planted rice in Texas or throughout the Gulf Coastal Plain, studies in other regions have demonstrated disrupted aquatic food webs in rice agricultural landscapes (Takeshita et al., 2020; Yamamuro et al., 2019). Emerging research suggests that many seed-treated pesticides have significant negative effects on nontarget vertebrates such as wetland-dependent birds (Kuechle et al., 2022). Carbamate and organophosphate insecticides often used in rice production exhibit acute neurotoxicity by impeding activity of acetylcholinesterase, an enzyme involved in nerve signal transmission, leading to adverse reproductive effects and mortality (Colovic et al., 2013; Fulton et al., 2013). Organochlorine pesticides, a class of chemical compounds that includes dichlorodiphenyltrichloroethane (DDT) and endosulfan, are now formally banned for use in agricultural applications, but these compounds are still present at varying concentrations in many vertebrates and wetland soils (Hidalgo et al., 2021; Land et al., 2019; Mora et al., 2020). Other pesticides still widely used in rice agriculture also pose a serious risk to human health. Exposure to compounds like 2,4-dichlorophenoxyacetic acid, a heavily used pesticide in Texas rice agriculture to control the growth of broad-leaf plants, is documented to significantly increase the risk of Non-Hodgkin's lymphoma in adults (McDuffie et al., 2001). Neonicotinoids, a popular class of chemical compounds used to treat insect pests in rice and other crop agriculture, have also been measured at relatively high concentrations in public drinking water and human urine (Thompson et al., 2023). A report by the U.S. Food and Drug Administration (2016) identified neonicotinoids as the most common pesticide found in baby formula and infant food in the United States. Neonicotinoids are persistent in the environment and unlike most pesticides cannot be washed off food prior to consumption (Bonmatin et al., 2015; Chen, 2014). Although studies required for pesticide registration showed neonicotinoids to be less toxic to humans than to insects, toxic effects such as an increase in cancerous liver tumors in mice were noted (Gibbons et al., 2015). More recent research has begun evaluating productivity in trending furrow-irrigated rice practices to reduce water consumption (Chlapecka et al., 2021). In the case of furrow-irrigation production, rice fields no longer hold a shallow flood throughout the growing season but rather experience short pulses of water and lack surface-water ponding. If trends in limited water availability continue, rice production may function more similarly to a dryland crop and result in a reduced overall value for wetland-dependent taxa that have used summer rice fields under traditional production practices (King et al., 2010).

Up until the mid-2000s, land conversion to agriculture was the largest driver of coastal wetland loss in Texas (Entwistle et. al., 2018). However, on the coast, this has been surpassed by loss from urban development and sea level rise (Armitage et. al., 2015; Keese, 2018). This loss is compounded by indirect effects of urban expansion. Impervious surfaces concentrate stormwater runoff, contaminating remaining wetlands and causing eutrophication and permanent changes in hydrology (Deegan et. al., 2012). Introduction of nonnative, ornamental plants can cause invasions and localized eradication of native wetland vegetation, decreasing the water filtration and nutrient capture capacity of natural wetlands (Havens et. al., 1997; Wetzel, 2005). The Integrated Climate and Land-Use Scenarios project administered by EPA predicts a 69% increase in urban land cover by 2100 statewide under the Shared Socioeconomic Pathways (SSP5) Representative Concentration Pathway scenario 8.5 (RCP85 climate and conversion scenario (EPA, 2017).

CONSERVATION AND MANAGEMENT STRATEGIES FOR TEXAS WETLANDS

Policy and Legal Framework

The Clean Water Act (CWA) is a federal law (CWA, 2000) enacted in 1972 that regulates the discharge of pollutants and fill into the waters of the United States, including wetlands. The CWA is designed to protect the chemical, physical, and biological integrity of the nation's waters by establishing basic structure and requirements for regulating pollutant discharges into the waters of the United States, including wetlands. The CWA requires individuals and entities seeking to discharge dredged or fill material (i.e., pollutants) into wetlands to obtain a permit from the U.S. Army Corps of Engineers (USACE). This permit process requires an evaluation of the potential impact on the wetland, as well as a consideration of alternative approaches that may be less harmful to the wetland. The CWA also establishes water quality standards for wetlands and other waters of the United States and requires states to develop programs to ensure these standards are met. It also provides for citizen suits against entities that violate the law, allowing individuals and groups to take legal action to protect wetlands in Texas and other states.

On May 25, 2023, the Supreme Court of the United States (SCOTUS) issued an opinion in *Sackett v. EPA,* a case challenging the proper way to determine whether a wetland is jurisdictional under the CWA. Before the opinion was issued, a wetland was considered jurisdictional under the CWA if it was 1) traditional navigable waters, territorial seas, and interstate waters; 2) impoundments of Waters of the United States (WOTUS); 3) tributaries to navigable waters or WOTUS impoundments; 4) wetlands adjacent to navigable waters or wetlands adjacent to waters with a significant nexus; or 5) intrastate lakes, ponds, streams, or wetlands that meet relatively permanent standard or significant standard. According to EPA, a significant nexus exists if the water body (alone or in combination) significantly affects the chemical, physical, or biological integrity of the traditional navigable waters, territorial seas, or interstate waters. As wetlands are dynamic, wetlands need not be permanently ponded or maintain a continuous connection to navigable waters via surface water to fall under federal jurisdiction. The law originally allowed for hydrological variability, including periodic drought and flooding, inherent to most wetlands. In the *Sackett v. EPA* ruling, the court narrowed the definition of WOTUS to include only wetlands that maintained a constant surface water connection to a navigable waterway. The interpretation of the language used in both the official ruling by SCOTUS and the subsequent policy enacted by EPA to accommodate the decision is heavily contested within and amongst agencies. Courts and regulatory bodies are now faced with defining "constant" surface water connection and other conditions in which an intermittent hydraulic connection may suffice to substitute this requirement. Interpreted in its most literal terms, the new definition of WOTUS significantly reduces the federal protection afforded to wetlands by excluding those subject to dry periods, flooding, and pulses of dense vegetation growth that may temporarily provide a barrier between the wetland and a nearby navigable waterway. Ignoring wetlands that experience periodic disconnection to larger water bodies may result in a substantial loss of wetlands across the United States. According to the NWI classifications of wetlands, this ruling effectively removes federal protection for approximately 93% of wetlands in Texas (USFWS, 2023b).

The Coastal Zone Management Act (CZMA) of 1972 (16 U.S.C. ch. 33 § 1451 *et seq.)*, administrated by NOAA, encourages coastal states to develop and enact coastal zone management plans that preserve, protect, develop, and where possible, restore or enhance the resources of U.S. coastal zones. The CZMA creates three national programs: the National Coastal Zone Management Program, the National Estuarine Research Reserve System, and the Coastal and Estuarine Land Conservation Program. These programs provide financial and logistical resources to coastal states in their efforts to satisfy CZMA-defined goals.

The Emergency Wetlands Resources Act (EWRA) of 1986 (1983) provides for the collection of entrance fees, 30% of which may be used for refuge operations and maintenance. The act also calls on the secretary of the interior to establish and periodically review a national wetlands priority conservation plan for federal and state wetlands acquisition, complete NWI maps for the contiguous United States by September 30, l998, and to update the report on wetlands status and trends at 10-year intervals. Section 303 of the EWRA amended the Land and Water Conservation Fund (LWCF) to require that each Statewide Comprehensive Outdoor Recreation Plan specifically address wetlands as an important outdoor recreation resource. It also requires that the state wetlands plan be developed in consultation with the state agency responsible for fish and wildlife resources, which in Texas is TPWD. Finally, TPWD has used guidelines of the secretary of interior, as authorized by the National Wetlands Priority Conservation Plan (NWPCP), to evaluate proposed acquisition of lands when using LWCF monies. The National Park Service provides approval authority to ensure that the expenditure of LWCF funds is guided by the Texas Outdoor Recreation Plan (TORP), the TORP Action Program, and the state's LWCF grant project selection process.

