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Best Management Practices for Firefighting in the Karstic Edwards (Balcones Fault Zone) Aquifer of South-Central Texas

Geary M. Schindel[1]*, Rudolph A. Rosen[2]

Abstract: Karst aquifers are vulnerable to contamination from hazardous pollutants that can harm drinking water supplies, species inhabiting aquifers and springs, and other karst water resources. This paper presents best management practices (BMPs; Appendix I) designed for use by first responders and for use in developing training curricula and tools to assist first responders in protecting karst water resources. Training and tools based on the BMPs will help first responders prevent or reduce runoff of potentially hazardous materials that can rapidly enter an aquifer during firefighting and other responses to emergencies in locations where hazardous materials are stored, such as in retail centers, warehouses, industrial and agricultural facilities, and in vehicles and rail cars along transportation corridors. Emergencies can include fire caused by accident or arson, terrorist attack, flood, high wind, lightning, and explosion in structures and transport vehicles. BMPs are provided for preplanning, response during an emergency, and cleanup after an event. Future work will include these BMPs in first responder training curricula and a georeferenced database that will include recommendations for protective action in areas containing karstic features (Appendix I) where hazardous materials may be present.

Keywords: best management practices, Edwards Aquifer, karst aquifer, water quality, aquifer recharge zone

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Terms used in paper

Acronym / Initialism	Descriptive Name
BMP	best management practice
DNAPL	dense non-aqueous phase liquid
EAA	Edwards Aquifer Authority
FFPs	firefighting products
GIS	geographic information system
RM	released material
RQ	reportable quantity

INTRODUCTION

In 2007, the Texas Legislature directed the Edwards Aquifer Authority (EAA; Appendix I) to work to protect the water quality of the karstic (Appendix I) Edwards Aquifer from the impact of fire control in the Edwards Aquifer's recharge zone (Senate Bill 585). The Legislature was responding to concern over potentially catastrophic aquifer pollution events that can occur in the recharge zone during fire control or other emergency responses where hazardous materials (Appendix I) are present. The event that prompted action by the Legislature was a fire called "Mulchie" that burned for three months in an eight-story high, thousand-foot-wide, mulch and debris pile on the edge of the Edwards Aquifer's recharge zone near San Antonio.

The mandate from the Legislature called for reducing impacts on aquifer water quality from fire control activities in the presence of hazardous and other polluting materials in the Edwards Aquifer's recharge zone. This includes locations where there are existing threats to water quality due to on-site storage, production, or transport exchanges of hazardous materials, as well as along transportation corridors such as roadways, rail lines, and airports.

Work by the EAA on developing techniques to protect water quality has been underway since that time. This paper describes the development of best management practices (BMPs) to protect karstic watersheds and important groundwater resources from potentially catastrophic hazardous materials releases. Hazardous materials can enter karst aquifers directly or be mixed in water or other fire suppressant runoff from firefighting in response to emergencies. Examples of emergencies that could jeopardize the water quality of the aquifer include fires caused by accident or arson, terrorist attacks, floods, high winds, lightening, and explosions in structures and along transportation corridors where hazardous materials are being stored or transported. Locations that may contain hazardous materials include retail centers, manufacturing and agricultural facilities, warehouses, and in vehicles, rail cars, and pipelines.

These BMPs are a critical component of a more comprehensive project now underway to develop training curricula using the BMPs as a basis for first responder instruction and for developing plans and specialized techniques and tools for use by first responders. These will include a georeferenced database and user interface that will provide data displaying sensitive karst areas, direction of water flow across the landscape, and embedded recommendations for protective action. We expect the BMPs, curricula, training, and tools to serve as a model national standard for emergency response in karst watersheds.

KARST SYSTEMS AND RISK TO WATER QUALITY

In the United States, 20% of the land surface is karst and 40% of the groundwater used for drinking comes from karst aquifers. The U.S. Environmental Protection Agency has recognized karst aquifers as the groundwater type most vulnerable to hazardous contaminants and pollution (Schindel et al. 1996; USEPA 2002). Karst aquifers are unique because of their

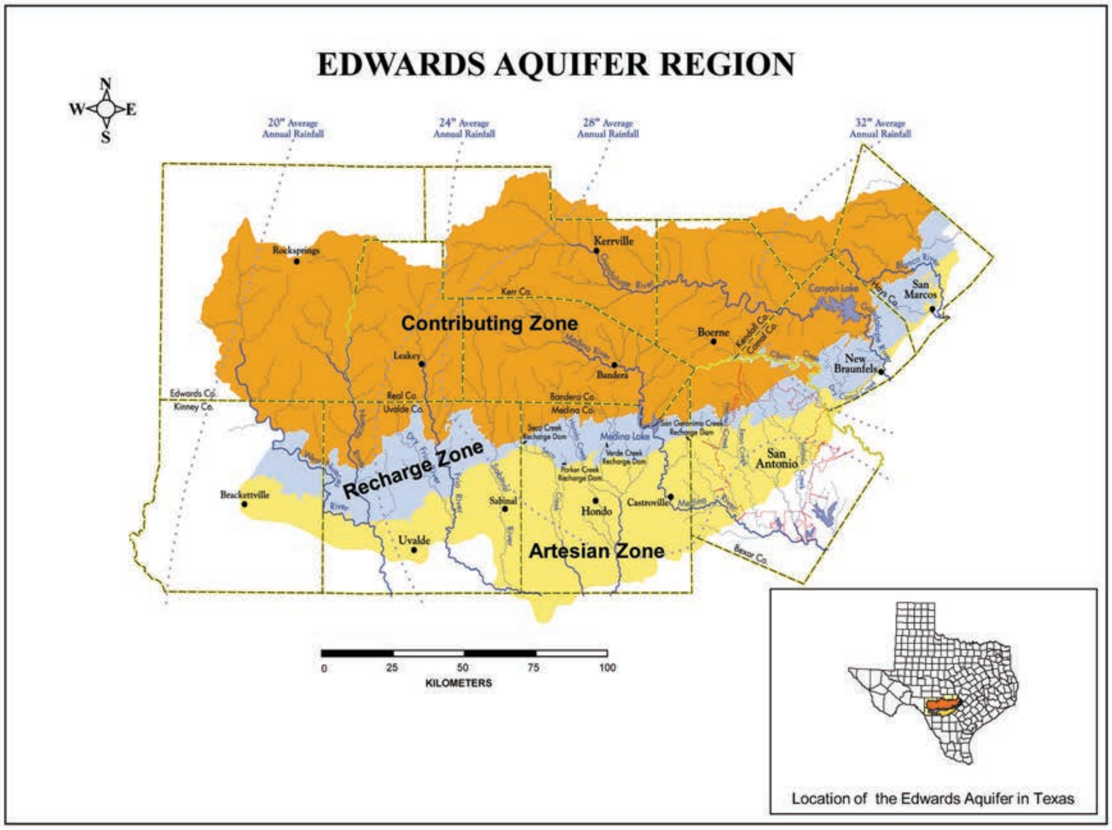

Figure 1. Location of the Edwards Aquifer of Southcentral Texas and the contributing, recharge and artesian zones (Illustration: Edwards Aquifer Authority).

direct connections to land surfaces that allow contaminants to rapidly enter the subsurface and aquifer. Karst watersheds are underlain by limestone or other highly soluble rocks, such as dolostone and gypsum. These rock types are partially dissolved over geologic time by chemical reactions with water (Schindel 2019). The dissolution process creates interconnected openings in the rock, thereby increasing its porosity and permeability. Karst terrains (including the surface and subsurface) are characterized by the presence of sinkholes (Appendix I), sinking streams (Appendix I), caves (Appendix I), interconnected voids, subsurface streams, enlarged fractures and faults, and other conduits (Appendix I) for water movement, including springs that discharge water to the surface. Karst groundwater systems can be the source for large springs that form the headwaters of large river systems. Openings, such as caves or cracks in limestone at the surface, allow direct exchange of surface water with the subsurface and groundwater, providing for little or no filtration or biological treatment of potential contaminants in the water. Water can move quickly in karst aquifers with velocities as high as thousands of feet to several miles per day. These conditions allow for rapid transport and spread of contaminants that may harm the quality of public and private water supplies (Appendix I) and may even impact surface water. Contaminants released into the aquifer can also imperil sensitive cave and aquatic ecosystems that are home to endemic and endangered species.

The Edwards (Balcones Fault Zone) Aquifer

The Edwards (Balcones Fault Zone) Aquifer was the first sole-source aquifer designated in the United States and currently serves as a primary source of drinking water for more than two million people in San Antonio and surrounding areas (Schindel et al. 2004). San Antonio is the seventh largest city in the United States and serves as a major hub for medical, military, technology, and transportation industries. The Edwards Aquifer is noted for some of the largest production wells in the United States, as the source of water for the two largest springs in the Southwest, and for rapid groundwater velocities in the recharge zone (Schindel 2019). The Edwards Aquifer and associated springs are also home to numerous rare endemic and listed endangered species. The aquifer is the primary source of water for municipal, agricultural, and industrial use in South-Central Texas. The aquifer spans over 2 million acres stretched across 180 miles and five counties (Figure 1). This karst aquifer and associated watersheds will serve as the model for application of BMPs, training, and tools to protect water quality.

Like all karst aquifers, the Edwards Aquifer is highly vulnerable to contamination from surface activities. Liquids or solids mobilized by precipitation or flooding, releases of hazardous materials, firefighting products and runoff, or septic waste from sanitary sewers can quickly enter the subsurface and result in degradation of groundwater and surface water resources. This can then result in contamination of public and private water supplies (Johnson et al. 2010; Schindel 2018; Schindel 2019a) and impact species habitat.

Water Quality and Quality of Life at Risk

San Antonio is the first major urban area along the transportation route between Laredo, the largest inland port of entry in the United States, and the rest of the country. Significant quantities of many kinds of hazardous materials are stored in or transported through the city and region due to the nature of local industries and the volume of goods passing through. The release of hazardous materials has occurred in the past, and future releases are inevitable given the scale of development and nature of activities over the Edwards Aquifer's contributing and recharge zones. The same may be said for many karst watersheds elsewhere in the United States.

Private and public water supplies using groundwater commonly only use chlorination as the major component of their water treatment system. Hazardous materials released into water supply systems during emergency response can result in Safe Drinking Water Act standards to be exceeded and may require expensive treatment systems or outright abandonment of a well. This can cost private or municipal owners millions of dollars to either treat contaminated water or replace their water supply. Given the potentially high direct and indirect dollar cost of even a single catastrophic release of contaminants that impact the quality of a municipal water source (Appendix I), first responders need to be supplied with the training and tools needed to protect aquifer water quality during emergency response activities.

BEST MANAGEMENT PRACTICES

BMPs are actions designed to be taken in the course of responding to floods, sewer line breaks, or other emergencies involving water (e.g., in the case of this work, response to fire emergencies) to minimize negative impacts on public health and the environment. While BMPs are typically developed for use by water quality experts, the BMPs presented herein were designed to be readily usable in emergency management curricula and training courses for first responders involved in emergency management, hazardous materials response, and fire control. However, the potential benefits of BMPs to protect the aquifer during an emergency response extend beyond just protecting water quality, even during a single emergency event. Benefits include protecting quality of life, the local economy, the environment, and threatened and endangered species that depend on the aquifer. These BMPs may also be applicable for use by state, county, city, municipal, and government employees and their contractors responsible for responding to or regulating spills and releases of hazardous materials. The BMPs described herein can be applied anywhere across the aquifer's contributing and artesian zones (Figure 1).

The BMPs presented in this paper are based on well-established scientific information for karst areas. These BMPs were reviewed by an expert panel familiar with water quality protection in the Edwards Aquifer and development of emergency response training curricula for hazardous materials and fire control (Schindel 2019b), and thus could serve as a national standard for responding to the release of hazardous materials in karst watersheds.

Emergency firefighting activities and critical pathways

Runoff associated with spills of hazardous materials, sanitary sewer spills including overflows and discharges, and fire control runoff can rapidly enter the subsurface through a variety of pathways (p. 5) on or near the location of the spill or runoff. Rapid groundwater velocities in the recharge and contributing zones (Johnson et al. 2010) can cause released materials (RMs; Appendix I) and firefighting products (FFPs; Appendix I) to move into a public or private water supply within hours or a few days after entering the subsurface. In addition, RMs can volatilize and form explosive or hazardous vapors that can migrate into structures. Released materials and associated runoff should be managed through addressing the nature of potential contaminants and the various pathways runoff can take to enter the aquifer or affect water quality before, during, and after an emergency response.

The nature of hazardous materials

Contaminants commonly take three forms when they enter groundwater. The first form is contaminants that are insoluble in water, existing in suspension or depositing in the substrate. Deposited, insoluble contaminants may remain sequestered in soil or groundwater or become suspended during high-flow events. They may remain a source of low-level contamination over extended periods of time.

The second and third forms are contaminants that are soluble in water. These contaminants are either lighter than water—light non-aqueous phase liquids (LNAPLs)—or heavier than water—dense non-aqueous phase liquids (DNAPLs; Appendix I)— once their solubility is exceeded. LNAPLs can float on the surface of the groundwater and volatilize , becoming a gas.

An LNAPL gas can migrate into sewer lines and into buildings through crawlspaces and cracks in foundations resulting in explosive or poisonous atmospheres. Gasoline is a common example of an LNAPL that can create an explosive condition if exposed to an ignition source (Quinlan et al. 1991).

DNAPLs are heavier than water and will sink. They may be redistributed by turbulent flow in the groundwater, where they may resolubilize and reenter the water column. Common examples of DNAPLs are polychlorinated biphenyls and perchloroethylene.

Contaminants that are soluble in water may exceed drinking water standards as defined under provisions of the Safe Drinking Water Act (Safe . . . 1974). Contaminants of all types can be extremely difficult and expensive to investigate and remove from a public water supply source and may require abandonment and replacement of the supply. Contaminants can also affect species that depend on aquifer water quality.

Pathways for contamination

The many caves, sinkholes, fractures, faults, and other sensitive features characteristic of karst terrains described earlier provide direct pathways and allow rapid discharge of runoff into groundwater. Likely most such sensitive features remain hidden, are buried near the surface under shallow soil, and have yet to be discovered. Hidden features have not yet been recorded in a Geographic Information System (GIS; Appendix I) resource or in other available sources (Rosen et al 2020). Unrecorded sensitive features may only become apparent on-site during emergency responses or after contaminant release events have occurred. In addition, many recharge features, known and unknown, are located within drainage ways (Appendix I) and may be obscured by gravel, cobble, and other types of sediment. These features may not be directly visible or leave any discernable evidence of their existence on the surface, but they will readily receive and convey water inflow to the aquifer.

Water wells and Class V injection wells, which are used to inject non-hazardous fluids underground, are also potential conduits for contaminants to enter the subsurface of karst aquifers. Water wells include public water supply wells and privately owned and managed wells, which are common sources of water for domestic, municipal, industrial, livestock, and agricultural uses. Wells have been constructed in the past using a wide range of drilling and construction methods. Some may be fully cased and grouted to the water production zone, or they may be completed with little or no well casing or grout (i.e., an open hole). The top of the casing may be at or below land surface level. Wells may be in active use, abandoned, or unsecured. Poorly constructed or maintained wells can become conduits for surface water to rapidly enter karst aquifers (Green et al. 2006). Wells may also present a physical hazard to the public and first responders. The condition of wells and potential for wells to become a pathway for groundwater contamination should be determined where possible. Well evaluation commonly requires specialized expertise and equipment. Without readily available information about a particular well, it is best to assume that the well is an open conduit to the aquifer and should be protected from exposure to RMs and FFPs. Some stormwater retention systems may also be considered Class V injection wells if they allow infiltration into the subsurface. Stormwater retention systems in the Edwards Aquifer generally are sealed with a high-density polyethylene or concrete liner to prevent infiltration from the basin. Filtration of stormwater occurs through a sand filter or other system to reduce sediment load, and the water is then passed through a piping system and into a drainage channel.

BMPs FOR REDUCING RISKS

BMPs for pre-event site planning: actions before an emergency event takes place

Predicting when and where an emergency event might take place that involves RMs or FFPs that could threaten the aquifer is not possible. However, in advance of emergency events, it is possible to identify specific sites where hazardous materials are stored, transit-sensitive areas, and areas over the aquifer that are particularly vulnerable to contaminated water runoff. Such information can be placed on a map or provided as mapped layers of information on mobile GIS displays. The following BMPs cover advance planning to locate sites, develop plans to protect the aquifer in these sites, and communication, mapping, and training should an emergency event take place:

- Identify sites where hazardous materials are stored or cross sensitive areas that could present a risk of RMs or FFPs entering sensitive areas. Identify the specific risk if possible. Establish an order of priority to conduct pre-event planning for emergency responses at high-risk sites. Add sites to maps and visualization tools.
- In order of priority, identified high risk sites should be evaluated for potential runoff of RMs and potential for production of FFPs.
- The topography of each site should be evaluated and mapped to determine the direction of the likely flow of RMs or FFPs.
- Storm drains and water inlets should be identified and documented at each site, along with their expected outfall. Add sites to maps and visualization tools.
- Preplanning should include evaluating and documenting methods and means to capture potential RMs and FFPs before they reach sensitive features at or near vul-

nerable sites, such as caves, sinkholes, drainage ways, creeks, streams, storm and sanitary sewers, etc.

- Features at the site, such as stormwater retention basins, should be evaluated for use as temporary containment features for RMs and FFPs. These features should be added to maps and visualization tools and evaluated for the following:
  - o Whether and to what extent the outfall from basins can be closed (or otherwise contained) to prevent the outflow of contaminated liquids and other materials
  - o Whether and to what extent RMs and FFPs might rupture, penetrate, or dissolve the liner of the retention basin, resulting in the release of contaminated materials to the subsurface
  - o Whether removal of RMs and FFPs from a stormwater retention basin can take place quickly, allowing the basin to be returned to service as a stormwater retention basin
  - o Whether stormwater retention basins can be decontaminated and tested after being used to hold RMs and FFPs
  - o Whether the owner of the basin can ensure that the basin is being properly maintained so that it will operate as anticipated
- GIS resources should be used in areas targeted for pre-event planning efforts to help identify on-site topography and water flow pathways that could influence RM or FFP migration into nearby sensitive features, such as known caves, sinkholes, sinking streams, storm drains, stormwater retention basins, and active and abandoned water wells (Appendix I).
- GIS databases should be completed in order of priority, with the highest zones of risk completed first. High risk zones include highways, railroads, pipelines, regulated industrial and retail facilities, firefighting training areas, and sewage lift stations.
- Preplan ways to minimize the spread of RMs and FFPs where possible.
- Where feasible, on or near the site, preposition relevant emergency response materials (e.g., covers, rock socks, berms, booms, sandbag dams, or plastic sheeting) for use should an event take place. Prepositioning emergency response materials at strategic locations in sensitive areas may be done using a series of storage containers.
- Uplands and areas between draining features at the sites should be inspected and evaluated in advance to identify additional features that could potentially allow RMs and FFPs to enter the subsurface and impact the aquifer.
- Susceptible public and private water supply systems and irrigation systems should be identified in advance for their potential use as monitoring sites for the presence of contamination during or after an event. Contingency plans should be created to address the impact of contamination.
- Develop plans and training, and preposition materials to monitor the fate and transport (velocity and location) of liquid runoff from an emergency event through use of non-toxic fluorescent dyes. Fluorescent dyes may be injected into RMs and FFPs and monitored to estimate the fate and transport of contaminants detected in runoff. Fluorescent dyes have low detection limits and are relatively inexpensive, quick, and easy to use for tracking water movement through the subsurface and aquifer. Fluorescent dyes should be administered and tracked under the direction of a professional experienced in their use.

Emergency event mitigation: actions during the event

During emergency events, public safety should remain the utmost priority, but with proper planning, acquisition of essential data, and efficient communication, many environmental concerns can also be addressed. Depending on the volume of material generated, flows that enter a drainage way may travel downgradient for thousands of feet beyond the event boundary. The following guidance and emergency event mitigation BMPs are recommended:

- Act as quickly as possible to:
  - o Identify the leading edge of the contaminant flows along the ground.
  - o Identify the nearest downgradient points of potential entry into the aquifer (sensitive features such as caves, sinkholes, fractures and faults, sinking streams, storm drains, and active and abandoned water wells).
  - o Identify the best method or combination of methods for fire management, firefighting product control, and aquifer protection.
- Whenever possible, covers, rock socks, berms, booms, sandbag dams, or plastic sheeting should be used to prevent RMs and FFPs from reaching storm drains, drainage features, surface waters, other sensitive features, or other pathways into the subsurface.
- Whenever possible, no materials should be flushed into a storm drain, sinkhole, sinking stream, cave, fracture or fault, well, or drainage way.
- Use stormwater retention basins that are suitable for temporary storage of RMs and FFPs, based on compatibility and design analysis to minimize or exclude infiltration and conducted during event preplanning where available.

- Take all precautions to prevent hazardous materials and decontamination water from being discharged into streets, parking lots, storm drains, sinkholes, fractures and faults, sinking streams, caves, grass swales, solution features, wells, or other potential pathways into the subsurface.
- Use discharge pathways from the site as identified during event preplanning where available. Refer to maps or information showing water flow direction, if available. Discharges that enter a creek bed, drainage way, or other surface water conveyance will most likely enter a sensitive feature that will directly recharge the aquifer.
- Where appropriate or required depending upon the nature of the emergency and materials present, notify landowners, well owners, and relevant officials.
- Where appropriate and under the direction of trained personnel, non-toxic fluorescent dyes may be injected into RMs and FFPs during an event and monitored to estimate the fate and transport of contaminants if detected in runoff.

Post-emergency firefighting activities: Actions after release is controlled and clean up underway

These BMPs apply after a release is under control and personnel are available to conduct these activities:

- Liquids and materials contained in stormwater retention basins after an emergency event should be tested and, if necessary, removed as soon as possible and disposed of in an appropriate manner based on testing results. This is necessary to ensure that the basin can return to function as a stormwater retention basin as soon as reasonable to minimize the possibility of release of hazardous material when the basin next receives stormwater.
- Depending on the type and level of contamination in the material removed, the retention basin may require decontamination and testing before reuse.
- If the volume of RMs or FFPs released exceeds the reportable quantity (RQ; Appendix I), the Texas Commission on Environmental Quality (Appendix I), the EAA, other regulatory agencies as appropriate for the locality, and nearby public and private water supply owners and operators (within a 5-mile radius) should be notified of the RQ release and informed about any suspected contaminants in the release.

CONCLUSION AND IMPLEMENTATION

Contamination of karst aquifers can occur from natural causes, but most commonly contamination is caused by human action or inaction. The best means to secure karst groundwater supplies from becoming contaminated by hazardous or polluting materials is to prevent water or other liquids containing contaminants from reaching areas of entry to the aquifer. This paper provides a set of BMPs for use by first responders to protect the quality of water in karst aquifers from hazardous materials or other pollutants carried in runoff during emergency response actions, such as firefighting. BMPs are provided for preplanning, response during an emergency, and cleanup after an event. Ongoing work will include these BMPs in first responder training curricula and a georeferenced database that will recommend actions to protect sensitive areas where hazardous materials may be present. After implementation of curricula, first responder training, and initial implementation in San Antonio, we will evaluate the effectiveness and usability of BMPs by first responders. We hope to make improvements as appropriate based on use over time.

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Appendix I

Definitions

Term	Definition
Abandoned Water Well	A water well that is no longer in use. Abandoned water wells may not have been constructed to modern standards, maintained, or properly plugged. Abandoned wells and boreholes may provide a direct opening to the aquifer and serve as a pathway for contaminant transport.
Best-Management Practice	A set of actions designed to minimize negative impacts on public health and the environment.
Cave	A void in the subsurface rock large enough for a person to enter.
Conduit	A void ranging from about the size of a garden hose to large enough for a person to enter.
Dense Non-Aqueous Phase Liquid	A liquid that is both denser than water and is immiscible in or does not dissolve in water.
Dissolution Feature	A feature such as a fracture, fault or bedding plane parting that has been enlarged by geologic processes such as the chemical and physical action of flowing water.
Drainage Way	A rill, runnel, rivulet, gully, ditch, creek, brook, stream, river or any other feature that can convey water.
Edwards Aquifer Authority	A groundwater district in the state of Texas that was created by the 1993 Edwards Aquifer Authority Act. Its jurisdictional area includes all of Bexar, Medina, and Uvalde counties and portions of Atascosa, Caldwell, Comal, Guadalupe, and Hays counties. The Edwards Aquifer Authority is mandated to manage, conserve, preserve, and protect the Balcones Fault Zone Edwards aquifer.
Firefighting Products	Any liquid or solid material used or produced during firefighting operations.
Geographic Information System	A framework for gathering, managing, analyzing, and presenting data.
Hazardous Material	Any material that may impact public health and/or the environment.
Karst, Karstic	Any landscape and subsurface occurring in soluble rocks such as limestone, dolostone, and gypsum. Karst is characterized by sinkholes, sinking streams, caves, dissolution features and springs and rapid groundwater movement.
Karstic Feature	A cave, sinkhole, sinking stream, spring, or enlarged fracture, fault, or bedding plane parting that allows surface water or spilled liquids to enter the subsurface.
Light Non-Aqueous Phase Liquid	A groundwater contaminant that is not soluble in water and has a lower density than water therefore, it will float on the top of groundwater. Examples are gasoline and other hydrocarbons including oil.
Municipal Water Supply or Source	A water well used to provide drinking water to a community or city that is regulated under the Safe Drinking Water Act.
Public Water Supply or Source	A water supply well or spring with at least 15 service connections or serve at least 25 individuals for at least 60 days out of a year.
Released Materials	Any liquid or solid materials spilled on the land surface and generally considered potentially hazardous to the public health and the environment.
Reportable Quantity	The amount of a hazardous substance that must be released before EPA requires notification to go to the National Response Center. These quantities are based on volume. Reportable quantities are listed under 40 CFR part 302.4 under the Clean Water Act.
Sinkhole	A depression or opening in rock or soil with internal drainage. In south-central Texas, sinkholes may be as small as only a few feet in diameter and a few feet deep, or as large as hundreds of feet in diameter and tens of feet deep.
Sinking Stream	A stream or creek that loses water to the subsurface either at a discrete sink point or along its bed.
Texas Commission on Environmental Quality	The state regulatory agency tasked with maintaining clean air and water, and the safe management of waste in Texas.

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Storage and Regulation of River Flows by Dams and Reservoirs

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Abstract: Water management in Texas is driven by dramatic spatial and temporal hydrologic variability, continual rapid population growth, declining groundwater supplies, and intensifying demands on surface water resources. Dams and reservoirs are essential for providing reliable water supplies and reducing flood risks. Numerous reservoir projects, most constructed during the 1940s through 1980s era of large-scale water project construction nationwide, are operated throughout the state to store and regulate extremely variable river flows for beneficial purposes. This paper explores river system hydrology in Texas, operation of dams and reservoirs statewide to deal with extreme flow fluctuations, and associated complexities, issues, and water management strategies. The central focus of the paper is the role of large reservoirs in managing hydrologic variability and associated future uncertainty in an environment of growing demands on limited resources.

Keywords: dams, reservoir/river systems, hydrologic variability

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Terms used in paper

Acronym / Initialism	Descriptive Name
ASCE	American Society of Civil Engineers
AWRA	American Water Resources Association
BRA	Brazos River Authority
cfs	cubic feet per second
CRMWD	Canadian River Municipal Water District
DSS	data storage system
EFS	environmental flow standard
FWD	Fort Worth District of USACE
GBRA	Guadalupe-Blanco River Authority
HEC	Hydrologic Engineering Center
IBWC	International Boundary and Water Commission
LCRA	Lower Colorado River Authority
M&I	municipal and industrial
NF	naturalized flows
NFIP	National Flood Insurance Program
SB	Senate Bill
SRA	Sabine River Authority
SWPA	Southwest Power Administration
TRWD	Tarrant Regional Water District
TCEQ	Texas Commission on Environmental Quality
TWDB	Texas Water Development Board
TWRI	Texas Water Resources Institute
TRA	Trinity River Authority
USACE	United States Army Corps of Engineers
USBR	United States Bureau of Reclamation
USGS	United States Geological Survey
WAPA	Western Area Power Administration
WAM	water availability model
WRAP	water rights analysis package

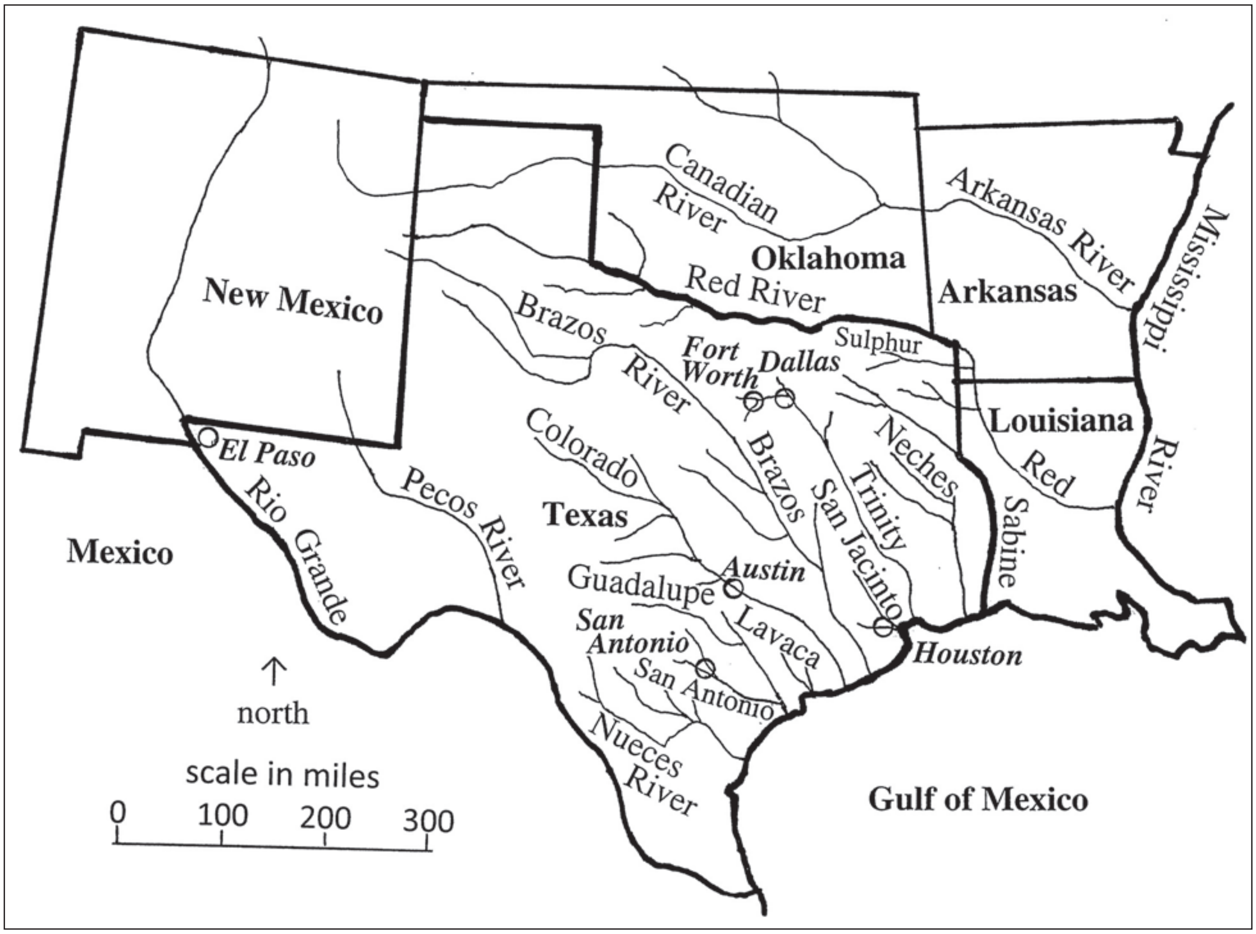

Figure 1. Major rivers and largest cities of Texas.

INTRODUCTION

This paper describes the major reservoirs of Texas and the hydrologic and institutional environment for reservoir operations and explores river regulation purposes, practices, challenges, and concerns. Dam and reservoir projects are fundamental to water management in Texas. Reservoir water conservation storage capacity is necessary to use highly fluctuating water resources of river basins for beneficial purposes such as municipal and industrial water supply, agricultural irrigation, hydroelectric power generation, and recreation. Constructed dams and appurtenant structures also regulate rivers to reduce damages caused by floods. Water quality, erosion and sedimentation, and protection and enhancement of fish, wildlife, and other environmental resources are important considerations in managing reservoir/river systems.

Climate, geography, economic development, water use, and water management practices vary greatly across Texas from the arid western desert to humid eastern forests, from sparsely populated rural regions to the metropolitan areas encompassing the cities shown in Figure 1. The state population increased from about 3,000,000 people in 1900 to 14,200,000 in 1960, 21,000,000 in 2000, and 29,500,000 in 2020, and is projected by the Texas Water Development Board (TWDB) to increase to 46,400,000 by 2060 (TWDB 1984, 2017). Municipal and industrial (M&I) water use continues to steadily increase along with a leveling off of agricultural irrigation due largely to limited water availability. Instream flow for ecosystem preservation is a major concern (National Research Council 2005; Wurbs 2017a). Declining groundwater supplies combined with population growth are resulting in intensified demands on surface water resources (TWDB 2017). Water supply was about 60% from ground water and 40% from surface water sources in 1980 (TWDB 1984). Water use data collected by the TWDB indicate that water use during 2018 was supplied from groundwater (54%), surface water (43%), and reuse (3%).

Hydrology in Texas varies dramatically from the extremes of devastatingly intense floods to costly multiple-year droughts, along with seasonal and less severe random between-year and within-year fluctuations in precipitation and stream flow. Construction of dam and reservoir projects has significantly reduced stream flow variability while increasing supply availability and reliability, but flows are still extremely variable. The hydrologically most severe drought since before 1900 for most of the state began gradually in 1950 and ended in April 1957 with one of the greatest floods on record. Major droughts in the 1910s and 1930s also affected large areas of Texas. More recent droughts were much more economically costly due to population and economic growth. The 2008–2014 drought is comparable in hydrologic severity to the 1950–1957 drought in some areas of the state (Winters 2013). For more than half of Texas, 2011 had the lowest annual precipitation since the beginning of official precipitation records in 1895 (Nielson-Gammon 2012). On the other extreme, 2015 was one of the wettest years on record, with multiple major floods. The several very costly floods since 2015 include those resulting from Hurricane Harvey in 2017 (ASCE 2018), Tropical Storm Imelda in 2019, and several storms during 2020.

Much of the quantitative information presented in this paper is from the water availability modeling (WAM) system maintained by the Texas Commission on Environmental Quality (TCEQ; Wurbs 2005; Alexander and Chenoweth 2020). The TCEQ WAM system consists of the Water Rights Analysis Package (WRAP) and simulation input datasets for all of the river basins of Texas. The WRAP modeling system (Wurbs 2019a, b, c; Wurbs and Hoffpauir 2019) developed at Texas A&M University (TAMU) is generalized for application to any river/reservoir system. Wurbs (2020b) describes the institutional framework for developing and implementing the WRAP/WAM modeling system in Texas. WRAP software and documentation are available at the TAMU WRAP website (https://wrap.engr.tamu.edu/), which links with the TCEQ WAM website, which provides an array of information including WRAP input datasets for all Texas river basins (https://www.tceq.texas.gov/permitting/water_rights/wr_technical-resources/wam.html). The generalized WRAP simulation model combined with an input dataset from the TCEQ WAM system for a particular river basin is called a water availability model (WAM).

The 20 WAMs covering all of Texas simulate over 3,400 reservoirs and other constructed water control and conveyance facilities, institutional systems for allocating and managing water resources, and river system hydrology. Eighty-two reservoirs with storage capacities exceeding 50,000 acre-feet account for about 92% of the total permitted conservation storage capacity of the over 3,400 reservoirs. WAM datasets are available for alternative water use scenarios. The authorized use scenario is based on the premise that all water right permit holders use the full amounts authorized in their permits. The current use scenario is based on recent actual water use.

The WAM system is used by TCEQ staff and water right permit applicants, or their consultants, in administration of the water rights system and the TWDB and regional planning groups, or their consultants, in regional and statewide planning. River authorities apply the modeling system in operational planning studies for their specific reservoir systems. The WAM system is employed in this paper to investigate the characteristics of river/reservoir system hydrology and water management capabilities throughout the state.

A data storage system (DSS) developed by the Hydrologic Engineering Center (HEC) of the U.S. Army Corps of Engineers (USACE) is integrated in the WRAP modeling system to manage time series data. The DSS interface HEC-DSSVue (HEC 2009) is employed to manage data and create the time series plots presented in this paper.

INVENTORY OF DAMS AND RESERVOIRS

Many thousands of reservoirs are scattered throughout Texas. Most of the storage capacity is contained in a relatively few of the largest reservoirs. The TWDB and this paper define a major reservoir as having a storage capacity of 5,000 acre-feet or larger at its normal operating level. This definition generally does not include flood control storage capacity that remains empty except during and immediately following floods.

The TWDB has delineated the 15 major river basins and eight coastal basins of the state and inventoried the reservoirs in each river basin with descriptive information. This inventory includes the 188 major water supply reservoirs and 20 other major reservoirs that serve no water supply function (https://www.twdb.texas.gov/surfacewater/rivers/reservoirs/index.asp). Map locations and historical and current storage levels and statistical storage data for 114 large reservoirs that represent 96% of the total conservation storage capacity of the 188 water supply reservoirs are available at https://www.waterdatafortexas.org/reservoirs/statewide.

The Texas state water plan includes discussions of both existing and proposed new reservoirs. The 1984 Texas state water plan (TWDB 1984) included 44 proposed new reservoirs to supply growing water needs. Over 4,500 individual strategies recommended by regional planning groups are included in the 2017 Texas state water plan for developing new water supplies by 2060 (TWDB 2017). These recommendations include 14 major reservoirs for future construction that would account for about 12% of new water supplies at a capital cost of about 16% of the total capital cost for new supplies.

Table 1. Reservoirs with total storage capacities of 500,000 acre-feet or greater.

	Reservoir/dam	River of dam	Owner	Initial storage	Area (acres)	Storage capacity (acre-feet)		
						Conservation	Flood control	Total
1	Texoma/Denison	Red River	U.S. Army Corps of Engineers (USACE) Tulsa District	1943	78,400	2,441,000	2,660,000	5,101,000
2	International Amistad	Rio Grande	International Boundary and Water Commission (IBWC)	1968	66,500	2,977,000	1,744,000	4,721,000
3	Toledo Bend	Sabine River	Sabine River Authority (SRA)	1966	182,500	4,453,000	–	4,453,000
4	Sam Rayburn	Angelina River	USACE	1965	112,600	2,888,000	1,099,000	3,987,000
5	International Falcon	Rio Grande	IBWC	1953	85,200	2,648,000	910,000	3,558,000
6	Wright Patman	Sulphur River	USACE Fort Worth District (FWD)	1956	18,200	145,000	2,509,000	2,654,000
7	Whitney	Brazos River	USACE FWD	1951	23,200	561,000	1,372,000	1,933,000
8	Travis/Mansfield	Colorado River	Lower Colorado River Authority (LCRA)	1940	19,000	1,132,000	779,000	1,911,000
9	Livingston	Trinity River	Trinity River Authority (TRA)	1969	32,600	1,740,000	–	1,740,000
10	Meredith/Sanford	Canadian River	Canadian River Municipal Water District CRMWD	1941	16,400	808,000	543,000	1,351,000
11	Richland-Chambers	Richland Creek	Tarrant Regional Water District (TRWD)	1987	43,400	1,109,000	–	1,109,000
12	Belton	Leon River	USACE FWD	1954	12,100	433,000	640,000	1,073,000
13	Ray Roberts	Elm Fork Trinity	USACE FWD	1987	28,600	796,000	265,000	1,061,000
14	Lewisville	Elm Fork Trinity	USACE FWD	1954	27,200	614,000	363,000	977,000
15	Buchanan	Colorado River	LCRA	1937	22,100	889,000	–	889,000
16	Tawakoni/Iron Bridge	Sabine River	SRA	1960	37,300	885,000	–	885,000
17	Lake O' the Pines	Cypress Creek	USACE FWD	1957	16,900	241,000	587,000	828,000
18	Canyon	Guadalupe River	USACE FWD	1964	8,310	372,000	395,000	767,000
19	Waco	Bosque River	USACE FWD	1965	8,190	207,000	506,000	713,000
20	Lavon	East Fork Trinity	USACE FWD	1953	20,600	419,000	292,000	711,000
21	Choke Canyon	Frio River	Corpus Christi	1982	26,000	693,000	–	693,000
22	Lake Fork	Lake Fork Cr	SRA	1979	27,300	636,000	–	636,000
23	Twin Buttes	South Concho	San Angelo	1962	8,450	178,000	454,000	632,000
24	Cedar Creek	Cedar Creek	TRWD	1965	1,560	631,000	–	631,000
25	Stillhouse Hollow	Lampasas River	USACE FWD	1968	6,480	224,000	391,000	615,000
26	Kemp	Wichita River	Wichita Falls	1922	15,400	318,000	248,000	566,000
27	Possum Kingdom	Brazos River	Brazos River Authority (BRA)	1941	16,700	552,000	–	552,000

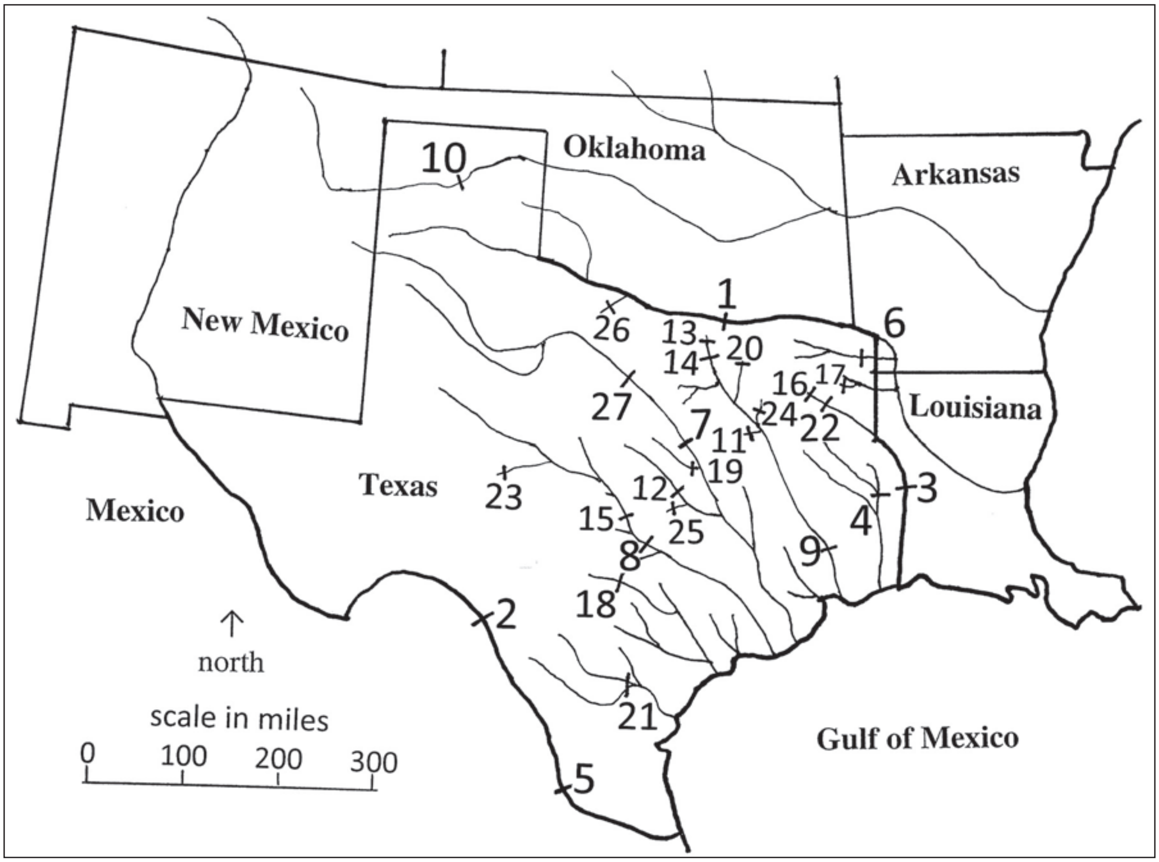

Figure 2. Locations of the dams of the 27 largest reservoirs in Texas listed in Table 1.

Largest reservoirs

Reservoirs located partially or completely in Texas with total capacities of 500,000 acre-feet or larger are listed in Table 1. The reservoir name is followed by the name of the dam if the names are different. These 27 largest reservoirs have conservation (water supply, hydropower, recreation), operator-controlled flood control, and total storage capacities totaling 28,990,000, 15,757,000 and 44,747,000 acre-feet, respectively, which represents about 71%, 97%, and 78% of the totals for all reservoirs located partially or completely in Texas. The total water surface area at top of conservation pool for the 27 reservoirs is 882,790 acres. Major portions of the storage capacity of International Lakes Amistad and Falcon on the Rio Grande, Lake Texoma on the Red River, and Toledo Bend on the Sabine River (Figures 1 and 2) are controlled by Mexico, Oklahoma, and Louisiana.

The conservation storage capacity estimates listed in Table 1 are primarily from the TCEQ current use scenario WAMs. The reservoir flood control storage capacities are from USACE and International Boundary and Water Commission (IBWC) information. The numbers in the first column of Table 1 reference the dam site locations on the map of Figure 2 as well as relative size ranked by total storage capacity.

Reservoirs with and without water right permits

The TCEQ WAM datasets include all reservoirs associated with water right permits. A dam with a storage capacity of up to 200 acre-feet can generally be constructed for domestic and livestock purposes without a permit subject to requirements in Texas law. Water right permits are not required for flood control storage. The fully authorized and current use scenario datasets include 3,460 and 3,446 reservoirs, respectively (Wurbs 2019a). The full authorization WAMs include existing and permitted but not yet constructed reservoirs. The current use datasets include only existing reservoirs. The 210 major reservoirs with 5,000 acre-feet or greater conservation storage capacities in the authorized and current use datasets contain 98.0% and 97.8% of the total conservation storage capacity of the 3,460 and 3, 446 reservoirs. The respective 62 and 58 reservoirs with capacities of 100,000 acre-feet or greater contain 89.3% and 89.5% of the total conservation capacity in the authorized and current use datasets (Wurbs 2019a).

The storage capacities of most of the reservoirs in the full authorization scenario WAMs reflect conditions at the time of construction. Capacities of many of the reservoirs for which sediment surveys have been performed have been updated in the current use scenario WAMs.

Thousands of farm and recreation ponds, urban storm water detention basins, and other storage facilities smaller than 200 acre-feet are not included in water right permits and the TCEQ WAM system. Flood control storage does not require a water right permit. The Natural Resource Conservation Service (NRCS) has constructed about 2,000 flood retarding dams in rural watersheds of Texas that are empty or have only minimal storage content during non-flood periods. Addicks and Barker Dams in Houston, with capacities of 204,500 and 207,000 acre-feet, are operated by the USACE Galveston District for flood control, storing water only during and after floods. Releases from Addicks and Barker Reservoirs are controlled by USACE personnel by operation of gated outlet structures. Flows through numerous storm water detention facilities and the approximately 2,000 NRCS flood retarding dams are controlled by ungated outlet structures without human operators.

Oldest and newest major reservoirs

Caddo Lake on Cypress Bayou on the Texas/Louisiana border is the only natural lake in Texas with storage capacity of 5,000 acre-feet or greater. However, a dam was constructed by a private company in 1914 to raise the water level and then reconstructed by the USACE in 1968–1971 to preserve the lake. Caddo Lake has a storage capacity of 129,000 acre-feet and surface area of 26,800 acres.

Wurbs (1985) inventories and describes conservation and flood control operations of the 187 major reservoirs in Texas that were either existing or under construction as of 1985. Although a few small dams were constructed in Texas before 1900, with the exception of Caddo Lake, Eagle Lake is the oldest of the major reservoirs still in existence (Dowell and Breeding 1967). Eagle Lake, with impoundment beginning in 1900, is a 9,600 acre-feet irrigation reservoir in the Colorado River Basin. The 35 major reservoirs in operation in 1935 were relatively small projects constructed for irrigation, M&I water supply, and/or hydroelectric power.

Lake Gilmer, constructed during 1999–2001 in northeast Texas, is the newest major reservoir in Texas that is actually in full operation. Lake Gilmer is owned by the City of Gilmer and has a water supply storage capacity of 12,720 acre-feet with a surface area of 895 acres.

The Lower Colorado River Authority (LCRA) Arbuckle Reservoir was substantially completed in 2019, but additional remedial work is required to mitigate seepage problems before water can be stored. The off-channel reservoir located in Wharton County will have a storage capacity of 40,000 acre-feet and cover an area of 1,100 acres.

Construction of the Bois d'Arc Reservoir project began in 2018 and is still underway in late 2020. This reservoir being developed by the Northeast Texas Municipal Water District will have a water supply storage capacity of 368,000 acre-feet and water surface area of 16,640 acres.

Construction of the Lake Ralph Hall municipal water supply project by the Upper Trinity Regional Water District is scheduled to begin in 2021 with water delivery expected by 2025. This lake on the North Sulphur River will have a surface area of 7,600 acres.

RIVER SYSTEM HYDROLOGY

Variability and stationarity of precipitation, reservoir evaporation, and stream flow are key considerations in the development and operation of reservoir projects. Hydrology varies greatly both temporally and spatially across Texas. Hydrologic variability over time includes multiple-year, year-to-year, seasonal, storm-event, and continuous fluctuations that include the extremes of floods and droughts as well as more frequent but less severe variations in weather and stream flow. Hydrologic variability and associated water supply reliability, flood risk, and future uncertainty are fundamental to water management. Stationarity, or lack thereof (non-stationarity), refers to long-term homogeneity over time with no permanent changes or trends. Stationarity, as well as variability of precipitation, evaporation, and stream flow, is important in exploring reservoir operations and other aspects of hydrology and water management.

Precipitation and reservoir evaporation depths

Precipitation and watershed evapotranspiration are climatic drivers of river flows, including inflows to reservoirs. Lake surface evaporation significantly contributes to the drawdown of the volume of water stored in a reservoir. The net difference between precipitation falling on the water surface and evaporation from the water surface is a major component of reservoir water budgets. General observations regarding variability and stationarity of precipitation, lake surface evaporation rates, and net lake evaporation less precipitation rates are presented as follows.

The TWDB maintains annually updated datasets of monthly precipitation rates beginning in January 1940 and monthly reservoir surface evaporation rates beginning in January 1954 for 92 one-degree latitude by one-degree longitude quadrangles comprising a grid that encompasses the state (https://waterdatafortexas.org/lake-evaporation-rainfall). The number of gages has varied over time, but now includes about 3,960

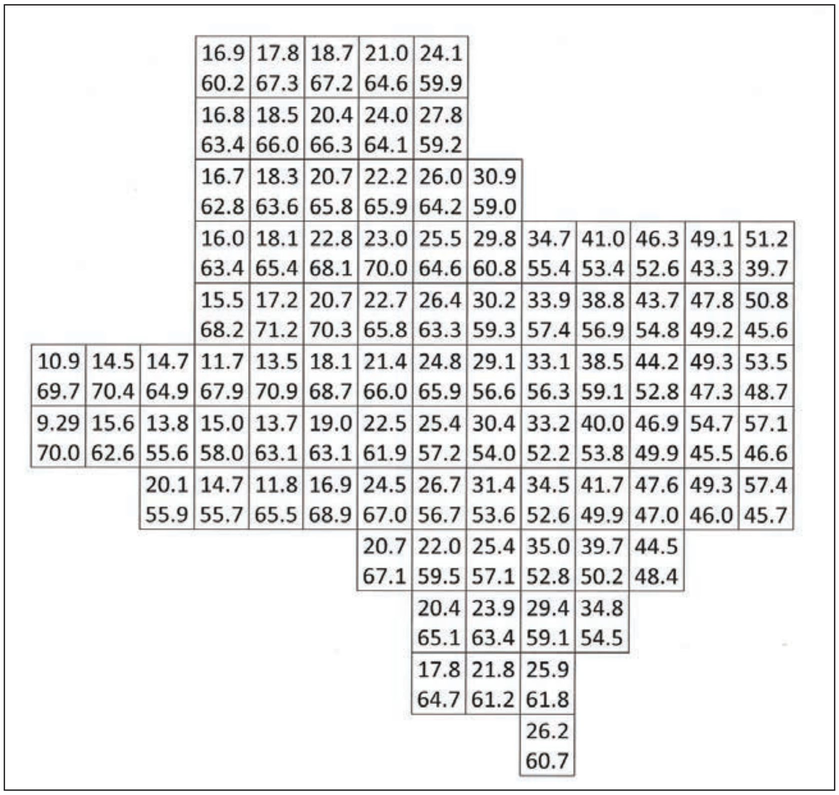

Figure 3. Mean annual precipitation and reservoir evaporation depths in inches.