The LWCF Act of 1964 (1964), established by the U.S. Congress and administered by the National Park Service, fulfills a bipartisan commitment to safeguard natural areas, water resources, and cultural heritage and to provide recreation opportunities to all Americans. The fund helps strengthen communities, preserve history, and protect the national endowment of lands and waters. Since its inception, the LWCF has funded $4 billion worth of projects in every county in the country.

On August 4, 2020, the Great American Outdoors Act (GAOA) was signed into law, authorizing $900 million annually in permanent funding for the LWCF. Prior to GAOA's passage, funding for the LWCF relied on annual congressional appropriations. At no cost to taxpayers, the LWCF supports increased public access to and protection for federal public lands and waters—including national parks, forests, wildlife refuges, and recreation areas—and provides matching grants to state governments for the acquisition and development of public parks and other outdoor recreation sites. Agencies also partner with landowners to support voluntary conservation activities on private lands.

LWCF monies are provided to state and federal agencies to assist in acquiring and developing federal, state, and local government public outdoor recreation areas.

Federal and State Conservation Programs

USFWS is responsible for preparing the NWPCP, authorized by the 1986 EWRA. The NWPCP's ongoing program provides decision-making guidance on acquiring important, scarce, and vulnerable wetlands and establishing other non-acquisition protection measure priorities.

Section 301 of the EWRA requires the secretary of the interior to establish, periodically review, and revise a NWPCP that identifies federal and state acquisition priorities for various types of wetlands and wetland interests. The NWPCP is an ongoing program and continues to provide guidance for making decisions regarding wetland acquisition. The NWPCP applies only to wetlands that would be acquired by federal agencies and states using LWCF appropriations.

The State Wetlands Conservation Plan (SWCP) for state-owned coastal wetlands was drafted in 1994 and finalized in 1997 by TPWD and the Texas General Land Office, with assistance from other agencies (Ch. 14.002, Texas Parks and Wildlife Code). The SWCP includes definitions of 18 specific items/actions required by current legislation, including a definition of the term "wetlands"; a goal of no overall net loss of state-owned wetlands; an inventory; wetland mitigation policies; a requirement of freshwater inflows to estuaries; a navigational dredging and disposal plan; education and research regarding boating in wetlands; reduction of nonpoint source pollution; improved coordination among existing federal and state agencies; a plan to acquire coastal wetlands; and other provisions. The plan focuses on voluntary, nonregulatory approaches to wetland conservation in Texas by providing financial, technical, and education incentives to private landowners.

The Agricultural Conservation Easement Program is a voluntary program helping farmers and ranchers preserve their agricultural land and restore, protect, and enhance wetlands on eligible lands. The program has two easement enrollment components: agricultural land easements and wetland reserve easements. Under the agricultural land easement component, the Natural Resources Conservation Service (NRCS) provides matching funds to state, tribal, and local governments and nongovernmental organizations with farm and ranch land protection programs to purchase agricultural land easements. Agricultural land easements may be permanent, or the maximum duration authorized by state law. Under the wetland reserve easement component, NRCS protects wetlands by purchasing directly from landowners a reserved interest in eligible land or entering 30-year contracts on acreage owned by American Indian tribes, in each case providing for the restoration, enhancement, and protection of wetlands and associated lands. Wetland reserve easements may be permanent, 30 years, or the maximum duration authorized by state law.

Signed by the United States and Canada in 1986 and by Mexico in 1994, the North American Waterfowl Management Plan (NAWMP) stands as the fundamental alliance for bird conservation in North America and serves as a cornerstone upon which numerous other partnerships have been established. Waterfowl were then, and are now, the most prominent and economically important group of migratory birds in North America. By 1985, an estimated 3.2 million people were spending nearly $1 billion annually to hunt waterfowl. An additional 18.6 million people spent $2 billion each year to observe, photograph, and otherwise appreciate waterfowl.

Abundance estimates of many waterfowl species plummeted to record lows in the years leading up to the establishment of NAWMP. Recognizing the importance of waterfowl and wetlands to North Americans and the need for international coop-

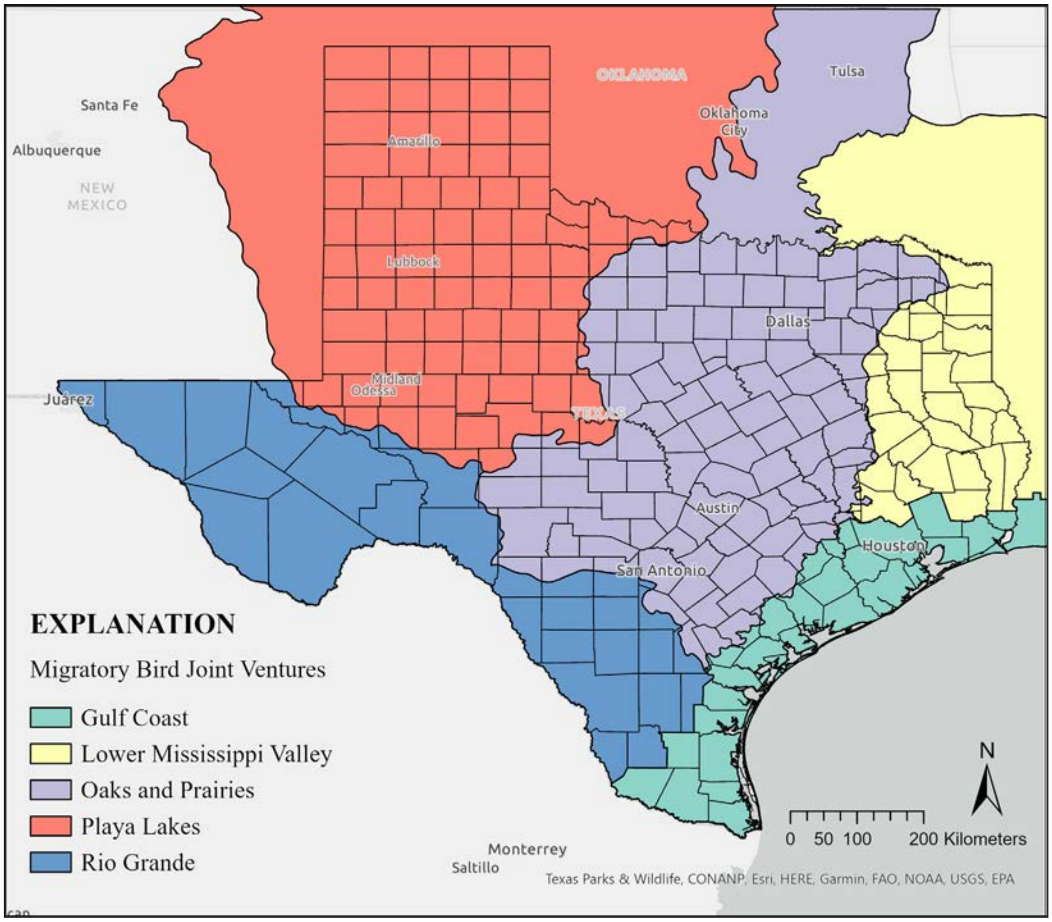

Figure 3. Administrative geographies of joint ventures in Texas as defined by the North American Waterfowl Management Plan.

eration to help in the recovery of a shared resource, the U.S. and Canadian governments developed NAWMP as a strategy to restore waterfowl populations through habitat protection, restoration, and enhancement.

NAWMP is uniquely enacted in its international scope but implementation at the regional level. Its success depends on upon the strength of partnerships: "joint ventures," comprised of federal, state, provincial, tribal, and local governments, businesses, conservation organizations, and individual citizens. Joint ventures develop implementation plans focusing on areas of concern within their geographies identified in NAWMP (Figure 3).

Partners' conservation efforts not only advance waterfowl conservation but also make substantial contributions toward the conservation of all wetland-associated species. There are 21 joint ventures actively working to implement NAWMP and other national/international bird plans in North America. The five joint ventures included in this text have a geographic scope and mission focused on conservation of important bird habitats, which include wetlands and associated species in Texas.

The Gulf Coast Joint Venture (GCJV) spans the coastal portions of Texas, Louisiana, Mississippi, and Alabama. As one of the joint ventures identified in the original NAWMP for its role in supporting wintering waterfowl, the GCJV maintains a strong focus on waterfowl and wetland conservation. As a continentally important region for shorebirds and waterbirds, too, the Joint Venture's work is dominated by wetlands. Science is focused on habitats that support mostly wetland-dependent bird populations, with special attention to the mottled duck, a resident species whose western Gulf Coast range is nearly coincident with the joint venture boundary.

The Lower Mississippi Valley Joint Venture (LMVJV) is a self-directed, nonregulatory, private–state–federal conservation partnership that implements the goals and objectives of national and international bird conservation plans within the Lower Mississippi Valley region. The LMVJV focuses on protection, restoration, and management of the birds found in the Lower Mississippi Valley as well as their habitats. The geographic scope of the LMVJV consists of the Mississippi Alluvial Valley and the West Gulf Coastal Plain, an area that includes a portion of East Texas.

The Oaks and Prairies Joint Venture is a regional, self-directed partnership of government and nongovernmental organizations, corporations, and individuals that works across administrative boundaries to deliver science-based bird conservation within the Edwards Plateau ecoregion and Oaks and Prairies ecoregion. The Playa Lakes Joint Venture is a nonprofit partnership of federal and state wildlife agencies, conservation groups, private industry, and landowners dedicated to conserving bird habitats in the Southern Great Plains, including rivers and streams, playas, saline lakes, and other wetlands. The Rio Grande Joint Venture is a regional, self-directed partnership that delivers science-based bird and habitat conservation in the Chihuahuan Desert (located in the Trans-Pecos region of Texas and north-central Mexico) and the Tamaulipan brushlands (located in South Texas and northeastern Mexico).

The Texas Coastal Management Program (CMP) was authorized by state legislation in 1989, with strengthening amendments in 1991. The Texas General Land Office was charged to coordinate and develop a long-term plan for the management of uses affecting coastal conservation areas, in cooperation with other state agencies including the Parks and Wildlife Department, the Attorney General's Office, the Texas Natural Resources Conservation Commission, the Texas Water Development Board, the Texas Department of Transportation, and the Railroad Commission of Texas" (Texas Natural Resources Code, § 33.052). The CMP directly affects only parts of the first tier of 19 counties of the Texas coast.

The focus of the CMP is to ensure that management of the uses of coastal natural resource areas is consistent with the CMP goals and policies. The program is organized to take advantage of existing authorities within state and local governments for an exclusive list of actions that must be consistent with the CMP. Consistency of an agency action is to be determined by that agency. Specific listed actions above certain thresholds may be reviewed by the Coastal Coordination Council with possible referral back to the action agency.

The National Estuary Program is a site-based program that aims to protect and restore the water quality and ecological integrity of estuaries of national significance. Currently, 28 estuaries located along the Atlantic, Gulf, and Pacific coasts and in Puerto Rico are designated as estuaries of national significance, including two in Texas. The two estuary programs located in Texas are described below.

The Coastal Bend Bays and Estuaries Program (CBBEP) is one of 28 estuary programs that fall under EPA's place-based, nonregulatory estuary protection program. The Galveston Bay Plan developed by the Galveston Bay Estuary Program advocates for an ecosystem approach to conservation that supports the maintenance of natural physical processes (e.g., sediment flows) and ensures the existence of an optimal variety and distribution of habitats. The primary goal of this program is protecting existing wetlands through acquisition.

The CBBEP provides a regional framework for conservation action in a 12-county area of Texas known as the Coastal Bend. The Coastal Bend includes three of the seven Texas estuaries: Aransas, Corpus Christi, and upper Laguna Madre. The CBBEP focuses on conservation of open water, submerged habitat, emergent wetland, and upland environments critical to the preservation of natural resources in the region. The CBBEP identifies regional conservation goals and calls for efforts to identify the most at-risk habitat types and work with landowners and local and state governments to preserve sufficient functional acreage of those habitats. It also identifies specific conservation tools necessary to attain this goal, including using conservation easements, tax abatements, or land acquisition.

To accomplish these goals, CBBEP has developed three subunits that manage separate environmental projects. The Land Conservation Program works with partners to conserve valuable habitats within the Coastal Bend. To date, CBBEP has conserved close to 13,000 acres and manages these lands for the long-term benefits for both wildlife and people. The Coastal Bird Program works to conserve birds along the Texas coast through on-the-ground habitat management, research, and education and outreach. The Delta Discovery Program aims to provide opportunities for classrooms and families to connect with nature and plant the seeds of stewardship in individuals whose decisions affect Texas estuaries.

The Midcontinent Shorebird Conservation Initiative (MSCI) is a multi-partner effort along interior portions of North and South America that implements a strategic conservation framework to support shorebirds throughout their annual life cycle. Wetlands in the midcontinent regions in the Americas (North, South, and Central), inclusive of Texas, provide wintering, migratory, and breeding habitat to more than 16.5 million shorebirds (64% of species found in the western hemisphere) annually. MSCI facilitates collaboration at the scales necessary to conserve migratory shorebirds and their habitats, enhancing stakeholder cooperation across 18 countries and 242 institutions. The strategic conservation framework gives partners the resources to identify and implement the management and legislation to meet their habitat and population objectives.

Wetland Loss Mitigation Strategies in Texas

In Texas, wetland/stream mitigation banks were created to answer the "No Net Loss" policy passed in a USACE–EPA memorandum of agreement in 1989. Mitigation banks are located off-site and identified for their potential to replace the exact functions and values of a wetland that will be negatively impacted by development activities. The natural resources replaced at a bank are quantified as a "credit" and then sold to developers to offset environmental impacts. Today, there are 48 wetland and stream mitigation banks, with an average size of

174 acres of permanently protected wetland considered mitigation for loss due to development (USACE, 2023).

Blue carbon, a term used to describe the carbon stored in oceanic and coastal ecosystems, has been a growing area of interest as Texas searches for the most efficient ways to battle climate change impacts. Given the relatively large carbon storage capacity of coastal wetlands, agencies such as TPWD, USFWS, and private organizations such as the Texas Coastal Exchange, The Nature Conservancy, and BCarbon have increased efforts to protect and restore coastal wetlands across both publicly and privately held land along the 3,355-mile (5,400-kilometer) Texas shoreline. BCarbon and TPWD have recently partnered to create the first blue carbon market in Texas that provides opportunities for commercial, industrial, and private landowners to participate in a blue carbon credit exchange. The protocol has a distinct focus on living shorelines to protect existing coastal wetlands for blue credit issuance.

Dozens of wetland restoration and conservation efforts are currently in place through resolutions passed by federal and state agencies.

CONCLUSIONS

Call to Action for Wetland Conservation and Management in Texas

Of Texas' 3,888,003 wetland acres, 389,150 (10%) are public (either federally or state managed). The remaining 90% are under private ownership and subject to individual stewardship and use (USFWS, 2023b). While sound management of public lands is important, programs that provide tools and resources to private landowners for the purpose of encouraging responsible and scientifically informed land stewardship are paramount in a state with such extensive private ownership. Existing private landowner programs (e.g., Texas Prairie Wetlands Project, Texas Playa Conservation Initiative) administered through TPWD have delivered over 400,000 acres of wetland habitat through restoration, construction, and repair statewide. Most programs available today to Texas landowners are jointly funded by state and federal agencies and nongovernmental organizations. Continued outreach and expanded access to funding for private landowners seeking to manage wetlands will likely continue to be an important component of successful conservation as Texas wetlands face intensifying threats due to population growth and climate change.