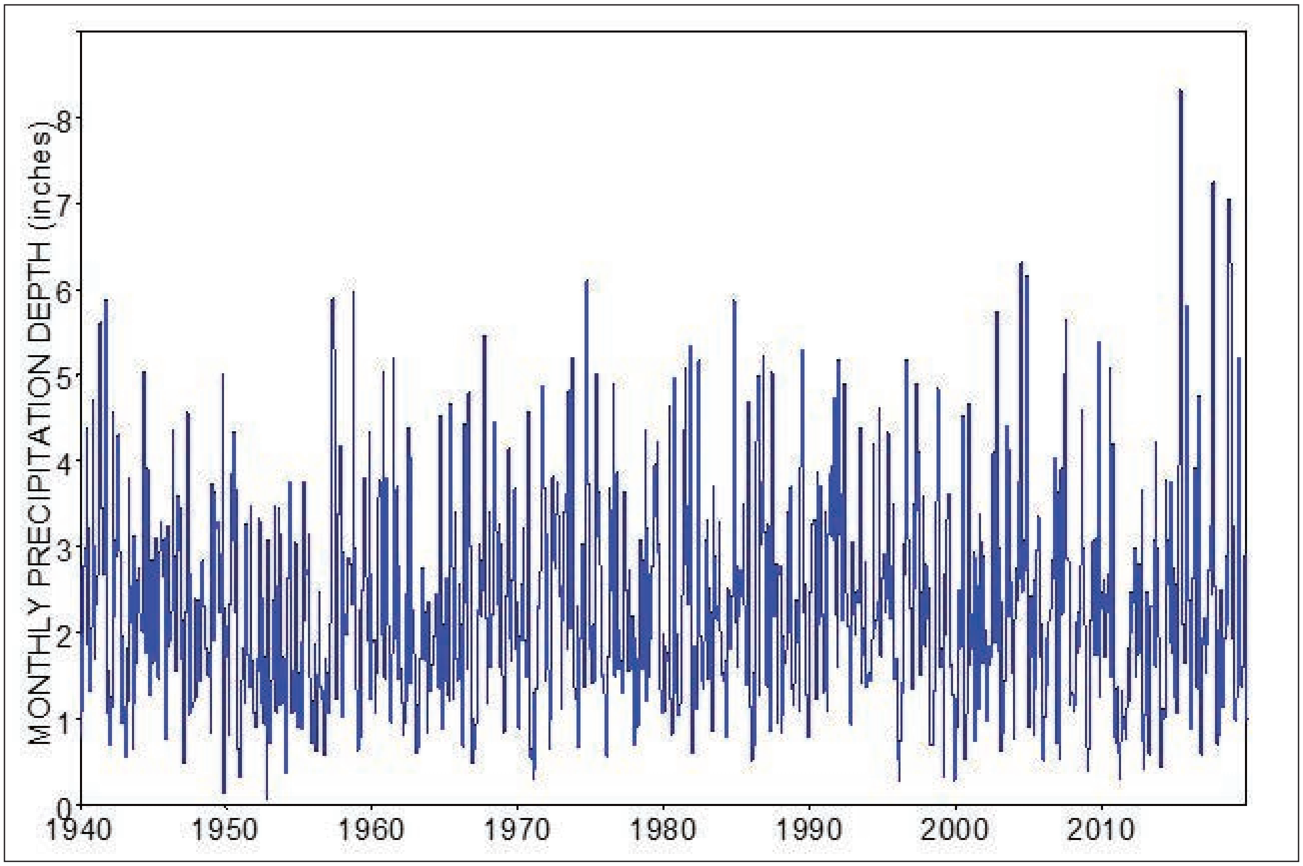

Figure 4. Statewide average 1940–2019 monthly precipitation depths in inches.

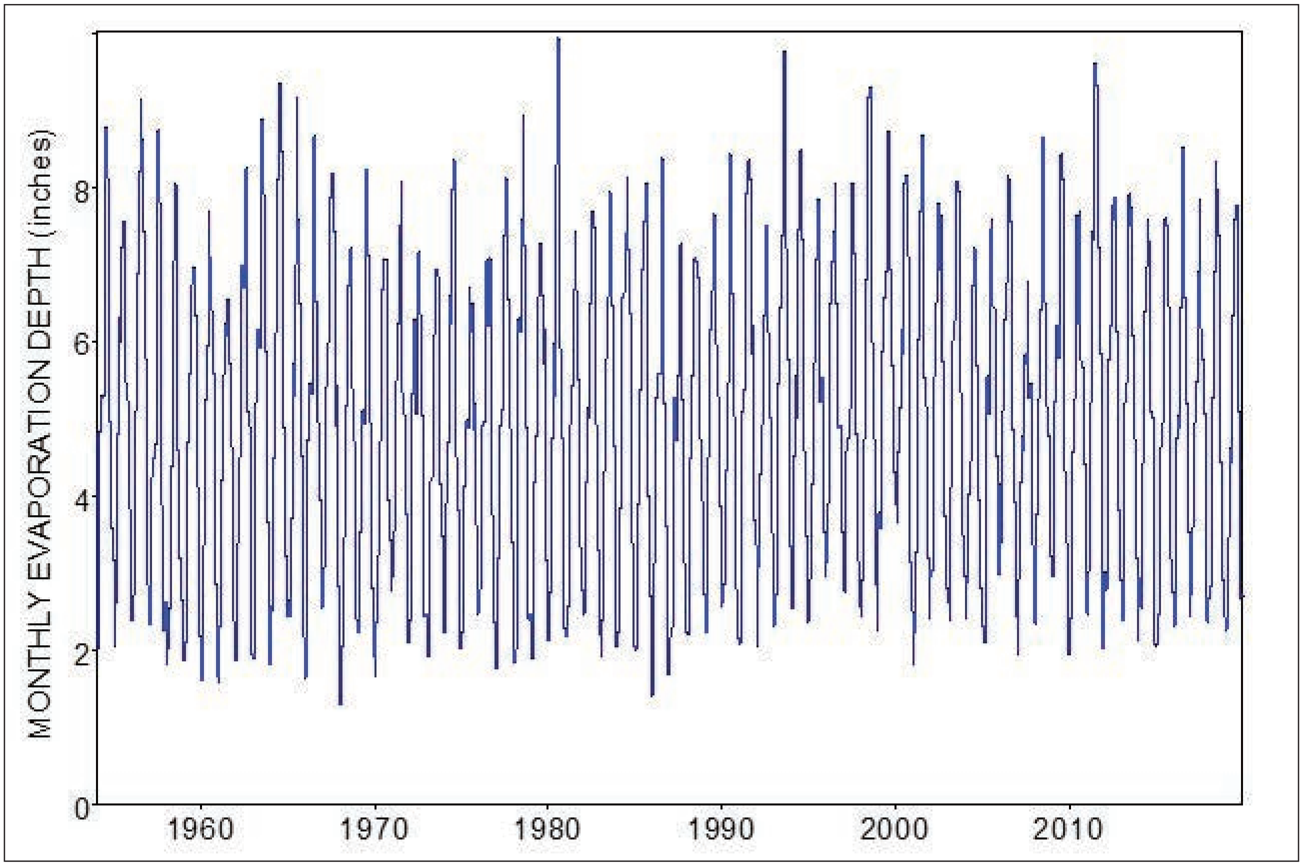

Figure 5. Statewide average 1954–2019 monthly reservoir evaporation depths in inches.

precipitation and 100 evaporation stations, most managed by the National Weather Service. The TWDB uses Thiessen networks for computing means for each of the 92 quadrangles for each month. The reservoir evaporation depths are estimated based on measurements from standard evaporation pans and lake/pan multiplier coefficients that vary over the 12 months of the year and with location.

The WRAP modeling system includes a feature that accesses the TWDB database and computes basic statistics including linear regression coefficients for each of the 92 quadrangles and area-weighted statewide average precipitation and reservoir evaporation rates (Wurbs 2019c). Monthly quantities, annual totals, and annual series of the minimum and maximum monthly value each year or moving averages for any specified number of months are computed and plotted.

The 92 quadrangles that encompass Texas are delineated in Figure 3, with each cell representing a quadrangle. The 1940–2019 mean annual precipitation and 1954–2019 reservoir evaporation depths in inches/year of each individual quad are tabulated in the upper and lower half of each of the cells. The extreme spatial variability of rainfall, evaporation, and evaporation less rainfall is illustrated by these quantities. One of the quadrangles in West Texas has a mean annual evaporation rate of 70.9 inches and annual precipitation of 13.5 inches, as contrasted with a quadrangle in East Texas with an annual evaporation of 45.5 inches and annual precipitation of 54.7 inches.

Both temporal variability and stationarity are illustrated by the time series plots of Figures 4 through 7 and the regression metrics of Table 2. The statewide averages of the 1940–2019 precipitation and 1954–2019 reservoir evaporation rates are 28.1 and 59.4 inches/year, respectively. Precipitation and reservoir evaporation rates exhibit great variability seasonally, between years, and continuously. Fluctuations between annual amounts are much greater for precipitation than evaporation. Seasonality is more pronounced for evaporation than precipitation. Temporal variability tends to be greater for individual quadrangles than for statewide averages.

The statewide averages of the 1940–2019 monthly precipitation and 1954–2019 monthly evaporation depths are plotted in Figures 4 and 5, respectively. Statewide annual precipitation and evaporation depths are plotted in Figure 6. The minimum and maximum monthly depths for any month in each year (January through December) are plotted in Figure 7.

Regression statistics for statewide averages for 1940–2019 annual precipitation, 1954–2019 annual evaporation, 1954–2019 annual net evaporation less precipitation, and annual

Table 2. Linear regression analysis results for nine annual time series variables.

Variable	Mean (inches)	Intercept (inches)	Slope (inches/year)	Number of slopes	
				Positive	Negative
annual precipitation	28.12	27.58	0.013391	66	26
minimum monthly precipitation	0.789	0.818	-0.000736	25	67
maximum monthly precipitation	4.640	4.179	0.011387	74	18
annual evaporation	59.39	57.51	0.056016	62	30
minimum monthly evaporation	2.139	1.867	0.008105	82	10
maximum monthly evaporation	8.051	8.042	0.000272	52	40
annual evaporation-precipitation	31.19	30.09	0.032897	51	41
minimum monthly evaporation-precipitation	-0.530	-0.287	-0.007259	44	48
maximum monthly evaporation-precipitation	6.152	6.084	0.002040	56	36

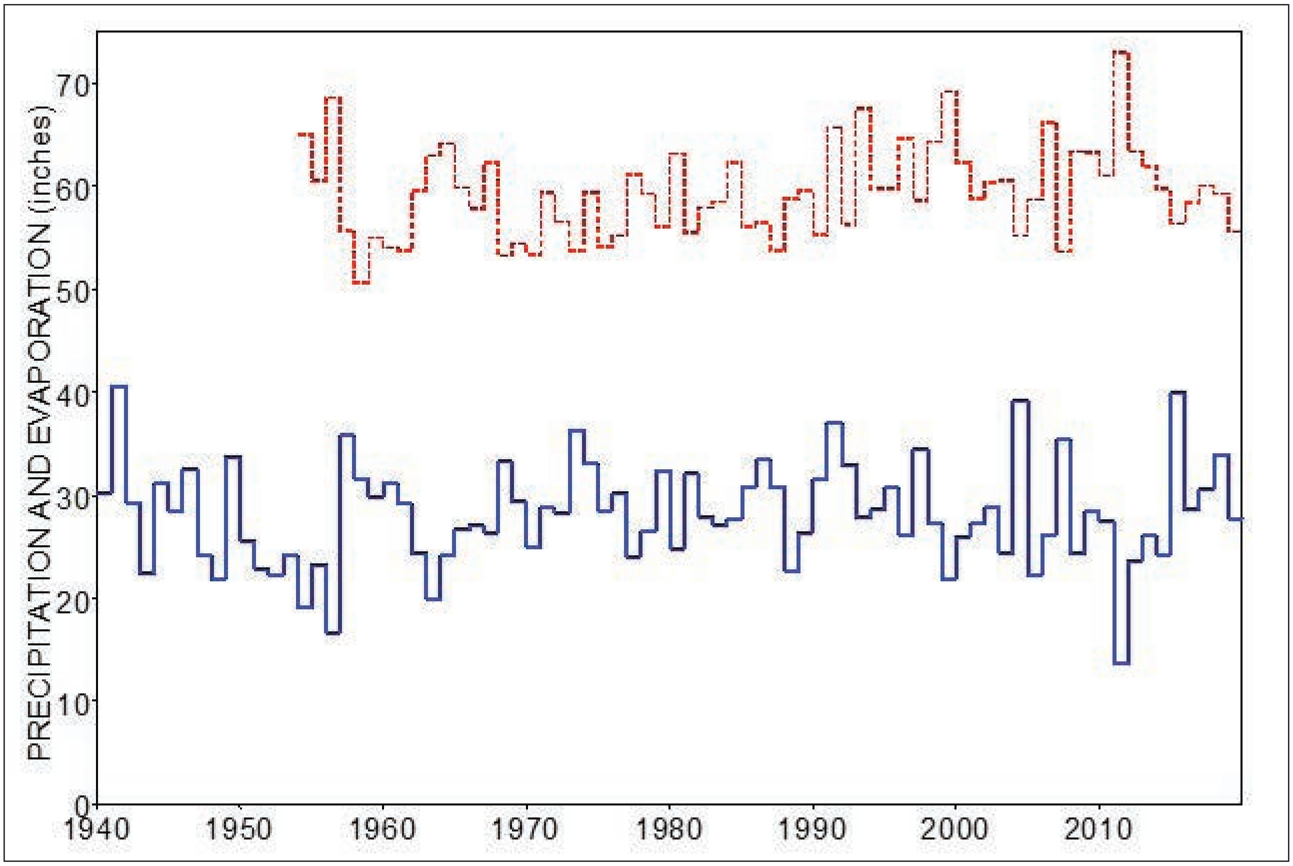

Figure 6. Statewide average of annual precipitation (blue solid) and annual evaporation (red dashed) in inches.

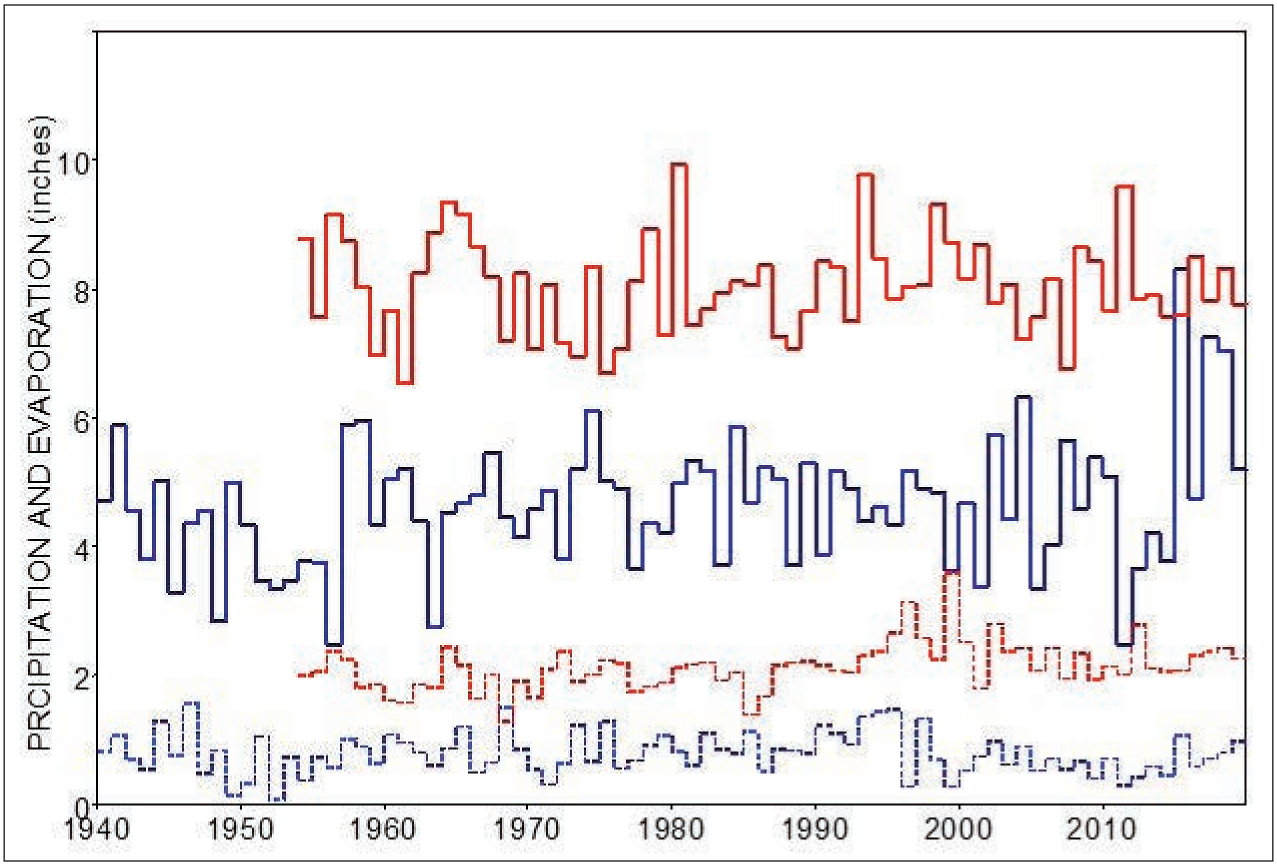

Figure 7. Statewide average of annual maximum (blue solid) and minimum (blue dash) monthly precipitation and maximum (red solid) and minimum (red dash) monthly evaporation.

monthly maxima and minima are tabulated in Table 2. In linear regression, an intercept equal or near to the mean and a slope of zero or near-zero implies the time series data exhibits no long-term trend. A positive or negative slope indicates an increase or decrease over time.

A linear regression trend line through the 80 years of annual statewide mean precipitation depths has a slope of 0.01339 inch/year tabulated in Table 2. Counts of positive and negative slopes for the nine annual time series variables for the 92 quadrangles are shown in the last two columns of Table 2. The trend slopes for total annual precipitation are positive for 66 of the 92 individual quadrangles (Figure 3) and negative for the other 26 quadrangles. The means of the minimum and maximum monthly statewide average precipitation depths (Figure 7) during each of the 80 years of 1940–2019 are 0.789 inch and 4.64 inches, respectively.

Analyses of time series plots and standard linear regression metrics provide meaningful insight regarding occurrence or non-occurrence of long-term trends. Permanent long-term trends, if they exist, are hidden by the great continuous variability in precipitation and evaporation. Regression slopes switch between increasing versus decreasing with different sub-periods of the 1940–2019 precipitation or 1954–2019 evaporation records. The statewide annual precipitation of 13.6 inches in 2011 and 40.0 inches in 2015 are notable. The statewide lowest annual precipitation and highest evaporation in the database occurred in 2011. The 2015 precipitation of 40.0 inches is exceeded only by the 1941 precipitation of 40.6 inches. Hydrology in Texas has always fluctuated dramatically. However, any past long-term trends or changes in the characteristics of monthly precipitation and evaporation rates have been minimal compared to the effects of water resources development and management on river flows discussed in the next section.

Cook et al. (2015), Cook et al. (2019), and others have predicted that weather will be more highly variable and droughts likely more severe in the American Southwest and Central Plains, including Texas, in the future due to long-term climate change. Nielsen-Gammon et al. (2020) assess future impacts and management strategies associated with droughts in Texas during the latter half of the 21st century that may be more severe than those experienced during the past hundred years or perhaps past multiple hundreds of years.

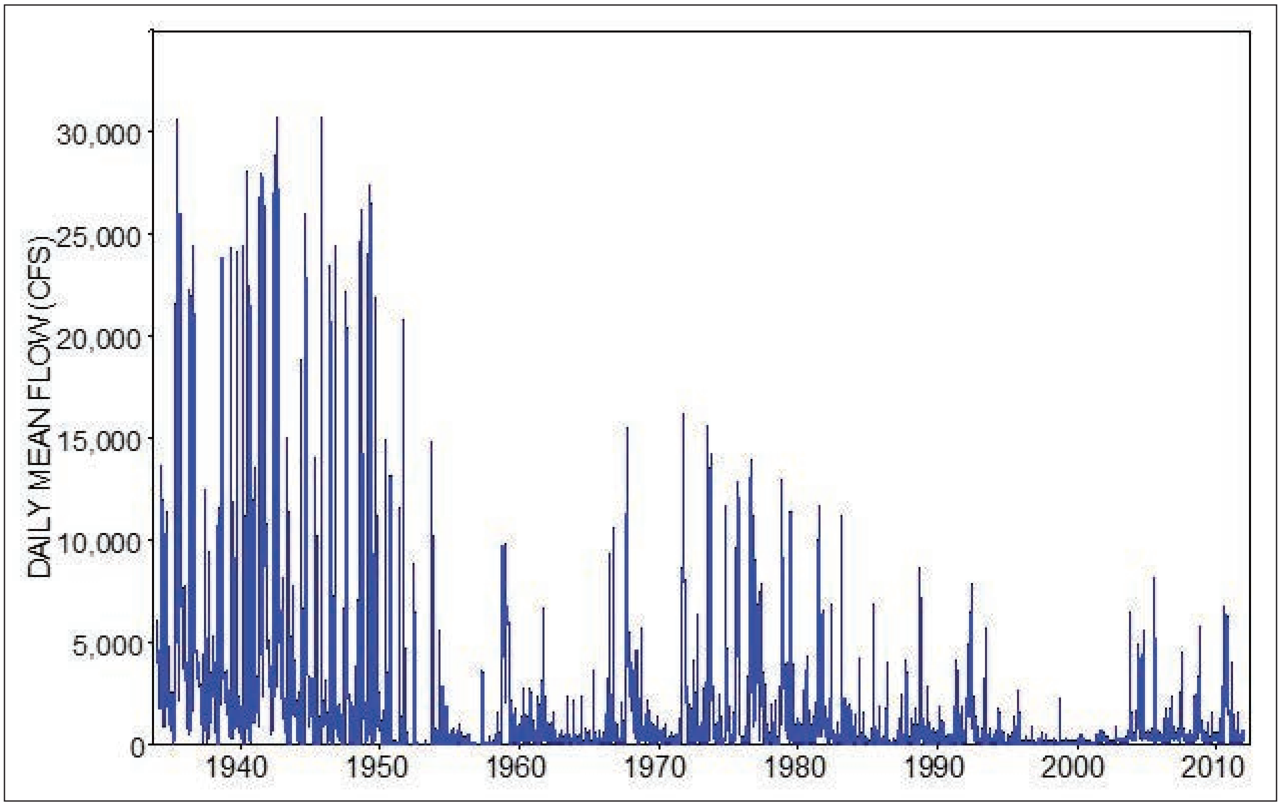

Figure 8. Daily flows of the Rio Grande at Brownsville from January 1934 through December 2011.

River flows observed at gage stations

River flows throughout Texas exhibit extreme variability, including severe multiple-year droughts and intense floods as well as continuous fluctuations. Flow characteristics have changed over time with construction of reservoir projects and other river regulation structures, increases in water supply diversions and return flows, and land use changes. Permanent or long-term stream flow alterations vary greatly with location. Regulation of rivers by dams reduces flood flows but may increase low flows at downstream locations. Flows immediately below dams are greatly affected by reservoir operations, but the effects diminish with distance downstream.

The National Water Information System (NWIS) website maintained by U.S. Geological Survey (USGS) includes 1,055 gages in Texas with historical daily data and 672 current condition sites with flows recorded at intervals of 15 to 60 minutes. Flow data for the Rio Grande is compiled by the IBWC. One IBWC gage and five USGS gage sites are selected in the following discussion to illustrate river flow characteristics. River flows are plotted in in Figures 8-15 in units of cubic feet per second (cfs).

Dramatic decreases in the flow of the Rio Grande illustrate the impacts of irrigated agriculture and large reservoirs in a dry climate. The Rio Grande Basin encompasses 356,000 square miles, but much of this area is flat desert that contributes no runoff to the river. Daily flows of the Rio Grande at Brownsville, located 49 miles above the river's outlet to the Gulf of Mexico, are plotted in Figure 8. The effects of International Falcon and Amistad Reservoirs on the Rio Grande with impoundment of stream flow beginning in 1953 and 1968 (Table 1) are evident in Figure 8.

The Canadian River is another extreme case of flows decreasing dramatically over the past several decades. Daily flows of the Canadian River at a USGS gage site about 70 miles downstream of Lake Meredith and 20 miles upstream of the Texas/Oklahoma border are plotted in Figure 9. Flows have been depleted by development of irrigated agriculture supplied mainly by groundwater along with municipal water use in this dry region of North Texas and New Mexico.

Illustrating the opposite extreme, flow of the San Antonio River below the City of San Antonio increased significantly over the last 80 years as a result of wastewater treatment effluent accompanying increased water supply from the Edwards Aquifer and increased impervious land cover due to urbanization. Flows of tributaries of the San Jacinto River in the Houston metropolitan area have similarly increased in response to return flows from M&I water use supplied by groundwater and interbasin import and increased runoff due to urban development.

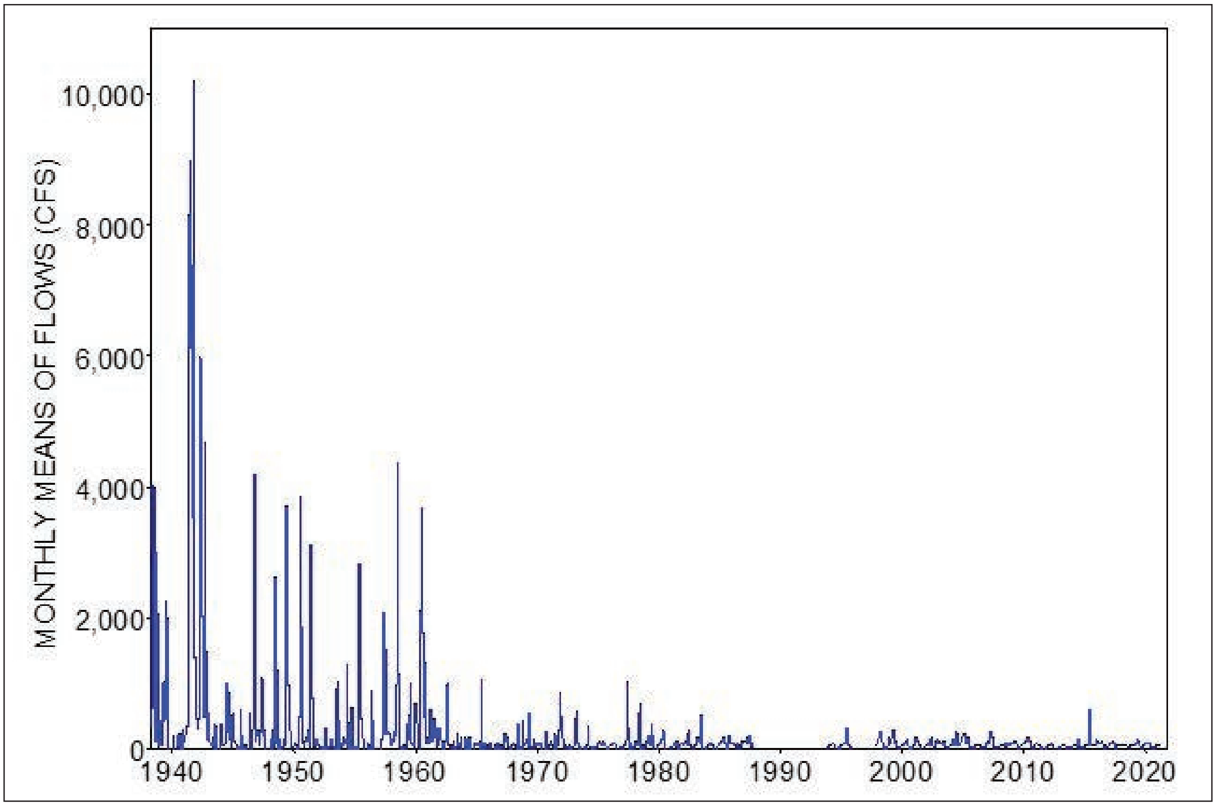

Figure 9. Monthly flows of the Canadian River downstream of Lake Meredith from November 1938 through September 1987; October 1993 through September 1996; and October 1997 through January 2021. Flow data are missing for October 1988 through September 1993 and October 1995 through September 1996.

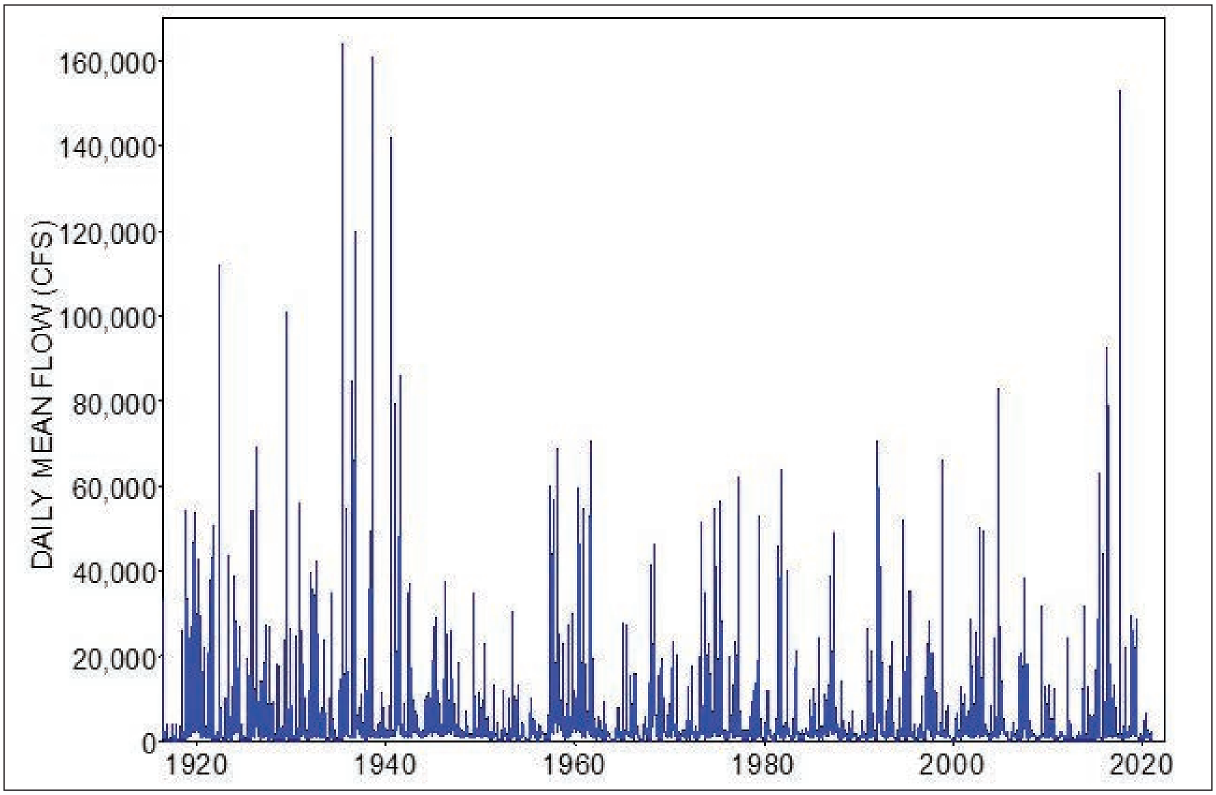

Figure 10. Daily flows of the Colorado River at Columbus from June 1916 through January 2021.

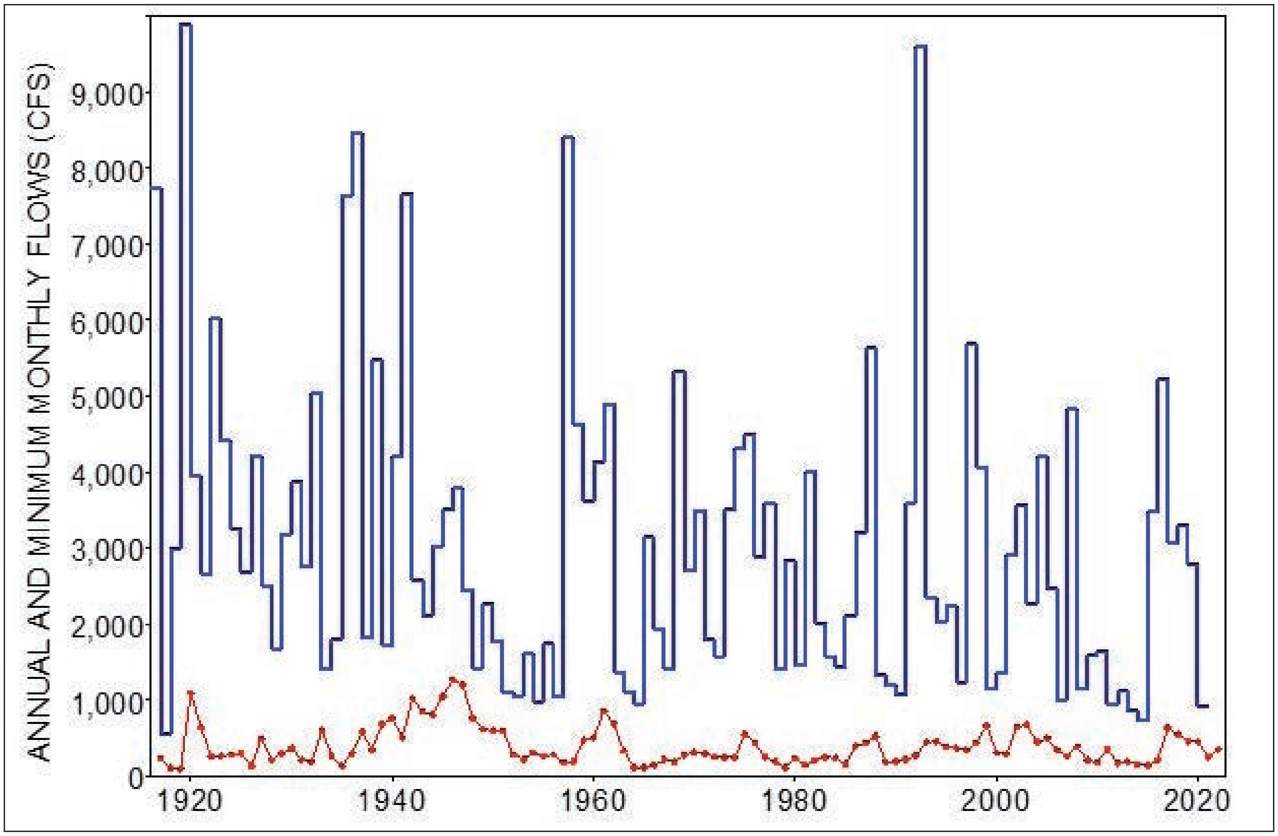

Figure 11. Annual means and annual minimum monthly flows of the Colorado River at Columbus from 1916 through 2020.

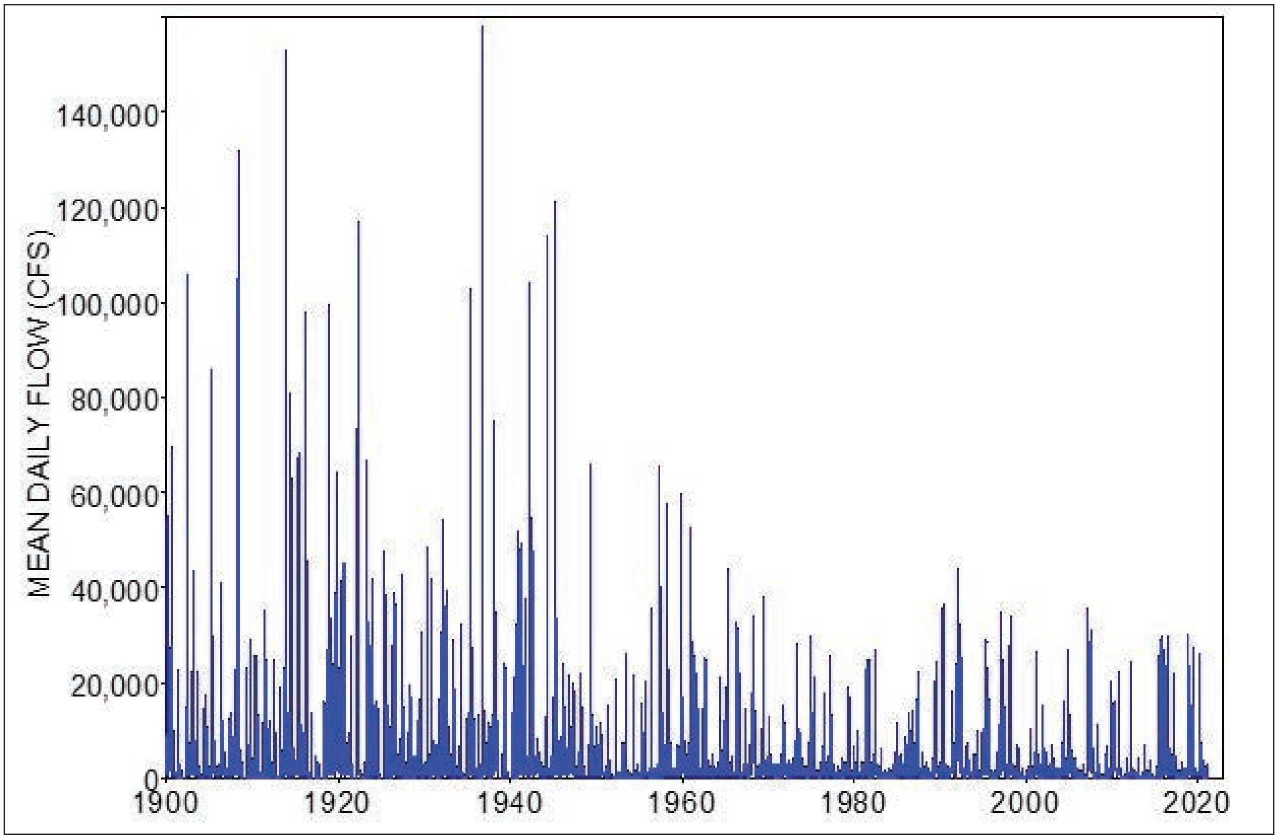

Figure 12. Daily flows of the Brazos River at Waco from January 1900 through January 2021.

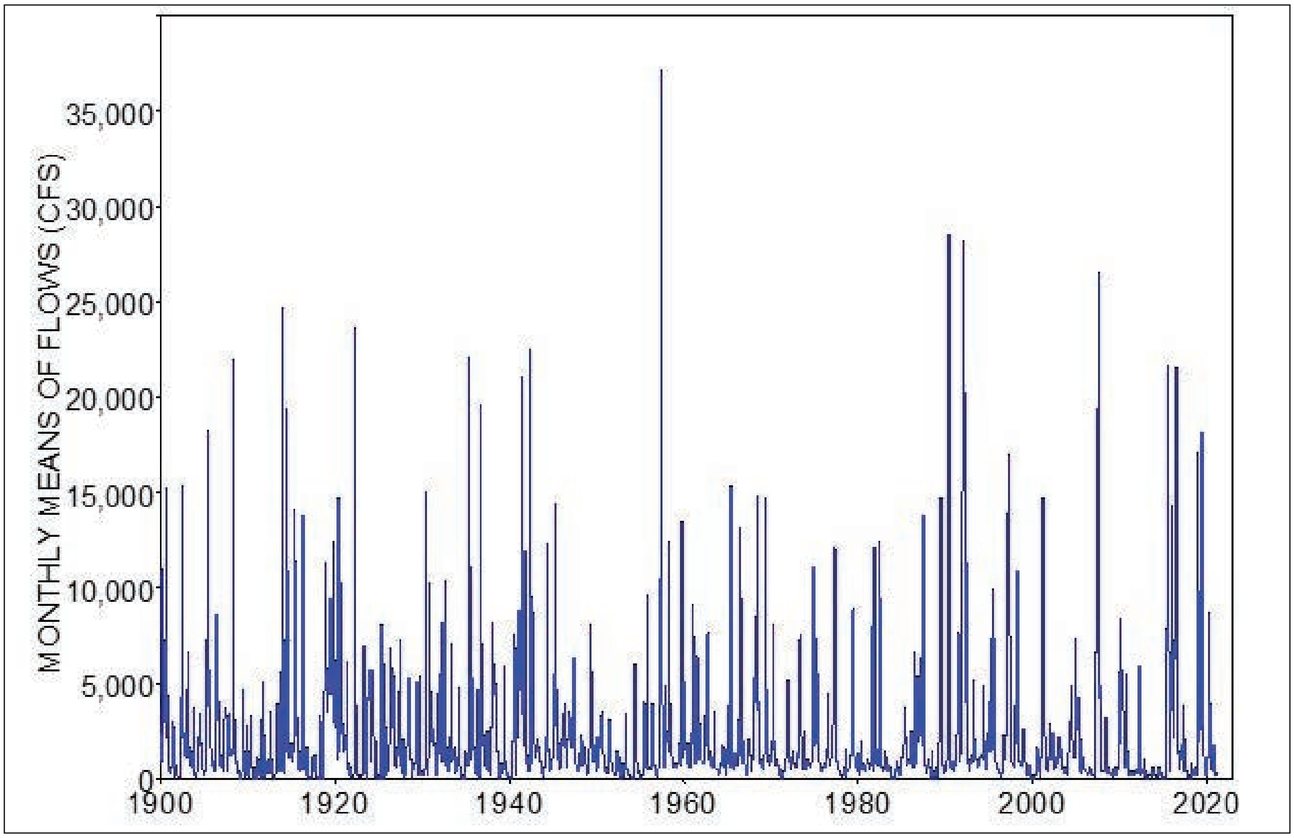

Figure 13. Monthly flows of the Brazos River at Waco from January 1900 through January 2021.

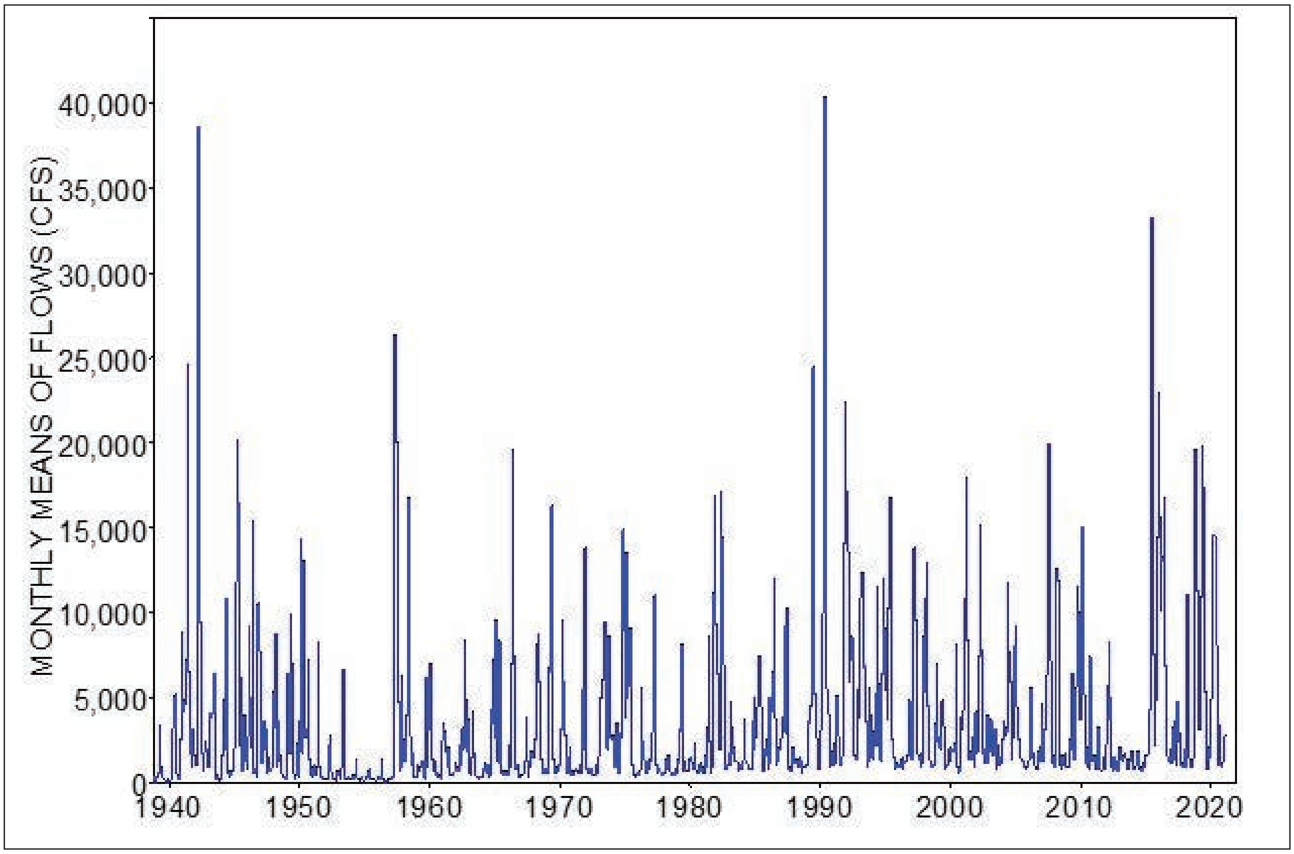

Figure 14. Monthly flows of the Trinity River near Rosser from November 1938 through January 2021.

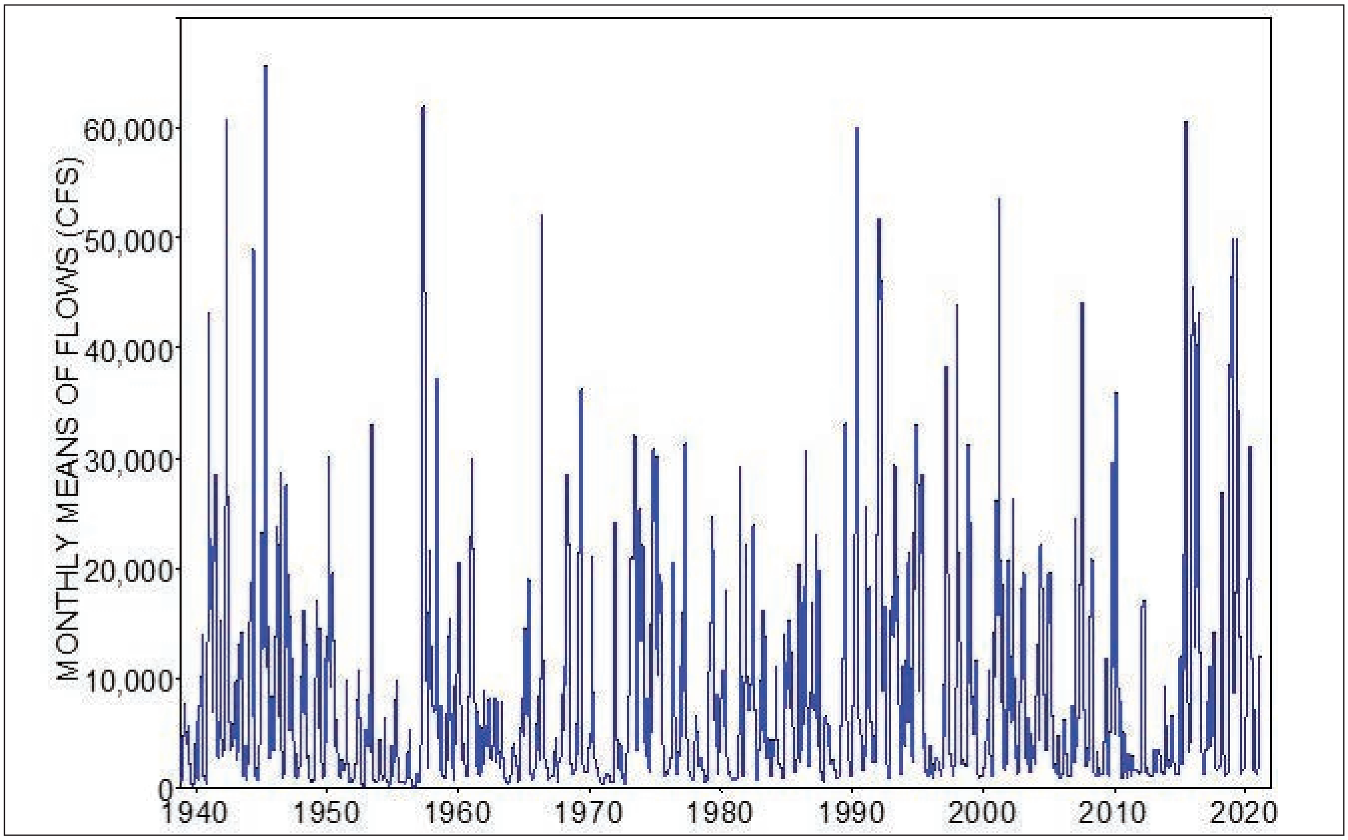

Figure 15. Monthly flows of the Trinity River at Romayor below Lake Livingston from November 1938 through January 2021.

Flows of the Colorado River at Columbus are plotted in Figures 10 and 11. This gage is about 100 miles below downtown Austin and has a watershed area of 41,600 square miles, of which 30,200 square miles contribute flows to the river. Daily means are plotted in Figure 10. Annual means and the minimum monthly flow in each year are plotted in Figure 11.

Flow variability characteristics vary significantly with choice of time interval for averaging flow rates, such as daily, monthly, or annually. Reservoir flood control operations may greatly affect instantaneous and mean daily flow rates with little or no effect on monthly or annual means, as illustrated by Figures 12 and 13. The effects of flood control operations of Whitney, Waco, and Aquilla Reservoirs (Table 1) on daily flows at a downstream gage on the Brazos River at Waco are evident in Figure 12. USACE flood control operations include an allowable flow rate of 20,000 at the Waco gage. These effects are dissipated in the monthly mean flows plotted in Figure 13.

Monthly flows of the Trinity River at Rosser and Romayor are plotted in Figures 14 and 15. These gages on the Trinity River have watershed areas of 8,150 and 17,200 square miles. The Rosser gage is 34 miles downstream of central downtown Dallas. The Romayor gage is 20 miles below Livingston Dam and 50 miles above the river outlet at Galveston Bay. The Dallas-Fort Worth metropolitan area in the upper Trinity River Basin has a population of 6.8 million people and has been one of the fastest growing metro areas in the nation during the past several decades. Many reservoir projects were constructed on the Trinity River and its tributaries during the 1950s to 1980s. The City of Houston, another large continually growing metropolitan area located in the adjoining San Jacinto River Basin, transports water by pipeline from Lake Livingston on the lower Trinity River. Low flows have increased with increases in wastewater treatment discharges. Significant decreases in instantaneous and daily flood flows are dissipated in the monthly flows.

Simulated reservoir storage

WRAP/WAM simulated reservoir storage provides a meaningful drought index as well as measure of water supply capabilities. Even though reservoirs were actually constructed at different times spanning many decades, all reservoirs with water right permits are operated in the simulation for a specified water use scenario continuously during a repetition of historical hydrology.