In a national survey conducted by the U.S. Geological Survey in 2017, most respondents reported being "very concerned" about the loss of wetland ecosystem services and least concerned about hunting opportunities and aesthetic value (Wilkins & Miller, 2018). Other polls have identified "availability of drinking water" as the most important water/wetland-related issue to the general (surveyed) public (Nesmith et. al., 2016). Among self-identified outdoor recreationalists, however, priorities differ slightly. Respondents to the same U.S. Geological Survey 2017 survey that identified as hunters reported being most concerned about loss of "wildlife habitat" as a wetland ecosystem service. The largest concern among both anglers and wildlife viewers was "pollinator habitat." All three recreationist groups still reported "clean water" in the top three concerns. Therefore, communication strategies that integrate the value of multiple ecosystem services, including a wildlife component, may be most productive. However, future outreach and education focusing on clean air, clean water, and water conservation, rather than hunting and recreational opportunities, may resonate with the widest variety of people. Evaluating the most effective communication methods may also prove beneficial, as most respondents preferred receiving their information by reading or accessing online content like video and other visual media (Wilkins & Miller, 2018). Additionally, of the 12,000 public comments received during the hearings of *Sackett v EPA,* a dominant concern was USACE and EPA's role in avoidance and minimization of wetland destruction and degradation (Hough & Robertson, 2009). An overwhelming majority of those who submitted public comments were in favour of strong federal regulation in U.S. wetlands management. While distrust of government remains common among some communities, Texas citizens demonstrate support for the regulation of shared water and other natural resources, especially as drought frequency and intensity increases and freshwater availability is threatened.

Attitudes towards climate change tend to be highly politically motivated in Texas. A 2019 poll by University of Texas and The Texas Tribune reported that two-thirds of Texas registered voters believe in the concept of climate change, but their urgency towards the issue varies considerably (Ramsey, 2019). Among those that identified as Democrats, 88% agree that climate change is happening, a view shared by 74% of self-identified independents and 44% of self-identified Republicans. Another poll administered by Climate Nexus and the Yale Program on Climate Change Communication reported nearly two-thirds (65%) of Texas registered voters support government action to address climate change, including more than one-third (36%) who strongly support it (Climate Nexus et al., 2019). Government action was most strongly supported by citizens residing in areas hardest hit by the effects of climate change in recent years. Seventy percent of Houston-area voters say their local area has been impacted by flooding, compared to almost half (48%) of Texas voters overall. More than a quarter of Houston-area voters (28%) reported having had to leave their home at least temporarily because of extreme weather. Successful strategies to combat climate change may involve increased research through reliable funding aimed at mitigation technologies with close cooperation between governmental agencies and the public to ensure legislative and regulatory action is representative of the concerns of the citizens of Texas.

Under the provisions of the EWRA, USFWS is required to assess and report on the status and trends of the nation's wetland resources at 10-year intervals, with the most recent report published in 2011: Status and Trends of Wetlands in the Conterminous United States 2004 to 2009. This series of reports is intended to help guide decisions by providing resource professionals and policy makers information on wetlands-related issues, such as the need for potential changes to incentive and disincentive policies, measures to conserve wetlands, funding priorities for wetlands protection, restoration and enhancement, and landscape-scale planning to address emerging issues that could negatively affect wetlands. The 2011 report measured trends by examining remotely sensed imagery for 5,042 randomly selected sample plots located throughout the conterminous United States. This imagery, in combination with field verification, provided a scientific basis for analysis of the extent of wetlands and changes that had occurred over the 4.5-year time span of the study.

In 2017, TPWD—in cooperation with private, state, and federal partners—produced a new 398-class, 10-meter spatial resolution land classification map for Texas to support statewide evaluation of wetlands and other vegetation communities. This was accomplished by attributing land cover and abiotic variables to 10-meter resolution image objects generated from the National Agriculture Imagery Program and then executing expert rules in the form of: land cover + abiotic variables = mapped type. In some regions, enhanced satellite land cover classification, landform modeling efforts, or other ancillary data were included to map important current vegetation types. More than 14,000 ground data samples were collected in support of the mapping effort, the largest effort of its kind in Texas. Significant overall improvements over existing maps included better spatial and thematic resolution as well as the mapping of many live oak types statewide, evergreen versus deciduous shrublands in appropriate regions, a wide variety of disturbance types, and types over unique soils (e.g., salty, deep sand, gyp-influenced). The vegetation database resulted in an accuracy of 74–90%. These products are used by a wide variety of partners in Texas for conservation planning and management. Ecologically significant wetlands and other vegetation communities are identified based on the habitat preferences of fish and wildlife identified by TPWD as species of greatest conservation need.

The regularity of these map products has been severely restricted by computational capacities (e.g., processing speeds, physical memory, storage). Wetlands are dynamic and subject to quickly changing land use practices and climatic conditions, making timely assessment and mapping crucial to sustainable management. Today, new technologies (e.g., cloud computing) allow for faster processing and the ability to manipulate and store big data. A typical image ("tile") from the Landsat 8 OLI/TIRS sensor, a commonly used sensor for landcover mapping, is 1.6 gigabytes for a coverage of 1.85 million acres. A single landcover map of Texas requires 93 tiles, or 149 gigabytes, of data. Processing all 7.7 trillion pixels has historically taken a significant amount of time, including post-validation and accuracy assessments. Cloud computing platforms like Google Earth Engine are publicly available geospatial analysis platforms capable of processing raw imagery, producing remotely-sensed products, and executing complex classification algorithms entirely in the cloud. The Google Earth Engine data catalog contains over 80 petabytes of geospatial data instantly available for analysis, expanding access to diverse data and drastically reducing processing and memory requirements. Cloud computing is now being used to automate map generation and update products yearly, monthly, and even daily (Amani et. al., 2020; Pan et. al., 2022; Pericak et. al., 2018). Future mapping, monitoring, and assessment of wetlands in Texas that capitalizes on advancing technologies would inevitably provide greater inferences for conservation and management.

Texas wetlands face intensifying challenges in the coming decades. Wetland systems not only underpin economic stability and uphold societal values but also play a significant role in storing GHGs and mitigating the effects of climate change. As Texas experiences rapid population growth, it is imperative to promptly address wetland loss and degradation to effectively mitigate the consequences of a shifting climate. Forward-facing regulatory and legislative actions that anticipate the current and projected effects of climate change, sea level rise, and urban expansion will likely aid in confronting ongoing and complex challenges. To this end, new and continued funding streams may help facilitate improved or novel infrastructure that protect coastal wetlands, their ecosystem processes, and the people that reside there. Incorporation of new technologies will allow for timely and cost-efficient large-scale monitoring of wetland loss and gain. Capturing the dynamic nature of wetlands is essential for the development and implementation of scientifically informed management, particularly in the wake of extreme weather events. The residents of Texas are largely in support of active management of the state's water resources, and we envision that the success of conservation initiatives will be strengthened when academic institutions, state and federal agencies, and conservation-minded private entities work together to ensure that the wetlands of Texas persist for wildlife and the generations to come.

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Appendix I

Characteristics and Distribution of Wetlands in Texas

Texas wetlands are diverse and cover vast acreage from the 367 miles of Gulf of Mexico coastline to the southern fringes of the Rocky Mountains system in West Texas. Wetland type varies according to soils, geology, and climatic norms and are summarized in Table 2.

Table 2. Estimated acreage of wetland types in Texas.

Wetland type	Acres
Forested shrub/scrub wetlands[1]	2,342,957[+]
Freshwater emergent	1,192,551
Playas[2]	392,648
Coastal freshwater marsh[1]	455,701
Other statewide[1, 3]	529,203[++]
Tidal or estuarine[1]	352,495

[+] inclusive of riparian zones
[++] inclusive of constructed wetlands and rice fields

[1] USFWS, 2023b
[2] Bogaerts, 2019
[3] USDA, 2023

PINEYWOODS

The forested and scrub-shrub wetlands of the East Texas bottomland hardwood forests are Texas' most extensive wetlands (Table 2; Dahl & Stedman, 2013; Purvis, 2007). The East Texas region is generally geographically defined by the state boundary to the east and north, coastally adjacent counties to the south, and the Trinity River to the west. These wetlands are mainly located in the floodplains of large East Texas rivers (Figure 4). As of 1980, Texas had an estimated 6.1 million acres of forested wetlands. Of these, 5.9 million acres were bottomland hardwood forests and 95,000 were open swamps and marshes (EPA, 2017). East Texas alone accounts for 71% of the state's forested wetland acres (40% of total wetland acres), with the remaining 29% located along riparian corridors across the state (Fretwell et al., 1996; USFWS, 2023b). The NWI now estimates only 2.3 million acres of forested and shrub-scrub wetlands remaining in Texas, a 61% decline in the last four decades (USFWS, 2023b).

Wetlands in East Texas have been extensively diked, cleared, and drained to make way for silviculture and other agricultural and industrial activities (Aust et al., 2020). While direct land conversion is partially responsible for the steep decline in these wetlands, hydrological disruption due to urban, suburban, and industrial expansion (e.g., oil and gas extraction remains the leading cause of wetland loss in the region (DeFauw, 2020). Bottomland hardwood forests and bogs are the result of decades, and centuries in some cases, of consistent hydrological cycles and are particularly sensitive to uncharacteristic flooding, nutrient loading, and altered flow (Hart & Davis, 2011).

Constructed wetlands, often created to satisfy NWMAP-defined mitigation requirements, attempt to restore or replace lost wetlands (USACE et al., 2002). However, these units typically support lower plant diversity, soil nutrient processing, and water quality relative to natural wetlands (Bishel-Machung et al., 1996; Craft et al., 1991; Hart & Davis, 2011; Shaffer & Ernst, 1999). Increases in runoff due to expanding development or redirection of water flow from channelization in natural wetlands can substantially disturb historic hydrological cycles in these systems, destroying decades or even centuries of stabilization necessary for nutrient and GHG sequestration, flood and pollution abatement, and wildlife habitat (Conner et al., 1981; Hart & Davis, 2011).

Texas' forested wetlands can be divided into five main vegetative groups according to hydrology and dominant species: cottonwood-hackberry-salt cedar brush/woods; pecan-elm forest; water oak-elm-hackberry forest; willow oak-water oak-tupelo forest; and bald cypress-water tupelo swamp (Messina & Conner, 2019). Bottomland hardwood forest ecosystems provide habitat for nesting, spawning, rearing, and resting wildlife. These wetlands also provide irreplaceable storage areas for storm and floodwaters, in addition to being natural groundwater recharge areas (Conner et al., 1981).

Flora and Fauna

Bottomland hardwood and swamp communities in Texas support over 180 woody species and 802 herbaceous species (Austin College & the Botanical Research Institute of Texas, 2020; Vines, 1977). Characteristic species in swamps include bald cypress *(Taxodium distichum)*, water tupelo *(Nyssa aquatica)*, water hickory *(Carya aquatica)*, water locust *(Gleditsia aquatica)*, water tupelo *(Nyssa sylvatica)*, American Sycamore *(Platanus occidentalis)*, buttonbush *(Cephalanthus occidentalis)*, and swamp privet *(Foresteria acuminata)*. Dominant species of bottomland hardwood forests are water oak *(Quercus nigra)*, willow oak *(Quercus phellos)*, water tupelo *(Nyssa sylvatica)*, American elm *(Ulmus americana)*, overcup oak *(Quercus lyrata)*, green ash *(Fraxinus pennsylvanica)*, pecan *(Carya illinoinensis)*, and possumhaw *(Ilex decidua)*. Periodic inundation prevents the establishment of upland species and maintains the functioning of these vegetation types. The bottomland hard-

Figure 4. Distribution and extent of forested and shrub/scrub wetlands in Texas. (USFWS, 2023b).

wood forests of central East Texas are geologically unique in that they contain the Weches Formation, a feature formed during the Eocene Epoch (56 to 33.9 million years ago; George & Nixon, 1990). The soil that defines this feature, fossiliferous glauconite rich sand, supports the only stands of Texas golden gladecress *(Leavenworthia texana)*, a federally listed endangered species and endemic to this region (George & Nixon, 1990). Glauconite soils are currently being investigated as an environment-friendly, slow-release fertilizer, which could have meaningful implications for future agricultural practices (Rudmin et al., 2019).

East Texas bogs, found in association with bottomland hardwood forests, occur when bowl-shaped terrain features restrict water drainage. These systems are usually wet year-round because of continuous groundwater seepage. Acidic conditions and poor soil aeration support plant communities containing a variety of specialized species, including carnivorous plants such as sundews and pitcher plants (members of the Droseraceae and Nepenthaceae families, respectively). Other plants include red maple *(Acer rubrum)*, wax myrtle *(Morella cerifera)*, alder *(Alnus* spp.), bladderwort *(Utricularia* spp.), orchid (members of the Orchidaceae family), fern (members of the Polypodiopsida class), and irises *(Iris* spp.).

Freshwater marshes in East Texas support both perennial and annual vegetation. Species occupying the fringe or shallow areas include several smartweeds *(Persicaria* spp.), arrow arum *(Peltandra virginica)*, spikerushes *(Eleocharis* spp.), arrowhead *(Syngonium podophyllum)*, maidencane *(Panicum hemitomon)*, and plumegrass *(Saccharum giganteum)*. These marshes also contain extensive stands of cutgrass *(Zizaniopsis miliacea)* in deep areas. Numerous submergent plant species are also found in deeper open water pools. Cutgrass marshes are seldom dry. Historically, during extreme, infrequent droughts, prolonged fires burned the organic peat soils of cutgrass marshes. These fires reduced or eliminated the dense herbaceous cover, which temporarily favored the growth of many annual plant species. Species composition is best maintained by periodic prescribed burns to control woody plants (Dickson, 1978; Rudolph & Ely, 2000).

Many faunae found in bottomland hardwood forests and freshwater marshes of East Texas are wetland-obligate (e.g., river otter, *Lontra canadensis;* American beaver, *Castor canadensis;* Allen et al., 2001; Coleman et al., 2008; Dickson, 1978). These wetlands provide crucial overwintering, migratory, and breeding habitat for many waterfowl including wood duck *(Aix sponsa)*, mallard *(Anas platyrhynchos)*, northern pintail *(Anas acuta)*, green-winged teal *(Anas crecca)*, blue-winged teal *(Anas discors)*, scaup *(Aythya* spp.), gadwall *(Mareca strepera*), American wigeon *(Anas americana)*, snow goose *(Chen caerulescens)*, and Ross's goose *(Chen rossii)*. Several of these species are considered highly valuable game animals. Waterfowl hunting in Texas generates an estimated $1 billion annually and supports over 14,000 jobs across the state (Table 1). Wetlands in East Texas also provide habitat for several declining, threatened, and endangered species including timber rattlesnake *(Crotalus horridus)*, alligator snapping turtle *(Macrochelys temminckii;* federally proposed threatened), wood stork *(Mycteria americana;* federally endangered, state threatened), red-cockaded woodpecker *(Picoides borealis;* federally endangered), and bald eagle *(Haliaeetus leucocephalus)*.

COASTAL PRAIRIES AND MARSHES

Texas coastal wetlands provide foraging habitat for both colony-nesting and overwintering waterbirds. Breeding species that nest on barrier islands, coastal bay islands, and the mainland include the American oystercatcher *(Haematopus palliatus)*, great blue heron *(Ardea herodias)*, great egret *(Ardea alba)*, reddish egret *(Egretta rufescens)*, tricolored heron *(Egretta tricolor)*, and roseate spoonbill *(Platalea ajaja)*. The location and size of these breeding colonies is directly linked to the availability of coastal wetlands (Gibbs & Kinkel, 1997), and wetland protection is critical to the long-term sustainability of colonies (Bates et. al., 2016; Gibbs & Kinkel, 1997).