The summation of daily storage of all reservoirs in daily Brazos, Trinity, and Neches fully authorized scenario WAM simulations are plotted in Figures 16 and 17 (Wurbs 2019d, 2019e, 2020a). These are developmental daily versions of the

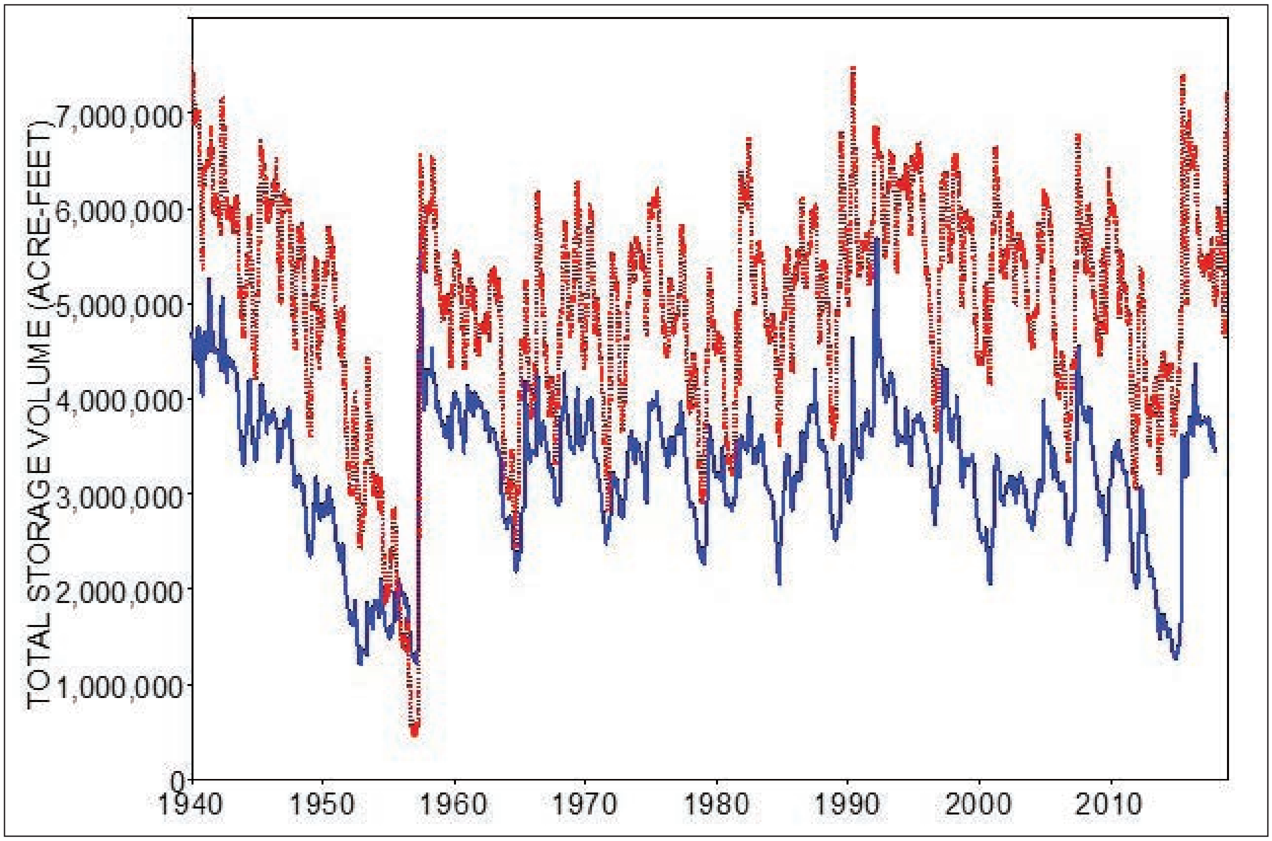

Figure 16. Simulated daily storage contents for the 680 reservoirs in the Brazos WAM (blue solid line) and 697 reservoirs in the Trinity WAM (red dashed).

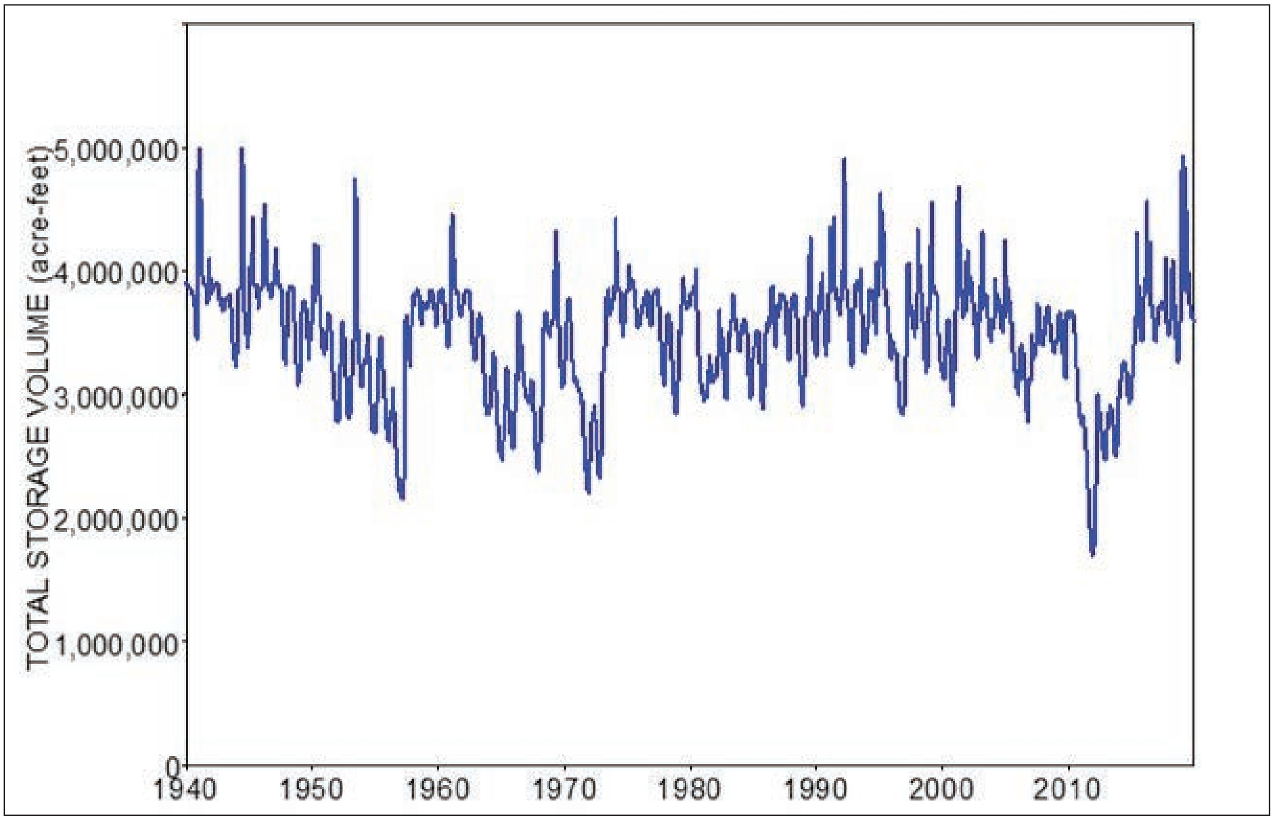

Figure 17. Simulated 1940–2019 daily storage contents for the 180 reservoirs in the Neches WAM.

Table 3. River basin characteristics.

River basin	Drainage area		Annual evaporation (inches)	Annual precipitation (inches)	Mean annual natural flow at outlet		Regulated flow (% naturalized flow)
	Total (miles²)	Texas (miles²)			(% precip)	(acre-feet)	
Rio Grande	182,220	49,390	64.0	16.1	2.60%	1,099,600	6.84%
Nueces	16,700	16,700	59.6	24.8	2.93%	647,930	68.0%
Guadalupe	10,130	10,130	54.1	32.3	12.7%	2,220,140	92.9%
Lavaca	2,310	2,310	50.8	39.7	17.6%	860,400	93.7%
Colorado	41,480	41,280	63.1	24.5	5.79%	3,118,790	61.2%
Brazos	47,010	44,310	60.2	29.4	10.4%	7,246,370	84.2%
San Jacinto	3,940	3,940	49.0	46.6	23.2%	2,270,090	49.3%
Trinity	17,910	17,800	55.1	39.4	17.6%	6,630,280	72.8%
Neches	9,940	9,940	48.5	48.7	24.1%	6,223,550	89.5%
Sabine	9,760	7,570	50.9	47.8	34.4%	6,633,090	93.3%
Cypress	2,930	2,930	48.9	47.2	22.7%	1,675,700	87.9%
Sulphur	3,770	3,580	50.1	46.6	29.1%	2,590,680	86.9%
Red	93,450	24,300	63.4	25.6	–	10,093,270	90.3%
Canadian	47,710	12,870	66.2	19.5	–	217,550	59.0%
Six Coastal	15,150	16,050	59.0	29.6	11.2%	2,902,510	104%
Total	504,410	263,100	59.4	28.1	11.8%	54,429,950	80.9%

WAMs with updated extended hydrology that have not been officially incorporated in the TCEQ WAM system for permitting purposes. The Brazos WAM has a hydrologic period of analysis of 1940–2017 and includes 680 reservoirs with full authorization storage capacities totaling 4,746,330 acre-feet. The Trinity WAM has 697 reservoirs with capacities totaling 7,445,690 acre-feet and a 1940–2018 period of analysis. The Neches WAM includes 180 reservoirs with a total permitted capacity of 3,904,100 acre-feet and 1940–2019 period of analysis. The daily Brazos, Trinity, and Neches WAMs also include operations of flood control pools of nine, eight, and one multiple-purpose USACE reservoirs, respectively. The three daily full authorization simulations are based on the premise that all reservoirs included in water right permits are operated during a hypothetical repetition of past natural hydrology occurring from 1940 to near the present. All water users use the full amounts to which they are legally entitled based on their water right permits, subject to water availability, throughout the simulations.

The timing and magnitude of simulated storage drawdowns for the Brazos and Trinity WAMs in Figure 16 are somewhat similar to each other. The Neches WAM storage plot in Figure 17 is notably different. The 1950–1957 drought and April-May 1957 flood are evident in Figure 16. Although the 2010–2012 drought was economically very costly, the residents of the Brazos and Trinity river basins have never experienced a drought as hydrologically severe as in 1950–1957 with present population and water needs and constructed facilities. The Neches River Basin is characterized by more abundant water supply capabilities relative to permitted use than the Brazos and Trinity river basins. The minimum summation of storage contents of the 180 reservoirs in the Neches WAM during the 1940–2019 hydrologic period of analysis simulation is 1,693,630 acre-feet, occurring on December 3, 2011.

Simulation results for individual reservoirs are of interest in most water availability modeling analyses. In general, storage fluctuations will be greater in individual reservoirs than in the summations plotted in Figures 16 and 17. The timing and magnitude of drawdowns and refilling vary between the different reservoirs. Summing storage contents of numerous reservoirs with locations scattered over the large river basins tends to average out or dampen fluctuations.

RIVER BASIN WATER BUDGETS

The 15 major river basins and eight coastal basins of Texas are modeled as 20 WAMs (Wurbs 2005, 2019a). The San Antonio River flows into the Guadalupe River and is included in the Guadalupe WAM. The Brazos River Basin and San Jacinto-Brazos Coastal Basin are combined as a single WAM. The Brazos-Colorado Coastal Basin is included in the Colorado River Basin WAM. The quantities in Tables 3 and 4 com-

Table 4. Water availability model (WAM) reservoir characteristics by river basin.

WAM river basin	Number of reservoirs		Storage capacity (acre-feet)	Storage capacity (% annual naturalized flow)	Mean storage (% capacity)	Reservoir evaporation (ac-ft/yr)	Diversion targets (ac-ft/yr)	Diversion reliability (%)
	Small	Major						
Rio Grande	73	7	3,499,070	318%	49.0%	304,110	2,228,870	81.7%
Nueces	123	2	959,827	148%	53.0%	201,600	637,040	87.4%
Guadalupe	235	6	756.527	0.034%	79.8%	158,120	420,780	90.9%
Lavaca	19	2	167,718	19.5%	92.6%	106,650	61,620	82.4%
Colorado	452	37	4,709,829	151%	69.5%	628,770	2,235420	82.5%
Brazos	671	45	4,015,865	55.4%	83.0%	1,026,530	1,519,140	93.3%
San Jacinto	110	4	587,529	25.9%	91.2%	2,197,590	520,360	83.2%
Trinity	653	33	7,356,200	111%	79.1%	2,546,030	6,617,850	86.9%
Neches	191	12	3,656,259	58.8%	98.2%	648,870	621,610	81.2%
Sabine	201	12	6,262,314	94.4%	97.6%	216,210	550,280	98.7%
Cypress	78	13	877,938	52.4%	85.9%	42,310	496,230	78.0%
Sulphur	53	4	718,699	27.7%	86.9%	55,810	242,070	99.2%
Red	212	25	3,780,342	37.5%	89.1%	328,420	860,600	97.2%
Canadian	44	3	879,824	404%	69.4%	62,270	94,160	95.4%
Six Coastal	121	5	184,660	6.36%	37.5%	66,220	267,900	95.5%
Total	3,236	210	37,656,830	70.44%	81.5%	10,375,250	17,373,930	86.6%

paring river basin characteristics are from river basin water budget studies based on current use scenario versions of the 20 monthly WAMs combined with information from other sources (Wurbs and Zhang 2014). The hydrologic periods of analysis vary between the different WAMs reflected in the tables, but all exceed 50 years. Six coastal basin WAMs are combined as a single line in Tables 3 and 4 for brevity.

Texas encompasses a total area of 268,310 square miles. Table 3 indicates that the watersheds of Texas have contributing drainage areas totaling 263,100 square miles. Some land in flat dry west Texas does not contribute precipitation runoff to stream flow because essentially all of the precipitation is lost through evapotranspiration and infiltration. A large area of the Rio Grande Basin in Mexico and New Mexico is non-contributing.

The WAM system is designed for assessing water availability and supply reliability in Texas. WAMs for the international and interstate river basins consider the entire basin to the extent necessary to assess water availability in Texas. State borders are treated as the outlets for the Canadian, Red, and Sulphur WAMs. The other rivers discharge into the Gulf of Mexico at their outlets. Although the Rio Grande WAM includes the Mexican share of the storage in Lakes Amistad and Falcon, the data in Tables 3 and 4 include only quantities allocated to Texas. Lakes Amistad and Falcon have total conservation storage capacities of 2,976,970 and 2,648,290 acre-feet, respectively, of which 1,303,910 and 1,096,390 acre-feet are allocated by treaty to the United States and used in Texas. Other interstate river basin data in Tables 3 and 4 include only reservoirs located wholly or partially in Texas but include their total WAM storage capacity.

The annual evaporation and precipitation depths in the fourth and fifth columns of Table 3 are spatially averaged over the area of the river basin encompassed within Texas. WAM naturalized flows (NF) represent natural conditions that would have occurred during the hydrologic period of analysis without water resources development and use. The sixth column of Table 3 expresses the WAM naturalized flow at the outlet as a percentage of the annual precipitation falling on the river basin area in Texas. The outlets are defined as where the flows leave Texas, which are either the Gulf of Mexico or a state border. The last two columns of Table 3 show the mean annual naturalized flow in acre-feet/year and the simulated regulated flow as a percentage of naturalized flow (%NF). The regulated flow of 104% of naturalized flow for the coastal basins reflects return flows from water supplies transported from adjoining river basins.

Table 3 is further explained as follows, using the Brazos River Basin as an example. The contributing drainage area of the Brazos Basin is 47,010 square miles, with 44,310 square miles in Texas and the remainder in New Mexico. The long-term mean annual precipitation and reservoir evaporation depths averaged over the basin are 29.4 and 60.2 inches/year. Without water development and use, the long-term mean natural flow to the Gulf of Mexico would be a calculated 7,246,370 acre-feet/year, which represents 10.4% of the precipitation falling on the basin. Mean current use scenario simulated regulated flow at the basin outlet is 84.2% of the natural flow.

Reservoirs are categorized as small versus major in Table 4 based on whether their storage capacity is less than 5,000 acre-feet. The total storage capacity for all reservoirs included in the WAMs are tabulated in acre-feet and as a percentage of annual naturalized flow at the basin outlet. Mean storage contents are expressed as a percentage of storage capacity.

Referring to Table 4, the 20 current use scenario WAMs include 3,446 reservoirs, of which 210 have capacities of 5,000 acre-feet or greater. Conservation storage capacities of the 3,446 reservoirs in the current use scenario WAMs total 37,656,830 acre-feet. Storage contents fluctuate greatly during the simulations but average 81.5% of capacity. The storage capacities for each river basin are expressed in the fifth column of Table 4 as a percentage of the mean annual naturalized flow shown in Table 3. Diversion targets are supplied in each month of the simulation to the extent that water is available from stream flow or reservoir storage. The last two columns of Table 4 show total volumes of water supply diversion targets for the current use scenario and the percentage of the target volumes supplied.

The long-term mean reservoir evaporation is calculated to be 10,375,250 acre-feet/year, which is 69.0% as large as the mean total water supply diversions. The calculated estimate of net annual evaporation (10,375,000 acre-feet) minus precipitation (7,835,000 acre-feet) is 2,540,000 acre-feet (Wurbs and Zhang 2014). Water surface evaporation is a major component of reservoir water budgets. Measures such as monomolecular films for reducing evaporation in reservoirs throughout the world, including Texas, have been extensively investigated (Barnes 2008; Wurbs and Ayala 2014). However, wind and wave action on the surface of major reservoirs severely constrain the feasibility of monolayer films and other evaporation suppression technologies.

Most of the reservoirs and storage capacity are located in the eastern half of the state. West Texas has low precipitation and high evaporation (Figure 3), with a large portion of the land area flat with minimal runoff and relatively few sites with topography suitable for reservoirs. Most of the reservoir capacity for storing runoff from western watersheds is in International Amistad and Falcon Reservoirs on the Rio Grande and Lake Meredith on the Canadian River. The Lower Rio Grande is the most productive surface water irrigation region of Texas. Agriculture in the Canadian River Basin and adjoining basins in the High Plains relies primarily on irrigation from the Ogallala Aquifer.

INSTITUTIONAL FRAMEWORK FOR RESERVOIR MANAGEMENT

Most of the large dam and reservoir projects in Texas and throughout the United States were constructed during the period from the 1930s through the 1980s, which has been called the construction era of water resources development. Other countries, most notably China, have dominated in building dams in recent decades. Economic, environmental, and institutional considerations severely constrain construction of additional dams in Texas and throughout the United States. Water management policy and practice have shifted to a greater reliance on managing floodplain land use, improving water use efficiency, and optimizing the operation of existing facilities.

Water resources development and management are accomplished within an institutional setting of organizations, traditions, programs, policies, financing mechanisms, and political processes (Wurbs 2015, 2017b, AWRA 2019). Surface water in Texas is a publicly owned resource, and its allocation and use are governed by treaties between the United States and Mexico, five interstate compacts with neighboring states, and two versions of a prior appropriation water rights permit system with 6,200 active permits (Wurbs 2013). The majority of the major reservoirs in Texas are owned and operated by private electrical and water utilities, river authorities, water districts, and cities. The majority of the storage capacity is contained in large federal reservoirs.

Federal reservoirs

The Civil Works Program of the USACE is the largest reservoir construction and management agency in the nation, with 537 reservoirs in operation nationwide (Patterson and Doyle 2018). The U.S. Bureau of Reclamation (USBR) operates 130 reservoirs in the 17 western states and has constructed many other projects turned over to local entities for operation (Billington et al. 2005). The Mexican and U.S. Sections of the IBWC jointly own and operate Amistad and Falcon Reservoirs on the Rio Grande.

The USACE has played a leading role nationwide in constructing and operating major reservoir systems for navigation and flood control. The USACE is responsible for flood control operations at projects constructed by the USBR as well as its own projects. The USBR was created by the Reclamation Act of 1902 to support economic development of the 17 arid and semiarid western states, including Texas, through large scale irrigation projects. The activities of the USACE and USBR have evolved over time to emphasize comprehensive multiple-purpose water resources development and management. Municipal and industrial water supply, hydroelectric power, recreation, and fish and wildlife enhancement are major purposes of USACE and USBR projects.

The USACE has constructed and now owns and operates 27 multiple-purpose lakes in Texas that contain water supply as well as flood control storage capacity, two flood control reservoirs that have no water supply storage, and a brine control dam. These 30 USACE reservoirs contain about 29%, 75%, and 43%, respectively, of the conservation, flood control, and total storage capacity of the major reservoirs of Texas. Twelve of the 30 USACE reservoirs are included in Table 1. Most of the USACE dams and reservoirs in Texas were authorized by omnibus legislative acts passed by the U.S. Congress during the 1940s and 1950s based on comprehensive basin-wide federal planning studies.

Reservoir projects owned by the USACE are maintained and operated by USACE district offices. Lake Texoma on the Red River, the largest reservoir in Texas, is operated by the Tulsa District. The Tulsa District also constructed and operates the multiple-purpose Pat Mayse Lake near Paris, Texas and the Truscott brine control dam in Knox County, both in the Red River Basin. The Addicks and Barker flood control reservoirs in Houston, which have no water supply storage, are owned and operated by the Galveston District. The other 25 USACE reservoirs in Texas are operated by the USACE Fort Worth District.

The USBR constructed the following five reservoir projects in Texas: Mansfield Dam and Lake Travis, Twin Buttes Dam and Reservoir, Palmetto Bend Dam and Lake Texana, Choke Canyon Dam and Reservoir, and Sanford Dam and Lake Meredith. All except Lake Texana are included in Table 1. These five reservoirs contain 7.7%, 9.6%, and 8.3%, respectively, of the conservation, flood control, and total storage capacity of the major reservoirs. Mansfield Dam and Lake Travis on the Colorado River was the first of the large multiple-purpose projects constructed in Texas by the federal government. The USBR constructed the project during 1937–1942. Lake Travis is now owned and operated by the LCRA. The USBR has also constructed water conveyance systems for agricultural and municipal use in the Texas portion of the Rio Grande, Colorado, and Canadian river basins. The USACE is responsible for flood control operations of reservoirs constructed by the USBR. Although the USBR owns and operates many reservoirs in other western states, reservoirs in Texas have been turned over to local sponsors that repaid reimbursable costs to the federal government. The Reclamation Acts of 1902 and 1939 established the policy that costs allocated to irrigation in federal projects be reimbursed by project beneficiaries. Congressional acts authorizing specific USBR projects have sometimes included repayment provisions tailored to the circumstances of the individual project.

Pursuant to the Flood Control Act of 1936, flood control storage in federal reservoirs is fully federally funded without cost-sharing. Nonfederal sponsors contract with the USACE and USBR for municipal and industrial water supply (M&I) storage capacity. All construction and maintenance cost allocated to M&I water supply are reimbursed by nonfederal sponsors in accordance with the Water Supply Act of 1958, as amended by the Water Resources Development Act of 1986 and other legislation (Wurbs 2016; USACE 2016). About 75% of the water supply storage capacity of the 117 USACE reservoirs nationwide that contain M&I supply is in the USACE Southwestern Division, mainly in Texas and Oklahoma (Institute for Water Resources 2003).

The International Boundary Commission was created in 1889. A convention in 1906 provided for the distribution between the United States and Mexico of the waters of the Rio Grande for the 89-mile boundary reach through the El Paso-Juarez Valley. A 1944 treaty distributed the waters of the Rio Grande from Fort Quitman, below El Paso, to the Gulf of Mexico and provided for construction and operation of Falcon and Amistad Reservoirs (Wurbs 1985, 2013). The International Boundary Commission was renamed the International Boundary and Water Commission (IBWC). The Mexico and United States sections of the IBWC are headquartered in Juarez and El Paso.

Three of the USACE reservoirs and the two IBWC reservoirs have hydroelectric power plants. The Western Area Power Administration (WAPA) markets the U.S. electric power generated at the two IBWC reservoirs. The Southwestern Power Administration (SWPA) markets the power from the USACE projects. WAPA and SWPA are two of several agencies of the Department of Energy responsible for marketing hydroelectric power from federal projects in various regions of the nation to electric cooperatives, municipalities, and utility companies.

Reservoir recreation is popular. Prior to 1965, recreation was included in federal projects as a fully federal expense. The Federal Water Recreation Act of 1965 established recreation at federal reservoir projects as a full project purpose subject to nonfederal cost-sharing. USACE lakes include significant areas of project-owned publicly accessible land around the shoreline. Many nonfederal reservoirs have privately owned land adjacent to much of the shoreline. Recreation is the primary purpose of the 18,100 and 8,000 acre-foot Buffalo and Coffee Mill Reservoirs in the Red River Basin owned and operated by the U.S. Fish and Wildlife Service and U.S Forest Service, respectively.

Nonfederal reservoirs

River authorities, water districts, and cities constructed and now own and operate 110 major reservoirs that contain about 45%, 0.1%, and 31% of the conservation, flood control, and total capacities of the major reservoirs. Several of these reservoirs are owned jointly by cities and water districts or river authorities. These numbers do not include the five reservoirs constructed by the USBR that are now owned and operated by nonfederal sponsors and the water supply storage capacity in 27 USACE reservoirs that nonfederal sponsors control through water supply contracts.

The Sabine River Authority (SRA) of Texas and the SRA of Louisiana jointly operate Toledo Bend Reservoir, which is the largest water supply reservoir in Texas. The SRA of Texas also operates Lake Fork and Lake Tawakoni. The LCRA operates the six Highland Lakes on the Colorado River, six hydroelectric power plants, four thermal-electric power plants, and two off-channel reservoirs that provide cooling water for the thermal-electric power plants. Established in 1929, the Brazos River Authority (BRA) is the first authority created in the United States to manage the water resources of a major river basin. The BRA owns and operates three reservoirs and has contracted for water supply storage capacity in nine USACE reservoirs. The Trinity River Authority and City of Houston jointly own and operate Lake Livingston. The Guadalupe-Blanco River authority owns and operates six small hydropower reservoirs on the Guadalupe River and contracts with the USACE for water supply storage capacity in Canyon Reservoir. The Lavaca River Authority owns Lake Texana, which was constructed by the USBR. Thirty-five water supply reservoirs are operated by 31 water districts. Forty-five cities own 48 water supply reservoirs.

Private companies own and operate 36 major reservoirs containing no flood control storage and less than 3% of the conservation storage of the major reservoirs. Most of these projects were constructed by electric companies to provide cooling water for steam-electric power plants.

RESERVOIR SYSTEM OPERATIONS

Managing hydrologic variability, supply reliability, flood risk, and future uncertainty is a central component of water management. Reservoir storage is necessary to manage extreme hydrologic variability to develop reliable water supplies. Dams and appurtenant structures also regulate rivers to reduce damage caused by floods. Reservoir system storage and release or withdrawal decisions can be categorized as operations during the following four conditions: (1) normal hydrologic conditions to optimize present day-to-day, seasonal, or year-to-year use of a reservoir system; (2) normal hydrologic conditions to maintain capabilities for responding to infrequent floods and droughts expected to occur at unknown times in the future; (3) floods; and (4) low flow or drought conditions. A reservoir may include conservation storage, flood control storage, or both (Wurbs 2016).

Reservoir storage pools

Reservoir operating procedures involve dividing the total storage capacity into the designated vertical zones or pool elevations illustrated by Figure 18. Water is normally removed

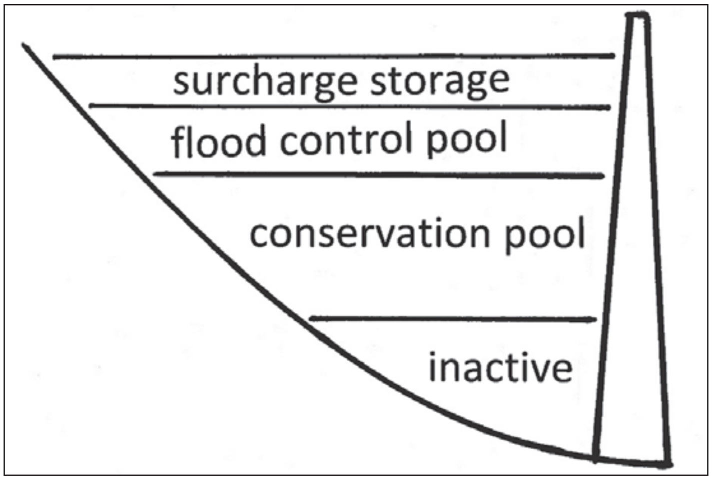

Figure 18. Reservoir storage pools.

from the inactive pool only through natural evaporation and seepage. The top of inactive pool elevation may be fixed by the invert of the lowest outlet or contractually set to facilitate lakeside withdrawals or releases from outlet structures that are higher than the lowest outlet structure. The inactive pool may provide part of the sediment reserve, head for hydroelectric power, and water for recreation and fish habitat.

Conservation storage purposes, such as municipal water supply, thermal-electric cooling water and other industrial supply, agricultural irrigation, hydroelectric power, and recreation, involve storing water during periods of high stream flow and/or low demand for later beneficial use as needed. The reservoir water surface is maintained at or as near the designated top of conservation pool elevation as stream flows and water demands allow. Drawdowns are made as required to meet the various needs for water.

The flood control pool remains empty except during and immediately following floods. The top of flood control elevation is often set by the crest of an uncontrolled emergency spillway, with releases being made through other outlet structures. Gated spillways allow the top of flood control pool elevation to exceed the spillway crest elevation.

Surcharge storage capacity is provided above the flood control pool or above the conservation pool if there is no designated flood control pool. The maximum design water surface, or top of surcharge storage, is established during project design from the perspective of dam safety. Reservoir design and operation are based on assuring that the reservoir water surface never exceeds the designated maximum design water surface elevation. The top of dam elevation includes a freeboard allowance above the top of surcharge pool for wave action and an additional safety factor against overtopping. The storage capacities cited in this paper and most documents referencing storage capacities do not include surcharge storage and dam freeboard.

Sedimentation and sediment reserve

Storage capacity is lost over time due to sediment deposits occurring throughout a reservoir. The rate of sediment deposition varies greatly between reservoirs, depending on stream flow inflow rates, sediment loads, and sediment trap efficiencies. Because sediment transport increases greatly during high flows, reservoir sedimentation varies greatly over time with the random occurrence of floods.

No attempt is made to estimate the volume and location of past or projected future sediment deposits for many smaller reservoirs. For most federal and other large reservoirs, reserve storage capacity is provided for sedimentation estimated to occur over a period of typically 50 to 100 years. The volume and location of the sediment deposition are predicted using methods outlined by the USBR (1987) and USACE (1995). Storage capacity reserved for future sediment accumulation is reflected in water supply contracts and planning.

Reservoir sedimentation surveys are performed occasionally. Because measurements of the bottom topography of lakes are expensive, many reservoirs have existed for decades without sediment surveys ever being performed. The TWDB has operated a hydrographic survey program since 1991. Reservoir owners contract with the TWDB to perform surveys to determine storage capacity, sedimentation rates, updated elevation-area tables, and bathymetric contour maps. Reservoir owners can also perform their own sediment surveys.

Flood control operations

The USACE is responsible for operating most of the large flood control reservoir in Texas and the nation. Flood control regulation plans are developed to address particular conditions for each reservoir and multiple-reservoir system. However, flood control operating rules for most reservoirs follow the same general strategy outlined as follows (Wurbs 1996, 2016; USACE 2017).

Flood control pool operations are based on minimizing the risk and consequences of making releases that contribute to downstream flooding, subject to the constraint of assuring that the maximum design water surface of the reservoir is never exceeded. Release decisions depend upon whether or not the flood control pool storage capacity is exceeded (Figure 18). Rules based on downstream flow rates at stream gages are followed as long as sufficient storage capacity is available without the water surface rising above the top of flood control pool. Operation is switched to an emergency operations plan, based on reservoir inflows and storage levels, during extreme flood conditions when the inflows are expected to exceed the remaining flood control pool capacity.

Overflow spillway and outlet conduit gates are closed when a flood occurs and remain closed until the flood has crested and flows are below the target levels specified at each of the downstream gages. The gates are then operated to empty the flood control pool as quickly as possible without exceeding the allowable flows at the downstream gages. The allowable flow rate associated with each gage site may be constant or may vary depending on the volume of water in storage upstream in flood control pools. Most flood control reservoirs are components of multiple-reservoir systems operated based on flow rates at several gages located various distances below the dams. Two or more reservoirs may have common downstream gages.

For an extreme flood event, limiting reservoir releases based on allowable downstream flow rates may result in the storage capacity of the flood control pool being exceeded. The overall strategy for operating the outlet works and spillway gates consists of two component types of regulation procedures. The regulation approach discussed above is followed until the release rate dictated by the emergency rules is higher than that indicated by the downstream allowable flow rates. Operations are then switched emergency release rules designed to absolutely assure that the maximum design water surface is never exceeded even though releases contribute to downstream damage. Emergency operating rules are specified as a function of current reservoir inflows and storage levels.

Conservation storage operations

Almost all of the major reservoirs in Texas have conservation pools serving primarily M&I, steam-electric cooling, and/or agricultural water supply. Hydroelectric power plants are operated at about 23 reservoirs. With the exception of Lake Texoma, hydropower generation is essentially limited to releases for downstream water supply diversions. Recreation is popular at most of the major reservoirs. Minimizing storage drawdowns and fluctuations generally enhances reservoir recreation.

Reservoir management in Texas is influenced more by the long-term threat of drought than seasonal fluctuations in stream flow and/or water use. Although storage may be significantly drawn down in several months, critical drought conditions usually involve a series of several dry years.

Essentially all water withdrawn from Texas streams for beneficial use is regulated by dams and reservoirs. Water supply operations are based on meeting demands subject to institutional considerations specified in water right permits, federal storage contracts, contracts between suppliers and customers, and for some reservoir systems, interstate compacts and/or international treaties. Although most surface water is used within the river basin in which it originates, several reservoir systems in Texas include interbasin transfers through pipelines.

Many water suppliers own and operate single reservoirs. System operations balancing storage and releases between multiple reservoirs occur in several river basins. Water supply withdrawals are made through pumping plants with intake structures located in the lake and/or at locations up to several hundred miles below the dams that regulate the flow. River flow at diversion sites may be a combination of releases from one or multiple reservoirs and unregulated flow entering rivers downstream of the dams. Some water users are supplied by run-of-river diversions with no access to reservoir storage. Reliabilities associated with run-of-river (no reservoir storage) water supply are generally very low.

COMPREHENSIVE INTEGRATED WATER MANAGEMENT

Multiple purposes are optimally served through integration of multiple management strategies. Integrated water management has been preached fervently over the past several decades nationwide. Texas has been a notable leader in effectively managing water resources in a comprehensive integrated manner. Reservoir operations are central to multiple objective endeavors. The remainder of this paper highlights current and potential future directions in improving water management in Texas. Successes and remaining challenges are highlighted with a focus on the role of reservoirs in developing and managing water resources.

Pursuant to water management legislation enacted by the 75th Texas Legislature in 1997 with the passage of Senate Bill 1 (SB1), the TWDB and 16 regional planning groups update 16 regional plans and a statewide water plan in a 5-year planning cycle with a 50-year future planning horizon. The 2002, 2007, 2012, and 2017 water plan reports are available at the TWDB website, and work on the 16 updated 2021 regional plans and the 2022 statewide plan is underway. The TCEQ administers a variety of regulatory programs involving water quality protection, water allocation, preservation of environmental resources, and dam safety. Consistency with relevant TWDB statewide and regional plans is a requirement for TCEQ approval of applications for new or amended water right permits.

Flood risk mitigation has been primarily federal and local community responsibilities, with involvement of state agencies focused on information dissemination. The Texas Legislature in 2019 significantly expanded the role of the TWDB in flood risk mitigation planning. The TWDB is presently initiating a statewide and regional flood planning process analogous to the SB1 planning process initiated in 1997. The TWDB is also creating programs to assist local entities in financing flood control projects similarly to long-established TWDB programs for assisting in the financing of water supply projects.

Flood risk mitigation

The federal government has played a dominant role nationwide, including in Texas, in large-scale flood protection through USACE reservoirs on major rivers, smaller reservoirs constructed by the Natural Resources Conservation Service in rural watersheds, and the National Flood Insurance Program (NFIP) administered through the Federal Emergency Management Agency. Local communities are responsible for flood plain management requirements of the NFIP and storm water management and drainage. As noted in the preceding paragraph, the TWDB has recently acquired significantly expanded responsibilities for flood control planning and financing. Additional funding has also been provided to expand TWDB flood data compilation and dissemination programs.

Coordination of floodplain management, reservoir flood control operations, and other structural and nonstructural measures has been a major nationwide endeavor since establishment of the NFIP and its requirements for local floodplain management pursuant to the Flood Disaster Protection Act of 1973. Reservoir storage reduces flood flows. Flood plain management reduces susceptibility of people and property to flood damage. Flood insurance is a risk management strategy. All three are essential. Optimal integration of the three strategies is challenging.

Emergency operations of USACE flood control reservoirs is a potential area for further research and development. The USACE (2017) outlines procedures employed during preconstruction design to establish the emergency operation component of flood control operating plans described earlier in this paper. An academic research study (Rivera 2004; Rivera and Wurbs 2004) explored a risk-based methodology for developing emergency operating rules based on stochastic generation of inflows that preserve the statistical characteristics of historical observed inflows. The Addicks and Barker reservoir system was employed as a case study for this research. Similar strategies using hydrologic data acquired since dam construction could be further investigated in the future.

Operations during major floods must balance flood risks upstream versus downstream of dams. Addicks and Barker Reservoirs in Houston, owned by the USACE, illustrate the problem of urban development adjacent to flood control pools as well as along streams (Wurbs 2002a). Most USACE reservoir projects include significant areas of government-owned land with no commercial or residential development allowed surrounding the reservoir for several vertical feet above the top of flood control pool. However, the planning, design, design revisions, and construction of Addicks and Barker Dams during the 1930s and 1940s resulted in purchase of areas of government-owned land upstream of the dams that may be exceeded by extreme flood events such as Hurricane Harvey in 2017. Likewise, releases from conservation pools of reservoirs with no flood control pool can transfer flooding between floodplains downstream and upstream of dams.

Operations during floods of non-federal water supply reservoirs that have no flood control pool is an important issue. The strategy of pre-flood releases from conservation pools based on flood forecasts has been investigated but is constrained by limited forecast capabilities and the lengthy time typically required to draw down conservation pool storage enough to significantly affect flood flows. Expanded flood forecasting capabilities and reservoir operating practices warrant continued research and development.

Dam safety and rehabilitation of aging structures

Risks of dam overtopping or breaching or structural failures of outlet gates are related to both flood risk mitigation and concerns nationwide and in Texas regarding rehabilitation of aging infrastructure (ASCE 2017). The TCEQ Dam Safety Program is responsible for safety oversight of 3,995 dams (https://damsafety.org/texas). These dams are classified as high hazard (1,352 dams), significant hazard (369), or low hazard (2,274) based on potential damage susceptibility of downstream life, property, and infrastructure. TCEQ dam safety staff inspect dams at 5-year intervals and provide technical information and assistance to dam owners. Dam safety regulatory policies are outlined in the Texas Administrative Code, Part 1 TCEQ, Chapter 299 Dams and Reservoirs, which is accessible online. Safety and rehabilitation concerns grow as dams and appurtenant structures age and watersheds and floodplains urbanize.

Dascher and Meitzen (2020) review the history of dam failures and removals in Texas. Fifty small mostly privately owned dams in Texas were removed between 1983 and 2016. Most were older small dams removed by private owners in response to liability concerns. Dascher and Meitzen (2020) found 328 instances of reported dam failures or related incidents in Texas since 1900. Several of the failures or incidents involve major reservoirs.

The Guadalupe-Blanco River Authority (GBRA) owns, operates, and maintains six dams on the Lower Guadalupe River that were constructed during the 1920s for hydroelectric power. The lakes also provide recreation. A spillway gate at Lake Wood broke loose from the dam in 2016, partially draining the lake. A spillway gate at Lake Dunlap similarly broke loose from the dam in 2019, partially draining Lake Dunlap. The GBRA announced in 2019 a planned systematic drawdown of all six lakes to ensure public safety. This action has been halted by a temporary injunction issued in favor of lakefront property owners interested in preserving the lakes to protect aesthetics and property values. Funding the rehabilitation of dams and appurtenant structures is a key issue.

Water supply reliability

Effective management of extremely variable stream flow requires assessments of water supply reliability. The TCEQ WAM system was implemented pursuant to the 1997 SB1 to support water allocation and planning. Reliabilities in meeting specified percentages of demand targets are computed in evaluating water right permit applications. Planning studies incorporate reservoir firm yield estimates. Firm yield is the maximum target demand that can be supplied continuously based on the premises and data reflected in the WAMs, including repetition of historical natural hydrology. Without reservoir storage, run-of-river firm yields are typically zero or near zero throughout Texas.

WAM simulations demonstrate that the target quantity of water supplied by a reservoir or multiple-reservoir system can be increased greatly by accepting risks of supply shortages during infrequent severe drought conditions. Reservoir operations with less than firm reliability can be combined as necessary with infrequent increased pumping from groundwater or emergency demand management. However, differences between ownership and regulation of groundwater versus surface water constrain these types of conjunctive water management operations (Young et al. 2018).

The BRA systems operation permit and associated water management plan approved by the TCEQ in September 2016 illustrate the significant improvements in water supply capabilities resulting from expanded WAM capabilities for assessing reliabilities of reservoir system operating strategies. Water supply capabilities of the 12-reservoir BRA/USACE system are enhanced by multiple-reservoir risk sharing, combining regulated and unregulated flows and firm and interruptible yield, and reuse of return flows. The BRA system operations permit and water management also includes the proposed Allen's Creek Reservoir in the lower basin that has not yet been constructed. However, the permit and management plan are designed for implementation with or without construction of the Allen's Creek Reservoir project.

The LCRA also combines firm (high reliability) and interruptible (lower reliability) yield in operation of the Highland Lakes to supply water users throughout the Lower Colorado River Basin. Austin and other M&I users contract with LCRA for firm yield. Agricultural irrigators are supplied through contracts based on interruptible yield. Water supply to interruptible customers is curtailed to varying degrees during droughts as the storage contents of Lakes Buchanan and Travis fall below set trigger levels. Reservoir operations are governed primarily by water supply requirements rather than hydroelectric power generation, but water supply releases pass through hydropower plants at the six dams, generating electricity and reducing costs of power production at the LCRA thermal-electric plants. The first version of the water management plan was approved in 1989, and the plan is periodically updated by the LCRA and submitted to the TCEQ for approval.

Several western states have watermaster operations for real-time management of water rights, but most states do not. Watermaster offices provide continuous accounting of water use and administer curtailment actions as necessary to enforce water right permit requirements. TCEQ watermaster offices have been established for some but not all river basins in Texas. For regions without watermaster operations, the TCEQ administers curtailment actions during drought and takes enforcement action anytime to stop reported unauthorized water use but does not otherwise closely monitor water use. Watermaster operations provide more detailed monitoring and accounting. The importance of TCEQ watermaster operations increases as less reliable reservoir water supply commitments are combined with backup plans such as temporary increased groundwater use or emergency demand management strategies.

The TCEQ Rio Grande watermaster office has maintained a detailed accounting for all Texas water right permits of storage in Lakes Amistad and Falcon and diversions from the lower Rio Grande since the 1970s. The South Texas and Concho watermasters patrol diversions for mainly run-of-river rights in the Concho River sub-basin of the Colorado Basin and Nueces, Lavaca, Guadalupe, and San Antonio river basins and adjoining coastal basins. TCEQ initiated a watermaster program in 2016 for the Brazos River Basin downstream of and including Possum Kingdom Reservoir. Establishment of watermaster programs for other river basins to regulate water use in accordance with water right permits continues to be investigated.

The prior appropriation water rights doctrine is a general guiding concept that is not necessarily feasible to implement absolutely with perfect precision in real world water management. For example, most water right permits assign a single priority date to both refilling reservoir storage and water supply diversions. Reservoir operation in Texas is based on long-term storage as a protection against severe multiple-year droughts. The supply reliability of a reservoir is diminished if upstream junior appropriators reduce inflows when the reservoir is not completely full and spilling. However, forcing junior diverters to curtail their water use to maintain inflows to an almost full or even significantly drawn-down senior reservoir is difficult and not necessarily the optimal use of the water resource. The senior reservoir will likely refill to capacity and spill later without failing to supply its own diversion demands even if the junior water supply diversions are not curtailed.

Reservoir storage reallocations

Wurbs and Carriere (1988), Johnson et al. (1990), and Wurbs (1990) outlined strategies for improving reservoir operations in response to changing conditions by reallocating storage capacity between project purposes, such as permanently or seasonally converting portions of flood control or hydropower pools to water supply. Patterson and Doyle (2018) and Doyle and Patterson (2019) explore issues and future potential for storage reallocations at USACE reservoirs nationwide.

Storage reallocations between flood control and conservation purposes are implemented by raising or lowering the designated top of conservation pool shown in Figure 18. The top of conservation pool can be raised and lowered seasonally in response to seasonal variations in flood and drought risks and water demands. Seasonal rule curve operations have been employed at Lake O' the Pines and Lake Wright Patman and occasionally at Lakes Amistad and Falcon. Permanent reallocations have been implemented at several USACE reservoirs in Texas. Reallocations have been studied but not adopted for other projects. In some cases, storage has been reallocated in existing reservoirs in conjunction with construction of other new reservoirs. Lakes Waco and Texoma are examples of several reservoirs where reallocations have been performed without modifying existing dams or constructing new reservoir projects.

Construction of Lake Waco by the USACE Fort Worth District was completed in 1965 with flood control, conservation, and sediment reserve capacities of 553,300, 104,100, and 69,000 acre-feet, respectively. The USACE reservoir inundated an existing nonfederal reservoir constructed in 1929. The conservation pool is committed to supplying water for Waco and adjacent smaller cities. In 2003, at the request of the City of Waco and BRA, the USACE raised the top of conservation pool 7 feet, converting 47,500 acre-feet of the flood control pool to water supply. The conservation capacity in Table 1 reflects the raised pool plus sediment reserve less estimated actual sedimentation.

Lake Texoma on the Red River in Texas and Oklahoma is the oldest and largest USACE reservoir in Texas. The project was constructed for flood control and hydropower while realizing that other purposes could become important in the future. For many years, the conservation capacity was used solely for hydroelectric power and recreation. Natural salt pollution in the Red River Basin has been a constraint to water supply use. However, motivated by growing water needs in both Texas and Oklahoma, hydropower storage has been reallocated to M&I water supply in several increments as needed over the past several decades. Desalination is used with the increased M&I supply.

Water quality

Pollution from agricultural or oil field activities in watersheds or M&I wastewater effluents often cause reservoir water quality problems. Eutrophication is a common problem resulting from excessive addition of organic matter, plant nutrients, and silt to reservoirs at rates sufficient to cause increased production of algae and rooted plants. Natural salinity is the water quality problem causing the greatest constraint on water supply capabilities of large reservoirs in a large region of Texas.

Salinity in lower reaches of Texas rivers may be increased by saltwater intrusion from the Gulf of Mexico, from sources in the upper river basins, or from combinations of multiple sources. Seawater propagates further upstream in rivers during low flows. For example, salinity levels of flows of the Brazos River at water supply pumping plants located about 25 miles and 60 miles upstream of the river outlet are dependent on river flow levels that are affected by reservoir operations.

Shallow geologic formations in the Permian Basin region underlying the upper watersheds of the Rio Grande, Pecos, Colorado, Brazos, Red, and Canadian Rivers in New Mexico, Oklahoma, and Texas contribute large salt loads to the rivers (Wurbs 2002b). The mineral deposits consist largely of sodium chloride, with moderate amounts of calcium sulfate and other dissolved solids. The USACE, USBR, water districts, and river authorities have investigated measures for dealing with the natural salt pollution. Several of the many proposed salt control plans have been implemented, as illustrated by the examples noted below (Wurbs 2002b). Water supply capabilities of many large Texas reservoirs could potentially be significantly increased by further planning, design, and implementation of salinity control strategies.

The Truscott brine storage facility constructed by the USACE Tulsa District in 1987 above Lakes Kemp and Texoma captures and permanently stores salt from a primary salt source watershed. A levee constructed around Estelline Springs prevents high salinity spring flows from entering the Red River. Red Draw, Barber, and Mitchell County Reservoirs are salt pollution control projects constructed in the upper Colorado River Basin to reduce salt loads into Lakes Thomas, Spence, and O. H. Ivie, which are owned by the Colorado River Municipal Water District.

A project implemented by the USBR near the Texas/New Mexico border during the 1980s to reduce salt loads of the Canadian River and Lake Meredith consists of shallow interception wells combined with deep-well injection wells to dispose of the brine. The Canadian River Municipal Water Authority blends high salinity water from Lake Meredith with lower salinity groundwater.

Salt control dams have been proposed by the USACE for the upper Brazos River Basin but have not actually been constructed. Dilution occurs in the middle and lower Brazos River as the BRA's high-salinity releases from their three upper Brazos River reservoirs combine with their releases from low-salinity tributary reservoirs and unregulated flows (Wurbs and Lee 2009).

Numerous desalination plants using reverse osmosis or electrodialysis processes are in operation throughout Texas and neighboring states for treating brackish groundwater and surface water for M&I use. Most are small. The two largest plants use electrodialysis reversal to treat water from Lake Granbury on the Brazos River and Lake Texoma on the Red River.

Environmental flow standards

Protecting instream flows in the river systems of Texas has been a concern for many years. Efforts to establish environmental flow standards have greatly intensified since 2001, when the Legislature authorized the Texas Instream Flow Program to advance scientific knowledge related to environmental flows. In 2007, the 80th Texas Legislature created the Senate Bill 3 (SB3) process to expedite the establishment of environmental flow standards (EFS) for priority river reaches based on the best currently available scientific information and expert opinion. SB3 required TCEQ to adopt EFS through rulemaking. EFS have been established and incorporated into the WAMs through the SB3 process for river systems flowing into the Gulf of Mexico. These standards are published in the Texas Administrative Code, Part 1 TCEQ, Chapter 298, Environmental Flow Standards for Surface Water, which can be accessed online. The SB3 process anticipates future improvements to the flow standards with advances in scientific knowledge.

The EFS established through the SB3 process and incorporated into the TCEQ WAM system are defined based on seasonally varying flow regimes with subsistence flows, base flows, and high flow pulses (Wurbs 2017). Although preexisting water right permits are not subject to the SB3 EFS, applications for new water right permits or modifications to existing permits for new appropriations of water are subject to the adopted standards. Various issues related to interactions between the SB3 EFS and reservoir operations warrant continuing investigation.

CONCLUSIONS

Water resources development and management are driven by spatial and temporal hydrologic variability. Thousands of dams and reservoirs have been constructed in Texas, with most of the storage capacity contained in a relatively small number of the largest federal and non-federal projects. River flow characteristics have been significantly altered by reservoirs, but flows are still extremely variable. Long-term mean river flow volumes are very large, but most of the flow occurs during flood events or infrequent periods of very high flows, separated by long periods of fluctuating low-to-moderate flows that may include severe multiple-year droughts. Conservation storage is essential to provide reliable water supplies. Flood control storage is an essential component of integrated flood risk mitigation. Reservoir operations are central to essentially all aspects of comprehensive water management. Optimizing reservoir operations is an important component of the response to population growth and accompanying intensifying demands on limited water resources and river regulation infrastructure.

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Commentary: Fresh, Clean Water for Texans Now and for Generations to Come

Tracy O. King[1]*

Editor-in-Chief's Note: The Texas Water Journal invited Texas state Representative Tracy O. King, incoming chair of the House of Representatives Committee on Natural Resources, to share his thoughts on what is ahead for the Natural Resources Committee. 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.

Keywords: Texas House of Representatives, natural resources, Texas water policy

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Let me begin by thanking Texas House Speaker Dade Phelan for appointing me to chair the Texas House of Representatives Committee on Natural Resources in the 87th Session of the Texas Legislature. This will be my 11th term on the Natural Resources Committee but my first as chairman. Although I have chaired other committees in the Texas House of Representatives, I am particularly excited about this assignment. The district in southwest Texas that I represent is blessed with bountiful groundwater and several flowing rivers as well as the Falcon Dam reservoir in Zapata County. That has thrust us into many water issues over the years.

As everyone is well aware, the COVID-19 pandemic has disrupted most things, and the interim work of the Natural Resources Committee wasn't spared. In-person hearings were suspended, which meant the committee was unable to travel the state to receive testimony on issues big and small, local and statewide. The committee was unable to make site visits and see firsthand what the needs are of communities and industries across Texas. Nevertheless, the committee remained open to receiving electronic submissions of testimony on its interim charges, and Chairman Larson and his staff were able to put together a forward-looking report with many recommendations on how to address the future water needs of the state. I applaud Chairman Larson and the rest of the Natural Resources Committee members on their important work over the interim in spite of this worldwide disaster.

Since the dawn of time, it seems, every chair of the Natural Resources Committee has had the same goal: to enact a reasonable framework that allows Texans access to fresh, clean water now and for generations to come. The committee is essentially a planning one. Using the best tools, smartest experts, and latest technologies, it tries to protect what we have now and provide for the future. While I am still adjusting to the new role as chairman, I can say that this tradition will continue. I intend to run a committee that is deliberative but committed to action and that is fair but decisive. Above all, I intend to run a committee that strives to do what is best for this state and the people who call it home.

I look forward to steering the committee toward solutions that cradle Texas water policy within a predictable and reasonable yet protective regulatory architecture. Such a framework will allow Texas to continue to provide affordable and reliable water to an ever-expanding variety of users and consumers while encouraging the development and innovation of new, alternative water sources. I encourage stakeholders, experts, everyday Texans, or anyone else with a good idea to work with us so together we can meet these goals.

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Economic Analyses of the Seadrift Wind-Aided Wastewater Treatment Plant Operations

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Abstract: Seadrift is a city located on the Texas Gulf Coast with a population of 1,364 people as of the 2010 U.S. Census. In 2012, the city started operating a $610,878 wind turbine, dedicated to its wastewater treatment plant. The city contributed only 3% of the funds for the project, with the balance from state agencies or the state of Texas. The city hoped to save $25,500 yearly using wind energy to displace some of the plant's electrical demand. The plant's average load is 0.05 million gallons per day, requiring 236,000 kilowatt-hours (kWh; 8.05x10^8 British thermal units [BTU]) yearly. From 2012 to 2015, Seadrift saved $15,928 per year, with yearly wind energy production of 155,738 kWh (5.31x10^8 BTU) and net present value of $211,493 at the city level. Yet, the project's applicability to other locations is limited. Indeed, when considering the project's total cost and return, the economic results, driven by a lower than predicted wind speed, are negative. Still, the study serves as a valuable tool to aid government agencies and rural communities in devising alternative and sustainable solutions to water-energy nexus challenges in Texas and beyond.

Keywords: renewable energy, water, water-energy nexus, wastewater, wind energy

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Terms used in paper

Acronym / Initialism	Descriptive Name
BTU	British thermal units
COE	cost of energy
CRF	capital recovery factor
ECOE	effective cost of energy
EPA	Environmental Protection Agency
ERCOT	Electric Reliability Council of Texas
FERC	Federal Energy Regulatory Commission
fps	feet per second
ft	feet
HOMER	Hybrid Optimization of Multiple Energy Resources
hp	horsepower
IRR	internal rate of return
kWh	kilowatt-hours
m	meters
MGD	million gallons per day
mps	meters per second
MW	megawatts
NCF	net cash flow
NCSL	National Conference of State Legislatures
NPV	net present value
NREL	National Renewable Energy Lab
O&M	operations and maintenance
PURA	Public Utilities Regulatory Act
PURPA	Public Utility Regulatory Policies Act
QF	qualifying facility
RE	renewable energy
REP	retail electricity provider
ROI	return on investment
RPS	renewable portfolio standards
SCADA	supervisory control and data acquisition
SECO	State Energy Conservation Office
SPP	Southwest Power Pool
TDA	Texas Department of Agriculture
WWTP	wastewater treatment plant

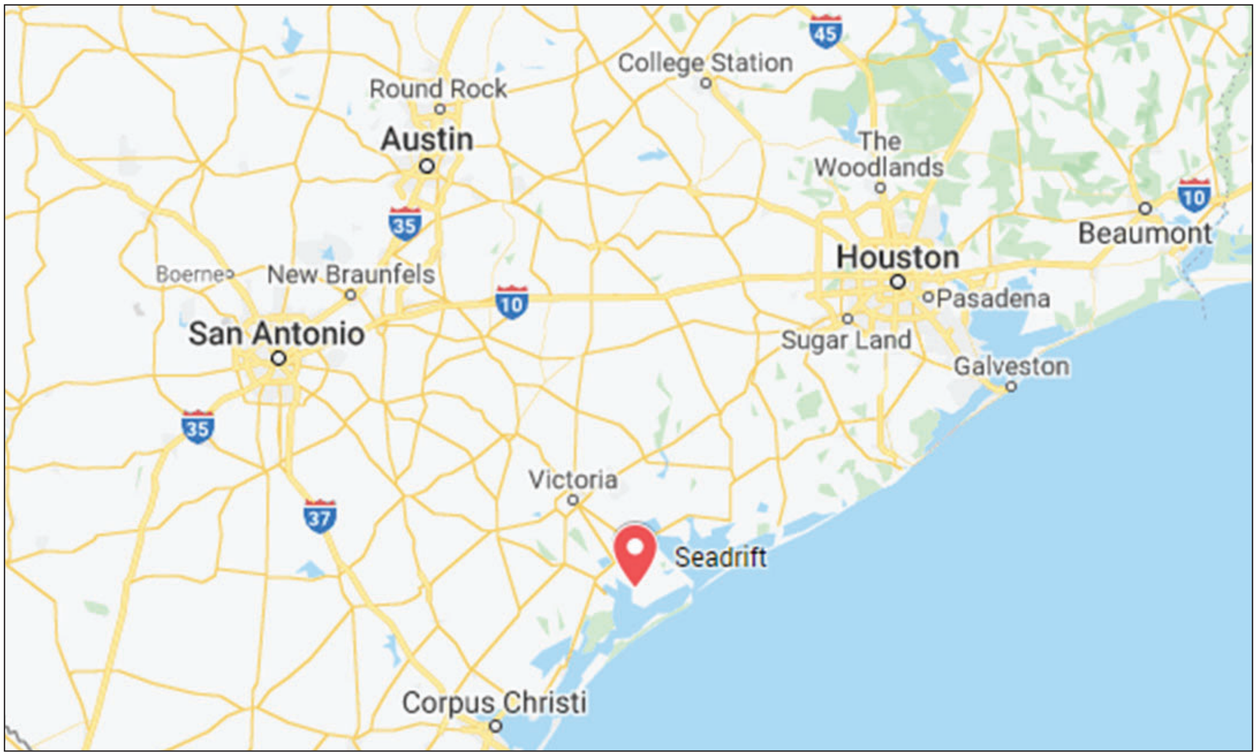

Figure 1. Vicinity Map Seadrift, TX. Map data ©2021 INEGI, Google.

INTRODUCTION

Recent research efforts on the integration of wind energy with water projects have dealt mostly with theoretical systems designed to simulate real applications. In their review, Mbarga et al. (2014) mentioned 25 wind-water systems. Of these, four were conducted in a laboratory (Park et al. 2011, 2012, 2013; Ben Ali et al. 2012), two were pilot projects (López-Ramírez et al. 2013; Rainwater et al. 2013), and all the others were simulated systems. Those contributions are helpful, but full-scale analyses of wind-water systems are needed to give decision-makers reliable data useful for future projects.

The study's primary objective was to perform an economic analysis for the city of Seadrift, Texas, which purchased a grid-connected wind turbine. The turbine would displace some of the grid energy used in its wastewater treatment plant (WWTP) and thereby reduce energy costs (bills) for the municipality. The project was also expected to show how other municipalities could use renewable energy (RE) resources to provide sustainable services to their residents. The project shows how a small community with limited funds can leverage different funding sources to finance RE projects.

The city of Seadrift is located on the Texas Gulf Coast in Calhoun County and has a population of about 1,364 people. The city is about 3 meters (m; 10 feet [ft]) above sea level. Figure 1 is a map of the geographical location of Seadrift. The city's WWTP has a rated capacity of 0.3 MGD with an annual historical average use of 0.05 MGD or 17% capacity. The city estimates that the WWTP consumes 236,000 kilowatt-hour (kWh; 8.05x10^8 British thermal units [BTU]) yearly, serving about 699 sewer utility customers. The WWTP is supplied by three energy sources: the grid, a wind turbine, and a generator in case grid power is interrupted.

Four lingering uncertainties attendant to wind-water systems are: (1) the real economic costs and benefits associated with wind projects, (2) accurate prediction of wind potential and intermittence at a location, (3) usefulness of manufacturer-provided power and energy curves, and (4) seamless integration of wind energy into the electrical grid. The literature review that follows provides context to evaluate the contribution of the Seadrift project to the challenges of the water-energy nexus. Then follows the technical and financial background of the genesis of the wind turbine project in Seadrift, including the pertinent economic metrics, the energy flows within the wind turbine-WWTP-grid system, and the results of our economic analyses of the wind-aided WWTP operations.

LITERATURE REVIEW

Wind energy systems have a different cost structure than fossil fuel energy systems. Customers using grid energy share the amortized cost of the generation and distribution infrastructure. Also, on-site diesel generators are typically less complicated and expensive than wind turbines, whose installation requires geotechnical, environmental, and construction considerations. Further, while fossil-fuel driven systems require fuel at a significant operational cost overtime, wind is free. Hence, capital costs are the largest component for wind turbine projects (Gude et al. 2010). Ackermann and Söder (2002) and Gude et al. (2010) found the costs of generation for wind energy to be competitive with grid energy costs in dollars per kWh, depending on the size and location of the project. For instance, costs of electricity varied across the state of Texas, ranging from about \$0.05/kWh to \$0.12/kWh during the 2009–2017 time period. Resale of excess wind energy to the grid typically received \$0.04/kWh. Still, Ackermann and Söder (2002) report that wind energy projects have been buoyed by government or third-party financial incentives such as tax credits in North America and feed-in tariffs in Europe. Energy costs can reach 30% of total cost of produced water in desalination systems (Gude et al. 2010). Thermal-based technologies (7–14 kWh/m^3 or 700–1400 BTU/ft^3) typically require about twice the energy per cubic meter of treated water compared to membrane desalination (2–6 kWh/m^3 or 2–6 BTU/ft^3), making combination with RE more challenging (Subramani et al. 2011).

Conventional energy sources (gas, oil, grid) are still typically cheaper to use than RE sources. One avenue to reduce produced water cost is to use hybridization, the mixing of different energy sources, to supply a load (Subramani et al. 2011; Kalogirou 2005; Karagiannis and Soldatos 2008). Karagiannis and Soldatos (2008) report desalinated water costs for solar-wind systems (Mohamed and Papadakis 2004; Kershman et al. 2005). García-Rodríguez (2003) mentions many hybrid wind-solar powered desalination systems, which used the complementarity of the two energy sources, relying mostly on insolation during the day and on wind energy at night.

Grid energy can also be hybridized with RE. Gude et al. (2010), recognizing the complementarity of RE and fossil fuel energy in capital and maintenance costs, reliability, and environmental impact, advocate combining both sources to reduce the cost and the environmental footprint of desalination projects. Rainwater et al. (2015) reported on a 50-kW (67-horsepower [hp]) wind turbine installed in Seminole, Texas that generated 47% of the energy needs for a brackish water well and an RO system, with the balance from the grid. Finally, cheap and reliable low-grade heat from conventional and nuclear plants can be hybridized with RE (Gude et al. 2010). Still, even in the absence of grid electricity, RE-driven water and wastewater treatment should always be considered in remote locations with robust wind or solar potential such as islands, because it usually is cheaper than the transportation cost of water or grid extension to the location (Gude et al. 2010; Ackermann and Söder 2002).

A clear identification of the costs of wind projects is challenging, and the myriad of RE-water system combinations precludes a meaningful taxonomy and comparison of systems across research efforts (Gude et al. 2010; Karagiannis and Soldatos 2008). Hence, costs must be assessed based on the specific constraints of every project. Further, project designers should consider total cost and total return on a project so that the economic assessment is complete. It has been proposed that life cycle analyses that go beyond economic values can give a more accurate picture of wind power's value than a mere economic analysis. Still, although life cycle-based analyses provide an attractive alternative to pure economic value, the life cycle approach works best when all the expense and revenue items have a common starting point. When the wind energy source is added into an existing system with previous operation constraints, as is the case in the Seadrift project, the life cycle analyses are problematic.

In grid-connected settings, the main economic advantage of wind turbine energy is that it displaces grid energy and thus allows economic savings by using wind as a zero fuel cost energy source (Ackermann and Söder 2002). During the planning phase of a project, investors use average wind speed at a location to estimate the future energy production of the turbine, which in turn indicates potential income generated by displacing grid energy or selling energy to the grid. Over the typical 20–25 year lifespan of a wind turbine, there is little variation in the expected energy generation, as the range of wind speeds at a location tends to remain consistent from one year to the next (Petersen et al. 1998, as cited by Ackermann and Söder 2002). This assumed relative stability in energy production allows project designers to estimate present value of future wind benefits and reduces the uncertainty in energy production for the lifetime of the project. In actual application, however, the variations in wind speed should be considered.

Intermittence is the stochastic nature of wind speed, which leads to fluctuations in the wind power from the wind turbine. Intermittence can also cause mismatches between wind production and energy demand, as illustrated in the inland Seminole project (Rainwater et al. 2015). Yet wind energy seems particularly suitable to islands, coasts, and mountains, which generally enjoy good wind potential (Gude et al. 2010). Subramani et al. (2011) recognized the challenge of matching intermittent wind energy production with constant electrical demand and recommended compressed air storage, battery storage or increased treated water storage to store wind energy.

Wind power is a function of the wind speed cubed until the wind speed reaches its design value, at which point, even as

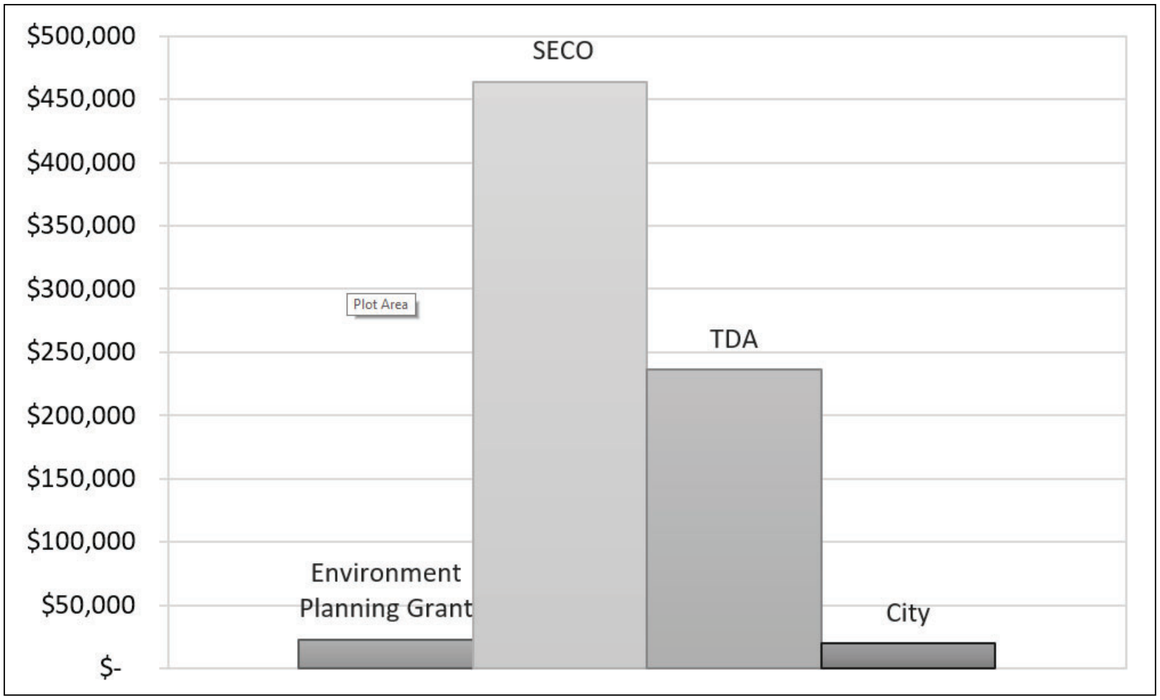

Figure 2. Sources of funds for the Seadrift wastewater treatment plant wind turbine project.

wind speed increases, the power is prevented from exceeding capacity by power-limiting mechanisms until the wind speed reaches shut-off speed. Wind turbines need a minimum wind speed (cut-in speed) to start generating energy, and they turn off if the wind speed exceeds the shutdown speed (20–30 meters per second [mps] or 66–98 feet per second [fps]). Turbines generate less than rated capacity at wind speeds below design wind speed, typically 12–16 mps (39–52 fps). Rainwater et al. (2015) reported that the Seminole turbine's cut-in speed was 5.5 mps (18 fps) and shut-down wind speed was 25 mps (82 fps), while its rated 50-kW (67 hp) power was reached at about 11 mps (36 fps). The median wind speed during the 17-month demonstration project was 5.4 mps (18 fps), while maximum wind speeds reached 23 mps (75 fps). Local wind data and the manufacturer's power curve were used to calculate the theoretical energy generation.

The key technical and economic parameter for the design and analysis of wind energy projects is the wind speed at the location, as it determines the productivity of the wind turbine and therefore its economic benefits. There exists a whole field of inquiry that is separate from the water literature and instead focuses on power grid design, with the HOMER software (Lilienthal et al. 2011) as the predominant design tool. An example is Sen and Bhattacharyya (2014) who address the intermittence of renewable energy by modeling a hybrid system as an effective alternative to grid extension in an off-grid location in India.

BACKGROUND

Project funding sources and organizations

The city of Seadrift purchased the wind turbine to help meet the WWTP energy demand by displacing some of the grid energy. Hence, city administrators applied for and received SECO (State Energy Conservation Office) grants totaling $464,000, grants from the Texas Department of Agriculture (TDA) totaling $236,000, and an additional TDA environmental planning grant of $23,000. The city itself paid $19,500 for the project. Total funds were about $742,500. The turbine cost $610,878, with additional costs for an access road, a connection fee, engineering, and general contract administration. The city has no operation and maintenance (O&M) cost, as the maintenance is the vendor's responsibility for 5 years per the contract with the city. A one-time interconnection fee of $10,451 was necessary to allow the turbine to feed excess electricity (i.e., not used by the WWTP) back to the grid. Note that the wind turbine can only operate while the grid is functioning to avoid electrocution of maintenance utility workers because of power going from the wind turbine to the grid. Other costs include an access road cost of $18,150, engineering costs of $51,112, and contract administration costs of $51,200. Total costs incurred were about $741,791. Figure 2 shows clearly that the project was financed mostly through external funds, as the city only provided about 3% of the total funds for the project.

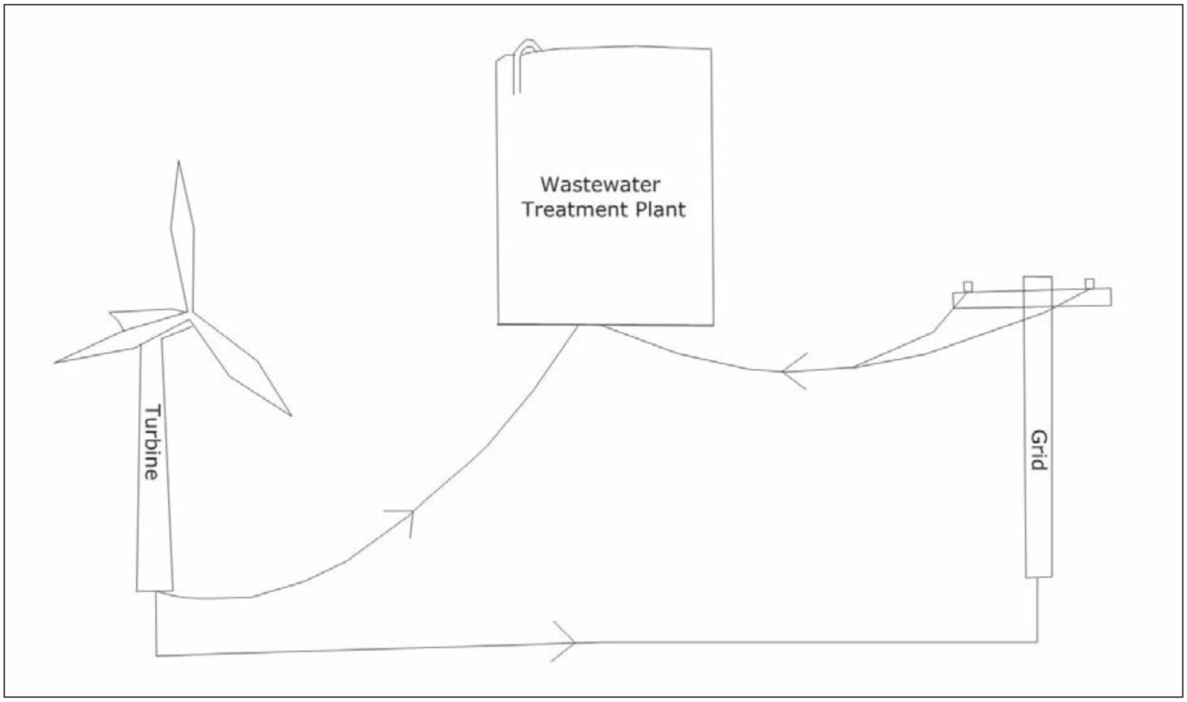

Figure 3. Seadrift wind-water-grid system schematic.

Different organizations contributed to the project. First, GrantWorks (www.grantworks.net) helped with grant applications as well as overall contract administration. GrantWorks then hired Wind Energy Consulting and Contracting, Inc. (http://weccsolutions.com; WECC), for the preliminary wind study at the proposed site. WECC also performed an economic analysis of the potential savings the city could obtain from the turbine. GrantWorks also completed an environmental assessment to ensure that whooping cranes, which pass near Calhoun County on their yearly migration, would not be threatened by the turbine. The study, submitted to the Texas Commission on Environmental Quality (TCEQ), showed that because the turbine was low enough to avoid disrupting bird migration, and because the turbine is a stand-alone, rather than a wind farm, the risk to birds was low.

After the preliminary studies, the city hired a geotechnical firm, Arias & Associates, Inc., to evaluate the subsurface and groundwater characteristics that were relevant to securely installing the turbine. G&W Engineers, Inc. provided the construction plans for the turbine, and Cascade Engineering was responsible for turbine installation, operation, and maintenance. Finally, after installation, G&W Engineers inspected the turbine.

The basic system consists of the turbine, the grid, and the WWTP, as shown in Figure 3. Arrows on the schematic indicate energy flow direction. The turbine supplies some of its energy to the WWTP, and excess energy is sold to the grid. The grid still supplies some energy to the WWTP. The wind turbine does draw some energy from the grid, but very little, even if the turbine is not operating (wind speed is lower than the cut-in wind speed), to maintain operation of the Supervisory Control and Data Acquisition (SCADA) systems and other components of the wind turbine.

Preliminary wind analysis

The cut-in wind speed is 10 fps. The preliminary study showed an average wind velocity of 6.4 mps (21 fps) at 50 m (160 ft), corresponding to a class 3 wind resource at 50 m (160 ft), according to the classification given by the National Renewable Energy Lab (NREL 2016).

Manufacturer's power and energy curves

The city purchased a Northern Power Systems (NPS 100/21) wind turbine with hub height at 37 m (120 ft), rotor diameter of 21 m (69 ft), and power rating of 100 kW (130 hp). The design life of the turbine is 20 years (NPS 2021). From the manufacturer's power curve, we note that the power system rating (100 kW or 130 hp) is realized at a wind velocity of 15 mps (49 fps). According to the manufacturer's energy curve (NPS 2021) if the average wind speed is 6.4 mps (21 fps), the wind turbine will generate about 250,000 kWh (8.50×10^8 BTU), which exceeds the 236,000 kWh (8.05×10^8 BTU) needed for the WWTP. The city based its preliminary analysis on the expected 6.4 mps (21 fps) wind speed and its corresponding 250,000 kWh/year (8.50×10^8 BTU/year) energy production. Hence, with an average cost of energy of $0.10/kWh, the wind turbine would help the city save about $25,500 per year.

METHODS

The economic analyses of the wind turbine-WWTP-grid system started with the cost of energy (COE), a key metric, defined by equation 1:

$$\text{COE} = \frac{\textbf{Monthly Electric Bill (\$)}}{\textbf{Grid WWTP Electric Consumption (kWh)}} \quad (1)$$

The second economic metric is the effective cost of energy (ECOE):

$$\text{ECOE} = \frac{\textbf{Monthly Electric Bill (\$)}}{\textbf{Total WWTP Electric Consumption (kWh)}} \quad (2)$$

Adding the wind turbine should lower the ECOE, since the electrical bill would decrease while the WWTP's electricity consumption (supplied by both the grid and the turbine) remains the same. To assess the profitability of the wind turbine, three more metrics are useful: (1) net present value (NPV), (2) internal rate of return (IRR), and (3) return on investment (ROI). NPV is defined as:

$$\text{NPV} = \sum_{N=1}^{20} \frac{NCF}{(1+i)^N} - C_0 \quad (3)$$

where C_0 is the initial cost ($19,500 for the city and $742,500 total cost) paid for the project, at time 0. NCF is the net cash flow in a year (positive cash flows minus negative cash flows in the year). The interest rate (%) is i, and N is the project lifetime (20 years)[1].

To perform NPV analyses, we use the capital recovery factor (CRF), the factor by which a present amount is multiplied to find its equivalent present value annuity payments over a period, at a specific interest rate. To raise money in capital markets, municipalities may issue debt obligations called municipal bonds. Where corporate bonds are issued by private companies and sovereign bonds are issued by national governments, municipal bonds are issued by smaller government entities such as states, counties, and cities. Although municipal bonds are generally exempt from federal taxes, they carry a higher risk than federal securities and therefore require a higher return. The MRSB (Municipal Securities Rulemaking Board) is the government agency responsible for the municipal bond market. The MRSB's factbook reported an average daily yield of 2.87%, 2.15%, 2.48%, 2.46%, 2.44%, 2.12%, 2.63%, 2.61%, and 2.11% for municipal bonds of value $500,001-$1,000,000 for years 2011 through 2019, in order. Here, we use an interest rate of is 2.84%, and the CRF is 0.0662:

[1] We will use the 20-year timeframe for the expected lifetime of the turbine. First the turbine's own documentation states that its design life is 20 years. The 20-year period is also an industry standard, because the IEC 61400-1 standard, established by the International Electrotechnical Commission (IEC), states that "the design lifetime for wind turbine classes I to III shall be at least 20 years." The turbine is an IEC IIA turbine. Third, 20 years is also the standard timeframe for research on wind turbines (Ziegler et al. 2018).

The presumption is that by increasing the useful life of the turbine, we also increase the benefits, supposing that operation and maintenance costs, coupled with the normal decrease in energy production efficiency due to age, do not overwhelm yearly benefit of the turbine. Sources of income include tax credits, sale of electricity to the grid, and displacement of grid electricity by cheaper wind-produced energy. Costs include the initial cost and operations and maintenance costs. The longer the turbine operates and produces energy efficiently, the better chance investors have to recover their initial capital.

A study of wind turbines in the United States by the Lawrence Berkeley National Laboratory (Hamilton et al. 2020) found what they called the "year-10 drop," an abrupt decrease in energy production between years 10 and 11 due probably to a reduction in operator maintenance effort, as the 10-year production tax credits (PTC) expire. While this study shows the sensitivity of turbine economic viability to tax credits, operators decrease operation and maintenance efforts but do not stop production after year 10. The authors mention also that the production at year 17 on average declines to 87% of initial production. Ziegler et al. (2018) point to the fact that tax incentives in Europe have a 20-year duration. At the expiration of the tax credits, the economic viability of wind projects is subject to the vagaries of turbine component repair and replacement cost and market prices in the energy market.

The 20-year timeframe is more an economic concern than a technical concern. Indeed, turbines typically do not fail catastrophically; it is components such as gear boxes or braking systems that fail and need to be repaired or replaced to continue operation. Based on manufacturer design expectations, industry standards, and research results, we feel a 20-year timeframe is reasonable for our analysis.

$$\text{CRF}(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1} \quad (4)$$

Another tool for financial analysis is the IRR, the discount rate (i) that makes the NPV equal to zero. A discount rate lower than the IRR makes the project profitable; hence, the higher the IRR, the better the investment. IRR is defined so that:

$$\text{NPV} = 0 = \sum_{N=1}^{20} \frac{\text{NCF}}{(1+\text{IRR})^N} - C_0 \quad (5)$$

Finally, the project's return on investment, over the 20-year holding period (ROI) and annually (annual ROI), can be used. A high ROI is preferred over a low ROI:

$$\text{ROI} = \frac{\sum_{N=1}^{20} \text{NCF} - C_0}{C_0} \quad (6)$$

$$\text{Annual ROI} = (ROI + 1)^{\frac{1}{20}} \quad (7)$$

DISCUSSION AND RESULTS

Wind turbine energy production

It is important to compare energy prediction to actual performance of the turbine. Often, wind speeds for preliminary studies are not measured at hub height, requiring raw measurements to be extrapolated to approximate actual performance. Modelers can use the power law equation for that purpose:

$$u_2 = u_{measured} \left(\frac{z_2}{z_{measured}}\right)^{\alpha} \quad (8)$$

where $z_{measured}$ is the anemometer elevation (meters), $u_{measured}$ is the wind speed at anemometer (mps), z_2 is the turbine hub height, u_2 is the wind speed at turbine hub (in mps), and α is the wind shear coefficient (power law exponent), dimensionless. The most common value used for α is 1/7. Wind power production is theoretically related to wind speed by the wind power density equation. Here P is wind power (in watts), A is turbine area (in m^2), ρ is the density of air in kg/m^3 (1.225 kg/m^3 or 0.00237 slugs per ft^3), and U is wind speed (in mps):

$$P = \frac{1}{2} A \rho U^3 \quad (9)$$

This relationship was used in the Seminole project to show the theoretical energy production at the site, as shown in Figure 4. We can observe the seasonality of the energy generation, with the months of April to about June 2013 and 2014 (late spring) having the highest energy, followed by a sharp drop in the months of July 2013 and July 2014, respectively. A comparison with actual energy produced in Seadrift also reveals a seasonal pattern shown in Figure 5, with the spring months of January through April having the highest energy generated and the summer months of June through August having the lowest energy production. On average, the turbine generates about 13,000 kWh per month. The highest wind energy production of 177,140 kWh (6.044x10^8 BTU) was in 2013. All years fell short of the expected energy production of 250,000 kWh (8.50x10^8 BTU). The average wind energy production (2012 to 2015) was 155,738 kWh (5.31x10^8 BTU).

Intermittence was also seen in both the Seminole and Seadrift studies, as shown in Figure 6 and Figure 7, respectively. For Seminole, an EW50 wind turbine from Entegrity Wind provided a portion of the electricity for a brackish water well and reverse osmosis water treatment system in a demonstration project. The minimum wind speed to generate power was 5.54 mps (18.2 fps), and wind speeds between that value and the cut-in value of 3.98 mps (13.0 fps) actually consumed small amounts of energy. In Seadrift, cut-in wind speed was 10 fps, while predicted wind speed was 21 fps.

When we compare the energy produced to the energy demanded by the WWTP in Seadrift (Figure 8[2]), we notice that the energy supply is lower than the energy demand, except during the months of March, April, and July. Hence, during this period, there can be a matching of the energy supply and the energy demand of the turbine.

The energy produced was used to displace grid energy consumption in the WWTP. On average, the WWTP used about 10,035 kWh (3.42x10^7 BTU) less monthly from the grid in years 2012–2015 than it did before the introduction of wind energy. Hence, 120,420 kWh (4.11x10^8 BTU) were displaced yearly by wind energy in Seadrift.

Energy savings translated to electrical bill savings for the WWTP. The electrical bill, in dollars, for the WWTP steadily decreased since the introduction of wind energy in 2012. The decrease in the WWTP electrical bill corresponded to a decrease in grid energy consumption, which led to monetary savings realized by Seadrift. The savings mentioned here exclude any income received by selling energy to the grid. On average, the city saved $908 per month on its electrical bill, about $10,900 per year.

Figure 9 shows the wind energy sold back to the grid and dedicated to the WWTP. In the years 2012 to 2015, the turbine generated 622,953 kWh (2.13x10^9 BTU) of electricity, 78% of which served the WWTP, while 22% was sold to the grid. It is preferable that wind energy displaces grid energy as grid energy costs an average $0.10 per kWh, while resale value to the grid is $0.04 per kWh.

[2] Effluent flow data extracted from EPA's Echo site (EPA 2020). WWTP energy demand is 0.915 kWh/m^3 (Bodík and Kubaská 2013).

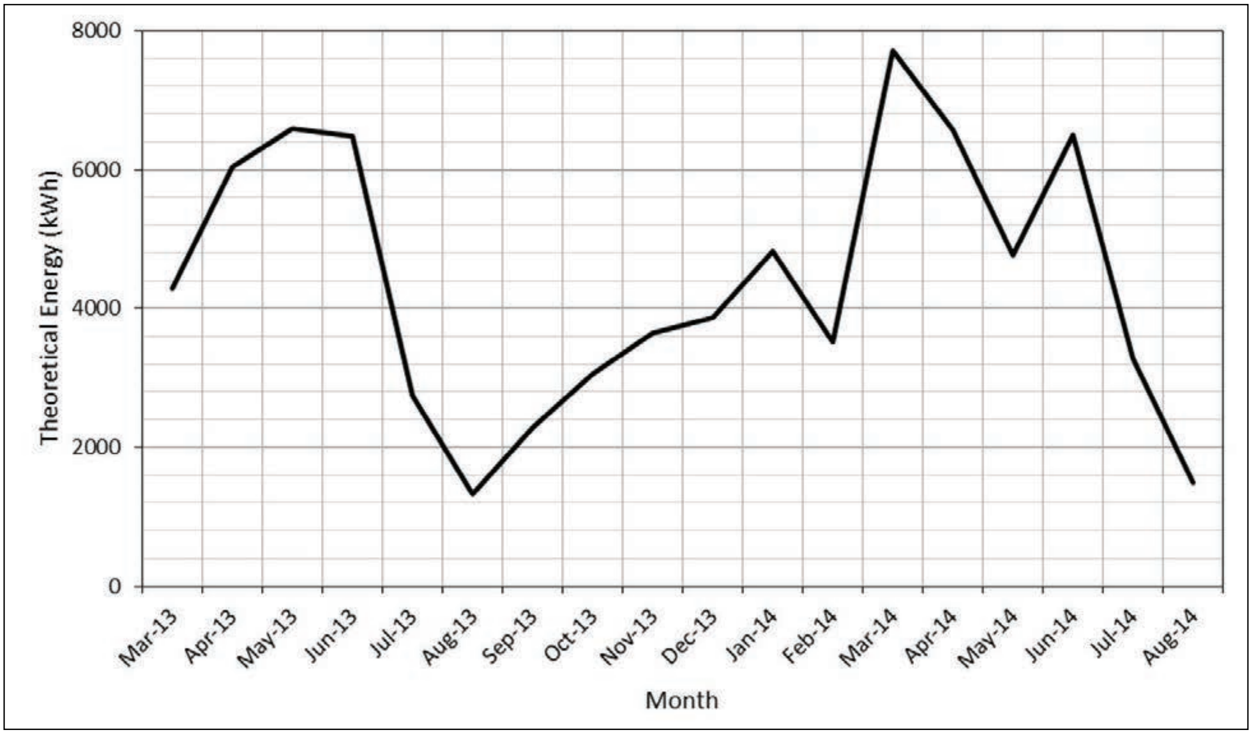

Figure 4. Seminole theoretical energy that could be generated each month.

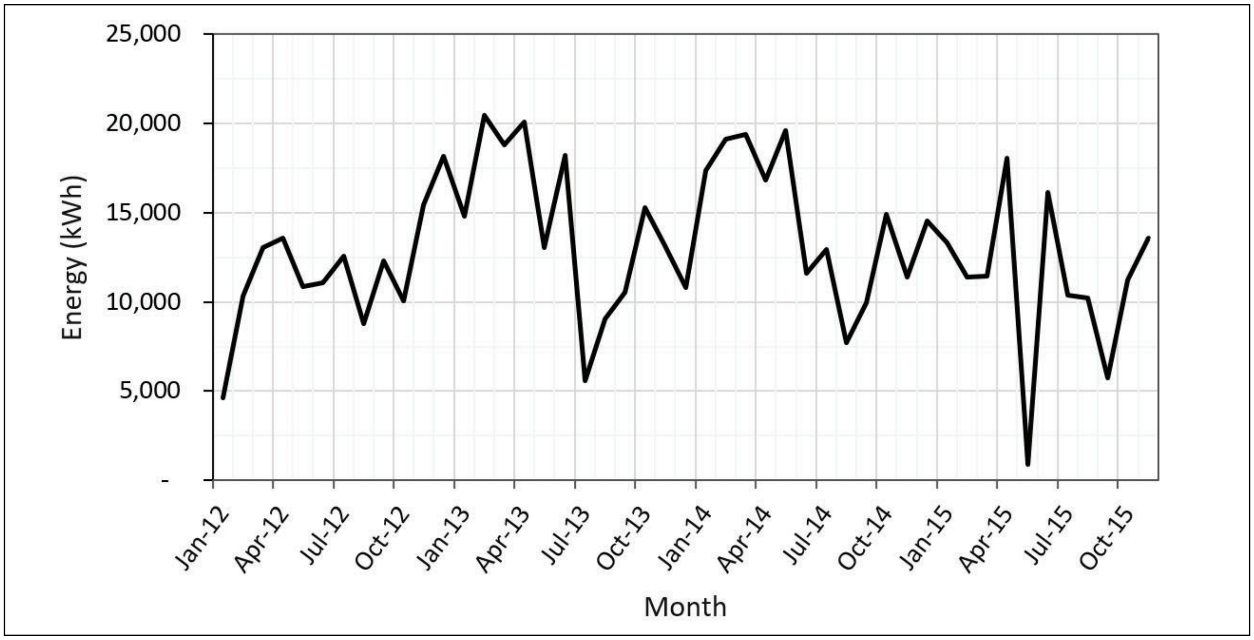

Figure 5. Seadrift actual energy generated in 2012 to 2015.

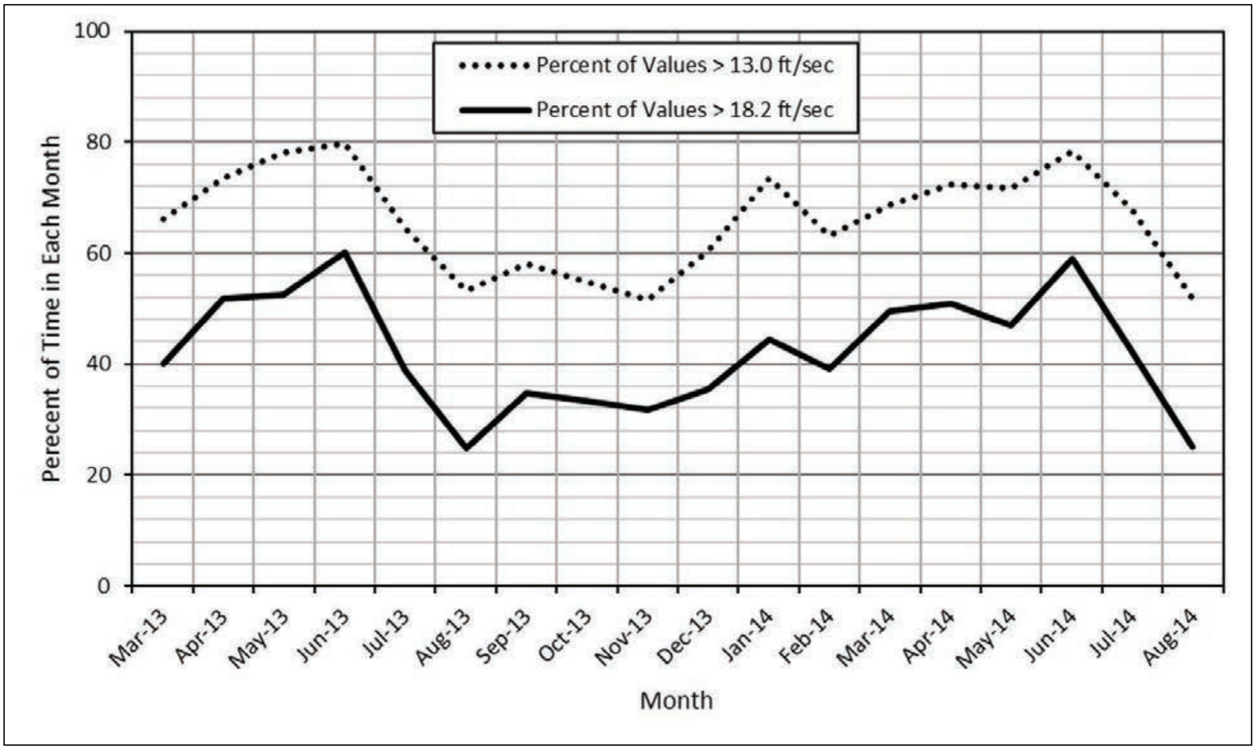

Figure 6. Percent of time each month that wind speeds exceeded 13.0 and 18.2 feet per second in Seminole.

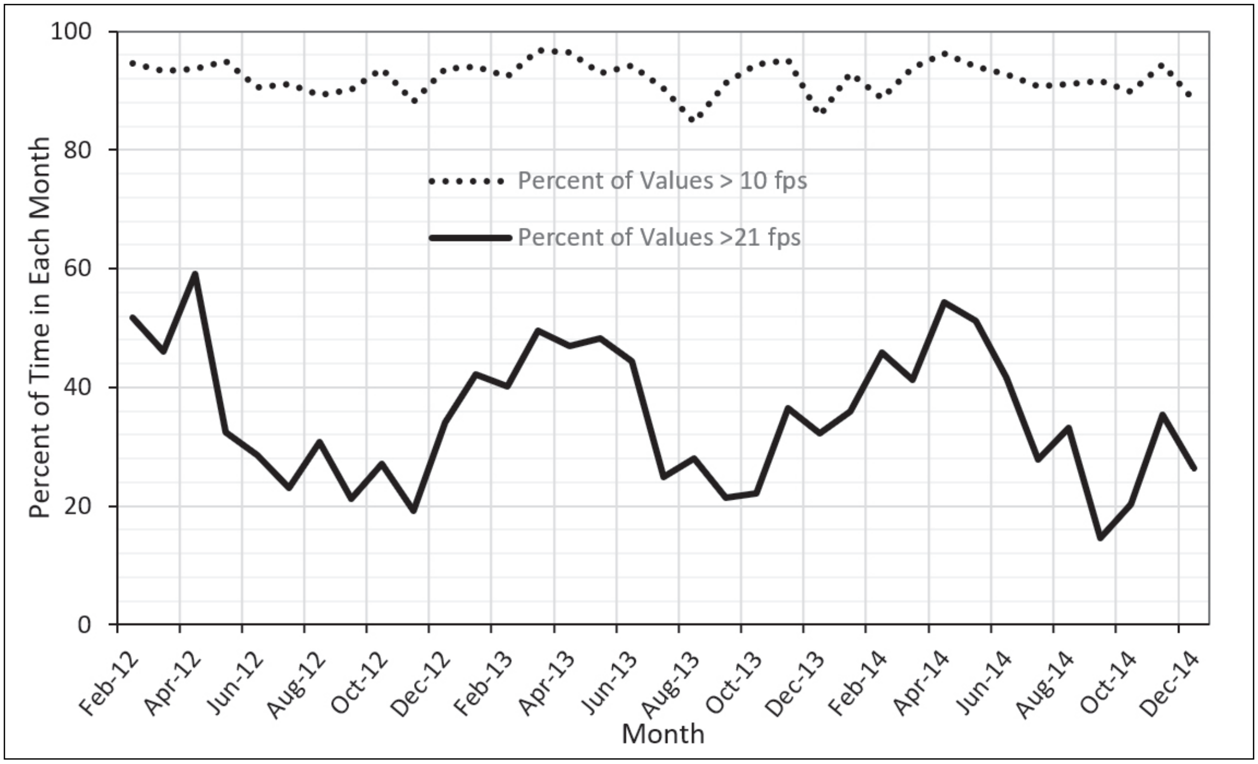

Figure 7. Percent of time each month that wind speeds exceeded 10 and 21 feet per second in Seadrift.

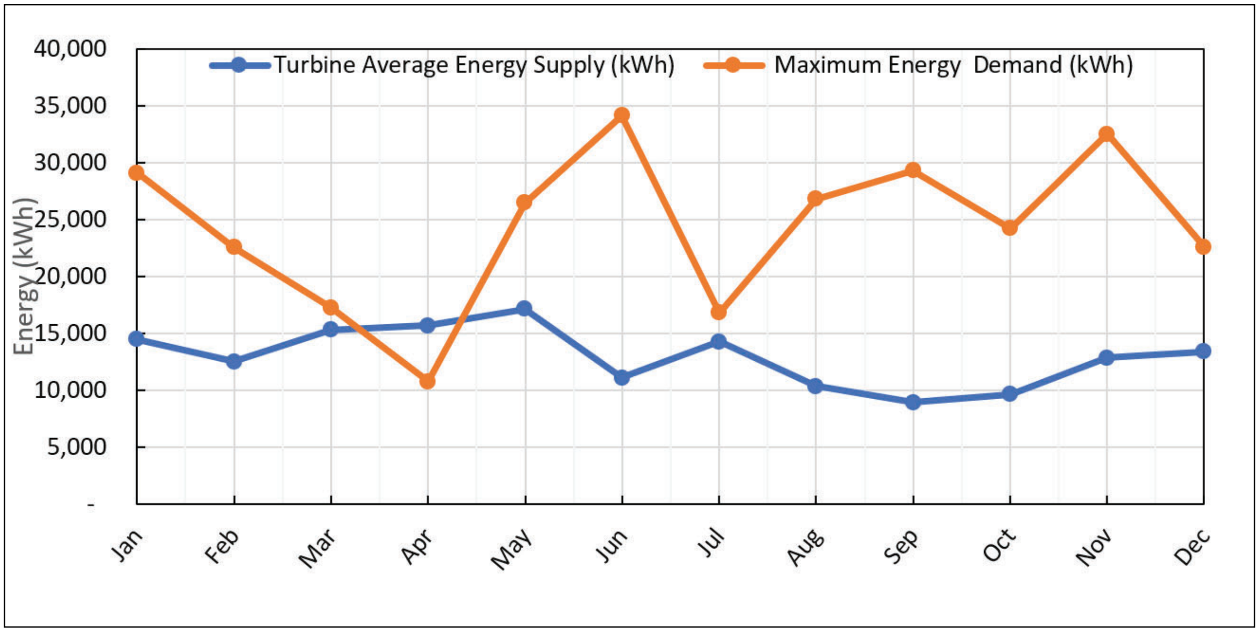

Figure 8. Average turbine energy supplied vs. wastewater treatment plant energy demand.

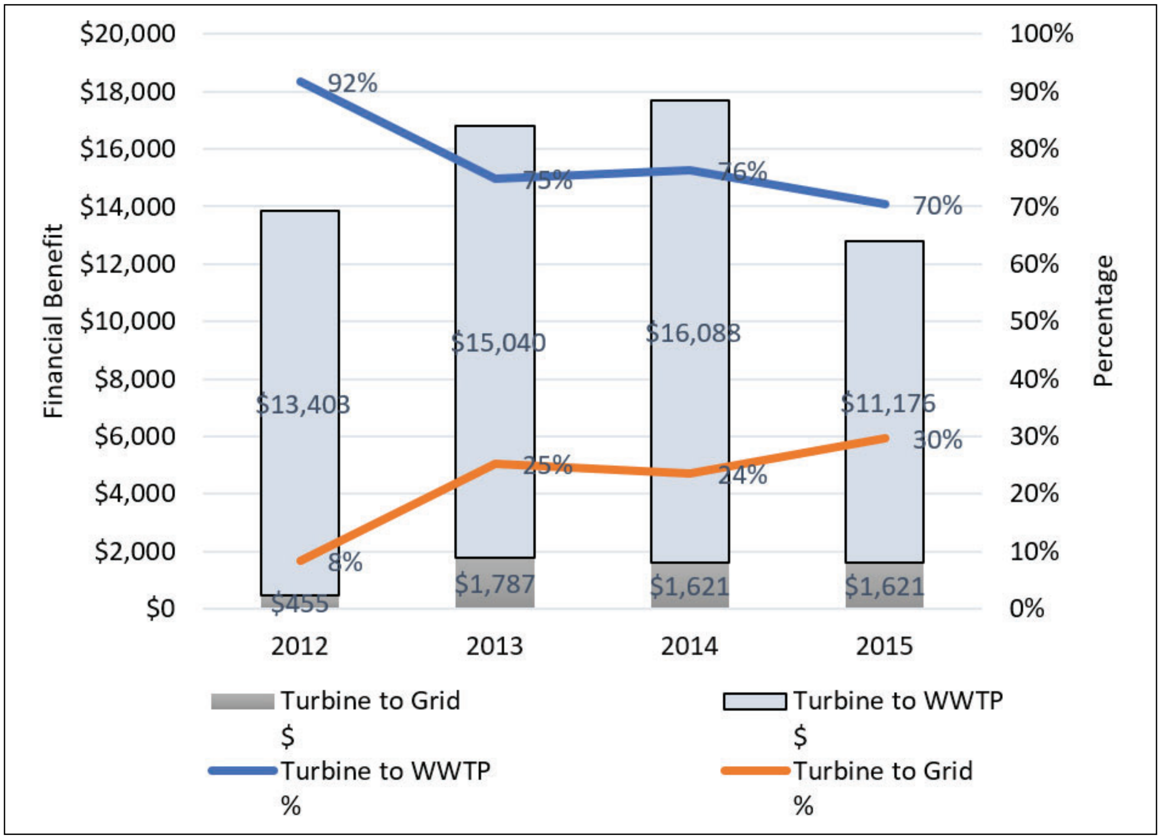

Figure 9. Distribution of turbine energy and savings to the wastewater treatment plant and grid.

Renewable Electricity Purchases in the State of Texas[3]

Within Texas, two rules impact the purchase of renewable energy: (1) the federally mandated purchase from qualifying facilities, which are confirmed by Texas' Public Utilities Regulatory Act of 2011, as amended in 2019 (PURA 2019), and (2) the renewable portfolio standard (RPS) of Texas. The Public Utility Regulatory Policies Act (PURPA 1978) is a federal law that mandates that retail electricity providers (REPs)—Direct Energy in the case of Seadrift—must purchase electrical energy and electrical capacity from qualifying facilities (QFs). QFs, according to the Federal Energy Regulatory Commission (FERC), fall in two categories: (1) facilities that generate at most 80 megawatts (MW) of non-fossil fuel energy such as hydro, wind or solar, biomass, waste, or geothermal energy or (2) cogeneration facilities, which produce both electricity and useful thermal energy "in a way that is more efficient than the separate production of both forms of energy" (FERC 2021a). In this work, the city of Seadrift is the qualifying utility, and it is paid $0.04/kWh by the REP (Direct Energy)[4].

The Texas RPS defines goals for the integration of renewable energy into the electrical grid. This requirement is usually an incentive for REPs to purchase energy from renewable energy producers. As stipulated in PUC § 25.173 (a)(1), Texas set and achieved a goal of integrating 5,880 MW of renewable energy into its grid by 2015 (PUC § 25.173 2009). Further, as of 2016, the state had already achieved its goal of integrating 10,000 MW of renewable energy into the grid by 2025 (NCSL 2016).

[3] Texas REPs and transmission and distribution utilities trade electricity in one of two markets: the Electric Reliability Council of Texas (ERCOT) market or the Southwest Power Pool (SPP) market. The ERCOT market covers most of the state, while the Southwest Power Pool covers portions of the Texas Panhandle (FERC 2021b). ERCOT transmission lines are strictly confined to the state of Texas and hence are subject only to federal rules and state rules as prescribed by the Texas Public Utilities Commission (PUC); they are not subject to interstate transmission rules as administered by the FERC.

[4] Texas mandatory purchase rules are detailed in PUC § 25.242 (f) (PUC § 25.242 2009). The policy mandates that REPs must purchase energy and capacity from QFs with design capacities of 100 kW or more. The QF notifies the REP of the availability of electricity. The law recommends that the QF make the electricity available within 90 days of the notice but does not prohibit longer time periods between notice and power delivery. The REP is then required to purchase the available electricity, unless it needs more time to set up the proper interconnection facilities. PUC § 25.242 (g) (PUC § 25.242 2009) dictates that the REP must purchase the available electricity at a price equal to or lower—but no greater than— than the avoided cost. Avoided cost is the energy production cost that would be incurred by the REP if the energy had not been bought from the QF. In this work, $0.04/kWh is the avoided cost for Direct Energy.

Economic analyses

For present value analyses, first NCF must be determined. From 2012 to 2015, the city realized an average benefit of $15,298 yearly; this is the NCF for NPV analyses. This NCF is different from the yearly $10,900 savings found in the previous section because it includes both the savings realized and the income received by selling back to the grid. Note that we assume that there is no loss of energy in the transition between the wind turbine and the WWTP, while the $10,900 figure is based on actual bills.

Seadrift's perspective

The resulting $15,928 economic benefit is lower than the $25,500 per annum the city expected to save. From the city's perspective, and because the original goal of the project was to help the city reduce its electrical bill, we could say that this is still a good performance, because the city only invested $19,500 in the project.