As of 2023, coastal wetlands comprise 710,300 acres of the Texas Gulf Coast (USFWS, 2023b). These wetlands are directly on the coast, adjacent to estuaries, or in or near tidal reaches of large, sluggish coastal rivers (Figure 5). Estuarine wetlands such as saltmarshes (emergent) and tidal flats (mostly unconsolidated-shore and -bottom) range from brackish to highly saline. Of the 710,300 acres of coastal wetlands, 60.8% are salt marsh, 38.7% are tidal flats, and 0.41% are forested/scrub-shrub wetlands (USFWS, 2023b). It is important to note that these estimates from the NWI do not include cultivated rice fields (extensive along the mid- and upper coast) as they are not able to support hydrophytic vegetation in the absence of artificial pumps (Dahl & Stedman, 2013). However, idle fields in rice rotations are often dominated by hydrophytic vegetation, regardless of pump operation. Further, idle rice fields have been documented as having similar densities of moist-soil seed production as units that are intensively managed as such (Marty et al., 2015).

Agricultural lands in rice rotation cultivations are unique in their characteristics and contributions to coastal wetland systems. Systems of low levees, necessary to guide irrigation flushing or flooding, provide infrastructure that often passively captures rainfall or actively manages targeted flooding for waterfowl hunting, crawfish production, or other purposes. Consequently, flooded rice lands provide some surrogate functions (e.g., waterbird habitat and water quality improvement) for the imbedded pothole wetlands they replaced and are an important component of the coastal wetland system (Huner et. al., 2002; Manley et. al., 2004).

However, the conservation value of flooded rice fields for wetland-dependent taxa, particularly birds, is nuanced and continues to evolve.

Flora and Fauna

Wetlands along the Texas Gulf Coast are located at the interface between freshwater and saltwater and are thus subject to tides (Lee et al., 2006; Megonigal & Neubauer, 2019). Fluctuating water levels drive cycles of vegetative growth and die-off, leading to thick, stratified layers of organic matter. This makes these wetlands nutrient-rich environments that support large populations of phytoplankton, algae, and biofilm (Megonigal & Neubauer, 2019). Biofilm is a complex community of microorganisms that attach to surfaces such as rocks, plants, and sediment (Lagos et al., 2016). It provides an important source of nutrition for shorebirds, as it contains a variety of small organisms that shorebirds can consume (Taft & Haig, 2005; Wieczorek & Todd, 1998).

Algae are also an important direct food source and can make up a significant portion of the diets of many species of shorebirds, including sandpipers and dunlins *(Calidris* spp.), plovers *(Charadrius* spp.), and dowitchers *(Limnodromus* spp.; Miller

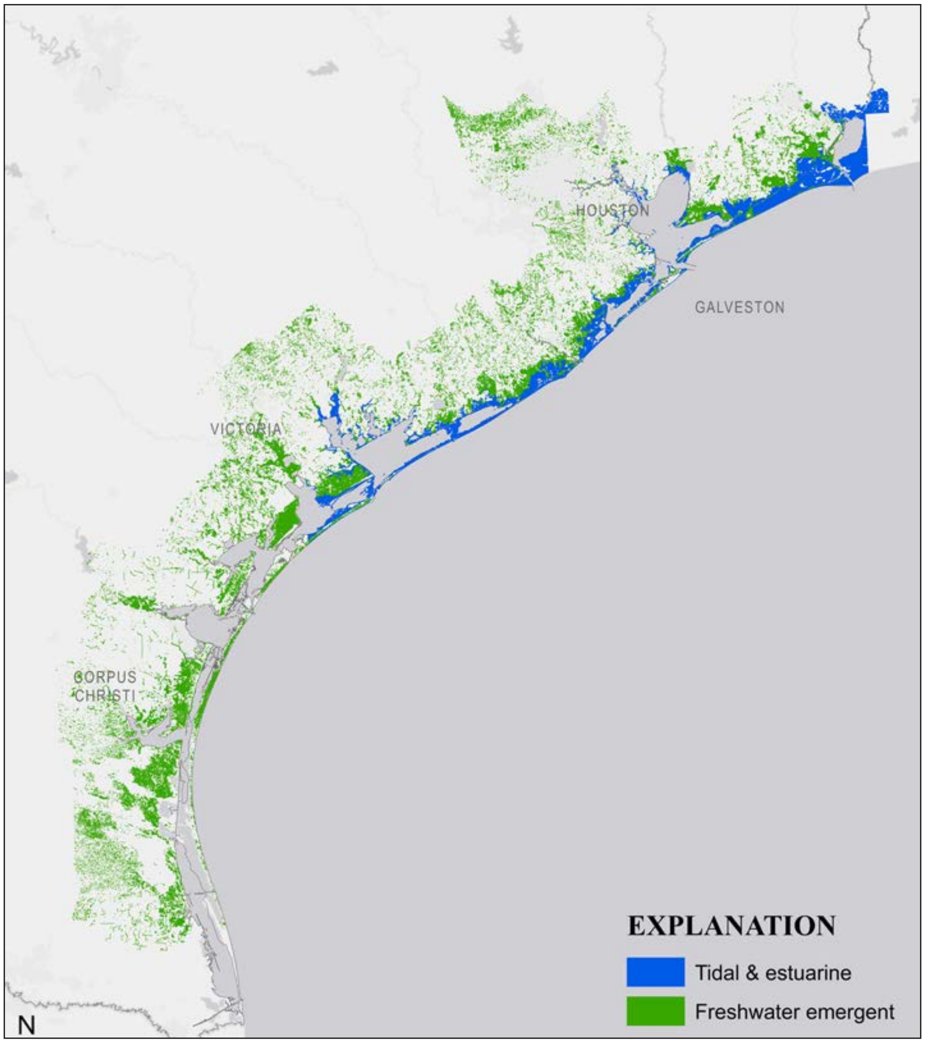

Figure 5. Distribution and extent of coastal freshwater emergent and tidal/estuarine wetlands in Texas (USFWS, 2023b).

& Ullman, 2004). Algae can form dense mats on the surface of water, providing rich feeding grounds that support migrating and breeding bird populations (Colwell, 2010; Taft & Haig, 2005). The availability of biofilms and algae can have a significant impact on shorebird populations. Excessive nutrient loading (e.g., from storm or agricultural runoff) can lead to an increase in algae, which in turn leads to a decline in the abundance of biofilm. Reduced availability of biofilm is known to have a negative impact on shorebird populations (Kuwae et al., 2021).

Coastal wetlands are continentally important as migration and wintering habitat for waterfowl, shorebirds, long-legged waders, colonial-nesting waterbirds, and secretive marsh birds. Texas coastal wetlands and associated grasslands support a significant portion of the world's population of year-round resident mottled ducks *(Anas fulvigula)*. Large concentrations of northern pintail *(Anas acuta)* and redhead *(Aythya americana)* rely on rice fields and freshwater wetlands on the adjacent mainland as winter food sources (Anderson, 1994; Ballard, 2007; Ballard et. al., 2021). Waterfowl forage on seeds of annual vegetation (e.g., *Echinochloa* spp., and *Persicaria* spp.), seeds and leaves of submersed aquatic vegetation (e.g., *Potamogeton pectinatus, Ruppia maritima,* and *Najas guadalupensis)*, and below-ground parts of many plant species (e.g., *Halodule wrightii* and *Vallisneria americana)* common in Texas coastal wetlands. Waterfowl, shorebirds, and many others forage on aquatic micro- and macro-invertebrates that are common in coastal wetlands. Waterbird species that breed in Texas coastal wetlands often do so in emergent aquatic vegetation, subsequently using such vegetation as escape cover during brood-rearing.

The largest population of the federally endangered whooping crane *(Grus americana)* spends nearly half its annual cycle in coastal wetlands in and around Aransas National Wildlife Refuge (Ritenour et al., 2016). The availability of coastal wetlands is thought to be the primary limiting factor to the population (Lumb, 2014). Relying on coastal salt marshes, tidal ponds, and upland freshwater ponds, whooping cranes feed mostly on blue crabs *(Callinectes sapidus)*, stout razor clams *(Tagelus plebeius)*, wolfberry fruit *(Lycium virginiana)*, and crayfish *(Cambarus hedgpethi;* Hunt & Slack, 1989). During periods of drought, their use of upland freshwater ponds increases due to high salinity along bays and estuaries (Kirkwood & Smith, 2018).