A project's success largely depends on investor expectations. The system performance was less than anticipated because the average speed over the period was 5.48 mps (18 fps) when it was expected to be 6.40 mps (21fps). Hence, while the city expected the turbine to generate 250,000 kWh per year, the actual total energy output was only 155,738 kWh during the period. Consequently, the economic yearly economic benefit was $15,298 instead of the anticipated $25,500 value. Yet, the turbine produced a significant amount of energy, and the economic metrics for the projects are all positive when analyzed at the city level, as shown in the analysis of ECOE, NPV, IRR, and ROI.

Figure 10 shows the COE by year, based on electrical bills per year provided to us by the city. Figure 10 shows a decrease in ECOE since the introduction of the wind turbine. Indeed, in the years 2009–2011, the COE and ECOE values were the same as the grid was the only source of electricity. Then, in the years 2012–2015, the ECOE is on average $0.04/kWh lower than the COE.

From the city's perspective, the return on investment is 14.7, meaning that the project will generate 14.7 times ($286,650) the city's investment ($19,500) over a 20-year period. This result also means that the investment has a growth rate of 15% in value per year. The project's NPV (20 years) is $211,493. The project's IRR is 78.45%, meaning that with a 2.84% municipal discount rate, this project is very profitable at the city's level.

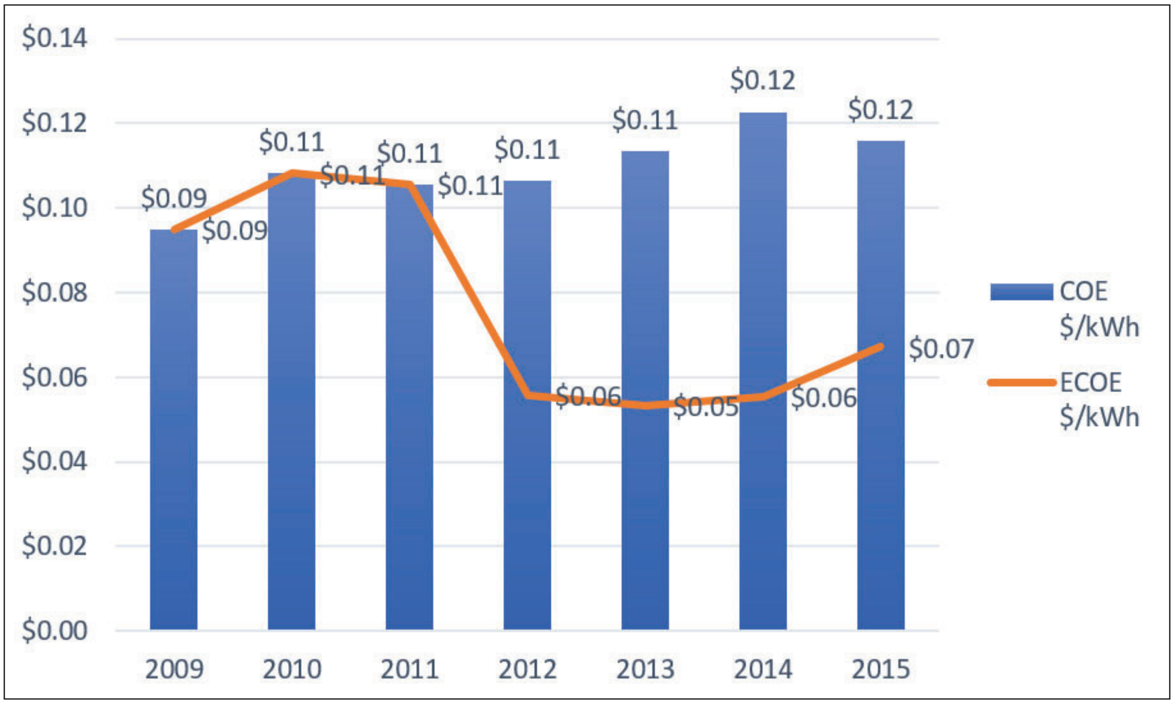

Figure 10. Cost of energy vs effective cost of energy.

Total cost perspective

The cost of a wind project is too high for a small city to shoulder, and the state has to contribute most of the money to make the project successful. However, at the state level, the economic performance is negative. The main difference here is that the state of Texas contributed a total of $742,500 (not $19,500) to the wind turbine. This is a more complete assessment of the economic performance of the project as it accounts for the project's total cost. Here the IRR is –7.27%; the state would have to be paid to borrow money to make the project profitable. Further, the project NPV is negative (–$500,000), and the annual ROI is negative (–4%). For the project to realize a positive NPV at the state level, the turbine would have to generate an economic benefit of about $49,000, or 556,818 kWh (1.9x10^{9} BTU) per year, with 80% to displace grid energy and 20% sold to the grid. Hence, even the $25,500 savings originally expected would not be sufficient to account for all costs. It would require three times the current economic benefit ($15,928), or 3.5 times the current wind energy production (155,738 kWh or 5.31x10^{8} BTU), for the project to be truly profitable.

Summary of economic analyses

The project reveals some of the structural parameters that can undermine the sustainability of wind projects. First, the initial cost of the project is so high that it is difficult to generate returns that repay that initial cost, especially given the 20–25-year lifespan of wind turbines. A small city alone cannot undertake such a project, but investors (even government investors) may not be willing to fund the projects given the limited returns. Second, wind potential at a location is a limiting parameter as it drives energy production and therefore offers economic benefits. It may be possible to increase the returns on wind projects by having multiple beneficiaries (not only one city, but many cities for example) use the turbine's energy output. Yet because of wind potential limitations, the turbine does not produce any excess energy. Third, even though the energy market permits resale of electricity to the grid, the resale price is still lower (i.e., $0.04/kWh) than the purchase price ($0.10/kWh), making it incrementally difficult to cover the original turbine cost, even though there is excess energy from the wind turbine.

To improve the profitability of these systems, project designers should consider the total cost, not only at the city's level but on a total cost basis. Indeed, the turbine performed less than expected, but even if it had produced the expected 250,000 kWh, it would still not have produced enough energy to cover all costs. A design based on total cost would inform the size and choice of adequate wind turbines that can produce enough energy to justify their cost. Further, the turbines can be chosen so they produce sufficient energy despite the wind potential constraints at the location.

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CONCLUSIONS

Wind projects such as Seadrift's offer an alternative to fossil fuel-based approaches for energy generation. Yet project designers must carefully study wind energy intermittency and seasonality at a location to anticipate the matching of wind energy supply with water and wastewater energy demands. Though the preliminary studies in Seadrift did not include such analysis, project designers can compare effluent water and wastewater energy requirements to better match the supply of energy with the demand as we showed in this study.

Further, to be sustainable, projects must be economically viable. State officials and decision-makers who are accountable for the allocation of scarce financial resources should consider whether the project is profitable for the state. In the case of Seadrift, the city only contributed 3% of the initial cost of the project, with all other funding coming from state agencies or the state itself. Cities may consider adding a surcharge to the water or wastewater bill to increase revenues on such projects. Yet this approach is challenging, as an increase in water rates may paradoxically reduce revenues for the city as consumers may decrease their water demand. City leaders may also face staunch resistance from customers who consider water and wastewater services as a basic right and therefore often reject rate increases. The design should also consider total costs and total return to inform sizing of turbines given wind potential and energy resale conditions at a location.

The yearly energy generation of 155,738 kWh or 5.31×10^8 BTU matched expected energy from manufacturer design. However, a cautious approach is warranted, especially in predicting average wind speed at a location. Indeed, a more accurate preliminary study would have revealed the lower average wind speed than predicted (18 fps, not 21fps) and alerted designers to lower energy production (5.31×10^8 BTU, not 8.50×10^8 BTU), and consequently lower yearly economic benefits ($15,928, not $25,500). All metrics, driven by wind speed, were lower than predicted.

In Seadrift, both the utility provider (Direct Energy) and the transmissions and distribution company (American Electric Power) cooperated with the city so that the wind turbine could be integrated in the grid system. The electricity firms also agreed to purchase power from the wind turbine. This case study hence demonstrates that more integration of renewable energy into energy systems is possible.

Overall, Seadrift installed a 100-kW wind turbine to displace some grid energy for its WWTP. The turbine's contribution allowed the city to realize a financial benefit of $15,928 per year on average while realizing a net present value of $211,493 over the 20-year design life of the turbine at the city level. The state's contribution is an example of its effort to share in the public good of all Texas residents, including those in smaller rural communities. Though due to study parameters, life cycle analyses could not be performed, they could be used in projects where wind projects are part of the original plant design rather than an addition to a pre-existing water-energy system. This case study provides an example for small communities looking for ways to manage their energy costs while providing basic services to their residents.

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Commentary: Texas Reimagines the Fight Against Floods

Peter Lake[1]*

Editor-in-Chief's Note: The Texas Water Journal invited former Chairman of the Texas Water Development Board (TWDB) and current Chairman of the Public Utility Commission of Texas, Peter Lake, to share his thoughts on the 2019 state flood assessment and other framework efforts. The opinion expressed in this commentary is the opinion of the individual author and not the opinion of the Texas Water Journal or the Texas Water Resources Institute.

Abstract: In response to the TWDB's 2019 state flood assessment and other efforts initiated in the wake of Hurricane Harvey, the 86th Texas Legislature developed a visionary new framework to fight future floods. The TWDB was tasked with overseeing and coordinating this new effort in conjunction with fellow state and federal agencies. In accordance with the guiding legislation, the TWDB is using a familiar framework based on key functional areas: science, planning, and financing. In the case of floods, that framework transforms into mapping, planning, and mitigation—the three pillars of fighting floods in Texas.

Keywords: Texas flood, flood planning, flood mitigation, flood mapping, floods

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Terms used in paper

Acronym / Initialism	Descriptive Name
AMHI	Annual Median Household Income
BLE	Base Level Engineering
FEMA	Federal Emergency Management Agency
FIF	Flood Infrastructure Fund
FIRM	Flood Insurance Rate Map
FLICC	Flood Information Clearinghouse Committee
HUC	Hydrologic Unit Code
InFRM	Interagency Flood Risk Management
LiDAR	light detection and ranging
NFIP	National Flood Insurance Program
NWS	National Weather Service
RFPG	regional flood planning group
SVI	Social Vulnerability Index
SWIFT	State Water Implementation Fund for Texas
TNRIS	Texas Natural Resources Information System
TWDB	Texas Water Development Board
USACE	United States Army Corps of Engineers
USGS	United States Geological Survey

INTRODUCTION

For more than 60 years, the Texas Water Development Board (TWDB) has been tasked with leading Texas efforts in securing the state's water supply through the conservation and development of Texas' water resources. The agency's framework for fulfilling this mission combines the three key functions of science, planning, and financing. The TWDB's scientific efforts identify and quantify Texas' water resources, laying the foundation for the state water plan, which guides billions of dollars of financing to build Texas' water supply through the State Water Implementation Fund for Texas (SWIFT) and other programs. In 2019, the 86th Texas Legislature tasked the TWDB with addressing the state's flood issues by providing a dramatically enhanced toolbox built on a framework similar to that used to secure water supply. The Legislature's vision of a comprehensive flood program that integrates science, planning, and financing establishes the state as a global leader in flood mitigation. Launching this groundbreaking effort is a monumental task, but thanks to the TWDB staff's determined efforts, the program's implementation is well under way.

BACKGROUND

Historically, the TWDB's efforts related to flood mitigation were substantial but piecemeal. These efforts have included providing more than $20 million in state-funded Flood Protection Grants, acting as the state's National Flood Insurance Program (NFIP) coordinator, executing the Federal Emergency Management Agency's (FEMA's) Flood Mitigation Assistance Grant Program, and participating in FEMA's Cooperating Technical Partners Program. In fiscal year 2019, the TWDB issued $47 million in FEMA Flood Mitigation Assistance grants. In the same fiscal year, the agency's Community Assistance Program staff also traveled 28,815 miles to provide technical assistance and conduct floodplain management workshops for local officials.

Most recently, the TWDB enhanced its services by creating the TexMesonet network of weather gages to monitor and report climatic data. This data is used to support flood monitoring and forecasting by the National Weather Service, river authorities, and emergency responders. In addition, the agency created the Texas Flood Viewer to provide near real-

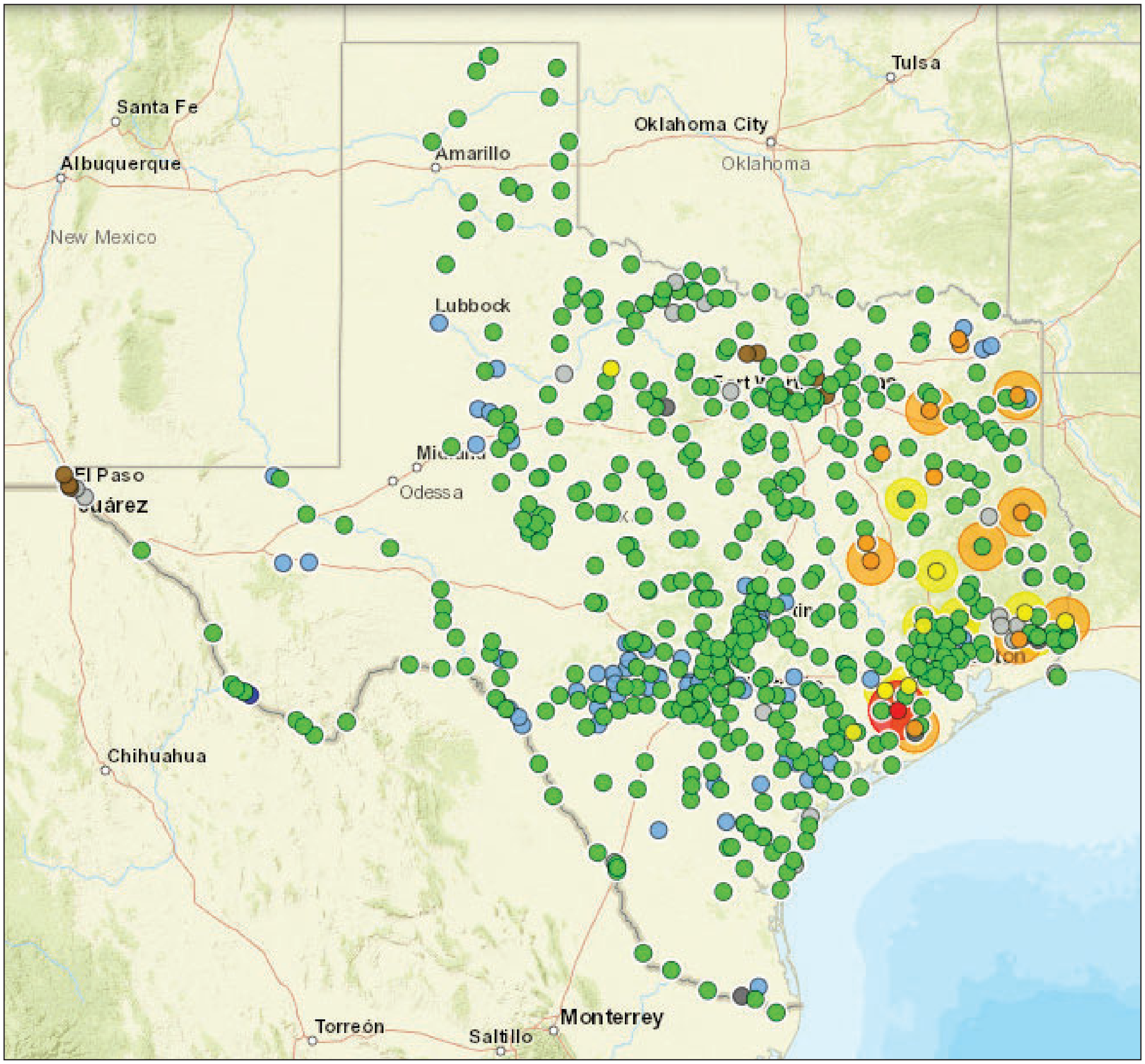

Figure 1. The Texas Flood Viewer website provides updates on flood conditions throughout the state.

time updates on current flood conditions across the state (Figure 1). Finally, after extensive stakeholder involvement, the TWDB generated a state flood assessment in 2019 to provide a comprehensive understanding of flood risks, challenges facing existing flood efforts, and needs for future flood mitigation. The assessment concluded that the lack of any coordinated planning efforts for flood events is a major shortfall, recognized that a substantial portion of Texas floodplain maps are woefully outdated, and that significant resources are needed to mitigate future flooding.

NEW FRAMEWORK

In response to the 2019 state flood assessment (TWDB 2019) and other efforts initiated in the wake of Hurricane Harvey, the 86th Texas Legislature developed a visionary new framework to fight future floods. The TWDB was tasked with overseeing and coordinating this new effort in conjunction with fellow state and federal agencies. In accordance with the guiding legislation, the TWDB is using a familiar framework based on key functional areas: science, planning, and financing. In the case

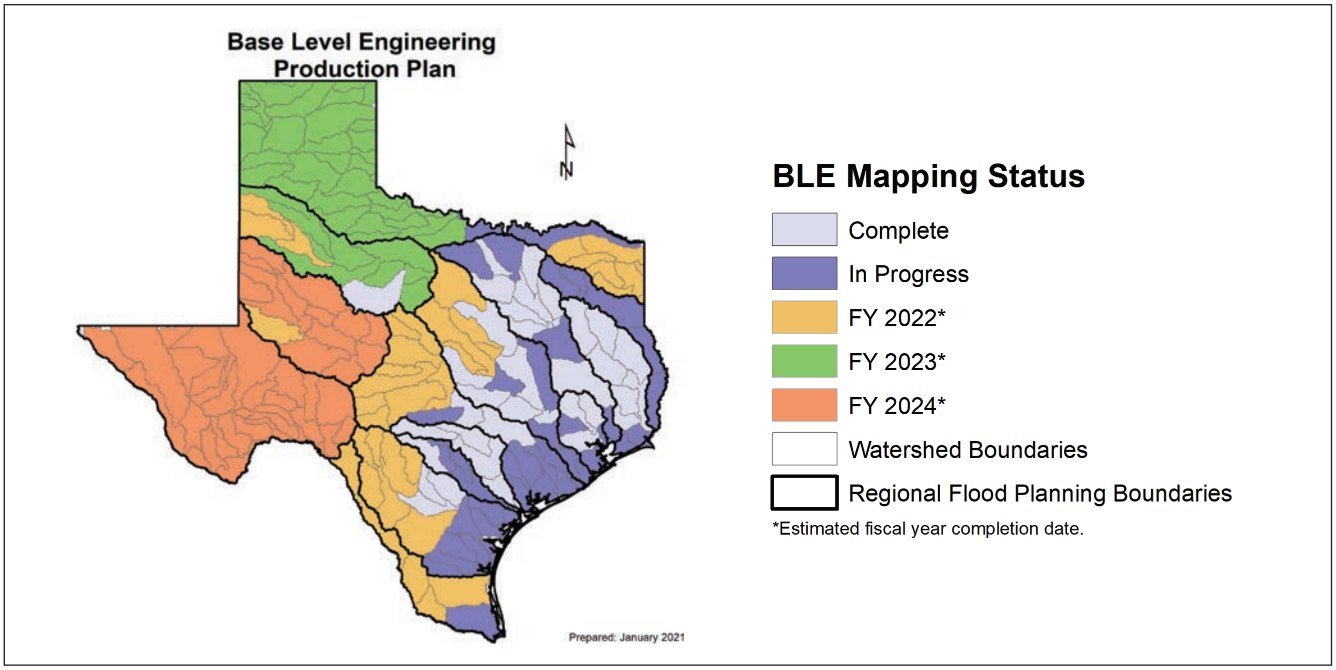

Figure 2. Base Level Engineering map schedule.

of floods, that framework transforms into mapping, planning, and mitigation—the three pillars of fighting floods in Texas:

1. **Mapping**: Updating and modernizing floodplain maps across the state and other flood science efforts
2. **Planning**: Coordinating flood mitigation efforts across watersheds and river basins in the form of a state flood plan
3. **Mitigation**: Financing studies and projects to mitigate the impacts of floods

Importantly, these three pillars of fighting floods—mapping, planning, and mitigation—are integrated in Texas' new flood program. To access mitigation financial assistance (Pillar 3), project sponsors must utilize the best and most recently available floodplain maps (Pillar 1) and have coordinated with other stakeholders within the impacted watershed (Pillar 2). Once the first state flood plan is established in 2024, project sponsors must not only participate in the regional flood planning process but also have that specific project approved as part of the state flood plan in order to access mitigation financial assistance. This integration ensures that flood mitigation projects are based on the best science available and are designed in coordination with other regional stakeholders across the watershed.

Pillar 1: Mapping

The first pillar, mapping, is the foundation for planning and mitigation. Accurate floodplain maps are critical for fighting floods, but much of Texas lacks modern and up-to-date floodplain maps. The scope of the problem is clear—approximately half of the counties in Texas have no Flood Insurance Rate Maps (FIRMs), and most of the remaining counties have not updated their FIRMs within the last five years. As of 2018, the average age of Texas floodplain maps was 13 years old. For reference, this means a staggering portion of Texas floodplain maps predate the existence of the iPhone, which was released in January of 2007. No community in Texas should have to rely on decades old information to fight floods.

Base Level Engineering

The TWDB's mapping efforts are currently focusing on Base Level Engineering (BLE) studies, which include LiDAR (light detection and ranging) mapping, hydrology, and hydraulics. In this way, the TWDB can provide updated flood hazard information that is immediately usable by a community to improve flood risk awareness, communication, and mitigation in a cost-efficient and timely manner. BLE studies can support the development of more detailed maps, local floodplain management, local hazard mitigation planning efforts, grant applications, flood insurance ratings, and disaster response and recovery activities. As a result, BLE studies will support the local decision-making process regarding flood mitigation and will be a key resource for broader regional planning that will occur as part of developing the state flood plan.

The TWDB will be generating BLE studies for the entire state and intends to update each part of the state approximately every five years (Figure 2). This biennium the TWDB is greatly expanding efforts to provide BLE mapping and data products statewide. Of the 208 Hydrologic Unit Code–8 (HUC-8) watersheds in Texas, 17 are currently under contract to be mapped using state funds, and an additional 25 are slated to go under contract in fiscal year 2021. In total, 30 HUC-8 watersheds have been mapped to date through combined TWDB and FEMA efforts. Mapping of the full state through this partnership is expected to be completed by 2024. The data and maps created by BLE studies are available online to view or download.

The data and analysis in the BLE studies will be important inputs for predictive flood modeling performed by TWDB partners at the United States Geological Survey (USGS) and the National Weather Service (NWS).

The BLE mapping efforts will not be creating FIRMs—generating an official FIRM requires a multi-year process that is very involved and costly. Only FEMA can officially approve and publish a FIRM. Official FIRMs generated by FEMA follow a rigid process involving four phases:

- **Phase 0**: Base Level Engineering—General mapping of the watershed
- **Phase 1**: Discovery—Outreach for public feedback on areas of interest/critical areas
- **Phase 2**: Flood Risk Study—Approximate and detailed mapping and modeling of areas of concern; initial demarcation of 1% and 0.2% probability areas
- **Phase 3**: Public Outreach and FIRM Production—FEMA invites public comment and makes final adjustments to the FIRM

An official FIRM is published after the completion of Phase 3. While generating official FIRMs is not the TWDB's current focus, the agency will be working closely with communities to ensure that their BLE studies will be compatible with the FEMA process and can be used to complete the remaining phases for any new FEMA FIRMs. As a result of the TWDB's efforts, countless Texas communities will be able to petition FEMA to complete the remaining phases and publish updated FIRMs much more efficiently than before.

As previously mentioned, there are three key components of BLE studies: LiDAR mapping, hydrology, and hydraulics. These three elements are important because they help define all elements of a flood. Put simply, a watershed or basin during a flood event is like an elongated bowl with an uneven bottom filling with water. LiDAR defines the shape of the bowl, hydrology defines how much water goes into the bowl, and hydraulics define where the water is going once it is in the bowl.

LiDAR generates high-resolution topographic data of the Earth's surface. In flood mitigation, LiDAR is a key factor because the land contours displayed in the output are the foundation on which accurate flood hazard modeling and mapping are built (i.e., the shape of the bowl). The Texas Natural Resources Information System (TNRIS), part of the TWDB, acquires LiDAR data through partnerships with other federal and state agencies. As of October 2020, all areas of the state now have updated LiDAR, which is available on the TNRIS website.

The second component of BLE studies is hydrology—measuring how much water goes into the bowl. The TWDB utilizes several tools to develop this information, but the primary source is gages of some variety. The vast majority of these are stream and flood gages, which measure water levels at specific locations across the state. Knowing how high the water is and how fast it is moving before and during a flood event is critical information that plays a vital role in determining the frequency of flooding and alerting local citizens of imminent danger. This information is also key in flood prediction models used to alert downstream communities and inform rescue and recovery operations. Another important tool is TexMesonet, which is a network of weather stations that measure rainfall, humidity, soil moisture, and temperature, among other data. Like stream gages and flood gages, TexMesonet stations help inform the vitally important flood prediction models. The TWDB, United States Army Corps of Engineers (USACE), NWS, and USGS are continually working together to link gages and weather stations and upgrade technology to provide as near real-time data updates as possible (approximately five minutes).

The final component of BLE studies is the hydraulic element—determining where the water is going. This exercise is largely captured in the flood prediction models developed by the USACE, and the TWDB works closely with the USACE in operating these models and producing approximate flood risk mapping data. In addition, the TWDB utilizes its expertise to analyze coastal bathymetry (analysis of coastal water depths and the terrain under the water) to help inform how riverine flows articulated in the flood prediction models will interact with ocean water at the coast.

Integrating and sharing the data and analysis

Once BLE data for a watershed is created, the results are incorporated into the USGS's Base Flood Elevation Viewer and other tools that allow the public to better understand flood risk at a particular geographic location. This online tool is part of a broader initiative called Interagency Flood Risk Management (InFRM). Products from the InFRM partnership allow the public access to a wide range of flood-related data and tools, including updated Atlas 14 rainfall data and watershed hydrology assessments that better estimate the potential magnitude of river flows, especially those controlled by large reservoirs. This collaborative effort is led by the NWS, FEMA, USGS, and USACE, but this partnership also includes close collaboration with the TWDB, among other agencies.

The Flood Decision Support Toolbox is one of InFRM's most powerful tools: it provides visualization of current flood-related weather conditions and integrated flood prediction modeling data. This information can be used by private citizens and community leaders alike to pre-plan for evacuation routes ahead of flood events and to coordinate rescue efforts during and after flood events. This unprecedented aggregation of flood-related data and analysis is granular enough to be utilized at the neighborhood level and will be a vital tool in mitigating flood impacts in Texas. Completed in January 2021, the first phase of a TWDB/USGS partnership to enhance the Flood Decision Support Toolbox will allow users to save maps they generate, view building footprints, and produce a summary of potential flood damage reports. The second phase, which is scheduled to be completed by September 2021, includes the creation of a dashboard to display damage data depending on various potential flood depth scenarios.

Another important tool is the TWDB's Texas Flood Viewer. This website provides near real-time stream gage information from a network of gages across the state. Individuals can also sign up for alerts from specific stream gages in their area; these alerts will send a message to the individual's mobile phone when the designated stream gage is entering a flood stage or is anticipated to enter into a flood stage.

Pillar 2: Planning

Of the three pillars used to fight floods, planning is the linchpin. Attempting to mitigate flood impacts without coordinated planning is, at best, an inefficient use of resources and, at worst, so counterproductive that it intensifies damage from flooding. What happens upstream impacts what happens downstream, and vice versa. For example, an upstream community that is proactively draining floodwaters at the same time a downstream community is retaining floodwaters does more harm than good. Under the TWDB's new framework, flood planning will be coordinated at the regional level in regional flood planning groups (RFPGs) based on watersheds. The results of these planning efforts will be compiled into individual regional flood plans and then the first-ever state flood plan. The three goals of this state flood plan are to 1) provide orderly preparation for and in response to flood conditions and to protect people and property; 2) serve as a guide to state and local flood control policy; and 3) contribute to water development where possible.

Ingredients of the state flood plan

To best position Texas for future flood events, the state flood plan will examine past, present, and future efforts to fight floods. Many local and regional leaders around the state have been actively working to mitigate flood risk but have yet to coordinate in such a comprehensive manner as this scale. This effort will include the following:

- A complete evaluation of existing flood infrastructure
- An analysis of completed, ongoing, and proposed flood control projects
- A list of projects that have received funding to date
- Identification of common standards and metrics for measuring floods and flood mitigation
- An analysis of development in the 100-year floodplain areas (as defined by FEMA)
- Recommendations for legislative policy changes needed to facilitate planning and project implementation in the future

Importantly, the members of the RFPGs—not the TWDB—are responsible for conducting this analysis and for designating the flood mitigation projects to be included in the state flood plan. The future of fighting floods in Texas will be built from the ground up by the people who are most directly impacted by floods in their unique corner of the state.

Regional flood planning groups

In April 2020, the TWDB designated 15 flood planning region boundaries (Figure 3), largely demarcated by major river basin boundaries. This designation was based on agency analysis and extensive stakeholder feedback. Due to the potential to be influenced by inter-basin flooding, ongoing coastal management efforts, and stream contribution to bays, coastal basins were combined with adjacent major river basins. In addition, smaller river basins were combined with larger basins due to similarity in types of flooding, relatively small populations, and administrative constraints limiting the number of regions that can be adequately supported by the TWDB. Of course, Texas has several large river basins as well. Some of these basins were split into two RFPGs to accommodate diverse geographies, topography, rainfall amounts, and land use patterns. Dividing select basins also eases the burden of RFPG logistics across such vast areas. In addition, RFPGs can divide themselves into smaller subgroups if they so desire (although the subgroups will still report up to the primary RFPG). Any such subgroups can be designated based on geography, land use characteristics, or other categories desired by the RFPG.

The most important element of the RFPGs is their members. They will identify current flood mitigation strategies, evaluate local and regional flood control policies, and designate future flood mitigation projects. These members, rather than the TWDB, will be deciding what is included in the state flood plan. The TWDB will provide administrative support and ensure quality control, but decisions about projects and infrastructure to fight floods in a particular region will be made

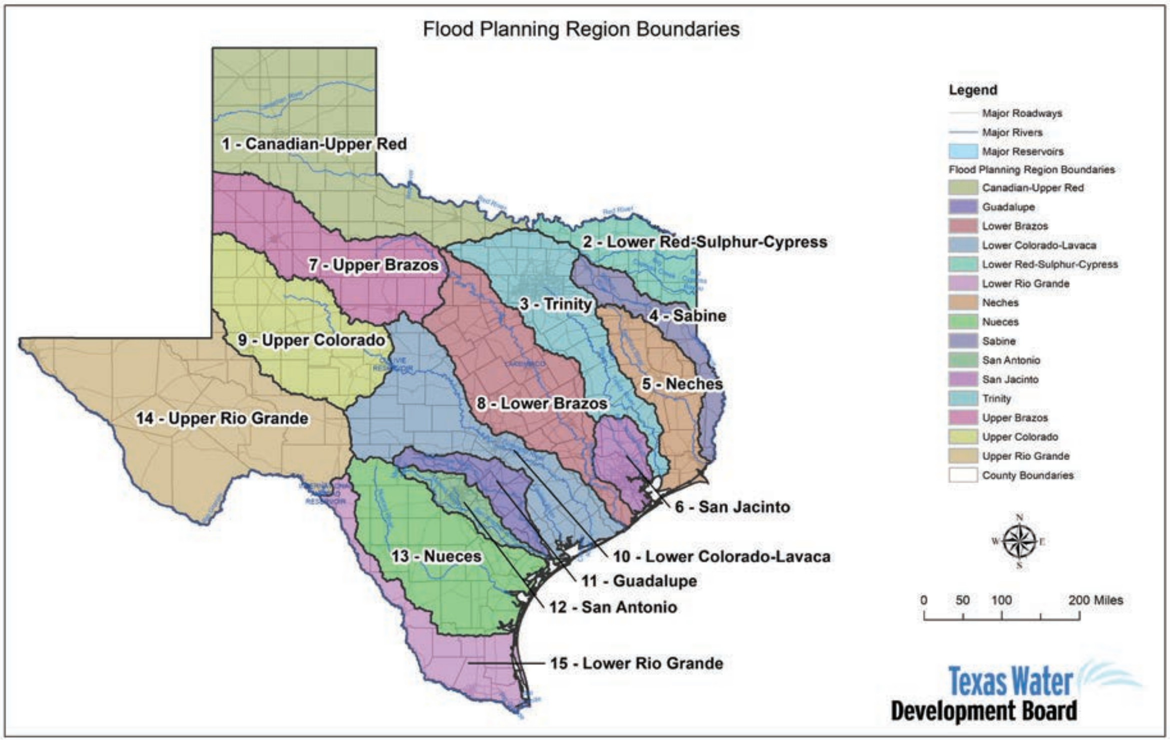

Figure 3. Regional flood planning boundaries.

by the members of that RFPG. Each group is required to have a member that represents one of each of the following interest groups:

- Agriculture
- Industry
- River authorities
- Counties
- Municipalities
- Water districts
- Electric generating utilities
- Public water utilities
- Environmental interests
- Small businesses

In order to fill the seats of RFPGs, the TWDB solicited applications from interested individuals across the state. Stakeholders around the state responded enthusiastically, submitting more than 600 applications for the 177 available seats. After a thorough evaluation, the TWDB appointed the RFPG members in October of 2020, and the first planning meetings occurred later that month.

Ultimately, the RFPGs must deliver their regional flood plans to the TWDB by January 2023. The mitigation projects included in those plans must be coordinated inside planning regions and across planning regions (if applicable), and most importantly, all projects must be approved by a vote of the RFPG members to be included in each regional flood plan. The TWDB will then aggregate those plans into the first-ever Texas state flood plan and present it to the Legislature by September 2024.

Pillar 3: Mitigation

The final pillar in Texas' new comprehensive flood program is mitigation—providing the financial resources to implement the projects needed to protect people and property from floods. To achieve this, the 86th Texas Legislature created the Flood Infrastructure Fund (FIF) and capitalized it with a one-time appropriation of $793 million. Importantly, the Texas Legislature and voters enshrined the FIF in the Texas Constitution so it will exist in perpetuity, outside of normal budget cycles and fiscal year limitations. Funds in the FIF are being used to provide grants and zero-percent interest loans for structural and non-structural flood mitigation projects across the state, including but not limited to planning efforts, warning systems, public education, levee networks, drainage systems, and retention/detention infrastructure. To ensure FIF funds are used in the most productive and efficient manner possible, the TWDB established minimum standards required for a flood mitigation project to be eligible for FIF. These standards include the following:

- **Best and most recent data**: The project must utilize current science, especially regarding floodplain maps

Table 1. Prioritization criteria for the Flood Infrastructure Fund.

Criteria	Number of points
Priority projects: Flood protection planning for watersheds (Category 1 projects)	Projects where county has an annual median household income (AMHI) that is ≤85% the statewide AMHI: 25
	All other projects: 22
Priority projects: Measures immediately effective in protecting life and property (Category 4 projects)	20
Rural applicant	Yes: 12
	No: 0
Emergency need due to recent or imminent failure or recent flood-related disaster declarations.	Recent failure: 10
	Recent flood-related disaster declaration for the proposed project area: 10
	Imminent failure: 5
	N/A: 0
Distributed benefits	Yes: 10
	No: 0
Estimated completion date	Within 18 months: 10
	Within 36 months: 5
	All others: 0
Additional criteria for planning, acquisition, design, and construction or construction projects only: water supply benefit	Yes: 10
	No: 0
Additional criteria for planning, acquisition, design, and construction or construction projects only: floodplain impacts (Scores are assigned relative to the responses for other proposed projects)	Top 25% of planning, acquisition, design, and construction or construction projects only: 12
	Top 50%: 9
	Top 75%: 6
	Bottom 25%: 3
Planning, acquisition, and design only (no construction/ rehabilitation funds requested)	12
Non-structural flood mitigation elements constitute at least 20% of the total project costs	5
Tiebreaker: Social Vulnerability Index (SVI)	The tie is broken in favor of the project with the highest SVI

- **Proof of coordination**: Written documentation confirming the project sponsor has coordinated with other stakeholders in the area to be impacted by the project
- **No redundant funding**: Funds cannot be used to solve a problem that another project or funding source is already solving
- **NFIP standards in place**: The political subdivision sponsoring the project must have flood ordinances in place that at least meet the standards of the federal NFIP
- **Benefit/cost ratio**: A preference for a ratio above 1.0 to justify investments in flood mitigation projects (but projects will not be prioritized based on higher or lower benefit/cost ratios)

Once the state flood plan is in place, only projects in the plan will be eligible for FIF funding.

Prioritization of projects

Unfortunately, the need for flood mitigation financing in Texas greatly exceeds current funding capacity. As such, the TWDB has worked diligently to develop a prioritization system by which to allocate funds in this first round of the FIF program (Table 1). This prioritization system is built on a number of factors, listed in order of impact on prioritization score:

- **Planning**: Studies that focus on flood protection planning across a watershed
- **Protecting life and property**: Projects that are immediately effective in preserving life and property, such as early warning systems and low water crossing barriers
- **Rural populations**: Projects in rural areas of Texas

- **Emergency need**: Projects that address a need arising from recent or imminent failure of existing flood infrastructure or recent flood-related disasters
- **Distributed benefits**: Projects that provide mitigation impacts to a broader range of stakeholders than just the project sponsor
- **Early completion date**: Projects that will be completed sooner rather than later
- **Water supply benefit**: Projects that will provide water supply in addition to mitigating the impact of floods, such as detention structures that also recharge groundwater supplies
- **Floodplain exposure reduction**: Projects that reduce large numbers of structures in a floodplain
- **Planning, acquisition, and design**: Projects that are not ready for construction funds but are actively being pursued and developed
- **Non-structural**: Projects that mitigate the impact of floods through means other than physical infrastructure
- **Social vulnerability index**: Projects impacting communities of need (this is a tiebreaker)

Given that many communities in Texas have limited or no flood protection plans in place, watershed-level planning was given significant priority. In addition, the TWDB factored in timing as it relates to shovel-ready projects compared to projects that need more extensive mapping, planning, or engineering before they are ready for implementation. Projects that are always effective, such as early warning systems, stream gages, and low water crossing barriers, were also given top priority in the ranking system. These types of projects can be implemented now and will immediately save lives during flood events.

Other projects are more structurally intensive, geographically expansive, and scientifically complex. Of these, some may have been based on sound science and planned in coordination with regional stakeholders; these projects are considered shovel ready. As long as they do not create upstream or downstream issues, these projects are also a focus of the TWDB's prioritization system. However, other projects may require more underlying science to be completed and additional studies to assess regional impact and may benefit from additional planning. The prioritization system emphasizes funding the initial studies and planning efforts related to these kinds of projects rather than immediately committing funds to eventual construction.

Allocating grants vs. loans

The FIF's enabling legislation allows the TWDB to use both loans and grants to finance flood mitigation projects. Grants minimize the cost of a project to the local project sponsor, but funds used as grants can only be used once—they never return to the FIF. Alternatively, loans require local project sponsors to build the project now but repay the borrowed funds eventually. However, loans benefit the broader FIF program by ensuring funds are returned to the FIF so they can be used to finance other flood mitigation projects in future years. Additionally, loan dollars returned to the FIF means the same state dollar can be loaned for a "local match" to draw down federal dollars many times over. The TWDB carefully evaluated the best balance of loans and grants for the FIF and allocated $231 million for grants (30% of the FIF) and $539 million (70% of the FIF) in zero-percent interest loans.

In determining which project sponsors would be eligible for grants, the TWDB focused on the economic need of each sponsor. While loan versus grant ratios vary by project type, in general the agency focused grant funds on project sponsors with the following characteristics:

- Low average median household income
- Rural and/or outside of a metropolitan statistical area
- High unemployment
- Declining population
- Nature-based projects

Floods impact all areas of the state, and flood waters do not stop at city limits or county lines. The TWDB is committed to financing effective flood mitigation projects to protect people and property across Texas in a manner that is both capital efficient and inclusive of as many viable projects as funding allows.

Implementation

The TWDB opened the first round of applications for the FIF in the spring of 2020 for the $770 million allocated by the TWDB for grants and loans. The $2.3 billion of requests for funding the agency received (corresponding to $3.4 billion of total project costs) indicates both the need for flood mitigation in Texas and also the statewide enthusiasm for the program. Across the 285 applications received, the smallest project amount requested was $35,000, and the largest project amount requested was $182.7 million. TWDB staff carefully evaluated initial (abridged) applications and formally adopted the prioritized list of projects in a ranked list on September 17, 2020. High-ranking projects were then invited to submit more comprehensive applications (full applications) throughout the fall based on expected funds available in the FIF. On December 3, 2020, the TWDB made the first financial commitments from the FIF for a combined $6.4 million that will be matched by an additional $5.2 million from federal funds. The agency will continue to make financial commitments for FIF flood mitigation projects throughout early 2021.

Interagency coordination

Given the scale and complexity of various state and federal funding sources for flood mitigation projects, the TWDB, the Texas Division of Emergency Management, and the General Land Office are coordinating their efforts. This coordination will prevent duplication of efforts, synchronize scientific data collection and mapping, and maximize leveraging of state dollars for federal dollars. In addition, this joint effort by the primary state agencies responsible for flood mitigation will provide local leaders across Texas with clear information regarding the options available to them.

Flood Information Clearinghouse

The primary mechanism of coordination among agencies is the Flood Information Clearinghouse website. This is a single stop resource for local leaders to enable them to access the resources they need in the most efficient and effective way possible. Launched in early 2020, the website includes an online “Request for Information” form that entities can utilize to get feedback on what state and federal financial assistance programs could best fit their unique flood mitigation needs. It also includes information on current funding opportunities, general project and entity eligibility by program, upcoming events related to flood mitigation financial assistance, and other resources. In the coming years, the TWDB will continue to work with state and federal partners to enhance the site and the process that entities use to seek financial assistance for flood mitigation projects.

Flood Information Clearinghouse Committee

The corresponding interagency Flood Information Clearinghouse Committee (FLICC) has been meeting regularly since May 2020 to review funding inquiries submitted to the Flood Information Clearinghouse website and to coordinate the use of state and federal funding for flood mitigation projects. After the FLICC reviews an entity’s “Project Information Form,” it notifies the entity of possible funding available for their project and the next steps needed to apply. The entity can then make the best decision for their community’s needs with the information and choices presented. The purpose of the FLICC is not to make choices for communities, but rather to provide them with information to enable their leadership to determine the best methods of mitigating floods in their area.

CONCLUSION

The landmark legislation from the 86th Legislature has ushered in a new era of fighting floods in Texas. Utilizing the TWDB’s history of water science, water planning, and water financing, the 86th Legislature’s Senate Bills 7 and 8 (Senate Bill 7; Senate Bill 8) developed a comprehensive flood program integrating mapping, planning, and mitigation. Requiring project sponsors to utilize the best available data and information and participate in the state flood planning process will advance science-based solutions and drive regional cooperation in a way never seen before. Already, the interagency cooperation occurring across state and federal agencies is unprecedented in the history of flood mitigation in Texas. The extraordinary effort of updating complex floodplain maps, establishing a new statewide planning program, and building large infrastructure will not happen overnight. Despite the TWDB’s aggressive timeline in implementing this program, the full benefits will not be realized for years to come. But as we move forward—map by map, plan by plan, and project by project—Texas will be better able to protect people and property from the devastating impact of floods.

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Water Rights Analysis Package Modeling System

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Abstract: The water rights analysis package (WRAP) simulates surface water development, allocation, management, and use and performs reliability and frequency analyses of simulation results. The computer modeling system facilitates assessments of hydrologic and institutional water availability and reliability in satisfying requirements for reservoir storage, water supply diversions, environmental instream flows, hydroelectric energy generation, and flood control. Salinity concentrations can also be modeled. Capabilities are provided for analyzing basin-wide impacts of water resources development projects and management practices. The modeling system is generalized for application anywhere, with input datasets being developed for particular river systems of concern. The water availability modeling system maintained by the Texas Commission on Environmental Quality and routinely applied by the professional water management community consists of WRAP and simulation input datasets for all Texas river basins. Model-users modify the input datasets as appropriate to evaluate alternative water use scenarios, development projects, and management strategies of interest. This paper explores concepts and methodologies incorporated in WRAP and other comparable modeling systems, as well as exploring implementation of water availability modeling in Texas and contributions to effective water management.

Keywords: rivers, reservoirs, water availability, reliability, simulation

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Terms used in paper

Acronym / Initialism	Descriptive Name
BRA	Brazos River Authority
cfs	cubic feet per second
CWMS	Corps Water Management System
DAY	WRAP daily flow parameter calibration program
DSS	Data storage system
DSSVue	DSS visual utility engine
EFS	Environmental flow standards
FIA	Flood impact analysis
GIS	Geographic information system
HEC	USACE Hydrologic Engineering Center
HEC-5	HEC model for simulation of reservoir systems
HEC-HMS	HEC Hydrologic Modeling System
HEC-PRM	HEC Prescriptive Reservoir Model
HEC-RAS	HEC River Analysis
HYD	WRAP hydrology data compilation program
IBWC	International Boundary and Water Commission
LP	Linear programming
ResSim	HEC reservoir simulation model
SALT	WRAP salinity simulation model
SB	Senate bill
SIM	WRAP monthly simulation model
SIMD	WRAP daily simulation model
SWAT	Soil and water analysis tool
TABLES	WRAP data organization and analysis program
TAMU	Texas A&M University
TCEQ	Texas Commission on Environmental Quality
TRA	Trinity River Authority
TWDB	Texas Water Development Board
TWRI	Texas Water Resources Institute
USACE	United States Army Corps of Engineers
USBR	United States Bureau of Reclamation
USGS	United States Geological Survey
WAM	Water availability model or modeling
WinWRAP	WRAP Microsoft Windows user interface
WRAP	Water rights analysis package

INTRODUCTION

Effective management of the water resources of river basins requires an understanding of the amount of water available at alternative levels of reliability under various conditions. Water availability depends on hydrology, constructed facilities, institutional water allocation systems, water management practices, and basinwide water demands. Water resources are shared by numerous water users for various types of use. Streamflow is highly variable, reflecting the extremes of severe droughts and floods as well as more normal seasonal and continuous instant-to-instant fluctuations. Future streamflow, reservoir storage availability, and associated water supply capabilities must be expressed in terms of probability, frequency, percent of time, risk of shortage, and/or supply reliability.

The modeling and analysis strategy implemented in the water rights analysis package (WRAP) consists of simulating a specified scenario of water resources development, management, allocation, and use during a postulated repetition of past natural river basin hydrology. Supply reliability and storage and flow frequency metrics are developed from the results of the simulation. The river/reservoir/use system being simulated may range in complexity from a single water user being supplied by a single reservoir to complex systems with numerous water users being supplied by many multipurpose reservoirs.

The water availability modeling (WAM) system maintained by the Texas Commission on Environmental Quality (TCEQ) consists of the generalized WRAP modeling system and simulation input datasets for all the river basins of Texas. A WRAP simulation input dataset from the TCEQ WAM system for a particular river basin is combined with the generic WRAP software that performs the simulation computations. Twenty WAM datasets simulate river system hydrology for all river basins of Texas, operation of 3,460 reservoirs/dams and other constructed facilities, 6,200 water right permits, various water supply contracts, and the effects of several interstate river basin compacts and treaties between the United States and Mexico.

The latest editions of the WRAP software and documentation are available on the WRAP website maintained at Texas A&M University. WRAP is documented by a set of manuals (Wurbs 2009, 2019a, b, 2021a, b; Wurbs and Hoffpauir 2021) published as Texas Water Resources Institute (TWRI) technical reports available on both the WRAP and TWRI publications websites. The TCEQ WAM website links with the WRAP website and provides simulation input datasets and an array of WAM information.

Water right permit applicants or their consultants apply the WAMs to assess reliabilities associated with proposed actions. TCEQ staff use the WRAP/WAM modeling system to evaluate water right permit applications. The Texas Water Development Board (TWDB), regional planning groups, and their consultants employ the modeling system in statewide and regional planning. River authorities and other water management agencies apply the models in operational planning studies. The WRAP/WAM system is also used in research studies and various other types of water management endeavors.

The routinely applied WRAP/WAM modeling system is based on a monthly computational time step. The latest expanded WRAP software and manuals include daily modeling capabilities with monthly-to-daily flow disaggregation, routing, forecasting, flood control reservoir operations, and instream flow standards with subsistence, base, and pulse flow components. The primary motivation for adding the daily modeling features is to enhance the capability to model environmental flow standards established by the TCEQ in the WAMs.

MODELING OF RESERVOIR/RIVER SYSTEM OPERATIONS

Pioneering efforts in computer simulation of reservoir systems include U.S. Army Corps of Engineers (USACE) studies of six reservoirs on the Missouri River initiated in 1953 and International Boundary and Water Commission (IBWC) simulations of the Rio Grande in 1954 (Maass et al. 1966). TWDB began developing models in support of water planning in Texas in the late 1950s and 1960s, which resulted in several generalized river/reservoir system models (TWDB 1974; Martin 1983, 1987).

The massive literature on modeling and analysis of reservoir systems is dominated by thousands of university research papers published in journals and conference proceedings. Most of the published papers present mathematical programming methods for modeling reservoir system operations developed in academic research that have been applied only by the model developers and only for research case studies. Labadie (2004) reviews the extensive and complex research literature on reservoir system optimization models. Wurbs (1993, 1996, 2005a, 2012) presents state-of-the-art reviews of reservoir and river system analysis from a practical applications perspective.

Generalized modeling systems

Although the research literature is extensive, most actual practical applications of reservoir/river system management models in the United States have been performed with a relatively small number of generalized modeling systems developed by federal or state agencies or university research entities under the sponsorship of federal or state agencies. These generalized modeling systems have evolved through various versions over the past several decades (Wurbs 1993, 1996, 2012).

An online hydrologic modeling inventory maintained by TWRI and TAMU, organizes models under the categories of hydrology, hydraulics, water quality, and management and planning. Descriptive information for the following generalized modeling systems is provided under the category of management and planning: MIKE BASIN, developed by the Danish Hydraulic Institute; Water Resource Integrated Modeling System (WRIMS), formerly called CALSIM, developed by the California Department of Water Resources; MODSIM, developed at Colorado State University and applied by the U.S. Bureau of Reclamation (USBR) and others; RiverWare, developed by the Center for Advanced Decision Support at the University of Colorado and sponsored by the USBR and others; and WRAP, described in this paper. The hydrologic modeling inventory website provides model descriptions and website links to software and relevant documents.

Most large federal reservoirs in the United States were constructed and are operated by the USBR or USACE. These agencies developed many models for specific reservoir systems during the 1950s–1970s (Wurbs 1993, 1996). Many of the system-specific models have since been replaced with generalized models. The USBR currently employs MODSIM, RiverWare, and several system-specific models. The USACE Hydrologic Engineering Center (HEC) maintains a suite of generalized models that are widely applied by USACE offices, other agencies, consulting firms, and universities nationwide and abroad.

The HEC's Corps Water Management System (CWMS) has been deployed at 35 USACE district offices, including the Fort Worth and Galveston offices, to support real-time operations of flood control and multipurpose reservoir systems (McPherson 2019). The first non-USACE application of the CWMS was the Lower Colorado River Authority's modeling of real-time flood operations of the Highland Lakes in Texas. The CWMS combines data acquisition and management tools with simulation models that include the HEC Hydrologic Modeling System (HEC-HMS), HEC Reservoir Simulation (ResSim), HEC River Analysis System (RAS), and HEC Flood Impact Analysis (FIA). HEC-HMS and HEC-RAS are employed extensively, independently of the CWMS, by engineering consulting firms, city engineering staff, and university faculty and students in delineating floodplains and designing hydraulic structures and storm-water management facilities.

A HEC model called HEC-5 Simulation of Flood Control and Conservation Systems (HEC 1998) was employed during the 1970s–2000s in many USACE and non-USACE applications. HEC-ResSim (HEC 2013) succeeded HEC-5 during the 2000s. The HEC Prescriptive Reservoir Model (HEC-PRM) was developed in conjunction with USACE studies of reservoir systems in the Missouri and Columbia river basins and later applied to systems in California, Florida, and Panama. HEC-PRM is a linear programming model that minimizes a cost based objective function.

The HEC has developed a data storage system (DSS) for time series data that is used routinely with HEC models and also with other non-HEC modeling systems including WRAP, RiverWare, and WRIMS. Multiple models share the same data management and graphics software. Time series data are stored in DSS files in a direct access binary format. The HEC-DSS Visual Utility Engine (HEC-DSSVue) is a graphical user interface program for viewing, editing, manipulating, and graphing data in DSS files and performing statistical analyses and mathematical operations (HEC 2009). HEC-DSSVue has been adopted as an integral component of WRAP.

Linear programming models

Of the many mathematical optimization methods available, linear programming (LP) has been most often adopted in water management applications. LP is a mathematical formulation with standard solution algorithms based on maximizing a linear objective function subject to a set of linear constraints. The TWDB pioneered early applications of LP in modeling river/reservoir system water management. Yield simulation, water allocation, and river/reservoir system simulation models called SIMYLD-II, AL-V, and SIM-V developed by the TWDB during the 1960s–1980s, employed variations of the same capacitated network flow LP solver as the basic computational engine of the models (TWDB 1974; Martin 1983). These early TWDB models, the original CALSIM, and the original versions of HEC-PRM and MODSIM were all based on the same Fortran subroutine implementing the LP algorithm originally developed for the TWDB models. HEC-PRM and MODSIM were later updated with more computationally efficient LP algorithms.

HEC-PRM, the RiverWare LP option, and many other LP models reported in the literature recently, as well as over the past 50 years, are formulated to compute quantities for all time intervals simultaneously, which means operating decisions are based on perfect knowledge of future streamflows. Simulations with MODSIM, WRAP, HEC-ResSim, and non-LP options in RiverWare step through time with operation decisions reflecting no knowledge of future streamflows. The daily WRAP simulation model and HEC-ResSim include options that base operations on flow forecasts a specified number of days into the future.

An early version of a WRAP simulation model called WRAP-NET was created using the network flow LP solver developed for the TWDB models (Yerramreddy and Wurbs 1996). However, rather than adopting a LP formulation employing a generic solution algorithm, all later versions of the WRAP simulation model are based on computational methods developed specifically for WRAP. LP provides the advantage of incorporating in the same generic LP computational solver as a subroutine in multiple different computer programs, reducing programming time. However, the WRAP-specific computer routines provide greater flexibility in incorporating a variety of modeling features and are very efficient in minimizing computer runtime.

Comparison of alternative modeling systems

Wurbs (2005a, 2012) reviewed the literature and available generalized reservoir/river system operations models in general followed by a focused comparison of WRAP and the following three modeling systems:

ResSim (HEC 2013)
MODSIM (Labadie and Larsen 2007)
RiverWare (Zagona et al. 2001)

These simulation models compute reservoir storage and releases and streamflows for each sequential time step of a hydrologic period-of-analysis for a particular scenario of water resources development, management, allocation, and use. Although fundamentally similar, ResSim, MODSIM, WRAP, and RiverWare differ significantly in their organizational structure, computational algorithms, and user interfaces. The alternative modeling systems provide general frameworks for constructing and applying models for systems of reservoirs and river reaches. Each is based on its own set of modeling strategies and methods and has its own terminology or modeling language.

ResSim, MODSIM, and WRAP software and documentation can be downloaded free-of-charge at their websites. RiverWare is a proprietary software product marketed by the Center for Advanced Decision Support at the University of Colorado for a licensing fee. The software packages all run on personal computers operating under Microsoft Windows. The four alternative modeling systems and their predecessors have evolved through multiple versions over more than 20 years of research and development, with new versions being released periodically.

The modeling systems simulate flood control, hydropower, water supply, environmental flows, and other reservoir/river system management purposes. Whereas development of the other three models was motivated primarily by conservation storage purposes, ResSim is motivated largely by flood control, is limited to daily or shorter time steps, and provides greater flexibility for flood routing and simulating flood control operations. The other models were originally monthly but now include options for daily or other computational time steps. RiverWare and WRAP now have optional features for modeling flood control reservoir operations.

ResSim and WRAP have model-specific computational frameworks. MODSIM is built on an LP framework. RiverWare has alternative options based on both model-specific algorithms and LP. The LP-based models have additional model-specific computations along with their LP solver. All of the models have iterative algorithms for evaporation and hydropower computations.

Each of the alternative modeling systems provides certain advantages. The remainder of this paper focuses on WRAP, which provides comprehensive features for modeling the prior appropriation water rights permit system and other institutional water allocation mechanisms and priority-based operating rules. Although equally applicable to simple systems, WRAP is designed for efficient modeling and analysis of large complex datasets with many hundreds of reservoirs and water users. The TCEQ and its contractors and stakeholders have created and continue to update and maintain the large, detailed datasets required to simulate water management in Texas. Comprehensive, flexible modeling capabilities have resulted from evolution of WRAP within Texas with its diverse and challenging climate, hydrology, and water management practices.

TEXAS WATER AVAILABILITY MODELING SYSTEM

The creation of the TWDB and the inaugural 1968 Texas Water Plan were motivated largely by the 1950–1957 drought. The Texas share of the waters of the Lower Rio Grande was allocated by judicial action during the two decades following the 1950s drought. Diverse surface water rights for the remainder of the state were consolidated during the 1970s–1980s pursuant to the Water Rights Adjudication Act of 1967, establishing the foundation for the present water rights permit system administered by the TCEQ (Wurbs 1995). A drought during the 1990s resulted in omnibus water management legislation in 1997. That legislation, Senate Bill 1 (SB1), implemented a "bottom-up" approach to regional planning in the statewide cyclic planning process and creation of a WAM system (Wurbs 2015).

The TCEQ, as lead agency, in partnership with the TWDB and Texas Parks and Wildlife Department developed the WAM system during 1997–2003 to support water rights regulatory, regional planning, and statewide planning activities (Alexander and Henderson 2020; Wurbs 2005b). Consulting firms and university research entities working under contract with the TCEQ provided technical support. Reports documenting development of the original WAM datasets are archived in the Texas Water Digital Library.

WRAP was adopted for the WAM system based on recommendations of a committee representing the three agencies and the professional water management community. The committee developed a list of additional improvements and expansions to WRAP required for the WAM system. About 10 consulting engineering firms serving as primary contractors, with assistance from other subcontractors, developed WAM datasets and performed simulations for the individual river basins with

Figure 1. Texas river basins delineated by the TWDB.

alternative water use scenarios. The Center for Research in Water Resources at the University of Texas provided geographic information system (GIS) support in developing the WAM datasets.

The 15 major river basins and eight coastal basins of Texas delineated in Figure 1 are modeled as 20 WAMs. The Brazos River Basin and Brazos-San Jacinto Coastal Basin are combined as a single WAM. The Brazos-Colorado Coastal Basin is included in the Colorado River Basin WAM. The San Antonio River flows into the Guadalupe River and is included in the Guadalupe-San Antonio WAM. For the interstate and international river basins, hydrology and water management in neighboring states and Mexico along with interstate river basin compacts and treaties are considered to the extent necessary to assess water availability in Texas. Data for the full authorization scenario version of the WAMs as of 2014 are tabulated in Table 1, with six coastal basin WAMs combined as a single line for brevity (Wurbs and Zhang 2014).

Full authorization and current conditions scenario datasets, as well as supporting GIS data, are available from the TCEQ for each of the 20 WAMs. The full authorization scenario is based on the premise that all water right permit holders use the full amount of water to which they are legally entitled, subject to water availability. Return flows are not included in the full authorization scenario WAMs because return flows are not required by the water right permits. Permitted but not yet constructed projects are included. The current conditions scenario represents actual maximum annual use for each water right during a recent 10-year period and includes return flows and reservoir storage capacities reflecting updated estimates of sedimentation. The current use water supply demands are often smaller than the authorized use, which may include projected future use.

Model users modify the WAM datasets to reflect projected water needs, proposed projects, and management strategies of interest. The TWDB has developed WRAP simulation input

Table 1. Control points, water rights, and reservoirs in full authorization WAMs.

WAM	Number of Control Points		Model Water Rights		Number of Reservoirs	Capacity (acre-feet)
	Total	Primary	Number	(acre-feet / year)		
Rio Grande	957	55	2,584	2,228,870	113	3,499,070
Nueces	543	41	374	637,040	121	959,827
Guadalupe-San Antonio	1,338	46	848	420,780	238	756.527
Lavaca	185	8	70	61,620	22	167,718
Colorado	2,422	45	2,006	2,235420	518	4,709,829
Brazos	3,842	77	1,643	1,519,140	678	4,015,865
San Jacinto	412	17	150	520,360	114	587,529
Trinity	1,398	40	1,061	6,617,850	697	7,356,200
Neches	378	20	399	621,610	180	3,656,259
Sabine	387	27	321	550,280	212	6,262,314
Cypress	147	10	163	496,230	91	877,938
Sulphur	84	8	83	242,070	57	718,699
Red	448	47	507	860,600	247	3,780,342
Canadian	85	12	56	94,160	47	879,824
Six Coastal	775	47	316	267,900	125	184,660
Total	13,401	500	10,581	17,373,930	3,460	37,656,830

datasets representing projections of future water needs for use in planning studies.

In WRAP terminology, a water right is a set of water management capabilities and requirements for reservoir storage, water supply, instream flow needs, and/or hydroelectric energy generation. The simulation model provides considerable flexibility for defining water management and use requirements and capabilities. An actual water right permit may be represented by any number of model water rights representing various aspects of the permit. Model water rights are not necessarily required to be associated with a water right permit. The counts in Table 1 of model water rights with reservoir storage and/or water supply diversions total 10,581, which exceeds the total number of actual water right permits of about 6,200. The authorized annual water supply diversions for all of the water rights in the 20 WAMs as of 2014 totaled 17,373,930 acre-feet/year.

The TCEQ WAM datasets include all reservoirs associated with water right permits that authorize impoundment of state water inflows. A dam with storage capacity of up to 200 acre-feet can be constructed for domestic and livestock purposes without a permit. Water right permits are not required for flood control storage. The 80 reservoirs with conservation storage capacities exceeding 50,000 acre-feet account for about 92% of the permitted conservation capacity of the 3,460 reservoirs in the 20 WAMs of 37,656,830 acre-feet.

The spatial configuration of a river system is defined in the model by a set of control points, with the next downstream control point being specified for each control point. All reservoirs, diversions, return flows, hydropower plants, instream flow requirements, and other system components are assigned control point locations. Table 1 indicates that the 20 WAMs have a total of 13,401 control points, of which 500 are classified as primary. Primary control points are sites, usually U.S. Geological Survey (USGS) gaging stations, for which hydrologic period-of-analysis sequences of monthly naturalized streamflows are included in the simulation input datasets. Naturalized flows at all other control points are computed within the simulation from the naturalized flows at primary control points and watershed parameters included in the datasets.

The WAMs combine the authorized or current use scenario (or some modification thereof) for water management with historical natural river system hydrology. The TCEQ updates the water rights data in the WAMs as individual applications for new permits or revisions to existing permits are approved. The original hydrologic periods-of-analysis for naturalized streamflows and net reservoir evaporation-precipitation depths for most of the WAMs extend from 1940 or before through 1996, 1997, 1998, or 2000. Some of the hydrology datasets have been extended one or more times by the TCEQ or other agencies. The Sulphur and Colorado WAMs were recently updated by water management entities in those basins in cooperation with the TCEQ. In House Bill 723 in 2019, the Texas Legislature authorized the TCEQ to update the hydrology input datasets for the Rio Grande, Red, Neches, and Brazos WAMs. The TCEQ has contracted with consulting firms to perform these WAM hydrology updates, and the work is anticipated to be complete by August 2021. WRAP includes features for approximate preliminary hydrology updates between more detailed but less frequent updates.

The 2007 Senate Bill 3 (SB3) created a process for establishing environmental flow standards (EFS) and incorporating the standards in the WAMs. SB3 EFS are defined with subsistence, base, and high pulse flow components that vary seasonally and in some cases with hydrologic conditions. The EFS are inserted in the WAM datasets with a priority based on the date that the designated science team submits recommended EFS to the TCEQ for review and approval. Existing senior water right permit holders are not affected. SB3 EFS have been established for all river basins draining to the Gulf of Mexico within Texas. Periodic future updates to the EFS are anticipated with advances in instream flow science and management.

The routinely applied WRAP/WAM modeling system is based on a monthly computational time step. The latest expanded WRAP software and manuals include daily modeling capabilities with monthly-to-daily naturalized flow disaggregation, routing, forecasting, flood control reservoir operations, and instream flow standards with subsistence, base, and pulse flow components. The primary motivation for adding the daily modeling features is to support modeling water rights permit applications and regional planning studies that require a more refined approach to incorporating SB3 EFS in the WAMs. A strategy has been proposed for computing daily instream flow targets for SB3 EFS in daily WRAP simulations that are aggregated to monthly instream flow targets for incorporation in the input datasets for the routinely applied monthly WAMs (Wurbs and Hoffpauir 2016, 2021; Wurbs 2019c).

EVOLUTION AND APPLICATION OF THE WRAP MODELING SYSTEM

Development, improvement, and expansion of the WRAP modeling system has progressed continuously over many years and is still underway. Research to develop and improve modeling capabilities has been integrally intertwined with application of the resulting modeling system.

Texas A&M University Water Rights Analysis Program (TAMUWRAP)

The original version of WRAP, then called TAMUWRAP, was conceived in a 1986–1988 research project called Optimizing Reservoir Operations in Texas, sponsored by the cooperative federal/state cost-shared university research program of the USGS and TWRI, with the Brazos River Authority (BRA) serving as non-federal sponsor (Wurbs and Walls 1989). A simulation study of a 12-reservoir system operated by the USACE and BRA using HEC-5 (Hydrologic Engineering Center 1998) investigated multipurpose, multiple-reservoir system operations for improving water supply capabilities by sharing risk between reservoirs, combining regulated and unregulated flows and firm and secondary yields, and reallocation of storage capacity between purposes (Wurbs et al. 1988). The need for expanded capabilities for modeling basinwide interactions of numerous water rights became evident, leading to the creation of the TAMUWRAP model (Wurbs and Walls 1989).

Expanded versions of TAMUWRAP, since renamed WRAP, were developed in conjunction with research projects sponsored by the TWRI, TWDB, USACE, and Texas Advanced Technology Program. The expanded versions included improved system operations, optional salinity tracking (Wurbs et al. 1994, Wurbs and Sanchez-Torres 1996) and an alternative version based on network flow LP called WRAPNET (Yerramreddy and Wurbs 1996). The TCEQ, TWDB, TWRI, USACE, National Institute for Global Environmental Change, and other entities have since sponsored improvements to the modeling system and/or research studies addressing particular water management issues using WRAP as a modeling and analysis tool (Wurbs 2020b, 2021a).

Application of WRAP and the WAM modeling system in Texas

WRAP has been greatly improved and expanded since 1997 under the auspices of the TCEQ in conjunction with the TCEQ-led creation and improvement of the WAM system. A WRAP additions and revisions report maintained at the WRAP website describes the modifications that have occurred between the evolving editions of the software and manuals. Current TCEQ-sponsored research and development at TAMU is focused largely on improving capabilities for incorporating SB3 environmental flow standards in the WAMs and refining daily simulations.

The TCEQ maintains the WAM system in conjunction with administrating the water rights permit system to assess reliabilities of proposed actions. Reliabilities of existing water right permit holders are protected from additional new water use because the WAMs incorporate the priority system. TCEQ staff apply the modeling system during the process of reviewing applications for new water right permits or amendments to existing permits. Permit applicants and their consultants apply the WAMs during preparation of water right applications. The list of pending applications maintained at the TCEQ water rights permit website included 152 applications as of early June 2021. Permit applications are often relatively simple but can be very complex, as illustrated by the BRA system operations permit approved in November 2016.

A BRA system operations permit with an accompanying water management plan approved by the TCEQ in November 2016 significantly increased water supply capabilities based on a better understanding of reliability provided by the WAM. The amount of water supplied by BRA under contracts with customers is limited to the total amount allowed by its water right permits. Previous BRA water right permits were issued for individual reservoir projects near the time of their construction. Much of the total water use is from diversions in the lower basin that are significant distances below the dams and can be supplied by releases from multiple reservoirs, which facilitates managing risk of shortages by balancing storage drawdowns. The new permit allows the BRA to use unregulated flow entering the river system below the dams along with releases from 11 reservoirs to supply its customers. Contracts can commit different levels of reliability called firm and interruptible for different types of water use and available alternative backup sources of supply and demand management plans. For example, municipal water supply commitments may be based on the conventional concept of firm yield while agricultural irrigation commitments may be based on lower levels of reliability with greater likelihood of interruption during droughts.

The TWDB and regional planning groups or their consultants apply the WAMs in the regional water planning process established by the 1997 SB1. Sixteen regional plans developed by planning groups and a consolidated statewide plan developed by the TWDB in collaboration with the water management community are updated in a 5-year planning cycle with a 50-year future planning horizon (TWDB 2017). The 2002, 2007, 2012, and 2017 water plan reports are available at the TWDB website, and work on the 16 updated 2021 regional plans and 2022 statewide plan is underway.

River authorities and other entities apply the WAMs in operational planning, project feasibility studies, and other endeavors. The modeling system also supports environmental flow studies, research investigations, and other water management activities. The National Wildlife Federation applied the WAMs to study freshwater inflows to the estuaries of Texas (Johns et al. 2004). The USACE has explored use of the modeling system in the federal Section 404 regulatory program (CDM Smith 2016). The USGS combined the Guadalupe WAM with the Soil and Water Assessment Tool (SWAT) watershed model to assess increases in water supply in Canyon Lake resulting from different brush management strategies (Asquith and Bumgarner 2014).

The Texas Water Conservation Association Surface Water Committee WRAP/WAM Subcommittee and other stakeholders provide feedback to the TCEQ and its TAMU contractor regarding water management issues and needs for expanded modeling and analysis capabilities and review research and development products. Eleven WRAP user group conferences held since 2006 have been attended by water professionals from the TCEQ, TWDB, river authorities, other agencies, engineering firms, and universities.

University research investigations of water management issues

Appendix A of the WRAP Reference Manual (Wurbs 2021a) is a *Bibliography of WRAP Related Publications* that includes 10 Ph.D. dissertations, 19 M.S. theses, and many technical reports, journal papers, and conference papers derived from research at TAMU. Several of the research studies performed at TAMU are noted as follows.

The effects of long-term future climate change associated with global warming on water availability in the San Jacinto and Brazos River Basins and adjoining coastal basin were modeled by combining WRAP with the SWAT watershed rainfall-runoff modeling system and output from a global circulation model maintained by the Canadian Center for Climate Modeling and Analysis (Muttiah and Wurbs 2005, Wurbs et al. 2005). The potential for incorporating indices of the El Niño Southern Oscillation or other multiple-year climatic cycles in forecasting short-term future water availability was investigated by Bista (2015) using WRAP short-term conditional reliability modeling features.

The SWAT modeling system was investigated but not adopted for use in transferring WAM monthly naturalized flows from gaged to ungaged sites (Wurbs 2006). Ryu (2015) investigated the use of SWAT to develop daily streamflow input data for the daily WRAP.

The salinity simulation component of WRAP was applied to investigate the impacts on water supply capabilities of natural salt pollution from geologic formations in the upper Brazos River Basin (Wurbs and Lee 2009, 2011). Natural salt pollution in the upper watersheds of several Texas river basins significantly constrain the use of water from many large reservoirs.

The 20 WAMs were used in a statewide investigation of reservoir evaporation, which was found to be a very large component of reservoir water budgets (Wurbs and Ayala 2014). Wurbs and Zhang (2014) employed WRAP and the WAMs in a statewide investigation of hydrologic characteristics of Texas river basins. Wurbs (2021c) explored statewide reservoir operations.

Hoffpauir (2010) researched and developed daily modeling methods for incorporation into WRAP. Wurbs and Hoffpauir (2013, 2016) and Pauls and Wurbs (2016) modeled SB3 environmental flow standards with the daily WRAP. Demirel and Wurbs (2017) modeled reservoir storage reallocations between flood control and water supply using the daily WRAP.

WRAP has been applied by researchers and practitioners, mainly in university research studies, in other countries and other states in the United States but not nearly to the extent as in Texas. The following publications report academic research in other countries. Koch and Grunewald (2009) present simulation results comparing WRAP and the WBalMo modeling system developed by the Danish Hydraulic Institute from the perspective of the European Water Framework Directive without concluding which of the two modeling systems is advantageous. Chen and Chan (2007), Zhang et al. (2010), and others have applied WRAP to river systems in China. Kim and Kim (2016) employed WRAP to establish operating plans for the Soyang Reservoir in Korea.

The author of this paper presented 5-day WRAP workshops for groups of professionals from multiple water management agencies in Armenia and Peru in conjunction with consulting projects sponsored by the U.S. Agency for International Development and National Institute of Development of Peru with the objective of implementing WRAP in those two countries. Limitations in institutional capabilities were found to be a key constraint to implementation of computer modeling systems in support of actual water management endeavors.

WRAP CAPABILITIES AND ORGANIZATION

WRAP simulation studies combine a specified scenario of river/reservoir system management and water use with hydrology represented by sequences of naturalized streamflows and reservoir evaporation, minus precipitation rates at pertinent locations, for each monthly or daily interval of a hydrologic period-of-analysis. Model application includes the following:

- Compiling, updating, or accessing water management and hydrology input datasets;
- Simulating water resources development, allocation, regulation, management, and use scenarios based on the hypothetical premise of a repetition of historical hydrology; and
- Developing water supply reliability and streamflow and reservoir storage frequency metrics and otherwise organizing and analyzing simulation results.

Simulation input datasets for alternative scenarios have been developed for all the river basins of Texas. Model users modify a simulation input dataset to reflect their proposed changes in water use, new projects to be constructed, and/or new or altered management strategies. WRAP applications outside of Texas require compilation of input datasets.

Applications range from simple to very complex. For example, the Lavaca-Guadalupe coastal basin WAM has only 10 water rights and no reservoirs. Wurbs (2019c) presents a simulation study comparing WRAP monthly simulation model (SIM) and WRAP daily simulation model (SIMD) results from the Brazos WAM with 680 reservoirs and over 2,400 model water rights.

WRAP software and manuals

The modeling system consists of a set of executable programs developed primarily in Fortran and documented in detail by a set of manuals. The latest versions of the WRAP executable programs, manuals, and other supporting materials can be downloaded free-of-charge from the WRAP website.

WinWRAP is a user interface for managing programs and data files in Microsoft Windows®. The other executable programs perform the four functions outlined below.

1. Development of hydrology input data for the simulation model
   - The WRAP hydrology data compilation program (HYD) develops and updates SIM input files containing monthly naturalized streamflows and reservoir evaporation minus precipitation rates.
   - The WRAP daily flow parameter calibration program (DAY) is used to calibrate routing parameters and otherwise compile daily hydrology input data for SIMD.
   - HEC-DSSVue reads, creates, and manages DSS files of time series data, plots the data, and performs frequency analyses and mathematical operations.
2. Simulation of the river/reservoir/water use system
   - SIM performs simulations using a monthly computational time step.
   - SIMD performs simulations using a daily computational time step.
3. Tracking salinity loads and concentrations through the river/reservoir system
   - The WRAP salinity simulation model (SALT) performs a salinity simulation by combining SIM simulation results with salinity input.
4. Organization and analyses of simulation results
   - The WRAP data organization and analysis program (TABLES) reads SIM, SIMD, and SALT simulation results, performs frequency and reliability analyses, and creates a variety of tables in user-selected formats to organize, summarize, and display simulation results.
   - HEC-DSSVue reads DSS files of simulation results or any other time series data, organizes the data, prepares plots, and performs statistical analysis.

The WRAP executable programs are documented by Reference, Users, Fundamentals, Hydrology, Salinity, and Daily Manuals (Wurbs 2021a, b, Wurbs 2019a, b, 2009; Wurbs and Hoffpauir 2021). The Reference Manual provides an overview of the modeling system and describes modeling and analysis concepts and methods. Logistics of applying SIM, SIMD, and TABLES are explained in the User's Manual. Additional daily features are covered in the Daily Manual. HYD and SALT are documented in the Hydrology and Salinity Manuals. Input datasets for the many examples in all of the manuals are available at the WRAP website along with the software and manuals.

The Fundamentals Manual provides a condensed tutorial of basics from the Reference and User's Manuals, employing a hypothetical but realistic example WAM with 11 control points, six reservoirs, 30 water rights, and a 1940–2018 hydrologic period-of-analysis. Several of the examples in the other manuals build upon and expand the example in the Fundamentals Manual. The Fundamentals Manual also describes the WinWRAP user interface.

HEC-DSS and its HEC-DSSVue interface are integral components of WRAP. The HEC-DSSVue software and user's manual (HEC 2009) are available at the HEC website. WRAP use of DSS and HEC-DSSVue to manage and analyze time series input and simulation results is explained in the WRAP User's Manual.

Conventional, firm yield, salinity, and short-term CRM modes

In the conventional long-term simulation mode applied in planning studies and evaluation of water right permit applications, a specified water management/use scenario is combined with naturalized flows and net reservoir evaporation rates covering the entire hydrologic period-of-analysis in a single or dual simulation. A dual simulation option in SIM/SIMD is useful in modeling multiple rights with different priorities associated with the same reservoir. Program SIM simulation results consist of hydrologic period-of-record sequences of monthly streamflows, reservoir storage, diversions, diversion shortages, and other quantities. The programs TABLES and HEC-DSSVue are used to perform reliability and frequency analysis, prepare time series plots, and otherwise organize, analyze, and summarize the SIM or SIMD time series results.

Program SIM has a feature that automatically repeats the complete hydrologic period-of-analysis simulation many times in a search for a firm yield. With the SIM yield-reliability option, one or more selected diversion rights start with a specified target that is iteratively incremented until the firm yield is reached. Options are also provided for computing safe yield versions of firm yield based on defined water supply reserves.

The WRAP program SALT reads a SIM simulation results file and salinity input file and tracks salinity loads and concentrations through the river/reservoir system. Frequency analysis and time series plots of simulated concentrations support assessments of the impacts of salinity on supply capabilities for alternative water management plans. The program SALT is documented by the Salinity Manual (Wurbs 2009). Wurbs and Lee (2009, 2011) demonstrate the salinity simulation features of WRAP in an investigation of natural salt pollution in the Brazos River Basin.

Conditional reliability modeling (CRM) is an alternative to the conventional long-term simulation mode. CRM supports short-term drought management and operational planning activities in which consideration of preceding reservoir storage levels is important. An array of options are provided for organizing CRM simulations and analyzing the simulation results. A CRM version of the example in the Fundamentals Manual is presented in the Reference Manual. Wurbs et al. (2012) demonstrate and explore various CRM options using the Brazos WAM.

In the short-term CRM mode, water availability over the next several months or one or more years is probabilistically conditioned on preceding reservoir storage. The hydrologic period-of-analysis is divided into many sequences within SIM, and the simulation is automatically repeated with each hydrologic sequence starting with the same specified initial reservoir storage contents. TABLES develops frequency tables from the SIM results showing the likelihood of reservoir storage contents exceeding various levels any number of months in the future given preceding storage levels. Flow frequency and water supply reliability metrics are also computed.

SIMULATION OF RESERVOIR/RIVER SYSTEM WATER MANAGEMENT

Hydrology input for the simulation model SIM consists of sequences of naturalized streamflows at primary control points and reservoir evaporation minus precipitation rates. The daily SIMD input dataset also includes daily flow pattern hydrographs used by SIMD to disaggregate monthly naturalized flows to daily while preserving the monthly volumes.

Watershed parameters for delineating incremental sub-watersheds and applying alternative flow distribution options are used in synthesizing naturalized monthly or daily flows at secondary control points. Total and/or incremental watershed areas are used in all the WRAP SIM/SIMD flow distribution options. Channel loss factors, curve numbers, and/or mean annual precipitation are also included as input parameters for some of the options. Although curve numbers and mean annual precipitation depths were compiled in the original development of the TCEQ WAMs, none of the WAMs currently adopt the SIM/SIMD flow distribution options requiring curve numbers and mean annual precipitation depths.

In WRAP terminology, sets of simulation model input information describing reservoirs and other constructed facilities, water use, management practices, and permit requirements are collectively called "water rights." Water right data and specifications input to the model include the following:

- locations of system components by control point;
- priority specifications;
- water supply diversion, instream flow, and hydroelectric energy targets for each of the 12 months of the year and optional specifications for varying the water use targets as a function of reservoir storage contents or streamflow;
- seasonal or annual limits on diversions, reservoir releases, or flow depletions;
- return flow specifications in various optional formats;
- conveyance of flow through pipelines and canals;
- reservoir operating rules including multiple-reservoir system operations, multipurpose operations, multiple-owner reservoirs, and off-channel storage;
- reservoir storage volume, surface area, and elevation relationships as tables or coefficients; and
- specifications for recording time series simulation results for control points, reservoirs, water rights, or specified groups of related water rights.

Simulation results include quantities for many variables computed in the simulation for each month or day of the hydrologic period-of-analysis. The model-user selects the control points, water rights, reservoirs, and the variables for which simulation results are recorded. Output variables include but are not limited to:

- naturalized, regulated, and unappropriated flows, streamflow depletions, return flows, and channel loss quantities for each selected control point;
- reservoir storage volume, net evaporation-precipitation, inflows, releases, diversions, and hydroelectric energy at each selected reservoir;
- diversion targets and shortages, return flows, available flows, flow depletions, and storage for each selected water supply right;
- hydropower targets, firm energy produced, secondary energy produced, energy shortages, and storage for each selected hydropower right; and
- instream flow target and shortage for each selected instream flow right.

Simulated naturalized, regulated, and unappropriated streamflow

A SIM or SIMD simulation generates period-of-analysis sequences of naturalized, regulated, and unappropriated streamflows at each control point. The program HYD facilitates developing naturalized flows by adjusting sequences of observed monthly flows at gaging stations to remove the historical effects of water resources development and management. SIMD disaggregates monthly naturalized flows to daily based on daily pattern flow hydrographs while preserving monthly volumes. SIM and SIMD include methods for transferring monthly or daily naturalized flows from gaged to ungaged control points (Wurbs 2006, 2021a).

A simulation begins with naturalized flows consisting of past streamflows adjusted to represent natural conditions with no human impact or some defined level of development. Adjusting observed streamflow to remove absolutely all effects of people is not feasible for developed river basins. For the WAM system, naturalized flows are ideally flows that would have occurred historically without the water management activities reflected in the water rights input data, but with all other aspects of the river basin reflecting constant defined conditions.

Regulated and unappropriated flows computed by SIM or SIMD reflect adjustments to naturalized flows for water right requirements representing a specified scenario of water resources development and use. Regulated flows are physical flows considering all water rights in the input dataset. Unappropriated flows are available for further appropriation after all the water rights receive their allocated share. Regulated flows may be greater than unappropriated flows due to instream flow requirements at the site or commitments to other rights at downstream control points.

Streamflow depletions are the quantities of water appropriated to meet water supply diversion requirements and refill reservoir storage. Diversion return flows, return flows from groundwater or other supply sources, and reservoir releases are added to streamflows. Channel losses are considered as flow adjustments are cascaded downstream. Daily flow adjustments are lagged and attenuated in an optional SIMD routing algorithm.

For example, naturalized flows at 40 primary control points stored in the Trinity WAM input dataset are distributed to 1,363 other secondary control points with each execution of SIM or SIMD. The simulated regulated and unappropriated flows computed in each of the 948 months or 28,855 days of the 1940–2018 simulation at each of the 1,403 control points reflect the effects of 1,057 model water rights with 697 reservoirs.

Observed and naturalized 1940–2018 monthly and annual flows of the Trinity River at the USGS gage near the Romayor, Texas, plotted in Figures 2 and 3, illustrate the tremendous variability that is characteristic of streamflow throughout Texas. This gage is located 20 miles below Livingston Dam and 50 miles above the Trinity River outlet at Galveston Bay. Annual summations of naturalized flows, regulated flows, unappropriated flows, and instream flow targets for SB3 EFS at this site from a monthly simulation are compared in Figure 4 (Wurbs 2019d). The targets for SB3 EFS include only flows in the river at the gage site. The freshwater inflow into Galveston Bay component of the SB3 EFS is not included in the model.

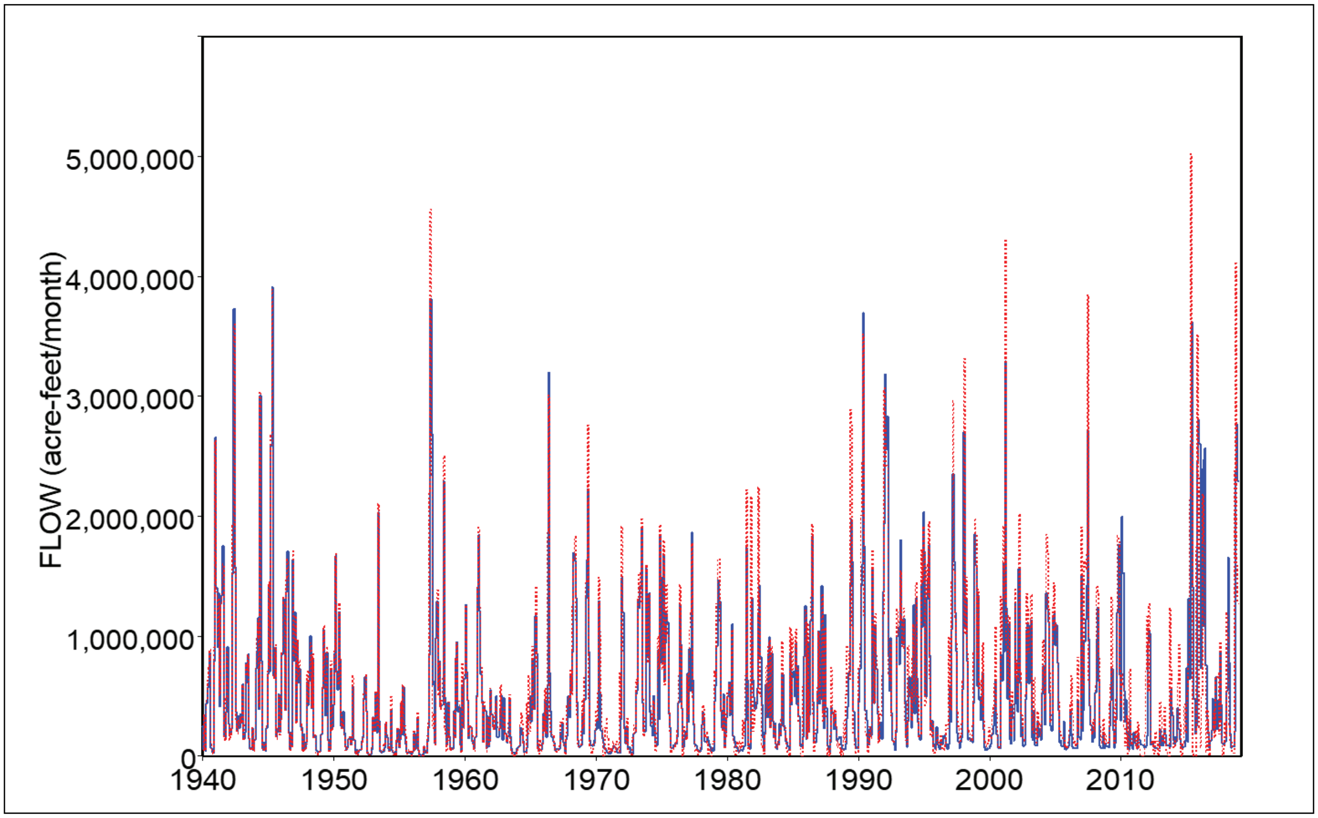

Figure 2. Monthly observed (blue solid line) and naturalized (red dotted line) flows of the Trinity River at Romayor.

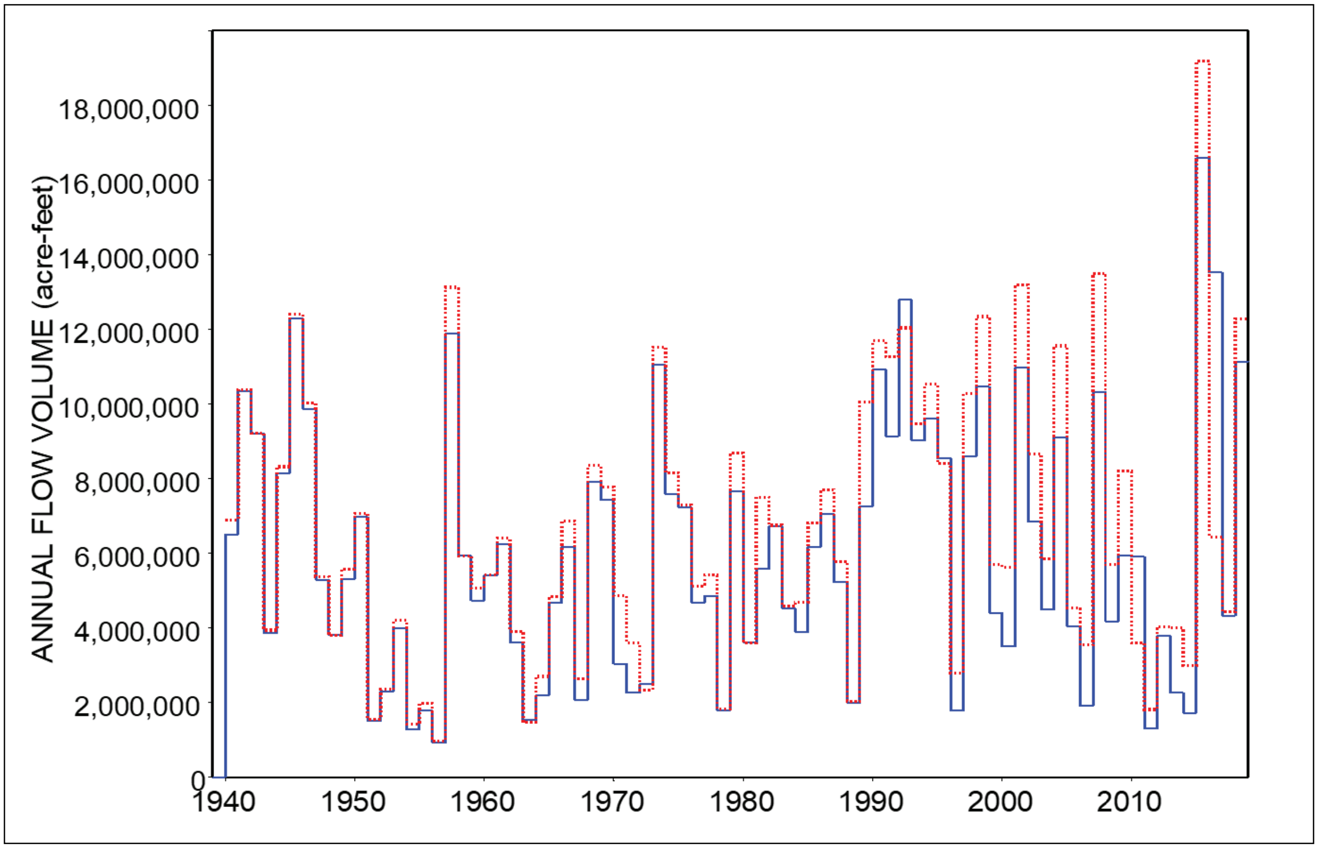

Figure 3. Annual observed (blue solid line) and naturalized (red dotted line) flows of the Trinity River at Romayor.

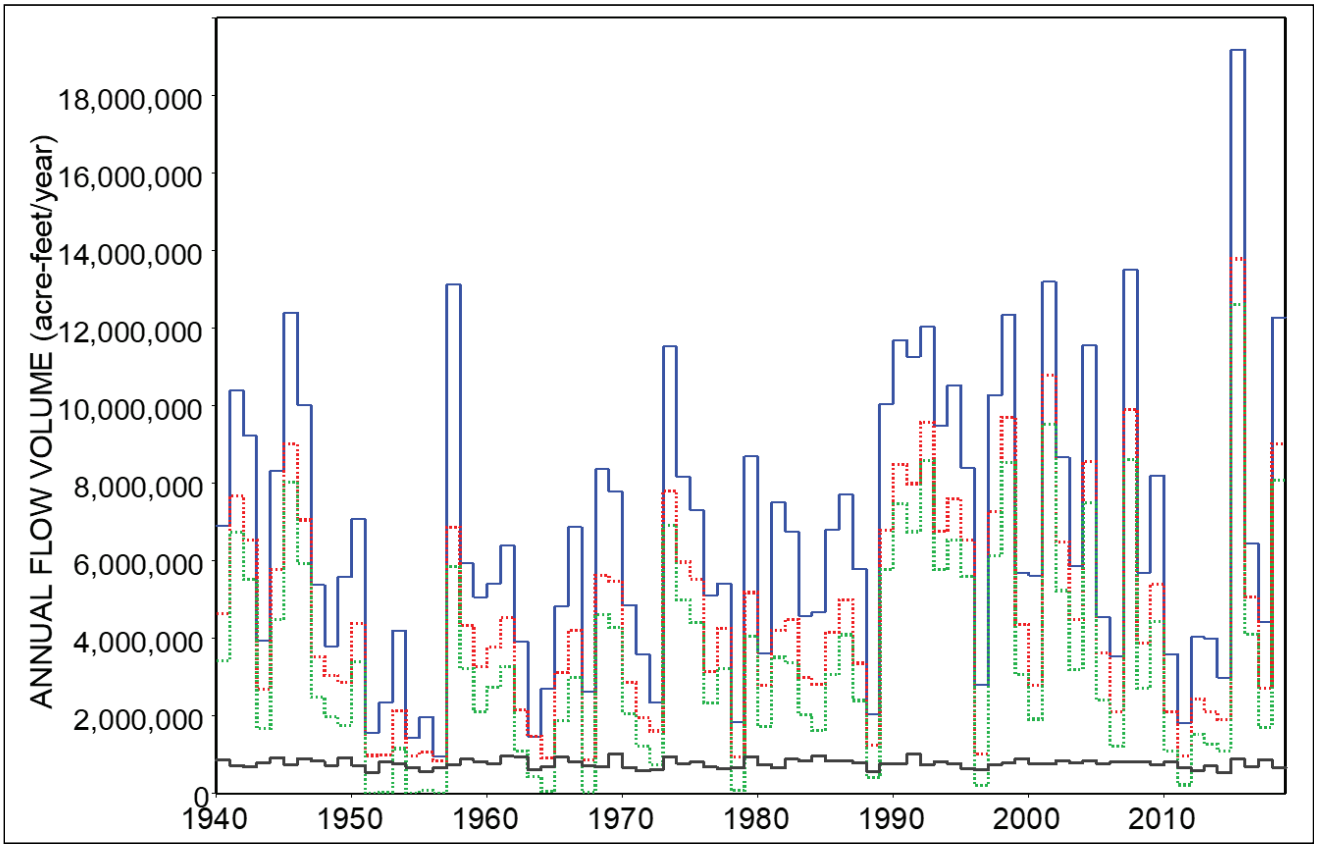

Figure 4. Annual naturalized flows (blue solid), regulated flows (red dotted), unappropriated flows (green dotted), and SB3 instream EFS Targets (black solid) for the Trinity River at Romayor.

Stepping through the time sequence and water rights priority sequence

SIM simulation computations are performed in a water rights priority loop embedded within either a monthly or daily time step loop. Model execution begins with reading and organizing input data. Water rights are sorted into priority order. The simulation steps through time. Naturalized flows for primary control points and net evaporation rates for reservoirs are read. Flows are distributed from primary control points to all other sites based on watershed parameters. Within each sequential month or day, water accounting computations are performed as each set of water use requirements (water right) is considered in priority order.

Priority numbers included in the SIM input datasets for each water right serve as the primary method for specifying priorities. A small priority number represents a more senior priority than a larger priority number. Only relative seniority is relevant. The Texas prior appropriation water rights system is based on including priority dates in the water right permits. A permit priority date of May 8, 1965, for example, is expressed as the priority number 19650508 in the SIM input dataset. This number is larger than the numbers for senior dates and smaller than the numbers for junior dates. However, other priority numbers may be assigned to water rights. For example, an assigned priority number of 9999999 makes a water right junior to all water rights with priorities based on dates. The SIM simulation model also includes an option for automatically assigning water right priorities in upstream-to-downstream order.

Water allocation and management are modeled by accounting procedures within the water rights priority loop. An array is maintained of streamflow available for appropriation at all control points. As each water right is considered in priority order, the following four tasks are performed:

1. The diversion, instream flow, or hydropower target is set starting with an annual amount and 12 monthly distribution factors provided as input. The target may be further modified as a function of the: storage content in any number of specified reservoirs; naturalized, regulated, or unappropriated flow at any control point; or other variables.
2. The amount of streamflow available to the water right is determined considering available flows at the control point of the water right and all downstream control points.
3. Water use requirements are met subject to water availability following specified system operating rules. Water

accounting computations are performed to determine the diversion, diversion shortage, end-of-month storage, and related quantities. Reservoir evaporation and hydroelectric power generation depend on both beginning-of-month and end-of-month storage and thus necessitate an iterative algorithm.

4. The available streamflow is adjusted for the control point of the water right and all downstream sites to reflect the effects of the water right. Channel loss factors are applied in translating adjustments for streamflow depletions and return flows to downstream sites.

Daily modeling system

The routinely applied WRAP and WAMs employ a monthly time interval. The daily simulation model SIMD has all capabilities of the monthly SIM plus the following additional features, used only in a daily simulation:

- disaggregation of monthly naturalized flows to daily using daily pattern hydrographs while preserving monthly volumes
- disaggregation of water use targets
- routing of streamflow adjustments to reflect lag and attenuation effects
- forecasting of future flows over a specified forecast period to protect senior downstream rights and support reservoir flood control operations
- simulation of flood control system operations of systems of any number of reservoirs
- simulation of high pulse flow environmental flow requirements

Wurbs (2019c, 2019d, 2020a) converted monthly Brazos, Trinity, and Neches WAMs to daily in research at TAMU sponsored by the TCEQ. The primary objective was to improve capabilities for modeling environmental flow standards (EFS) that have been developed pursuant to the TCEQ-managed process established by the 2007 SB3. The EFS include subsistence, base, and high flow pulse components that may vary seasonally and/or with hydrologic condition.

A modeling strategy was employed that is based on developing daily EFS instream flow targets in a SIMD simulation that are summed to monthly quantities within SIMD. The monthly instream flow targets from the daily SIMD simulation are incorporated in the SIM input dataset. This procedure works well from the perspective of modeling the appropriation of streamflow for the EFS and the impacts on other water rights that are junior to the EFS. However, EFS shortages as well as targets are important in studies assessing capabilities for meeting the EFS. Shortages in meeting the daily targets are normally assessed directly from the daily simulation results.

Various modeling issues were investigated in simulation studies performed in conjunction with creating the daily Brazos, Trinity, and Neches WAMs. The basic advantage of the daily computational time step is capturing the within-month variability of daily streamflow. Daily SIMD modeling is much more complex than monthly SIM modeling due primarily to SIMD routing, forecasting, and other options that may or may not be warranted for particular applications. Wurbs (2019c, 2019d, 2020a) outlines considerations in selecting an optimal set of SIMD options that achieve the objectives of a particular application while eliminating unnecessary complexity.

TWDB staff and consulting firms employed by the TWDB are applying modified versions of the Brazos, Trinity, and Neches daily WAMs during 2021 to assess capabilities for meeting SB3 EFS and the impacts of the EFS on water availability for supplying other growing water needs. Daily modeling studies are expected to extend to other river basins in the future.

Simulated reservoir storage as a measure of water supply capabilities

Many alternative simulations with the daily and monthly Brazos, Trinity, and Neches WAMs, with different options activated, are presented in three technical reports in a comparative exploration of alternative modeling methods (Wurbs 2019c, 2019d, 2020a). The selected final simulations described in the reports are adopted for Figures 2, 3, 4, 5, 6, and 7 and Table 2 of this paper. The Brazos, Trinity, and Neches WAMs employed in these simulation studies have hydrologic periods-of-analysis of 1940–2017, 1940–2018, and 1940–2019, respectively.

HEC-DSSVue plots of reservoir storage computed in monthly SIM and daily SIMD full authorization scenario simulations are presented in Figures 5, 6, and 7. A specific water right with a single reservoir or multiple-reservoir system is of interest in most applications of the modeling system. However, summations of end-of-month and end-of-day storage contents of all reservoirs in the WAMs are plotted in Figures 5, 6, and 7, reflecting a broader basinwide perspective for the brief discussion in this paper. Storage fluctuations in individual reservoirs tend to be greater than the basinwide totals. Timing differences in storage depletions result in summations of storage volumes in multiple reservoirs being averaged out to some extent.

Texas has thousands of dams/reservoirs, but most of the storage capacity is contained in a relatively small number of very large projects. The 210 major reservoirs in Texas with water right permits and storage capacities of 5,000 acre-feet or greater contain 98.0% of the total capacity of the 3,460 reservoirs in the 20 full authorization WAMs (Wurbs 2021c).

The full authorization Brazos, Trinity, and Neches WAMs referenced in this discussion have 680, 697, and 180 reservoirs, respectively, with authorized conservation storage capac-

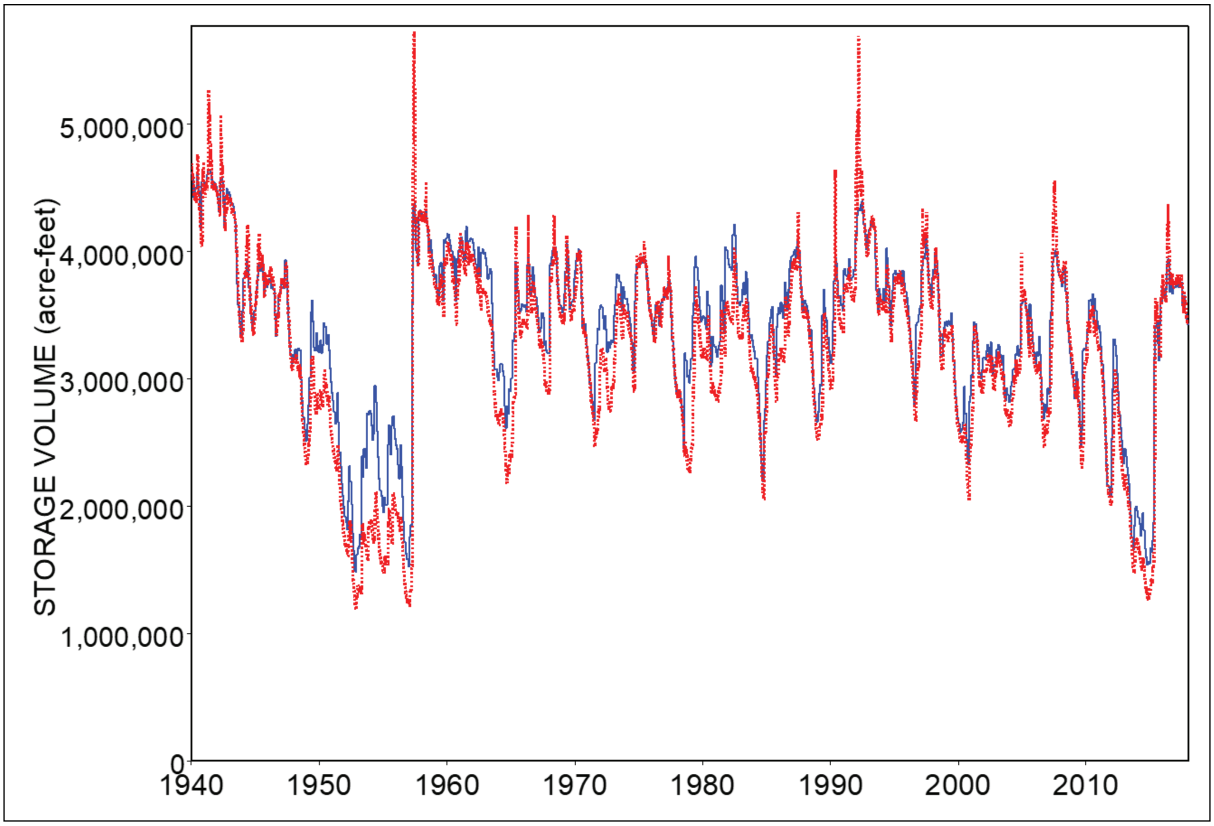

Figure 5. Storage contents of 680 reservoirs in the Brazos WAM from monthly SIM (blue solid) and daily SIMD (red dotted) simulations.