Coastal wetlands in Texas provide crucial spawning and nursery habitat for several species of fish and shellfish including black drum *(Pogonias cromis)*, southern flounder *(Paralichthys lethostigma)*, sheepshead *(Archosargus probatocephalus)*, red snapper *(Lutjanus campechanus)*, white shrimp *(Penaeus setiferus)*, brown shrimp *(Penaeus aztecus)*, blue crab *(Callinectes sapidus)*, and eastern oyster *(Crassostrea virginica)*. These species help to support a substantial commercial fishery on the Texas coast. In 2001, total landings from these fisheries amounted to $38.7 billion (Culbertson et al., 2004). Recreational saltwater fishing also generates an estimated $1.3 billion annually relying on aforementioned commercially landed species and others including Atlantic croaker *(Micropogonias undulatus)*, spotted seatrout, and red drum (Table 1).

Wetlands in this region are often dominated by cordgrasses *(Spartina* spp.), buttonbush *(Cephalanthus occidentalis)*, American water-willow *(Justicia americana)*, swamp milkweed *(Asclepias incarnata)*, Gulf Coast lupine *(Lupinus westianus)*, beach morning glory *(Ipomoea imperati)*, and beach evening primrose *(Oenothera drummondii)*, among others. These systems were historically controlled by fire, maintaining a state of succession suitable for the fish and wildlife species adapted to coastal wetlands. Suppression of fire to protect residential and industrial infrastructure on the coast has led to drastic shifts in vegetative assemblages. Increases in perennials and woody species have crowded out annuals and herbaceous species crucial for forage and refuge for many wildlife species including whooping crane, blue crab, brown shrimp, and American alligator *(Alligator mississippiensis;* Golden et al., 2022; Joanen & McNease, 1989; Pauly & Ingles, 1986). In addition to fire, freshwater inflows historically supported this estuarine system, defined as a mixing zone of salt and fresh water. Freshwater inflows have been drastically altered across the Texas coast by hydrologic alterations like drainage canals, the Gulf Intracoastal Waterway and its associated spoil banks, and over-allocation of many river waters for municipal, industrial, and agricultural use.

HIGH PLAINS

Playas are shallow, circular basins characterized by the presence of Randall clays and their sole dependence on rainwater (Bolen et al., 1989). These features spread across six states, of which Texas has the most (23,041 playas) and largest. Texas playas range in size from 1 acre to over 800 acres (mean 17 acres), cover a total of 296,000 acres, and account for 4% of Texas' total wetland acreage (Hoagland & Collins, 1997). They are the primary source of recharge (95%) for the Ogallala Aquifer, which is one of the largest underground freshwater sources in the world and is responsible for 30% of all water used for irrigation agriculture in the United States and 82% of the drinking water used within the boundaries of the Texas High Plains (Dennehy, 2000; USDA, 2011).

Playa wetlands are unique in that the hydrological cycle often includes extended dry periods (Rosen, 1994; Smith et al., 2011). Dry periods allow for the Randall clay soils to desiccate, causing large fissures in the clay basin and vegetation dieback. When rainfall returns, water travels along deep fissures and pores left by plant roots, reaching the aquifer below at a rate 10–10,000 times faster than via the surrounding ground. Eventually, the clay soil swells shut, allowing water to pool, which provides a vital water source for plants and wildlife in an otherwise arid to semiarid landscape. This hydrologic cycle makes playas particularly sensitive to changing fire, rainfall, and temperature regimes (Adams & Sada, 2014; Salley et al., 2022). Land use also presents a threat to playas via pits, ditches, road construction, and runoff from row crops. Today, only an estimated 4,080 playas in Texas remain functional (17.7%). Altered and nonfunctional playas demonstrate significantly reduced recharge and increased evaporative water losses relative to naturally functioning playas (Bolen et al., 1979; Bolen et al., 1989). The Ogallala Aquifer has historically been—and continues to be—pumped at a rate higher than recharge (Almas et al., 2004; Hornbeck & Keskin., 2014; Steiner et al., 2021). In some areas of Texas, the Ogallala Aquifer is now too depleted for any groundwater extraction, and those producers and municipalities have been forced to move or acquire water from elsewhere (Zellmer, 2007). Approximately 98% of the playa wetlands in the High Plains of Texas are found on private lands, creating challenges for conservation and restoration. Though most landowners know what playas are, few understand their function and role in water purification and aquifer recharge. Even fewer landowners are interested in conservation programs specific to playas due to conflicting agricultural and ranching interests.

Flora and Fauna

The flora of playa lakes is as diverse as the playas themselves, with the vegetation types influenced by surrounding land use, playa modification, and local rainfall patterns (Johnson et al., 2011). Species characteristic of playas include smartweeds, flatspine bur ragweed *(Ambrosia a canthicarpa)*, barnyardgrass *(Echinochloa crus-galli)*, blueweed sunflower *(Helianthus ciliaris)*, buffalograss *(Buchloe dactyloides)*, spikerushes, redshank *(Persicaria maculosa)*, western wheatgrass *(Agropyron smithii)*, and virginia pepperweed *(Lepidium virginicum;* Hoagland & Collins, 1997). The dramatic fluctuations of water in playas do not permit a Clementsian view of succession, but instead local vegetation appears to be the result of current and recent environmental conditions, a Gleasonian view (Bolen et al., 1989; Johnson et al., 2011).

Playa wetlands provide essential migratory stopover habitat for waterfowl species such as mallard, gadwall, northern pintail, and green-winged teal, blue-winged teal, and sandhill crane *(Grus canadensis;* Anderson & Smith, 1998; Anderson et al., 2000; Moon & Haukos, 2006). Approximately 90% of overwintering waterfowl in the High Plains inhabit playa wetlands (Nelson et al., 1984). It is estimated that as many as one-third of the northern pintails in the Central Flyway winter in this area, and even more migrate through this region. Estimates from recent (2010–2022) mid-winter surveys suggest that 308,000 ducks and 403,000 geese winter in this region (TPWD, 2022). These estimates are considerably lower than previous decades, due to changes in irrigation practices, playa modification, and sedimentation. Wet playas are often the only source of freshwater for hundreds of miles due to the episodic nature of rainfall and arid climate of this region. Many species rely on these oases, including 37 mammal species, including pronghorn *(Antilocapra americana)*, white-tailed deer *(Odocoileus virginianus)*, and black-tailed prairie dog *(Cynomys ludovicianus)*; 13 amphibian species, including Great Plains toad *(Anaxyrus cognatus;* federal listing under review), barred tiger salamander *(Ambystoma mavortium mavortium)*, and spadefoot toads *(Scaphiopus* spp.); 185 species of birds; and 350 species of plants (Gray et al., 2004; Smith, 2003; Smith et al., 2004a).

WEST AND CENTRAL REGIONS

The riparian zone of a river, stream, or other flowing water body refers to the land adjacent that is periodically subject to flooding. Riparian floodplain areas are transition zones that connect rivers, streams, and bayous to the associated upland forests, grasslands, and other habitats from which their waters flow (Jones-Lewey, 2016; Naiman et al., 2010).

Texas has approximately 191,000 miles of rivers and streams (Alldredge et al., 2014), and riparian areas with their associated woodlands are considered to be the most widespread wetland type in Texas (Haggerty & Meuth, 2015). Due to the vague definition of "riparian wetland," estimates of total acres in Texas are unavailable. The NWI is in the process of mapping riparian areas but has so far only completed a portion of the Texas Panhandle (USFWS, 2023b). However, Swift (1984) attempted to estimate riparian coverage nationwide using a synthesis of available literature, of which many methods included aerial imagery and ground surveys. This study estimated riparian coverage of 25–35 million acres as of 1984, a 25–47% loss since European settlement.