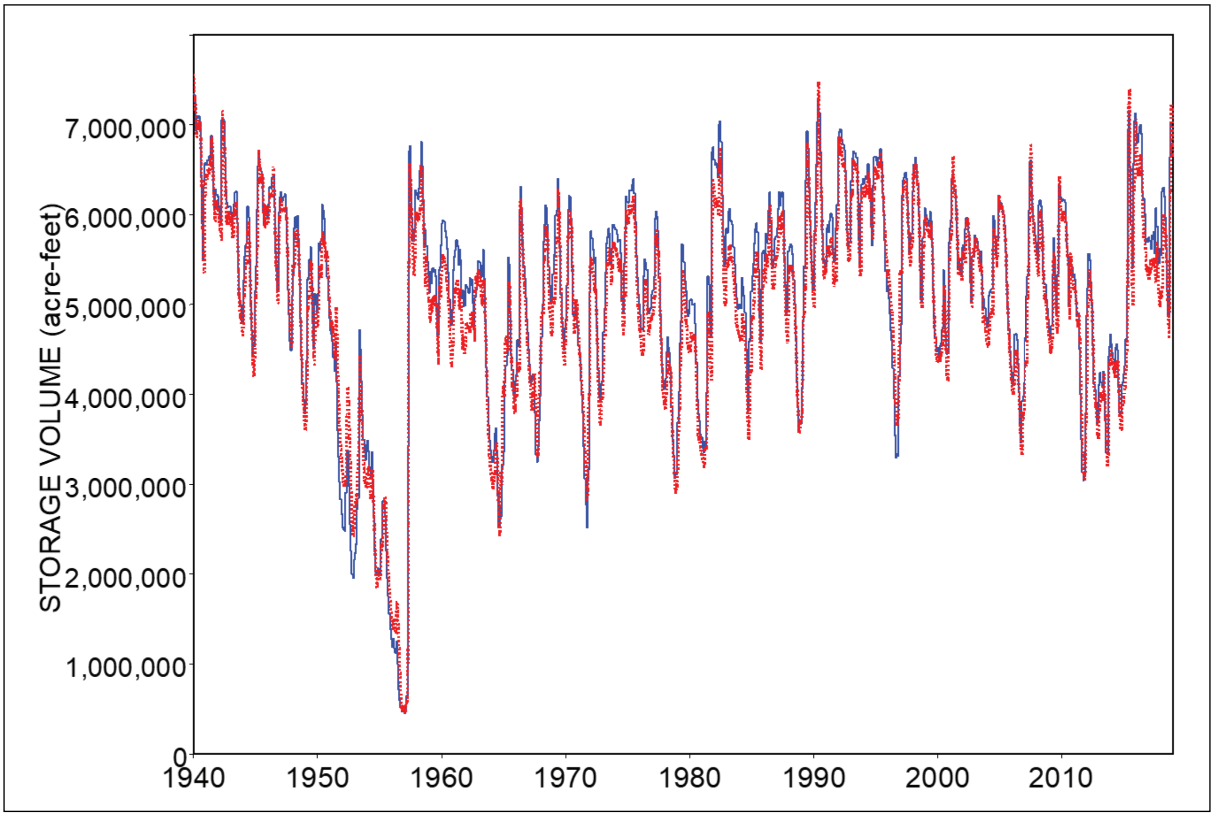

Figure 6. Storage contents of 697 reservoirs in the Trinity WAM from monthly SIM (blue solid) and daily SIMD (red dotted) simulations.

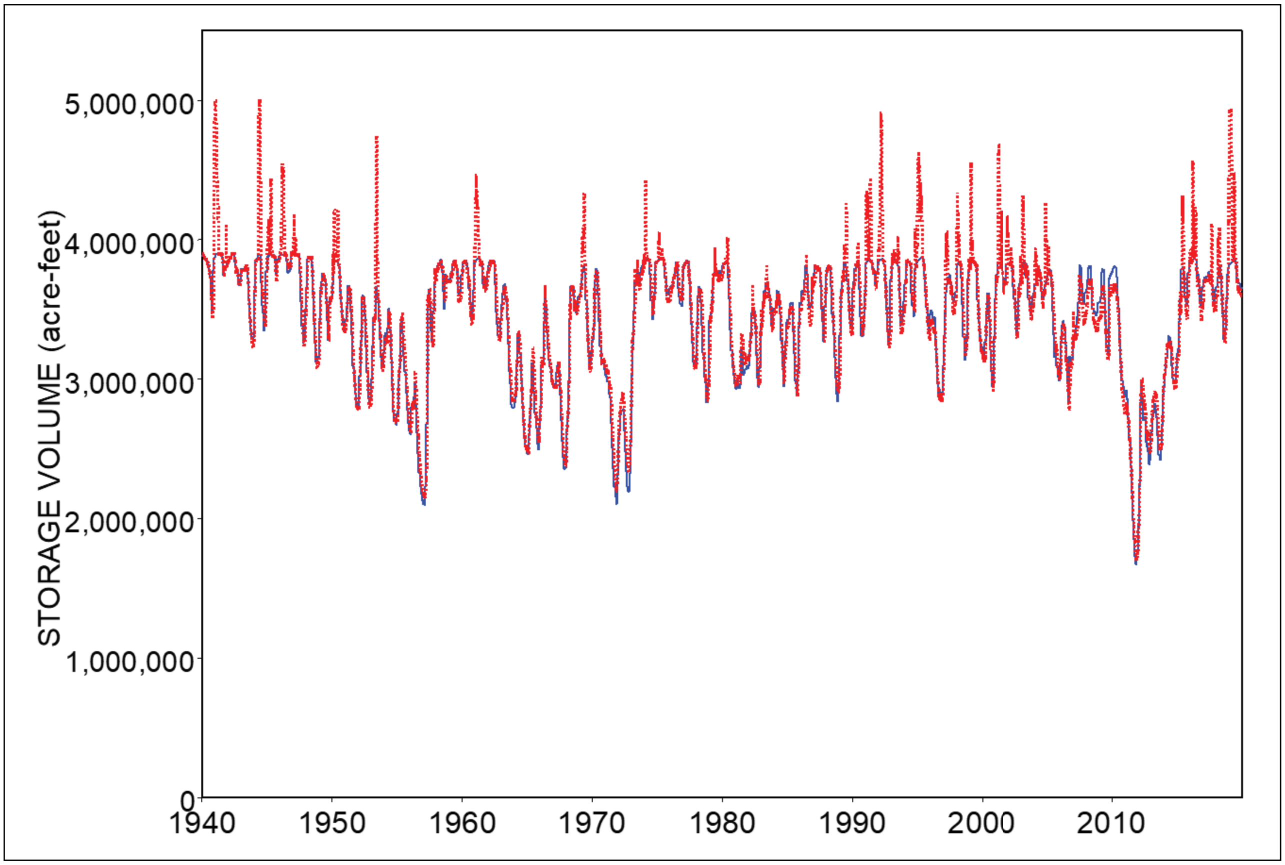

Figure 7. Storage contents of 180 reservoirs in the Neches WAM from monthly SIM (blue solid) and daily SIMD (red dotted) simulations.

ities totaling 4,746,300 acre-feet, 7,356,200 acre-feet, and 3,904,100 acre-feet. Flood control pools are not included in water right permits and the monthly WAMs. The daily Brazos, Trinity, and Neches WAMs include USACE flood control pools in nine, eight, and one multipurpose reservoirs, respectively. The volume of water in storage provides an insightful drought index and metric of water availability.

The simulations are based on the premise that all permitted water right holders store and divert the full amounts of water authorized by their permits during a hypothetical (computational) repetition of past hydrologic period-of-analysis natural hydrology. The storage plots of Figures 5, 6, and 7 illustrate the need for a long hydrologic period-of-analysis for a meaningful assessment of water supply capabilities. Most of the reservoirs were constructed during the 1960s or later. Almost none of the reservoir storage capacity and associated water needs existed during the 1950–1957 drought, which was the most hydrologically severe drought since before 1940 for the Brazos and Trinity River Basins. This drought began gradually during 1950 and ended with major widespread flooding during April–June 1957. Water users and managers have never experienced a drought as hydrologically severe as 1950–1957 with present conditions of population, economic development, and water resources development in these river basins.

The storage plots also provide a comparison of the three river basins. The Neches River Basin has more abundant water resources relative to demand than the Trinity and Brazos River Basins. The timing and severity of droughts is also different for the Neches. The minimum total storage contents of the 180 reservoirs the SIMD simulation is 43.4% of water supply storage capacity occurring on December 3, 2011. Sam Rayburn Reservoir contains 74.2% of the authorized storage of the 180 reservoirs and is the only reservoir with a flood control pool added in the daily model. Storage in the flood control pool is evident in Figure 7. Likewise, USACE flood control operations of nine and eight large multiple purpose reservoirs in the Brazos and Trinity River Basins are reflected in the daily simulations of Figures 5 and 6.

Figures 5, 6, and 7 also provide a comparison of water availability for daily versus monthly simulations. Differences are due to combinations of various aspects of the simulations.

Frequency analyses of reservoir storage volumes differ from streamflow in regard to effects of different time intervals. End-of-month and end-of-day storage volumes are defined at an

Table 2. Statistics for monthly SIM and daily SIMD naturalized (Nat), regulated (Reg), and unappropriated (Una) flows of the Trinity River at Romayor in cubic feet per second (cfs).

	Monthly SIM Simulation			Daily SIMD Simulation		
	Nat (cfs)	Reg (cfs)	Una (cfs)	Nat (cfs)	Reg (cfs)	Una (cfs)
Mean	9,129	5,986	4,361	9,114	6,204	4,790
Standard Deviation	11,162	8,692	8,710	14,100	11,826	11,748
Minimum	0.00	0.00	0.00	0.00	0.00	0.00
99%	0.00	141	0.00	0.00	0.00	0.00
98%	78.5	415	0.00	53.3	0.00	0.00
95%	275	730	0.00	225	0.00	0.00
90%	585	1,026	0.00	479	0.00	0.00
85%	922	1,132	0.00	723	504	0.00
80%	1,391	1,196	0.00	1,017	834	0.00
75%	1,831	1,370	0.00	1,336	1,016	0.00
70%	2,283	1,513	0.00	1,688	1,127	0.00
60%	3,337	1,897	0.00	2,506	1,434	0.00
50%	4,734	2,288	0.00	3,712	1,891	0.00
40%	7,158	2,668	662	5,638	2,383	0.00
30%	10,593	4,742	3,060	8,826	3,727	1,692
25%	12,264	6,994	4,730	11,052	5,658	3,532
20%	15,349	9,295	7,935	13,908	8,323	6,211
15%	19,038	12,570	10,880	17,770	11,856	10,026
10%	23,251	15,782	14,720	23,871	17,339	15,568
5%	31,122	23,746	22,376	35,660	28,263	26,930
2%	44,629	35,241	33,309	53,662	45,412	44,172
1%	55,634	45,082	43,400	69,862	60,139	58,838
Maximum	81,644	66,272	64,551	204,661	183,101	182,476

instant in time. Flow quantities represent averages over a time interval, which are different for monthly versus daily intervals. Daily flows are more variable than monthly flows, which is not necessarily the case for 28,855 daily versus 948 monthly storage volumes in a 1940–2018 simulation.

FREQUENCY AND RELIABILITY ANALYSES

The WRAP simulation models SIM and SIMD record time series results in DSS and text file formats that are read by the programs TABLES and HEC-DSSVue. The WRAP program TABLES organizes simulation results and input data in various user-specified formats including time series tabulations of selected variables, summary tables, water budgets, and various types of frequency and reliability metrics. HEC-DSSVue is used for managing time series data, preparing plots, mathematical operations, and statistical analyses.

Statistical frequency analyses

The program TABLES includes flexible statistical analysis features with a variety of options that can be applied to any of the SIM, SIMD, and SALT time series input and simulation results time series variables. HEC-DSSVue also includes statistical analysis features applicable to any time series dataset. Other statistical analysis software can also be employed with WRAP-generated data. The HEC-SSP Statistical Software Package (HEC 2019) was designed originally for detailed flood flow frequency analyses but includes general statistical capabilities. The Indicators of Hydrologic Alteration (IHA) software available from the Nature Conservancy (2009) computes ecologically relevant statistics for daily streamflows for environmental instream flow studies and assessments of changes in streamflow characteristics over time. The Hydrology-based Environmental Flow Regime (HEFR) is a Microsoft Excel spreadsheet based statistical analysis tool with metrics similar to the IHA (Opdyke et al. 2014). These statistical analysis software packages, like the WRAP programs, include HEC-DSS file management capabilities. The programs can be conveniently employed with WRAP time series datasets to perform various types of analyses.

Exceedance frequency computations in TABLES are usually performed based on either Equation 1 or Equation 2, where m is the rank and N is the number of months or days in the period-of-analysis. Alternatively, the normal or log-normal probability functions may be employed. The Equation 1 option has been adopted for most WRAP/WAM applications in Texas.

$$\text{Exceedance Frequency} = \frac{m}{N}\ (100\%) \tag{1}$$

$$\text{Exceedance Frequency} = \frac{m}{N+1}\ (100\%) \tag{2}$$

Frequency metrics can be computed with TABLES for a specific month of interest, for example July, with N equal to the number of years as well as for all months or days. The software has options for computing moving averages and developing annual series of minima or maxima in each year. For example, frequency analyses can be performed for annual series of 7-day (or any number of days) minimum flows derived from a daily simulation. The log-normal or log-Pearson type III probability distributions can be applied to annual series of the maximum daily flow or reservoir storage occurring during each year.

Frequency metrics in Table 2 for daily and monthly naturalized, regulated, and unappropriated flows are computed with TABLES from the monthly SIM and daily SIMD simulation results. The metrics include the mean, standard deviation, minimum, maximum, and quantities equaled or exceeded during specified percentages of the 948 months or 28,855 days of the 1940–2018 hydrologic period-of-analysis (Wurbs 2019d). The quantities are tabulated in cubic feet per second (cfs) rather than acre-feet per month or day to facilitate comparison of the variability of daily versus monthly flows. Daily flows exhibit greater variability due to within-month fluctuations.

SIM and SIMD accommodate any consistent set of flow units, though units of acre-feet per month or day have always been used for applications in Texas. TABLES includes options for converting simulation results to mean monthly or daily flow rates in cfs. Conversions of acre-feet/month to cfs consider variations among 28, 29 (leap year), 30, and 31 days in each month.

Water supply and hydropower reliability analyses

Volume and period reliabilities computed by TABLES from the results of a SIM or SIMD simulation provide concise metrics for evaluating capabilities for meeting water supply and hydroelectric energy requirements. Volume reliability (R_V) is defined by Equation 3 as the ratio of the volume of water supplied or electrical energy produced (v) to the target (V), converted to a percentage. Period reliability (R_P), computed with Equation 4, is the percentage of the total number (N) of periods (days, months, years) of the simulation during which the specified target is either fully supplied or at least a specified percentage of the target is supplied. R_P is an expression of the percentage of time that the full demand target or a specified percentage of the demand target can be supplied. Equivalently, R_P represents the likelihood or probability of the target being met in any randomly selected day, month, or year. Reliabilities may be tabulated with TABLES for all or selected individual water rights, the aggregation of all rights associated with individual control points or reservoirs, or user-selected groups of water rights.

$$R_V = \frac{v}{V}\ (100\%) \tag{3}$$

$$R_P = \frac{n}{N}\ (100\%) \tag{4}$$

In evaluating applications for new water right permits for irrigation, the TCEQ criterion is that an agricultural irrigation right should supply at least 75% of the proposed diversion target at least 75% of the time. Reliabilities of 100% are required for approval of new municipal water right permits subject to certain exceptions in the TCEQ's rules. In May 2020, the TCEQ updated its water availability assessment rules to include criteria for new water rights for aquifer storage and recovery and aquifer recharge.

WRAP provides flexible options for developing a variety of reliability metrics. Frequency and reliability computations for short-term conditional reliability modeling (CRM) are analogous to, but interpreted differently than, the metrics for conventional long-term simulations. A particular water supply diversion target may have an estimated probability (likelihood, frequency, reliability) of 80.0% of being supplied at least 90.0% of the time over some unspecified long planning horizon in a conventional analysis. CRM analyses are organized in terms of the probability or likelihood that various reservoir storage levels will be equaled or exceeded at some time a specified number of months in the future, or water supply demands will be supplied during this period, given a known amount of water presently in storage. For example, for specified reservoir storage contents at the beginning of the irrigation season, the probability of supplying at least 90.0% of a particular agricultural water supply diversion target during the next irrigation season may be estimated in a CRM analysis to be 80.0%.

TABLES creates an optional vulnerability and resiliency table that includes the maximum monthly shortage, average sum of consecutive shortages, maximum number of consecutive shortages, and other shortage indices. This table has not been used very much to date.

Firm yield is commonly computed in planning studies. Firm yield is the maximum demand target that can be supplied with reliabilities (Equations 3 and 4) of 100%, estimated based on the premises reflected in the simulation model. SIM includes an option to compute firm yields based on automated iterative repetitions of the simulation. This feature includes options for computing a safe yield defined as the firm yield that still preserves a storage reserve. The storage reserve may be defined as a specified number of months of water supply or by other quantities.

CONCLUSIONS

The evolution of computer modeling of river/reservoir system development and management that began in the 1950s with predecessors to WRAP and the other modeling systems referenced in this paper is still underway and will continue. Modeling systems continue to be improved and expanded in response to advances in computer technology and intensifying water management and decision support needs. Modeling applications have grown in complexity from both technical and institutional perspectives. Administration of water rights and integration of water resources planning and water allocation have become a central focus of river basin management. Water availability modeling is complex, requiring compilation and management of voluminous datasets and understanding diverse water management practices, but is essential for effective water management.

Implementation of the Texas WAM system, under the leadership of the TCEQ, required collective efforts of the water management community. The WAMs play important roles in water management throughout the state. The shared use of the modeling system has significantly contributed to integrating administration of the water rights permit system; statewide, regional, project, and operational planning; research and development; and other water management endeavors. The system simulation and statistical analysis tools facilitate water availability assessments that combine extremely variable natural river system hydrology, complex operations of extensive constructed infrastructure, and water allocation systems that grow in importance with increasing demands on limited resources.

The generalized WRAP modeling system is readily available and documented in detail for use by engineers, scientists, and other water management professionals for a variety of different types of applications. Comprehensive, flexible modeling and analysis capabilities are provided for applications that may vary from relatively simple to very complex. WRAP capabilities have benefited greatly from the interactive development and application of the modeling system within the very progressive Texas water management community in an environment of extreme hydrologic and economic diversity and diverse water management practices.

ACKNOWLEDGEMENTS

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Pricing Options on Water in Texas

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Abstract: Water scarcity is a growing concern globally, in the United States, and in Texas. As Texans plan to meet this challenge, it is important to introduce new tools to help mitigate water shortages. Market mechanisms have historically provided methods to increase the allocative efficiency of scarce resources, though applying these mechanisms to facilitate water trading is not widespread. Cash markets have successfully been implemented under the Watermaster in the Rio Grande Valley, but the use of water markets is not prevalent throughout Texas. In addition to cash transactions for water, the ability to effectively price water options would allow an additional market-based product to facilitate more flexible transactions. As people from municipalities, agricultural interests, industry, environmental interests, and other groups look for adaptable methods to offset uncertainty surrounding future water needs and supplies, water options would be useful. This paper establishes a method to price water options on agricultural water and applies that method to a cash crop in Texas. Market mechanisms will not be a panacea for water woes, but they are an important and effective tool for helping planners deal with increasing demand amid uncertain supplies.

Keywords: water options, water trading, water markets, water pricing

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Terms used in paper

Acronym / Initialism	Descriptive Name
ac-ft	acre-feet
BSM	Black-Scholes-Merton model
EAA	Edwards Aquifer Authority
FR	Fruitful Rim
HEFR	Hydrology-Based Environmental Flow Regime
PG	Prairie Gateway
RGV	Rio Grande Valley
SAC	Science Advisory Committee for Environmental Flows
SB	Senate Bill
TCEQ	Texas Commission on Environmental Quality
USDA	U.S. Department of Agriculture
VISPO	Voluntary Irrigation Suspension Program Option

INTRODUCTION

Purpose

Noted geographer John Wesley Powell used the 100th Meridian as the dividing line between the wet and arid regions of the country. This line runs through Central Texas; roughly half of the state is positioned where it is wet, the other half where it is arid (Powell 1879). More recently, it has been shown that the dividing line has shifted to the east (Figure 1) and now runs down the 98th Meridian, which means the state is getting drier (Seager et al. 2018). Climate change is altering patterns in precipitation, which makes future planning—especially around water—challenging given this increased variability (Chang et al. 2016). Even if the dry line is shifting slowly, much of Texas is on the arid side. Population is also projected to increase in Texas and will put upward pressure on water demands (Dore 2005). The Texas Water Development Board estimates that if plans are not implemented to secure more water and there is a drought of record in the year 2070, a third of municipalities will only have half of the water they need to serve their citizens, much less the environment (TWDB 2017). Adaptable solutions are needed because half the state is historically dry, more of the state may be getting drier, and projections predict increased scarcity resulting from a variety of factors.

Planning to meet water needs has two temporal components: what is needed today and what will be needed in the future. This work is focused on the latter and seeks to illustrate how future needs can be addressed using the concepts of financial derivatives to build an option market for water. An option allows a buyer to purchase a contract for a cash payment (premium) that entitles them to make a future purchase of a specified amount of something at a specified price within an agreed-upon timeline at a specific location. For example, consider a t-shirt manufacturer who buys cotton for production and the company is profitable when they buy cotton for $0.75 per pound or less. Today, the price of cotton is $0.70 per pound and the t-shirt manufacturer is concerned about rising prices. The manufacturer could simply buy cotton today, but this presents three main problems: the manufacturer must store it, they may not get shirt orders to require the cotton, and the price of cotton could go down, putting the t-shirt maker at a disadvantage.

Here is where the option is useful. When a company buys options, they are securing the right to an amount of cotton at a price by a specific date. This privilege does cost the manufacturer some money (called the premium) but allows the t-shirt maker to mitigate their risk if prices climb. Options increase flexibility in planning for future needs as they allow the buyer to adapt to changing conditions affecting both supply and demand and allow the buyer to mitigate some of the risk associated with future uncertainty (Colby et al. 2014; Hearne and Donoso 2014). While most options in the United States are built with 3month lifespans—particularly those widely traded on established exchanges such as the Chicago Board of Options Exchange—water contracts in this work will be considered using longer horizons (5–10 years).

Figure 1. The "dry line" in the United States has shifted approximately 2 degrees (from the blue line to the yellow line) to the east over the past 100 years, this means more of Texas is receiving less rain. Adapted from Seager et al. (2018).

The initial motivation for this research stemmed from trying to find a tool to help interested parties obtain water for the environment. Environmental flows of water into bays and estuaries provide critical ecological functions to the system, and those flows have been greatly diminished by human extraction and impoundment upstream (Meijer and Van Beek 2011; Montagna et al. 2009; Montagna et al. 2018a). In naturally occurring low flow years, human needs persist. During these times, it would be beneficial if environmental managers had access to water that could be left in stream to flow to the coast. Obtaining additional flows in times of drought could significantly aid in protecting the water quality at the head of the bay in low flow years. This would give estuarine-dependent fauna a refuge from the low flow conditions and shorten recovery times. This strategic deployment of freshwater has been referred to as "focused flows" (Montagna et al. in press).

Protecting and securing environmental water has proven to be difficult in Texas as regulations regarding environmental considerations only pertain to new permits, and spot market transactions are challenging to execute in markets that do not have well established institutional support (Meadows Center: Texas environmental flows initiative 2019; White et al. 2017; Yoskowitz 1999). Derivatives, options in particular, are a viable solution to deliver the kind of situational adaptivity required to meet demands for reliable water. The applicability and utility of these water contracts goes beyond environmental uses. People from municipalities and industry, farmers, and anyone exposed to the risks associated with the uncertain reliability of water supplies can benefit from the use of water contracts.

Option pricing efforts to date

Efforts have been made to price water options in foreign and domestic markets (Cui and Schreider 2009; Villinski 2003; Williamson et al. 2008). Although much of this work has been done using traditionally accepted pricing mechanisms, novel work has been conducted to price options based on the cost of the next least expensive alternative, with the difference representing price (Michelsen and Young 1993). While the previous work does advance the understanding of the price of water as an option, it does not calculate a price for the premium. In other words, the method offers no way to calculate the cash price to be paid to the seller for the assumed risk of the option being exercised (known as being "called"). There have been other pricing efforts like Michelsen and Young's based on scarcity. This scarcity pricing can be tied to the cost of the alternative (à la Michelsen), based on changes in operating costs, or more dynamic pricing that sets a schedule based on readings of a chosen scarcity metric like dam levels (Frontier Economics 2011). These efforts have improved the understanding of how water contracts can be constructed but have not resulted in definitive pricing methodology. However, efforts have been made to construct these contracts. Facing drought in the 1990s, California took steps to enhance allocative strategies with the establishment of a Water Bank and water supply options (Jercich 1997). This fledgling market was in the process of issuing options, but market activity was curtailed when rains came and ended the drought.

One issue with pricing water options in Texas and other locations throughout the United States is the limited availability of cash market pricing on which to base options values, particularly if the method uses traditional pricing mechanisms. The most popular pricing model for options is the Black-Scholes-Merton (BSM) model, which is the foundation for derivatives theory (Glantz and Kissell 2013). To address challenges created by data deficiency, previous work has been conducted in California to build options based on 72 years of simulated price data extrapolated from an actual 18-month price history (Williams 2007). Simulating price data can be difficult, as simulated data can only act within the bounds of the sample it is based on, and market price and the variables that drive them often set new highs and new lows, and act in new ways.

The Rio Grande Valley (RGV) has the most active spot (cash) market in Texas. It was in the RGV that Villinski (2003) tried to use traditional option pricing mechanisms (BSM) but found markets to be too thin to yield reliable prices using these methods. The RGV does offer a natural water delivery system via the Rio Grande River and a Watermaster system conducive to trade, so this region may still be a good candidate for trading options in the future. There are four Watermaster areas in the state—the Brazos, Concho, Rio Grande, and South Texas (Figure 2)—and the ability to facilitate trading in the different Watermaster areas varies. For a more in-depth discussion of water rights in Texas and the role of the Watermaster, see The Case for a Texas Water Market (White et al. 2017). Institutional characteristics for trading surface water efficiently across Texas is not consistent and lacking in many cases; for example, the junior rights provision is a significant barrier to trade (White et al. 2017). In economic terms, efficiency is the idea that goods are allocated to their most valuable uses, and waste is reduced as much as possible.

There are examples of options used for environmental water in Texas. The Edwards Aquifer Habitat Conservation Plan offers options styled programs available to irrigation permit holders (Patoski n.d.). One is the Voluntary Irrigation Suspension Program Option (VISPO), which pays enrolled rights holders on an annual basis for participating in the program and makes an additional payment in years the triggering event occurs. This water is not called at the discretion of the buyer but happens automatically if a triggering event takes place. The trigger is the water level of the J-17 Index Well located at the base of the water tower near the national cemetery at Fort Sam Houston in San Antonio. If the water level is at or below 635 feet on the October 1 of each year, the participants suspend use of their water for the following year (Patoski n.d.). In short, VISPO is designed to leave groundwater in the system when levels are low. The Edwards Aquifer, located in the southern half of central Texas, is comprised of a contributing zone, a recharge zone, and an artesian zone (Figure 3).

The Edwards Aquifer is managed by the Edwards Aquifer Authority (EAA), which was created in 1993 by the Texas Legislature in response to legal battles of spring flow levels and endangered species (Patoski n.d.). There are many important aspects of the creation, implementation, and growth of the EAA, but regarding VISPO, there is one administrative feature regarding water rights that is particularly important. When the EAA allocated water rights, it provided two acre-feet (ac-ft) for every acre of irrigated land. One of these ac-ft can be traded away at the farmers' discretion, even if this involves changing the use of the water. In this way, irrigators can enter the for-

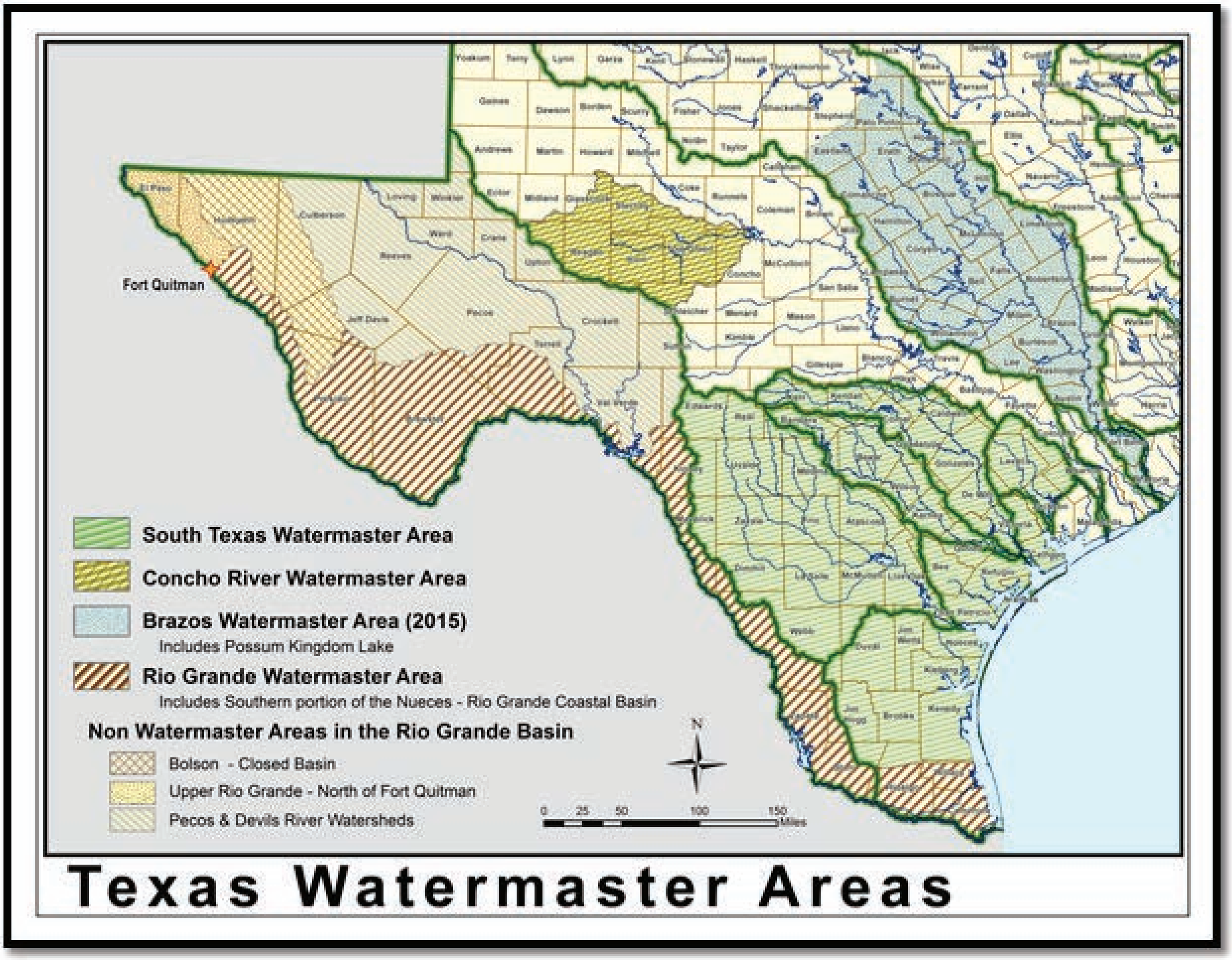

Figure 2. Texas Watermaster Areas, tceq.texas.gov.

bearance program without having to file a change-of-use application—as they would in the case of surface water—with the Texas Commission on Environmental Quality (TCEQ), who administers water rights in the state.

This change-of-use component" is important for burgeoning water markets (spot or option), as the more regulatory hurdles there are, there are often increased uncertainty and administrative barriers to entry. If a sale, lease, or other transfer of a surface-water right from one entity to another involves a change in the use of the water allocated by that permit, then an application must be filed with TCEQ (Dowell 2013). It is important to note that VISPO is designed to option water from irrigators accessing groundwater. In the case of the Edwards Aquifer, there is some crossover because the groundwater does feed the Comal and San Marcos springs, thus becoming surface water. While our work is concerned with developing water markets for surface water, the pricing of water by the EAA is used for comparison due to the limited availability of transactional data surrounding surface water outside of the RGV.

METHODS

Study site and approach

The approach to building a long-term water option in Texas is a synthesis of a novel pricing mechanism for water options combined with elements commonly found in derivatives. This methodology can be applied anywhere water is traded, but in this case, it was applied to Texas. While Texas may be too large to price an option that can be used statewide, the method described here is best suited for a basin level approach. Regardless of pricing difficulties across regional geographies, if the water is to be delivered, the limiting factor will likely be conveyance rather than price. There are two components that comprise an options contract: the elements that make it a contract and the elements that define it as an option. To be considered a contract in general, the agreement must have mutual assent, offer and acceptance, adequate consideration, capacity, and legality (Legal Information Institute 2019).

Figure 3. Edwards Aquifer contributing zone, recharge zone, and artesian zone. From the Edwards Aquifer Recovery Implementation Program.

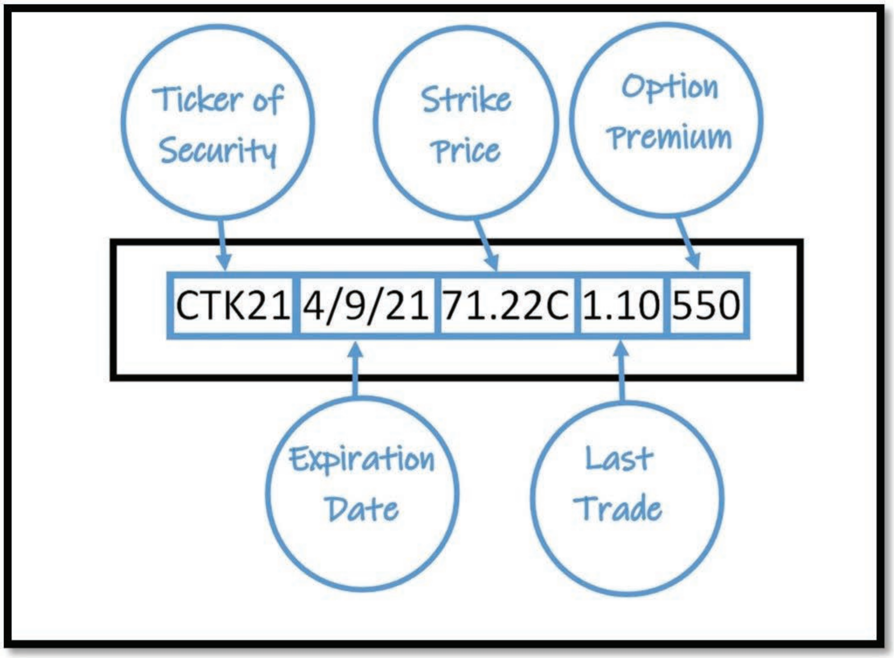

Figure 4. Example of an option description with labels.

To make a contract an option, it needs to be an arrangement where the holder (who bought the contract for consideration) can buy or sell an amount of an underlying asset during a specified time at a specified price (Windcli et al. 2001). In the case of a water option, the buyer of an option would be buying the right to take delivery of a specific amount of water from the seller anytime between the time of purchase of the option and an expiration date, with payment for the water due when exercised. Much of the important information regarding an option contract offered for sale is found in its listing (Figure 4).

The ticker symbol is the asset the option is based on; for CTK21, the CT is cotton, the K represents the month code (May), and the 21 is the year 2021 (Figure 4). The expiration date is the date by which the option must be exercised, or it expires worthless, and the strike price is the price at which the asset can be optioned, with the C next to it indicating it is a call (the right to buy). The last trade is the last transaction price as expressed in terms of option points (here one option point equals $500), which translates to $550 in option premium the buyer pays the seller for the contract. There is no mention of contract size, as by definition cotton contracts represent 50,000 pounds (approximately 100 bales), for example. In the United States, one stock option is generally worth 100 shares of common stock. The expiration date indicates the date when the option contract is no longer valid. The strike price is the price per share (or by volume in commodities, i.e., one cotton contract represents 50,000 pounds, about 100 bales) at which the option may be exercised, and the option price is how much the option contract costs initially. This work takes the common elements of an option contract and adjusts their application so that they may be applied to water; call options are constructed by using standard elements in an options contract and combining them with an approach to pricing water using opportunity cost.

WATER OPTION SPECIFICATIONS

Contract size

The amount of water that an option contract represents can be anything the buyer and seller agree on, but for ease of standardization a common volume is useful. If one contract equals one ac-ft, many contracts would have to be executed to transact meaningful quantities of water. If contracts are set at 100 ac-ft, it would be onerous to create one-off contracts for sizes under that. For utility, one contract might represent 10 ac-ft to accommodate the sub-100 acre-foot market, another standard contract could be set to 100 ac-ft, and a 1000 ac-ft contract would facilitate the execution of larger transactions. Again, these volumes can be set to anything, but there are benefits of standardization in the marketplace. By standardizing contracts, market efficiency is increased, legal fees are lowered, product knowledge is simplified, and competition is encouraged by making it easy to compare terms (Patterson 2013).

Prices: Options and water

Price will be a critical component driving the success or failure of water option contracts. The sale of the permanent water right is not being considered here, only the use of the water allocated to that right in a given year. These would be considered cash or spot transactions if they occur at the time the trade is consummated. They can also be referred to as short-term leases because when an individual sells their water in a given year, they are effectively leasing out the water right (Brown 2006). This distinction is important, because when aggregating data for cash transactions, some transactions may be recorded as short-term leases but are effectively cash transactions.

An option for surface water has two payments: one for the option and one for the water itself. This arrangement is akin to the composition of commonly traded options for stocks and commodities: there is the premium (the payment for the option) and the cost to pay for the underlying asset when called (at the strike price). The payment for the water would be constructed first, then the payment for the option would be produced as a function of that price. This method may be useful to price water diverted from any use, but in this case the water being priced would have been used for irrigation as outlined in a permit.

As spot markets develop, it may be possible to use modelling techniques and volatility calculations to price U.S. water options. However, these techniques depend on markets with continuous trading that are operating efficiently. Until there are more robust spot markets in the United States, these methods may not work reliably, considering the BSM model of options pricing uses the cash price as an input (Black and Scholes 1973). Existing water transactions can provide the range of current and historical prices, but this range is so great, and the geographic variability so high, that historical pricing information will be of limited utility to formulate an option pricing tool that can be broadly applied. While the pricing information may help inform a localized market, the following discussion of price history will illustrate the breadth of range and variation.

In the United States there are often price differences between geographies and price disparities between user groups. The general trend is that agricultural to urban trades are priced higher than those between agricultural interests (Brewer et al. 2008). Similarly, in the RGV, mining and oil and gas interests paid more for their water than the agricultural interests charged each other (Yoskowitz 1999). These price differences can be significant and persist over long timeframes (Table 1).

Table 1. Price differences between agricultural and urban interests from 1987 to 2005, compiled from the Water Strategist for Arizona, California, Colorado, Idaho, Montana, New Mexico, Nevada, Oregon, Texas, Utah, Wyoming, and Washington, in price per acre foot (Brewer et al. 2008).

	Ag-to-Urban Lease	Ag-to-Ag Lease	Ag-to-Urban Sales	Ag-to-Ag Sales
Mean price	$114	$29	$4,366	$1,747
Median price	$40	$10	$2,643	$1,235
# of observations	189	178	1,013	169

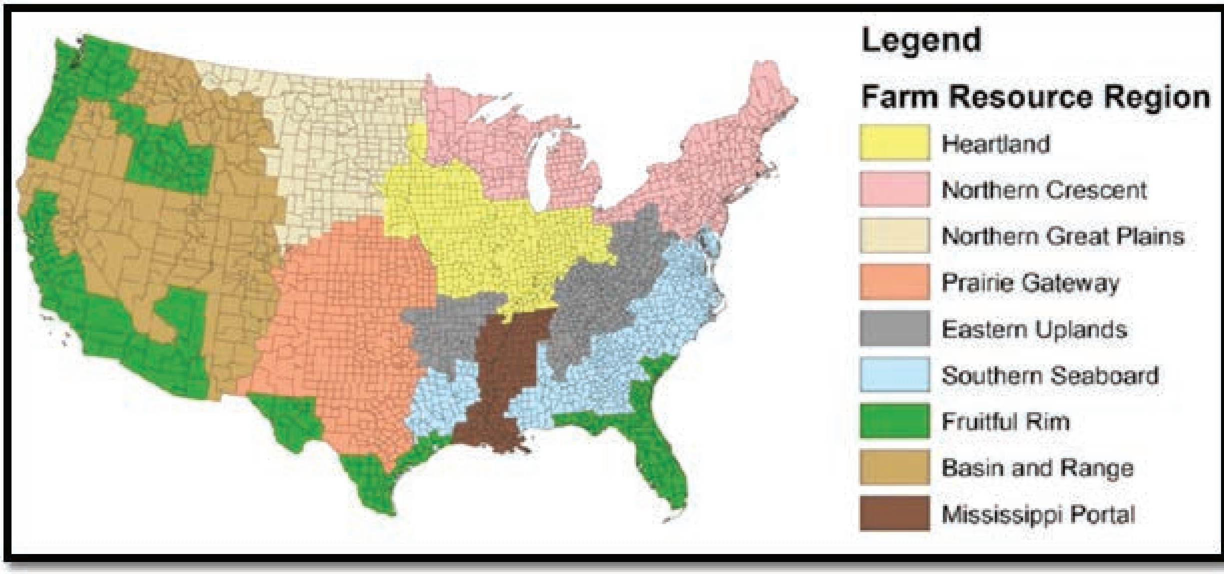

Figure 5. Farm Resource Regions defined by USDA in 2000 to compartmentalize farming specialization by region (West et al. 2011).

Prices not only differ when user groups are compared but across different geographies as well. For example, in Southern California's Imperial Irrigation District in 2001, farmers were paying $13.50 per ac-ft, while a real estate developer near the South Rim of Grand Canyon National Park was willing to pay $20,000 per ac-ft for water from the Colorado River (Brewer et al. 2008). With these regional and user anomalies, it will be very difficult to create an option contract that can accommodate all situations. The method for valuation may be transferable, but the resulting prices may deter transactions in some locations and market participants can expect price differences across geographies.

However, the reason for the price disparities may illuminate how to construct an option. Price disparities exist as an expression of the sellers' understanding that water can be transferred to a higher value use and their desire to be compensated for it (Table 1). It is unlikely that potential sellers will be willing to lose money in a transaction with a lower-value user, but they might be willing to trade if they are paid what they would have made had they kept it and used it themselves, with the knowledge that the resulting use equates to equal or lesser economic value. For example, a farmer would have used that water as an input for crop production and, given the right conditions, would have earned a profit from producing and selling the crop. If farmers can be compensated for at least the amount of profit foregone, the gate may be opened for an opportunity for water to flow to a use with a higher ecological value, and there is evidence that buyers will participate (Yoskowitz and Montagna 2009).

The approach used here to price options finds the monetary value of what the user is sacrificing (the opportunity cost) by leasing out their water for environmental or other purposes. This valuation method has been explored in the Pacific Northwest to boost streamflow to sustain native fish by having farmers decrease their level of irrigation (Jaeger and Mikesell 2002). To find pricing tools, water sales and leases were examined

Table 2. Cost and return data for the 2018 cotton crop in the Prairie Gateway (PG) and Fruitful Rim (FR) regions, excluding government payments; all numbers are U.S. dollars per acre unless otherwise stated (Commodity Costs and Returns 1997–2020).

2018 cost / return (in U.S. dollars unless stated otherwise)	**FR**	**PG**
Gross value of production		
Primary product cotton lint	$732.60	$313.17
Secondary product cottonseed	131.67	48.51
Total gross value of production	**864.27**	**361.68**
Operating costs		
Seed	81.70	47.61
Fertilizer	78.27	20.47
Chemicals	94.00	34.83
Custom services	31.18	8.99
Fuel, lube, and electricity	80.33	42.98
Repairs	67.49	43.44
Ginning	150.19	56.14
Purchased irrigation water	35.97	0.02
Interest on operating inputs	6.47	2.66
Total operating costs	**625.60**	**257.14**
Allocated overhead		
Hired labor	40.66	13.80
Opportunity cost of unpaid labor	33.03	49.46
Capital recovery of machinery and equipment	207.02	130.33
Opportunity cost of land	157.14	40.89
Taxes and insurance	15.30	10.21
General farm overhead	33.72	11.24
Total allocated overhead	**486.87**	**255.93**
Costs listed		
Total costs listed	**1112.47**	**513.07**
Net		
Value of production (less total costs listed)	**-248.20**	**-151.39**
Value of production (less operating costs)	**238.67**	**104.54**
Supporting Information		
Yield (pounds per planted acre)	740	429
Price (dollars per pound)	0.99	0.73
Cottonseed yield (pounds per planted acre)	1197	693
Cottonseed price (dollars per pound)	0.11	0.07
Enterprise size (planted acres)	370	931
Production practices		
Dryland (percent of acres)	46%	72%
Irrigated (percent of acres)	54%	28%

Table 3. Components of allocated overhead in farm operations, if they will be included in adjusting water payments, and the reason.

Allocated overhead	Included in payment? (Y/N)	Reason
Cost for hired labor	N	Not needed that year
Opportunity cost of unpaid labor	N	Farmer can look for work
Capital recovery of machinery	N	Book as depreciating asset
Opportunity cost of land	N	Farmer can lease or use it
Taxes and insurance	Y	Remain a fixed liability
General overhead	Y	Remain a fixed liability

Table 4. Fruitful Rim and Prairie Gateway adjustments to prices to buy cotton farmer's water in 2018 U.S. dollars.

Adjustment components	Price (U.S. dollars)	
	Fruitful Rim cotton	**Prairie Gateway cotton**
Gross value of production	864.27	361.68
Total operating costs	625.60	257.14
Net	**238.67**	**104.54**
Allocation cost adjustments		
Taxes and insurance	15.30	10.21
General Farm overhead	33.72	11.24
Total water payment	**287.69**	**125.99**

as well as estimates derived from land sales, economic models, and contingent contracts, with the contracts operating on a triggered basis similar to VISPO (Jaeger and Mikesell 2002). Other environmental water pricing methods have been explored when the federal government was evaluating how to acquire water; the methods include bilateral bargaining, standing offers, and auctions (Simon 1998). The opportunity cost method may also afford the seller some benefits in addition to their water payment. For example, the seller may rest their field in years the water is called, take time off, or perform farm maintenance. Furthermore, the farmer could decide to switch crops and convert to dry land farming for the year, essentially allowing them to work the land twice that year. They would be paid for the water they did not use and be paid for the dry land crop they raised in place of the irrigated crop.

Calculating the monetary value of the water in an option

An irrigator's water is priced at the intersection of what they are willing to accept and what a buyer is willing to pay. To help find a reasonable pricing mechanism based on opportunity cost, the U.S. Department of Agriculture (USDA) publishes cost and return statistics for crops in various geographies (Figure 5; Commodity Costs and Returns 1997–2020).

When considering these statistics, it is important to note the differences for the same crop among regions. This is largely driven by variations in yield. For example, the difference in cotton costs and returns for 2018 between the coastal Fruitful Rim (FR) and the Prairie Gateway (PG) are considerable (Table 2).

Price differences among regions highlight the benefit of having an option contract that allows for locally adjusted price information to be used when water options contracts are structured (Table 2). For both FR and the PG cotton, and across the spectrum of crops generally, there is a consistent theme in the net category; net value of production less total listed costs is generally a loss, and net value less operating costs generally shows a profit (Commodity Costs and Returns 1997–2020). Neither of these scenarios account for government payments, so government payments aside, the payment to the irrigator for water will probably need to be between the net of operating costs and total cost numbers to account for some overhead that will remain a liability even in years the land is not farmed.

To illustrate what may incentivize the irrigator to engage in an options contract, the water for 1 acre of cotton from the FR and the PG will be priced. First, the value of production and operating costs will be taken at face value, though these numbers could be adjusted during negotiations with sellers to account for local farm gate pricing or other variables such as silage costs. Allocated overhead should be examined considered and is where adjustments may have to be made to the net (Table 3). Given that the farmer will not incur operating costs, those costs are deducted from the value of production to arrive at a net number (Table 4).

Cost for hired labor can be removed, as there is no need to hire help to produce the crop that the water would have been used for. Opportunity cost of unpaid labor can also be removed, as in any year the water is called the farmer has an opportunity to look for other work (Table 2). Capital recovery of machinery can be removed as the farmer can book this as a depreciating asset for tax purposes. Opportunity cost of land can be omitted, as the farmer is free to lease or farm it with a dry land crop in a called year. Taxes and insurance still need to be paid as does the general overhead, so they are added to the net to calculate a total water payment (Table 4).

The above calculations are a blueprint of how the opportunity cost pricing mechanism can work and is only intended to illustrate a starting point for negotiations between a farmer growing cotton and a potential buyer. It is important to remember that the decision setting includes a complex combination of economic and hydrological conditions and multiyear agreements, and the timing of contract utilization will affect how irrigators' returns are impacted. Also, if it is found that the average seller lacks the capacity to execute this analysis, a third party may need to be engaged to provide guidance. When establishing payment, a calculation involving the amount of precipitation the sellers' location receives during the growing season will need to be factored in to understand how much irrigation water is going onto an acre of land. In addition to the listed operating and allocated costs, there may be other considerations important to sellers that come to light as further research is conducted. Given the differing financial realities in various locations, having an instrument that can suit these unique situations may encourage participation in an options market.

There is also a significant consideration in the data regarding the cost of irrigation (Table 2). The cost to irrigate the FR is almost $36.00 per acre, while the cost is $0.02 per acre for the PG. These prices are distorted as they represent a weighted average cost with a large proportion of the cost being diluted by the zero-irrigation cost in the dryland acres; this illustrates why it is critical to replace the USDA cost numbers with actual costs in the geography where options are being priced. This variability in the data is also important because the option contact must specify how much water it represents, and an irrigator can only option water they can deliver, so when identifying likely markets, an understanding of how much irrigation is a result of precipitation is important. Therefore, the pricing must be clearly communicated in terms of how much water goes with the contract, as well as the specific point of delivery.

To determine what crop price a farmer receives for water may entail looking at their farming activity and basing the price on the highest percentage of land cover, on farmers' most valuable crop, or on a prorated basis based on land use.

To begin trading options contracts, it might be easiest to find areas in Texas where farmers generally rely on an ac-ft of irrigation per acre of irrigated land. This would mean that to lease a farmer's water by paying them lost revenue for 100 acres of crop, the buyer would receive a 100 ac-ft of water. This one-for-one arrangement would facilitate transactions by making the terms clear and easy to understand. While this will not work for all situations (consider if groundwater is a portion of a farmer's irrigation strategy) nor for all geographies, it will be a good place to begin executing transactions to demonstrate the method.

In addition to paying for the water, the buyer will also have to pay a premium to the seller for entering the transaction. Historically, the value of an option premium has been calculated using BSM (Black and Scholes 1973; Villinski 2003; Williamson et al. 2008). The value of an option premium using this method includes components that are not available for the methodology outlined here, but there is a useful lesson in BSM for pricing the option premium. The maximum value that BSM will produce for an option premium is the cash value of the underlying asset, and that premium allows the buyer to exercise the option one time. In the absence of an existing method to price the value of the premium on these long-term water options in Texas, using the maximum value might be a reasonable place to start.

Expiration and call features

Options for many U.S. securities have a 3-month lifespan, expiring on a quarterly basis. The options discussed here focus on longer-term contracts. As mentioned above, this work was initially conceived to craft a mitigating solution to the longer-term implications of low flow years affecting environmental flows, and for an option to be relevant in this space it needs to have a lifespan that can accommodate inter-annual variability of water flow rates. Therefore, options are constructed with 5- and 10-year expirations to give buyers a high degree of long-term risk management.

With a traditional American option, the buyer of the option can exercise it once or before expiration date. To make long-term water options as useful as possible, this call feature will be expanded. In addition to greater flexibility, expansion of the call feature will help lower the number of transactions that buyers need to achieve their risk management goals. For water options, call features have been constructed to align with the probable needs of the buyers based on statistical frequency of low flow years.