Riparian wetlands are often identified by presence of depositional soils, topographic relief, and vegetation adapted to episodic inundation. No single definition for "riparian wetland" has been universally accepted by relevant federal agencies; thus, the diversity within this wetland type is tremendous. Riparian zones in Texas are identified by watershed in Figure 6. Riparian areas play a vital role in improving water quality by filtering out pollutants and sediment from runoff before it reaches larger creeks, tributaries, and rivers (Revenga & Kura, 2003). Riparian wetlands can remove up to 90% of the phosphorus, 50% of the nitrogen, and 80% of suspended sediment (among other herbicides, pesticides, and heavy metals) from storm and agricultural runoff (Bash & Ryan, 2002; Phillips, 2017; Wu et al., 2023). A healthy, well-vegetated riparian zone has a diversity of native plants of various age classes that help ensure proper function by slowing and infiltrating stormwater, trapping and holding sediments, and reducing streambank soil erosion and downstream flooding. The increased infiltration recharges groundwater and ensures continued spring flow. Shade from riparian vegetation reduces daily temperature fluctuations, which benefits aquatic and terrestrial animals and decreases water loss due to evaporation. Woody debris provides instream structure that is used by aquatic organisms for shelter, while leaf litter contributes nutrient inputs to the food web (Jones-Lewey, 2016). These wetlands provide essential food, water, and shelter for a wide variety of resident plant and animal species, as well as providing protected migration routes and stopover habitat for a variety of animals.

Flora and Fauna

Plant and wildlife species characteristic of riparian zones vary widely by location and watershed. Most plant species found in these wetlands are adapted to episodic flooding and frequent inundation, including American sycamore *(Platanus occidentalis)*, willows *(Salix* spp.), box elder *(Acer negundo)*, eastern cottonwood *(Populus deltoides)*, hackberry *(Celtis occidentalis)*, loblolly pine *(Pinus taeda)*, pecan, river birch *(Betula nigra)*, iris, cattails *(Typha* spp.), and spiderwort *(Tradescantia* spp.). As these wetlands are as diverse as they are unique, they provide habitat to several endemic, threatened, and endangered species. Texas wild-rice *(Zizania texana)* is a federally endangered perennial aquatic grass found only in the spring-fed streams of the San Marcos River in Central Texas (Poole, 2008; USFSW, 1978). Due to its extreme rarity (in five or fewer populations) and limited distribution, Texas wild-rice was one of the first plants listed as a critically imperiled species at high risk of extinction (USFSW, 1978; Wilson et al., 2017). Efforts to restore this species in its natural range through increased protection measures and supplemental planting have been moderately successful. A recent study demonstrated an exponential increase in Texas wild-rice coverage over 30 years, likely due to increased protection measures and supplemental planting (Poole et al., 2022).

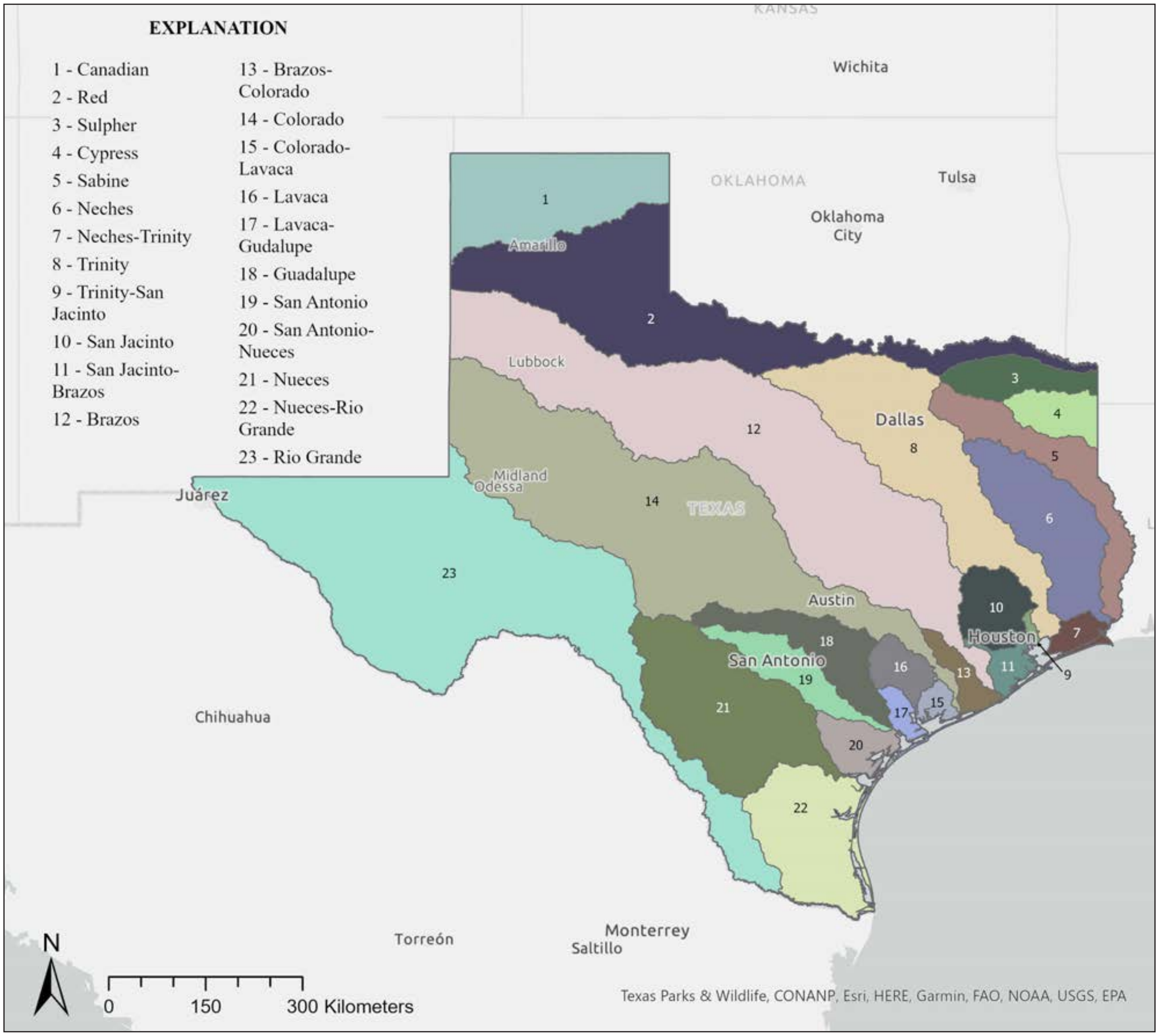

Figure 6. Representation of the 23 major watersheds in Texas.

The Texas blind salamander (federally endangered) is an endemic, cave-dwelling, salamander with distribution limited to a few locations in Central and South Texas (Hillis et al., 2001). This species has adapted to a completely dark environment, completing its full life cycle below 58 meters in the Edwards Aquifer (Krejca et al., 2007). Being confined to the aquifer, the Texas blind salamander is completely reliant on groundwater and is continually threatened by nutrient-rich runoff, typically filtered by riparian wetlands, and reduced recharge (Kuczek & White, 2023; Shockey, 1996).

The resacas in South Texas also fall under the umbrella of riparian wetlands. Resacas (or oxbow lakes) are formed by remnant river bends left by periodic floods and accrete soil from repeated flooding (McIntosh & McIntosh, 2014). On the Rio Grande and its major tributaries, these wetlands ultimately produce rich, biologically diverse systems that support many plants, invertebrate, amphibian, fish, and migratory bird species in the semiarid environment of South Texas (Jahrsdoerfer & Leslie, 1988; McIntosh & McIntosh, 2014; Perez et al., 2017). Permanent resacas in Cameron County serve as habitat for another aquatic salamander, the endemic and threatened Rio Grande siren (*Siren intermedia texana;* LaFortune, 2015). Threats to these species are shared among many others found in riparian zones across Texas, with decreased volume and quality of downstream and spring flow being arguably the most imminent (Alldredge & Moore, 2014; Duke et al., 2007; Poole et al., 2022; Schmidly & Ditton, 1979).

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