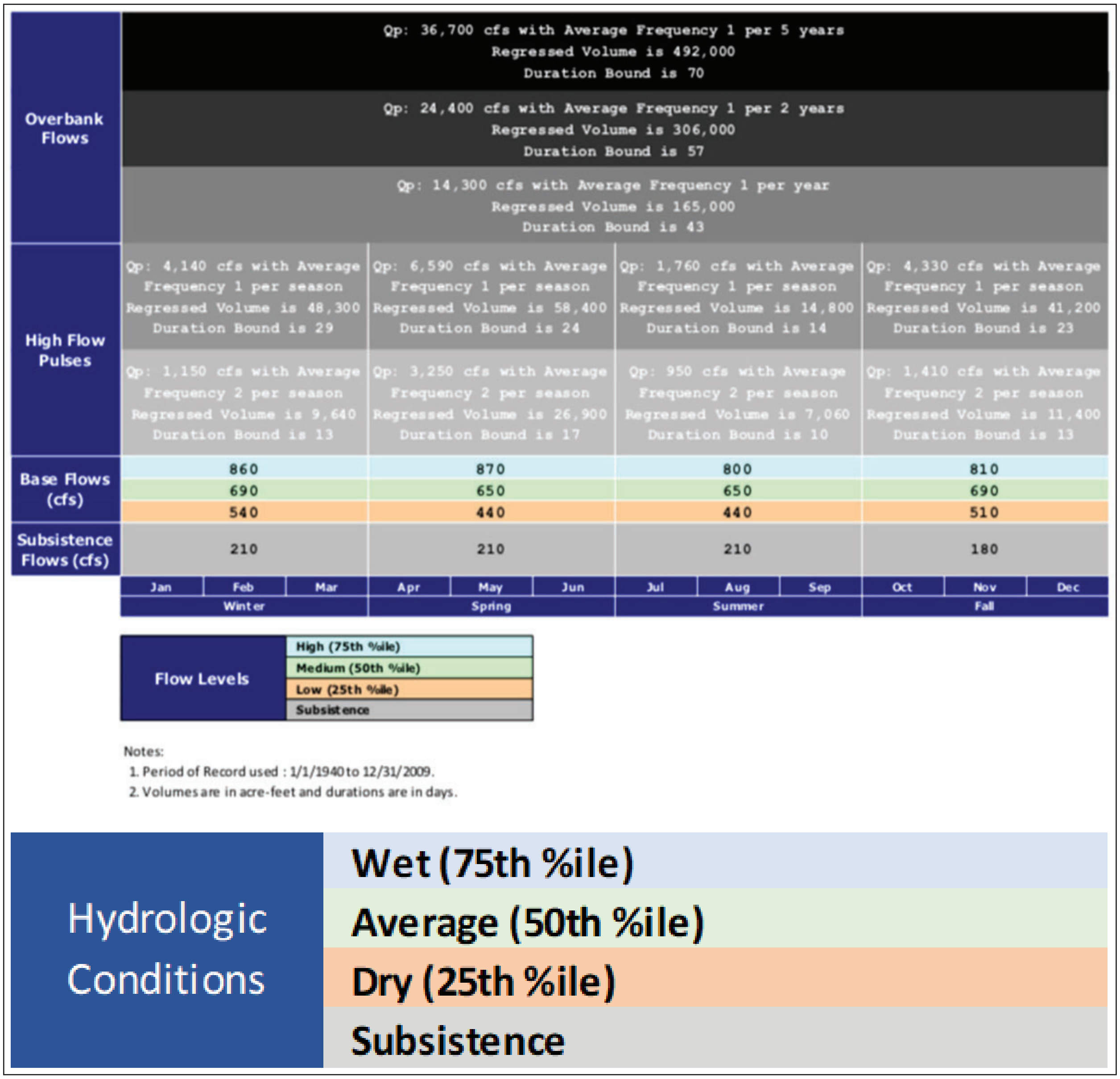

Figure 6. Environmental flow regime recommendation for the Guadalupe River at Gonzales and a zoomed view of how the flow levels are described (GSA BBEST 2011).

Senate Bill 3 (SB 3, 80th Texas Legislature) was designed to determine environmental flow standards for the major bay systems and major river basins in Texas (Statewide Environmental Flows n.d.). From there, the SB 3 Science Advisory Committee for Environmental Flows (SAC) offered guidance to use the Hydrology-Based Environmental Flow Regime (HEFR) to help basin advisory groups develop flow recommendations (Sabine-Neches BBEST 2009). HEFR methodology is described in detail in the Sabine-Neches BBEST guide (2009), where they offer a two-step process that outputs a flow matrix of values for wet, average, and dry conditions. Using an approach that characterizes the frequency curve by bounding the average conditions at the 25th and 75th percentile to mark the dry and wet conditions has been used in the past (Richter et al. 1996, 1998). This is not the only accepted method in use. The standard precipitation index approach has been modified to establish probabilities for wet and dry conditions at 31% each, and normal conditions at 38% (McKee et al. 1993; Svoboda et al. 2002). Hydrological systems are dynamic and complex and involve base flows and pulse events, which both affect ecological functions, so the best method to discuss frequency will be partly determined by the use intended (Ramírez-Hernández et al. 2015). In the environmental flows recommendations reports, recommendations are made that characterize the frequency curve of available water in terms of quartiles (Figure 6, bottom left).

Table 5. Essential Elements of a water options contract.

Element	Description
Expiration	This describes the lifespan of the contract. Options contracts contain a date that specifies the date by which the contact can be exercised before it expires and is no longer valid. The key difference between water options and other options is that the lifespan is expected to be much longer (5–10 years instead of a few months).
Call feature	This describes how and when the buyer may exercise the contract. Options on other assets can generally be called once. Given the longer-term nature of water options, a starting point for negotiations would be to have 5-year options callable once and 10-year options callable twice; this approximates the 25% frequency of low flow years produced by the HEFR methodology.
Strike price	This specifies how much the buyer will pay the seller for the asset in the event the option is exercised. The opportunity cost method would make this payment equal to the income forgone by the seller incurred by not using water in the called year. Again, a point of negotiation will be if this price is determined when the contract is signed or is based on market value in the called year.
Premium	This is the option price—how much the buyer pays the seller for entering the contract. The maximum value BSM can output is equal to the cash value of the asset and could be used in discussions around premium. An important discussion point will be how this is structured in the 5-year option as opposed to the 10-year.

For structuring the call feature of a water option, we use the value classifications outlined in Figure 6. The conditions are usually associated—in terms of frequency—with the 25th percentile, median, and 75th percentile of the frequency curve; thus HEFR outputs are designed to identify low flow conditions at the values on the curve associated with the 25th percentile of occurrence or at a point specified by the user (Figure 7; Opdyke et al. 2014).

Flow frequency curves are readily available (Figure 7) and can be used by buyers and sellers to align call features with their preferred mitigation strategy. If buyers of water options are concerned with risk mitigation in low flow years, then aligning the call feature with the probability of occurrence presented by the HEFR output should meet their needs, so an option should be callable around 25% of the time. To mesh with this percentage, options could be structured to have lifespans of 4 or 8 years, making the call feature 1/4 or 2/8 years. While there will likely be negotiations around the specifics, options contracts for water will share some essential elements (Table 5).

DISCUSSION

Water options in Texas

Based on the success of the cash markets in the RGV and the success of the option-styled VISPO arrangements, it certainly seems plausible that there is enough demand for water trading products to take them to the next level. The methods set out here illustrate how an agricultural irrigator might be compensated. However, the goal was to find a method that can work knowing that some of the details will have to be negotiated. We used a specific example to illustrate the idea of an option market in Texas, but it is only a beginning for many conversations around unique instruments that can be used to facilitate the transfer of water. When possible, standardization of as many contacts as possible helps market participants and can create efficiencies.

Irrigators have shown willingness to engage in long-term contractual commitments involving their water. VISPO has offered 5-year and 10-year enrollment options and has had success with both. VISPO has been successful in offering water purchase programs that are based on a triggered style of water option. The more traditional option outlined here enhances the trading product in two primary ways. In terms of the buyer, the contract is exercised at buyers' discretion, giving them greater control over when the contract is called as opposed to when call features are triggered by an event. From the sellers' standpoint, these contracts have a clear path to pricing that attempts to adequately compensate them for the revenue they will lose by participating through fair determination of strike price, plus an added incentive to participate in the arrangement via the premium payment.

There may be additional sellers who are willing to use a pricing structure based on payments to irrigators to option some of their water. For example, river authorities may be willing to option some of their water if their current needs are met. Additionally, industrial interests hold permits representing large amounts of water. For example, Dow Chemical Company holds many permits adding up to millions of acre-feet of water. When the company is experiencing a slow business cycle, production may be down, so some of that water may not be in use, which could create an opportunity to engage them as a seller of water options.

In negotiating with irrigators, it is important to remember that farming and ranching have a unique and deep-rooted cultural identity and ownership, and use of water is a big part of that identity (McSweeney and Raish 2012). In addition, while not within the scope of this work, it is imperative to consider the economic implications to farming and ranching communities when taking arable land out of production or reducing the amount of cattle. There could be significant ripple effects resulting from the execution of water options contracts that need to be considered. In future work, attention will be given to what percentage of farming activity may be suspended in a region before the impact of those economic ripples is unacceptably high. The experience of the Owens Valley dealing with the city of Los Angeles at the dawn of the 20th century provides an extreme example of what effect these ripples can have. Whether or not the gains Los Angeles made by purchasing the water from Owens Valley justify the cost to the latter is debatable. Regardless, the effects on the Owens Valley were tremendous, ultimately killing the farming industry and communities (Reisner 1986).

The opportunity cost pricing method may be useful in establishing guidance for options contracts when the alternative use for the water has less measurable value than the foregone crop but may not effectively compete with high value buyers willing to bid for water. For example, if the opportunity cost method is applied to a corn crop and calculates a payment to the farmer of $125 per acre, a manufacturing interest may be willing to pay a much higher price for the same water. Knowing that these buyers exist may hinder sellers' willingness to enter long-term contracts where their payments are determined by the profits from their land use instead of a negotiation between what the buyer is willing to pay and what the farmer is willing to accept. The combination of the opportunity cost pricing method with the enhanced call feature (at buyers' discretion in lieu of triggering) and the long-term lifespan of the contracts eliminates some of the issues raised in pricing in the Pacific Northwest and when procuring water for the U.S. government (Jaeger and Mikesell 2002; Simon 1998). Long-term contracts reduce transaction costs as compared to bilateral bargaining and avoid the possibility of collusion that accompanies auctions for water markets. A key requirement will be establishing and maintaining credible commitments by the parties involved in the transactions (Simon 1998).

The permitting process may also hinder these transactions, particularly if a change of use necessitates TCEQ approval for a contract. Even if the change of use applications is approved for the years of an option where water is called, it is at best an administrative barrier to trade. At worst, this requirement could effectively deter market participants from conducting business because the risks associated with buying and selling contracts that have no guarantee of being approved by TCEQ may present too many challenges.

When should options be exercised?

Existing forbearance programs have aspects that resemble options, but one notable difference is that the option is triggered by water levels as opposed to simply being called at the option holders' discretion. The options described in this work are intended to be callable at the buyer's discretion. Along the longitudes that Texas covers, there is incredible variation in the amount of precipitation, and there are several very diverse groups that use large volumes of water in the state (TWDB 2003; Montagna et al. 2018b). Therefore, it is impossible to craft a call metric that will be useful to all user groups across geographies, but a brief description may offer guidance as to how these metrics might be constructed for the environmental manager and an authority that manages supplies. For example, one buyer might be primarily concerned with salinity at a particular time of year, while another might be concerned with dissolved oxygen, pH, or overbank flows.

Environmental managers concerned with environmental flows of water to bays and estuaries could use existing HEFR outputs to establish their own triggering mechanisms. If a manager is not satisfied with HEFR, they could possibly use salinity as an indicator of flow levels. Work has explored both salinity values as well as the amount of salinity variation, and one or a combination of these measurements could inform decisions (Montagna et al. 2009; Montagna et al. 2002; Montagna et al. 2018b). Additional information, such as reference conditions or the optimum conditions of their chosen metric, could provide additional information about a system that may be under duress. With changes in precipitation across the state come changes in flow regimes, so it is important to remember that each system will have its own salinity values and variations that indicate normal functioning.

Municipalities could look to their reservoir levels and make some determinations about what levels would cause them to act to secure additional water. These decisions can be made proactively, as having the reservoir is akin to having a bank. If water options are procured upstream and then called, the municipality can augment supplies to avoid imposing water restrictions or even sell the water downstream. These options can offer great flexibility to organizations that can bank their own water and would allow organizations the ability to option water to account for potential future growth. If the growth comes, the option can be called, and if the growth does not ensue, the option cost is a fraction of alternative infrastructure.

The RGV offers a good example of an active spot market for water in Texas, making it a strong candidate for implementation of an options market (Villinski 2003; Yoskowitz 1999). However, the Watermaster system in place in the RGV gives that market some unique characteristics not found throughout the state, such as the surface rights being correlative. Correlative rights are allocated differently than rights under a seniority system. Instead of curtailing water delivery to junior rights holders when supplies are low, all users' allocations are reduced proportionally when shortages occur (TWDB 2003). The implication is that if options contracts are successfully marketed in the RGV that are based on these characteristics, it does not assure that similarly structured contracts will be of use elsewhere in Texas. Institutional frameworks in each basin system that provide the space for effective markets to develop will be critical. It may be possible to design options for use under a Watermaster using more traditional pricing methods and use the method outlined here for other parts of the state, but there is no reason that the methods designed here could not be applied to areas with a Watermaster.

CONCLUSION

The flexibility that options contracts offer make them a promising solution to the issues of scarcity facing Texas. These contracts can be an attractive tool to the myriad of water users throughout the state, including the environment. To bring these contracts to market, more work will have to be done to make sure that buyer and seller needs are met in the product. A logical next step would be to engage those user groups to better understand how interested they are at different price points and what elements would have to be present in the contracts to buy or sell them. There are regulatory hurdles that will have to be addressed to allow for the development of water markets and their attendant derivatives in Texas. Even with the roadblocks to progress, these contracts offer the possibility of enough benefits that further investigation and development of them is warranted, and if transactions are kept between participants in the same basin, they may be deployable under current governance. Pricing options using more conventional tools would require more transactional data from cash water markets. To help those markets grow, water pricing models have been built and are being refined and distributed (McColly 2020). The model outlined here offers a method to price water options and is applied in Texas, but this model will likely need to be adapted to accommodate unforeseen issues. This is a starting point for negotiations that can advance the growth of water options along a trajectory leading to opportunities for implementation statewide and possibly beyond.

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Commentary: 87th 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 2021 session. The opinions expressed in these summaries are the opinions of the individual organizations and not the opinions of the Texas Water Journal or the Texas Water Resources Institute.

Organizations:

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

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Terms used in paper

Acronym / Initialism	Descriptive Name
CCN	Certificate of Convenience and Necessity
DFC	desired future condition
DIR	Texas Department of Information Resources
EDAP	Economically Distressed Areas Program
EPA	United States Environmental Protection Agency
ESPC	energy savings performance contract
ETJ	extraterritorial jurisdiction
GCD	groundwater conservation district
HB	house bill
PUC	Public Utility Commission
SB	senate bill
SUD	special utility district
TAGD	Texas Alliance of Groundwater Districts
TCEQ	Texas Commission on Environmental Quality
TXD	Texas Desalination Association
TOMA	Texas Open Meetings Act
TPWD	Texas Parks and Wildlife Department
TRWA	Texas Rural Water Association
TWCA	Texas Water Conservation Association
TWDB	Texas Water Development Board
TWF	Texas Water Foundation
WSC	water supply corporation

TEXAS WATER CONSERVATION ASSOCIATION SUMMARY OF THE 87TH LEGISLATIVE SESSION

By Sarah Kirkle, Director of Policy and Legislative Affairs

The Texas Water Conservation Association (TWCA) is a nonprofit 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 87th Texas Legislature adjourned *sine die.* Legislators filed 7,327 bills, fewer than in the 86th legislative session but still a high number given expected constraints due to COVID-19. Only 1,175 of those bills passed both chambers by *sine die,* providing for a relatively low 16% bill passage rate (the Legislature passed between 19% and 22% during the last three legislative sessions). Governor Greg Abbott vetoed 20 bills, the fewest number of vetoes since 2005, and only one of which TWCA tracked related to performance bonds for public works contracts.

While the legislative session was expected to focus on the budget, redistricting, and pandemic response, legislative discussions took a sharp right turn after Winter Storm Uri. Discussions around the near failure of the state's electric grid largely dominated the legislative docket, followed by various social issues, such as constitutional carry, abortion, and elections. As in past legislative sessions, TWCA closely followed bills that could impact its members. Staff tracked 569 bills and designated 97 of those bills as high priority. Of TWCA's tracked bills, 81 (about 14%) made it to the finish line, with 15 of those being high priority. Summaries of the most significant bills that may be of interest to water professionals are provided below.

Emergency water operations

In light of widespread power and water outages resulting from Winter Storm Uri, the Legislature passed Senate Bill (SB) 3 (Schwertner/Paddie), an omnibus bill aimed at increasing power and water reliability through weatherization and emergency operation requirements. While most of the bill relates to electric power, the bill expands requirements for emergency water service during a power outage to any retail public utility, exempt utility, or provider or conveyor of potable or raw water to more than one customer. Requirements for emergency water service during a power outage previously only applied to the Houston area, and the bill keeps requirements around Houston largely the same. In doing so, the bill grants flexibility in meeting requirements of an emergency operations plan, which must be submitted by affected utilities to the Texas Commission on Environmental Quality (TCEQ) by March 2022 and implemented by July 2022. The bill also prohibits certain retail public utilities from imposing late fees or disconnecting service during an extreme weather emergency. Affected utilities must submit information on water and wastewater facilities that qualify for critical load status by November 1, 2021. The bill is effective immediately.

Surface and groundwater

TWCA's Surface Water Committee, which has more than 150 members, met in advance of the 87th legislative session and considered four issues, ultimately recommending one proposal move forward as part of TWCA's legislative agenda. SB 997 (Nichols/Harris) is a TWCA-initiated bill that creates certainty for all parties to a wholesale water rate appeal by providing for the immediate judicial review of a public interest determination before the Public Utility Commission (PUC) holds a hearing to prescribe a just and reasonable rate. The bill also promotes settlement of disputes by allowing the parties to amend a contract before PUC begins rate proceedings. The bill is effective for petitions filed on or after September 1, 2021.

TWCA's Groundwater Committee also worked in advance of the session to develop consensus-based legislative proposals. More than 150 TWCA members served on the committee, which took up six issues and ultimately recommended two proposals move forward as part of TWCA's legislative agenda. These proposals, one providing a process to petition a groundwater conservation district (GCD) for rulemaking and another clarifying which desired future condition (DFC) should be included in a management plan when a DFC is petitioned, were both included in SB 152 (Perry/Harris). That bill became the main vehicle for groundwater discussions during the legislative session but ultimately failed to reach the finish line due to disputes among policy makers and stakeholders related to the provision on attorney's fees. This legislative session marks the first session in many years where no key groundwater-specific bills passed the Legislature.

Other notable water-related bills that passed include:

- **House Bill (HB) 531 (Walle/Huffman)** requires a landlord to provide written notice to a tenant detailing whether a leased dwelling is located in a 100-year floodplain and other flood information.
- **HB 2225 (T. King/Zaffirini)** requires the Texas Parks

and Wildlife Department (TPWD) to encourage and facilitate the dedication of water rights in the Texas Water Trust and to manage the rights to maximize environmental benefits.

- **HB 2951 (Jetton/Kolkhorst)** limits the authority of a commissioner's court to fill a vacancy on a board of a levee improvement district to a district with an appointed board and to only remove board members previously appointed by the commissioner's court.
- **SB 387 (Schwertner/Wilson)** further authorizes ratepayers who reside outside the corporate limits of a municipally owned utility to appeal an increase in rates when the municipally owned utility takes over the provision of service to ratepayers previously served by another retail public utility. The bill provides certain exceptions.
- **SB 600 (Perry/T. King)** requires a river authority to provide information to TCEQ regarding the operation and maintenance of each dam under the river authority's control. Prescribed information must be provided each year and in the event of significant changes. TCEQ must create and maintain a website that contains the information, subject to federal and state confidentiality laws.
- **SB 601 (Perry/Burrows)** creates the Texas Produced Water Consortium hosted by Texas Tech University to study the economic, environmental, and public health considerations of beneficial uses of fluid oil and gas waste and technology needed for those uses. The consortium consists of the host university, an agency advisory council, a stakeholder advisory council, a technical and economic steering committee, and private entities. The consortium must produce a report by September 1, 2022, that includes suggested policy changes, an economically feasible pilot project for state participation in a produced water facility, and an economic model for using produced water in an economic and efficient way. The agency advisory council and the host university must create a fee structure for private entities to participate and contribute to research and investigation.
- **SB 905 (Perry/Frank)** requires TCEQ to develop a regulatory guidance manual to explain TCEQ rules that apply to direct potable reuse. Direct potable reuse is defined as the "introduction of treated reclaimed municipal wastewater either: (1) directly into a public water system; or (2) into a raw water supply immediately before the water enters a drinking water treatment plant" (SB 905 2021).
- **SB 1160 (Taylor/Paul)** creates the Gulf Coast Protection District to establish an instrumentality, including bond, tax, and eminent domain authority, for protecting the coast in Chambers, Galveston, Harris, Jefferson, and Orange counties.
- **SB 1642 (Creighton/Canales)**, among other provisions, authorizes a navigation district to respond to and fight a fire, explosion, or hazardous material incident that occurs on or adjacent to a waterway, channel, or turning basin in the district's territory and to assess fees to cover certain expenses.
- **SB 2154 (Schwertner/Paddie)** increases the PUC from three to five members. At least two commissioners must be qualified in the field of public utilities and utility regulation. The bill prohibits a former commissioner from lobbying for one year after ceasing to be a commissioner.

Transparency and government operations

Despite anticipation that the Legislature might make permanent the temporary disaster exceptions to the Texas Open Meetings Act (TOMA), all bills that would have granted additional flexibility for public meetings by videoconference died during the legislative session. The Legislature did pass several bills related to open records and transparency:

- **HB 872 (Bernal/Menendez)** excepts certain utility customer information from public disclosure unless requested by the customer.
- **HB 1082 (P. King/Zaffirini)** excepts the personal information of elected public officials from public disclosure.
- **HB 1154 (Jetton/Kolkhorst)** requires certain special purpose districts to post prescribed information on a website and on a water bill and amends requirements for public meeting locations for rural area districts.
- **HB 2723 (Meyer/Bettencourt)** requires the Texas Department of Information Resources (DIR) to develop and maintain an easily accessible website that lists each property tax database maintained by a chief appraiser and includes guidance to assist a property owner in identifying the appropriate tax database for their property.
- **SB 1225 (Huffman/Paddie)** requires a governmental body to continue to respond to requests for public information even when it closes its physical offices but requires staff to continue to work remotely. The bill provides that if a catastrophe prevents a governmental body from complying with requests, the body may suspend responses to requests only once for each catastrophe.

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

- **HB 692 (Shine/Creighton)** prescribes retainage provisions to be included in a public works contract by a governmental entity. In general, the bill provides that retainage may not exceed 10% of the contract price for a public works contract of less than \$5 million and 5% for a contract of \$5 million or more.

- **HB 1118 (Capriglione/Paxton)** amends cybersecurity training requirements to include appointed officials, in addition to local government employees and elected officials, but limits the requirements to those employees and officials who both have access to a local government computer system or database and use a computer to perform at least 25% of the employee's or official's required duties. The bill provides certain exceptions and requires local governments applying for certain grants to comply with cybersecurity training requirements.
- **HB 2581 (Kacal/Hancock)** prescribes how a governmental entity must value price in its consideration of a proposal for a civil works project. Upon request, a governmental entity must provide certain information about the evaluation of an offeror's submission to a request for qualifications for a construction project.
- **HB 2730 (Deshotel/Kolkhorst)** makes comprehensive reforms to the eminent domain process, including relating to a landowner's bill of rights, licensing requirements for persons involved in negotiations on easements or rights-of-way, and various procedural requirements.
- **SB 19 (Schwertner/Capriglione)** prohibits certain contracts between a governmental entity and a company unless the contract contains a written verification from the company that it does not or will not discriminate against a firearm entity or firearm trade association.
- **SB 58 (Zaffirini/Turner)** adds cloud computing services to the definition of personal property for the purposes of government contracting.
- **SB 157 (Perry/Craddick)** allows certain school districts, municipalities, counties, and water districts to electronically file an abbreviated annual eminent domain report when information previously reported is unchanged.
- **SB 726 (Schwertner/Leman)** increases from two to three the number of actions a condemning entity must take to demonstrate actual progress toward the public use for which the land was condemned for the purposes of determining the right to repurchase condemned real property. The bill makes exceptions for a navigation district, port authority, or a water district implementing a project in the state water plan.
- **SB 968 (Kolkhorst/Klick)** places limitations on the authority of political subdivisions related to a pandemic and prohibits use of a vaccine passport by a governmental entity, among other health-related provisions.

Looking ahead

As of August 2021, Governor Abbott has called legislators back for two special sessions to address elections and other key topics important to the governor. Because most House Democrats left the state, the House of Representatives has been unable to meet quorum requirements necessary to conduct business. Governor Abbott is expected to call at least one more special session to address redistricting now that the state has received data from the U.S. Census Bureau necessary to update political district maps. While Governor Abbott has not included items on the call that directly impact TWCA members, TWCA continues to monitor bills, such as public funds on lobbying, to see how they might impact TWCA's work in the water policy arena. Also during the interim, all of the key water-related agencies (TCEQ, Texas Water Development Board [TWDB], PUC, and the Texas State Soil and Water Conservation Board [TSSWCB]) are scheduled for review by the Sunset Advisory Commission, a comprehensive review process that identifies key management and statutory changes intended to make the agencies operate more efficiently and effectively. So while the 87th may not have been a water session, the 88th looks like it will be flooded with water issues.

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TEXAS ALLIANCE OF GROUNDWATER DISTRICTS SUMMARY OF THE 87TH LEGISLATIVE SESSION

By Leah Martinsson, Executive Director

Texas Alliance of Groundwater Districts (TAGD) is a 501(c)3 created in 1988 to provide to a centralized means for GCDs to stay current on the quickly evolving world of groundwater science, policy and management. TAGD currently has 90 GCD members and 38 associate members.

The 87th Texas Legislature adjourned *sine die* on May 31 after a legislative session that was truly like no other. The early months of the legislative session were notably lacking in both ceremonial and social activities as a result of COVID-19 restrictions. Indeed, COVID-19 cast a long shadow throughout the legislative session. The first order of business was establishing COVID-19 pandemic protocols for the two chambers to ensure safe functioning. After a few weeks with most everyone entering the capitol getting tested and wearing masks, protocols began to change with increases in vaccination rates and the removal of the mask mandate. As anyone walking the halls of the capitol could attest, the pandemic impacted access and participation in the legislative process throughout the legislative session. Early on, many anticipated that the COVID-19 pandemic would result in a decrease in the total number of bills filed as compared to prior legislative sessions. That was not the case however, with over 7,300 bills filed—slightly fewer than the 86th legislative session but more than either the 84th and 85th legislative sessions. Although, it likely did impact the overall passage, with only 1,175 bills (~16%) passing both chambers.

Big picture priorities and leadership

In the months leading up to the legislative session, many had anticipated that the budget, redistricting, and COVID-19 response would dominate the session. That did not play out quite as planned for several reasons. Winter Storm Uri and the near failure of the state's energy grid caused a swift shift in priorities and quickly became a primary focus of the legislative session. While the state's budget outlook looked grim last spring, it had improved in the months leading up to the legislative session. Also, the Legislature is charged with redrawing the Texas electoral maps every 10 years, which falls this year, but delays in census data meant that this redistricting was not completed. This was not a surprise, and Governor Abbott will call a special session later this fall to complete redistricting.

On the first day of the legislative session, the Texas House of Representatives elected Representative Dade Phelan (R-Beaumont) as Speaker of the House. This meant new committees, new committee chairmen, and a new power structure in the House. Of particular significance to TAGD and the groundwater stakeholders, Representative Tracy King (D-Uvalde) was newly appointed as chair of the House Natural Resources Committee. A long-serving House member with an extended tenure on the House Natural Resources Committee, Representative Tracy King brings a deep understanding of groundwater to this role. On the Senate side, Lieutenant Governor Dan Patrick (R-Houston) opted to merge the Agriculture Committee with the Water and Rural Affairs Committee and appointed the experienced Senator Charles Perry (R-Lubbock) to chair that committee for the third time.

Groundwater bills

No one really expected the 87th legislative session to have a significant focus on groundwater, which was demonstrated by the relatively few groundwater bills that were filed. A number of those bills were refiled bills, reflecting unsettled issues from prior legislative sessions. COVID-19 prevented committee hearings on interim charges, with only a single Senate Water and Rural Affairs committee hearing in January 2020 where groundwater management was discussed. This convergence of factors made for a legislative session that—for the first time since the Texas Water Code underwent major revisions during the 75th legislative session in 1997—there were no changes to Chapter 36 enacted. However, just as many of these bills were continuations of discussions from prior legislative sessions, it is likely that many of the groundwater bills from the 87th will return.

Throughout the 87th legislative session, TAGD tracked legislation that could impact GCDs and groundwater management. TAGD has a legislative committee that tracks pending legislation and determines if a bill warrants action by TAGD. This committee will then vote on relevant bills and will only take a position if a 75% consensus standard is achieved. This is subject to confirmation by TAGD's Executive Committee.

There were six bills filed that sought to make substantive changes to the provisions of Chapter 36 of the Texas Water Code. While one of these bills was an omnibus bill with four 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.

In addition to priority groundwater bills, TAGD tracked selected bills affecting individual GCDs, general water, and administrative law/governance of political subdivisions for its membership. In total, TAGD tracked over 120 bills of interest to GCDs.

SB 152/HB 668

The omnibus SB 152/HB 668 (Perry/Harris) was the main focus of groundwater-related discussions leading up to and during the legislative session. The bill included four distinct parts. First, it would have changed the mandatory award of attorney's fees to groundwater conservation districts when a district prevails under Section 36.066(g) to be discretionary. Second, it would have clarified which DFC should be used in a GCD's management plan if the adopted DFC is petitioned to be unreasonable under the provisions of Chapter 36. This provision came out of the consensus process conducted by TWCA's groundwater committee in which TAGD and many TAGD members participated. Third, the bill would have added a new section to Chapter 36 allowing a person with groundwater ownership to petition their GCD to adopt or modify a district rule. This provision also achieved consensus at the TWCA groundwater committee. Lastly, SB 152 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.

TAGD voted to support three of the four components of SB 152—all except the proposed change to the attorney's fees provision contained in Section 36.066(g). Bills to modify the attorney's fees provisions of Chapter 36 have been filed for at least the past three legislative sessions and have consistently reflected a point of disagreement, with TAGD opposed to such a change. After SB 152 passed the Senate with the provision to change attorney's fees intact, a committee substitute was offered in the House Natural Resources Committee that removed that change. That committee substitute garnered support from TAGD, was voted favorably from committee, and subsequently passed the full House. Ultimately, however, the Senate did not vote to concur or appoint a conference committee on the version of the bill returned to the Senate. As a result, the entire bill died. While it is still too early to make predictions, it does appear likely that the provisions of this bill will again be part of interim discussions and portions of the bill may be refiled in the 88th legislative session.

Other groundwater bills

Because groundwater bills that are not successful one session have a habit of returning in future sessions, it is worth briefly mentioning the other bills from the 87th legislative session that would have modified Chapter 36. These included:

- **HB 2851 (Lucio)** would have required TWDB to calculate the managed sustained groundwater pumping of the state's aquifers as a way to provide greater context to the total estimated recoverable storage number. This bill was a refile from earlier legislative sessions, and the concept originated in the TWCA consensus process. 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.
- **HB 3619/SB 946 (Bowers/Eckhardt)** would have added registered exempt wells to those to be considered in permitting decisions. Similar versions of this bill have been filed in prior legislative sessions and first emerged through the TWCA consensus process. TAGD supported this bill. Like HB 2851, this bill was approved by the House but did not receive a hearing in the Senate Water, Agriculture, and Rural Affairs Committee.
- **HB 966 (Burns)** sought to eliminate the mandatory award of attorney's fees under Section 36.066(g) and 36.102(d). TAGD opposed this bill. This bill did not receive a hearing in the House Natural Resources Committee.
- **HB 3972 (T. King)** sought to add a bonding requirement for petitioners other than the applicant in a contested case hearing to cover both the district's and applicant's costs (SB 1314 [Lucio] included a similar but not identical concept). TAGD was neutral on this bill. This bill was voted favorably from the House Natural Resources Committee but did not receive a vote in the House.
- **HB 3801/SB 2157 (Metcalf/Creighton)** contained the same provision regarding unreasonable DFCs as was included in SB 152. 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.
- **HB 2103 (Bowers)** would have clarified that meetings of GCDs within groundwater management areas are subject to provisions regarding video and telephonic meetings contained in the Texas Government Code Section 551.125 and 127. This bill was approved by the House but was not referred to a committee in the Senate.

Groundwater-adjacent bills

While not directly affecting Chapter 36 of the Texas Water Code, another bill that was filed this legislative session and received attention was HB 2095 (Wilson). This bill would have directed the Bureau of Economic Geology at the University of

Texas at Austin to conduct studies of surface water and groundwater to improve on data gaps, integrate models to characterize water resources, and make determinations on water availability. In a lengthy Senate Water, Agriculture, and Rural Affairs Committee hearing, questions were raised regarding potential confusion and overlap with other legislatively funded models relied on for the regional and state water planning process, and the bill was left pending in committee. However, the dialogue on this topic suggests that how to best fill and fund data and modeling gaps, including interactions between groundwater and surface water, could be a subject for interim study.

Finally, a bill with potential future implications for groundwater management that did pass this legislative session was SB 601 (Perry/Burrows). This bill creates the Texas Produced Water Consortium at Texas Tech University, which will study the economic, environmental, and public health aspects of beneficially using water produced during oil and gas operations and will recommend a pilot project. The potential to reuse produced water could provide a viable alternative to disposal through underground injection and may offer future opportunities for beneficial use outside the industry to meet water demands, if the produced water is treated to meet all water quality and groundwater protection standards.

Government bills

After over a year of countless meetings and hearings held virtually, pursuant to Governor Abbott's temporary suspension of certain provisions of TOMA, it was anticipated that the 87th legislative session would bring changes to TOMA that would provide additional opportunities for governmental entities to utilize virtual meetings. Several bills were filed that would have granted governmental entities this increased flexibility, and there was early movement of those bills at the committee level. However, as the legislative session progressed, these efforts met resistance in the Senate. As a result—and pursuant to Governor Abbott's recent declaration—the suspension of certain provisions of TOMA will expire on September 1 and governmental entities will be required to fully comply with the unchanged TOMA.

There were, however, several bills affecting government operations and transparency that did become law and were of interest to TAGD members:

- **HB 1118 (Capriglione/Paxton)** expands the cybersecurity training requirement to include appointed officials while limiting the requirement only to those employees and officials that have access to the government's computer system and who use a computer to perform at least 25% of their required duties.
- **HB 1154 (Jetton/Kolkhorst)** requires certain special purpose districts to post specified information on a website. It also amends requirements regarding public meeting locations for districts in rural areas.
- **HB 1082 (P. King/Zaffirini)** exempts certain personal information of elected public officials from public disclosure.
- **SB 1225 (Huffman/Paddie)** provides that a governmental entity may only suspend responses to open records requests once for each declared catastrophe. It also requires that a governmental entity make a good faith effort to continue to respond to open records requests even when it closes its administrative offices but requires remote work.
- **HB 2723 (Meyer/Bettencourt)** requires DIR to develop and maintain a property tax database on the internet and requires that tax notices from taxing entities reference how to access that local property tax database.

Looking forward

As of August, there is a special session underway that was called by Governor Abbott to address election integrity, bail reform, and a few other key topics. Next up for the Legislature will be another special session later this fall to complete redistricting. It is unclear if redistricting will impact the timing for issuance of interim charges by Speaker of the House Dade Phelan and Lieutenant Governor Dan Patrick, which typically occurs late in the fall. Almost certainly, the upcoming interim will see the return of in-person interim hearings on those charges.

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 be monitoring the upcoming sunset review process for TWDB and TCEQ. Given the fate of groundwater legislation during the 87th legislative session and continuing pressure caused by population growth on the water resources of the state, it would be unsurprising to see a strong focus on groundwater in the 88th legislative session.

WATER, RESILIENCE, AND EQUITY IN THE 87TH TEXAS LEGISLATURE

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.

In a typical legislative season, a certain distribution of subjects can be expected. Some are anticipated and developed over months of interim hearings, some focus on advancing a special interest, some are designed to retain voting segments, and a handful can be best described as left fielders. The 87th Texas Legislature was not typical, and the probability of a successful water agenda was murky at best. The Legislature convened following a tense change in administration, at the height of the COVID-19 pandemic, and had barely named its new Speaker of the House when a catastrophic winter storm brought the state to a grinding halt. Interim hearings were not held, party politics were loud, and where consensus efforts presented legislation, the urgency of disaster took priority.

Of the 7,327 bills filed during the 87th Texas legislative session, almost 200 related to or impacted water in Texas. Atypical in every way, it was surprising to see the volume of water-related legislation filed this season, but unsurprising to see few cross the finish line.

Beyond the water bills that were filed or passed, three unusual observations can be made of this legislative session that might inform where water policy goes during special sessions and beyond:

1. "Resilience" and "climate variability" made appearances is several pieces of legislation;
2. Texas almost made permanent virtual participation in public meetings; and
3. The significance of Winter Storm Uri's water security crisis was largely absent.

The emergence of resilience

A word of particular resonance this year found its way into the Legislature again. Resilience, a term used across disciplines from engineering to psychology, was cited in 32 different pieces of legislation. Of those, 25 were infrastructure-, energy-, or water-related. The 86th Texas Legislature saw similar uses of the term, whereas the 85th Texas Legislature saw almost none. Whether referencing Winter Storm Uri, past disasters, or the recognition of the need to plan, it is evident that the ability to recover and the role of critical infrastructure has made an inroad into public debate.

Related to the emergence of resilience is the slow introduction of bills that reference climate change — but only a handful of the bills called it so. Instead, about 20 bills reference planning for "climate variability," "danger of climatic activity," "projected changes in weather," "weather extremes," and "abnormal weather conditions." The 86th Texas Legislature, on the other hand, saw a greater number of bills that reference climate change specifically. Whatever the term, planning for the impact of climate change and references to water security have established a small but significant momentum.

Transparency, equity, and access

In response to the COVID-19 pandemic, Governor Abbot issued a temporary disaster exception to TOMA allowing governmental bodies to conduct meetings by telephone or video conference. In a surprising attempt, several bills were filed that would make permanent the ability to hold public meetings by videoconference. While none of those efforts passed, and the relaxed provisions of the Open Meeting Act are expected to end on September 1, the discussion on best practices for public participation poses interesting questions for Texas water.

With the passage of the 1997 SB 1, Texas fundamentally shifted its water planning from a top-down to a bottom-up approach. Texas' decentralized, stakeholder-driven planning is a celebrated model and plays well with the concept of local control. It is also, however, premised in opportunity for public input. With increasingly urgent calls for diversity, equity, and inclusion, to what extent could the permanent expansion of TOMA support diverse and equitable participation in important public meetings? Despite the financial and technical concerns held by public entities, pandemic learning might suggest that virtual opportunities for public input increase and improve participation.

Winter Storm Uri and funding

Despite the emergence of the terms "resilience" and "climate variability," the 87th Texas Legislature was audibly silent on the significance of the water security disaster that ensued after Winter Storm Uri. Committee and floor discussions focused on accountability for the energy grid failures and addressed water outages in terms of emergency response, calling for weatherization and emergency operation requirements. But almost 15 million Texans were without potable water for over a week, and many thousands remained without water long after the pipes had thawed. There was no discussion on why the water outages were as significant as they were, why certain communities were more impacted than others, and where investment in public infrastructure is needed to make us more resilient for future disasters.

Winter Storm Uri exposed more than the need to plan for disasters. It exposed a fragile and aging infrastructure that impacts every aspect of Texas' economy, health, and security. As utilities and state agencies perform after-action reviews, TWF expects that discussion to emerge. Looking forward, Texas can only hope that the Legislature will consider allocating American Rescue Plan Act of 2021 funds to invest in a resilient water future.

WADING THROUGH A NON-WATER SESSION

By Ken Kramer, Water Resources Chair, and Alex Ortiz, Water Resources Specialist

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.

Conventional wisdom would say that the regular session of the 87th Texas Legislature was not a "water session." Indeed, compared to some previous legislative sessions (such as in 1997 and 2019), water issues were not the dominant topics of this year's regular session, nor were they among the priorities identified by the presiding officers of the House and Senate or the governor.

However, virtually every regular session of the Legislature sees numerous significant water-related bills introduced and discussed, and this session was not an exception. The reason for the biennial outpouring of water bills is simple: water is a critical issue in a state that endures endless cycles of drought and flood, continuing assaults on water quality, and the need to provide water for an ever-growing population.

In addition to the appropriations bill, which funds state water agencies and the entirety of state government, approximately 200 water-related pieces of legislation were filed in this "non-water session." This total does not include the large number of bills filed during the session—and indeed every session—creating municipal utility districts or similar districts to facilitate water and wastewater service for real estate development in unincorporated areas of Texas counties.

The topics those 200 bills covered ranged widely, including: groundwater management; transparency of water information; preservation of flowing rivers; surface water management; maintenance of water service during extreme events such as winter storms; disposition and use of produced water from oil and gas operations; state financial assistance for water and wastewater services in economically distressed areas; water quality protection; soil and water conservation; water and wastewater rates; and others, including some specific to geographic areas or watersheds.

Of course, not all of the 200 bills were acted on. Only about 35 of these bills actually passed and were sent to the governor. None of those were vetoed.

Groundwater legislation

In general, there was no pattern as to which water bills passed and which did not, and no one category of water issues dominated the bills that were successful. An exception was groundwater management legislation. Only one stand-alone groundwater bill passed: SB 1441 (Campbell/Lopez), which dealt with water withdrawals from the Edwards Aquifer to supply a military installation.

Although the reasons for the outcomes of specific groundwater bills varied, one factor was a clear message from Senator Charles Perry, Chairman of the Senate Committee on Water, Agriculture, and Rural Affairs, that the fate of some groundwater bills would be affected by whether he would be successful in getting changes in the law governing the awarding of attorney's fees and other costs incurred in cases where the decisions of GCDs were challenged in court. Senator Perry has tried for three legislative sessions to prevent GCDs from automatically being awarded those fees and expenses in court cases where they prevail, and he was not successful in achieving that goal this session. Consequently, groundwater bills supported by GCDs or other groups that had passed the House did not get Senate hearings or otherwise achieve final Senate passage.

Conversely, the fall from power of a former legislative chairman in the House resulted in the demise of legislation attempting to study connections between groundwater and surface water. This legislative session, Representative Lyle Larson lost the chairmanship of the House Natural Resources Committee, a position he held in the previous two sessions. Although HB 2652 (Larson) was reported out of the Natural Resources Committee, it was stymied in the House Calendars Committee and never reached the floor. HB 2652 would have established an advisory board to study surface water and groundwater interaction. Apparently, Representative Larson's failure to back the right horse in the race for Speaker of the House knocked him and his bill off the saddle. That was unfortunate. The bill had widespread support, including the backing of environmental organizations.

Transparency and accessibility to water information

Groundwater management was not the only water issue left largely unaddressed this legislative session. As Texas began ramping up its COVID-19 vaccination program, the Legislature began to think of the state's transition to being open again. This prompted a new interest in environmental agency transparency. While Governor Abbott's executive orders on the pandemic were in effect, TCEQ and other agencies were posting permit applications online. In the wake of the pandemic, there has been a greater focus on information access for transparency purposes. However, two bills that aimed to provide greater transparency for water quality data—HB 2990 and HB 1143—ultimately did not pass.

HB 2990 (Morales Shaw) would have required TCEQ to make water rights and other environmental permit applications available to the public online. Online availability would have brought public access to permit applications in line with what the governor had required of state agencies while his COVID-19 orders were in effect and would have brought permitting transparency into the 21st Century. This would have benefitted community stakeholders by not requiring them to physically go somewhere (typically a public library) to see an application.

HB 1143 (Ramos) would have required TCEQ to create and maintain a public-facing website providing updates on waterborne pathogen data for waterbodies where recreation occurs. This bill likely came as a response to the rare instances of infections from deadly waterborne pathogens (specifically *Naegleria fowleri*) in Texas waters. Such pathogens were linked to the death of one six-year-old boy near Lake Jackson in 2020 (Associated Press 2020; Kesslen and Associated Press 2020). While these specific infections are rare, they also carry a fatality rate of 97% (CDC 2020). The bill may also have been used to provide state-level data on cyanobacteria (commonly called blue-green algae) in the Highland Lakes. Cyanotoxins from these bacteria have already resulted in the illness and death of several dogs in addition to posing threats to human health (LCRA 2021). Although HB 1143 and HB 2990 did not pass this legislative session, no doubt the issues raised by these legislative proposals will be discussed again in future sessions.

One piece of water-related legislation that did have a transparency aspect did pass: HB 531 (Walle/Huffman). HB 531 sets requirements for a landlord to give notice to a tenant regarding property being rented that may be located within what is defined as the 100-year floodplain.

Texas Parks and Wildlife water-related legislation

Environmental groups, hunting and angling organizations, and other conservation and public interest groups strongly pushed two pieces of legislation related to the role of TPWD on water issues. Indeed, these bills were priorities for the Sierra Club. One bill passed; the other did not.

HB 2225 (T. King/Zaffirini) was successful. This legislation directs TPWD to "encourage and facilitate the dedication of water rights in the Texas Water Trust through lease, donation, purchase, or other means of voluntary transfer for environmental needs, including for the purpose of maintaining or improving (1) instream flows; (2) water quality; (3) fish and wildlife habitat; and (4) bay and estuary inflows" (HB 2225 2021). HB 2225 also authorizes TPWD to manage rights in the Texas Water Trust, just as a private holder of a water right would be able to do to protect that right from infringement by others and to operate that water right to serve its intended purpose (in this case, environmental flows). The management of those rights must be consistent with the dedication of those rights to the Texas Water Trust and agreed to by the holder of the water right. The purpose of this legislation is to make the existing Texas Water Trust, a mechanism for protecting instream river flows and freshwater inflows to coastal bays and estuaries, more robust and effective in achieving its purpose.

On the other side of the ledger, HB 2716 (T. King) passed the House but received no consideration in the Senate. HB 2716 was legislation to restore the authority of TPWD to request and be a party in a contested case hearing on proposed surface water rights and other TCEQ permits such as wastewater discharge permits. TPWD had this authority for over 25 years prior to 2011, when one obscure sentence in an amendment to the TCEQ "sunset bill" (HB 2694, 82nd Texas Legislature) was added on the House floor to prohibit any state agency from contesting a TCEQ permit. The effort to restore the right of TPWD to protect its properties (such as state parks and wildlife management areas) as well as fish and wildlife resources from negative impacts of water diversions and pollution discharges was thwarted by organizations such as the Texas Chemical Council, the Texas Association of Manufacturers, and Texas Independent Producers & Royalty Owners. However, this issue will come back.

Water legislation addressing oil and gas activities

Three pieces of legislation on water issues related to oil and gas operations were enacted and signed by the governor, the most significant being SB 601 (Perry/Burrows). This bill created the Texas Produced Water Consortium. The purpose of the consortium is "to bring together information resources to study the economics of and technology related to, and the environmental and public health considerations for, beneficial uses of fluid oil and gas waste"1 (SB 601 2021). These wastes, sometimes referred to as produced water, are a byproduct of the extraction of oil and natural gas through fracking and traditional oil and gas production. Produced water typically includes brackish or saline water and other constituents, and in the case of fracking operations, even hazardous chemicals.

SB 601 passed with overwhelming bipartisan support in both the Senate and the House. There was substantial engagement by Sierra Club and other environmental groups on SB 601, especially concerning the initial exclusion of environmental interests and TPWD in the work of the consortium. As filed, the consortium would have focused entirely on the economic and technological feasibility of using produced water for beneficial purposes. As enacted, however, SB 601 includes environmental considerations and more robust stakeholder engagement.

[1] The bill uses the phrase "fluid oil and gas waste" to refer to produced water, as that term is defined in Section 122.001, Natural Resources Code.

The consortium will be composed of the host university (Texas Tech University), members that pay a membership fee, an agency advisory council made up of state agency-appointed representatives, a stakeholder advisory council, and a technical and economic steering committee. Each part of the consortium will be responsible for overseeing a different body of the consortium's work, with Texas Tech bearing the primary management responsibility. Additionally, the Texas Produced Water Consortium is obligated by law to consult with the existing New Mexico Produced Water Research Consortium on research, data, and any other matter related to the consortium.

The consortium membership costs will be developed by Texas Tech along with the agency advisory council, and members will have access to the consortium's research data proportional to their membership level. While some data will be made available to the public, other data will be protected by these membership agreements. Texas Tech will appoint paying members to the stakeholder advisory council, including members from oil and gas industry, agricultural interests, water utilities, landowners and water right holders, and environmental interests. If no selected member of the consortium matches a given interest, then the consortium may appoint someone from outside its membership to represent that interest.

The consortium must produce a report by September 1, 2022 that includes: "suggested changes to laws and administrative rules to better enable beneficial uses" of produced water ("including specific changes designed to find and define additional beneficial uses"), "guidance for establishing [produced water] waste permitting and testing standards," "a technologically and economically feasible pilot project for state participation in a facility designed and operated to recycle" produced water, and "an economic model for using [produced water] in a way that is economical and efficient and that protects public health and the environment." (SB 601 2021)

Whether this report will provide all the information necessary to evaluate possible beneficial uses of produced water is a concern, especially given that there are several constituent chemicals in produced water that lack US Environmental Protection Agency (EPA) approved analytical methods, toxicity, and/or radioactivity data. Suggesting changes to law or rules, especially in a way that could encourage additional untreated "beneficial use" discharges enabled by 40 CFR § 435 Subpart E, would be incredibly risky for the health of Texas waters, wildlife, and communities. However, the guidance establishing testing and permitting standards that are sufficiently protective of human health and the environment will be key to a safe regulatory scheme. What remains unclear is how, if at all, EPA will be engaged with the consortium.

In addition to SB 601, HB 3516 (T. King/Perry) was enacted this legislative session to give additional direction to TCEQ in adopting rules to govern the treatment and recycling of fluid oil and gas waste, including requiring minimum siting standards for recycling pits. Also, HB 2201 (Ashby/Nichols), as enacted, requires the Railroad Commission of Texas to establish standards for permissible locations for commercial oil and gas waste disposal facilities, and these standards must take into account whether the location proposed for a disposal pit has a history of flooding.

Responding to the winter storm: SB 3

An unexpected issue that became a priority in this legislative session was the need to respond to the failure of the state's electric grid and the subsequent failure of many water systems in the state as power was shut off or was intermittent during the winter storm that hit Texas in February. One of the bills filed and ultimately passed in response was SB 3 (Paddie/Schwertner). Although most of that bill dealt with weatherization of electric generating and natural gas facilities and other issues regarding operation of the grid and gas facilities, SB 3 also addressed the topic of emergency operations of retail public water utilities and wholesale water utilities.

The basic provisions of SB 3 in regard to retail and wholesale public water utilities set a standard for emergency operation of those water utilities; require each utility to adopt an emergency preparedness plan that must be submitted to and approved by TCEQ; enumerate possible components of such a plan; require TCEQ to create an emergency preparedness plan template; and require TCEQ to adopt rules to implement this part of the legislation. SB 3 as it passed the House included a provision authorizing TWDB to provide financial assistance to political subdivisions for projects to weatherize water and wastewater facilities, but that provision was not included in the bill as it finally passed. Thus, the onus is still on each water utility to make and finance its own emergency preparations, and the Legislature did not pass any blanket state law requiring that water utilities be granted critical load status during emergencies affecting the electrical service providers.

Funding the economically distressed areas program

A notable legislative action this session was the appropriation of additional debt service to TWDB for the Economically Distressed Areas Program (EDAP) via SB 1 (Nelson/Bonnen). EDAP is a program to provide state financial assistance for colonias along the Texas border with Mexico and other low-income communities elsewhere without adequate economic resources to provide basic water and wastewater services. The Legislature and the voters of Texas approved an additional $200 million in bond authorization for EDAP in 2019 because the program had committed all previously authorized bond money to qualified applicants. However, the debt service for those bonds comes out of general revenue, so additional funds needed to be appropriated for that purpose to allow TWDB to issue any new bonds.

The 87th Legislature responded by granting TWDB's exceptional item request for almost $2.6 million in new debt service for EDAP and further sweetened the pot with another $3.6 million, for a total of roughly $6.2 million in additional debt service. That should allow TWDB to issue over $70 million of the authorized $200 million in EDAP bonds. The new appropriation for EDAP was a priority for the Sierra Club during the legislative session. This additional money will be a significant boost to a program that is important in achieving greater equity in the use of state funds for the provision of water and wastewater.

Other water-related legislation of note

Some other water-related bills of interest to environmental and other organizations were enacted this legislative session. One of those was SB 905 (Perry/Frank), which requires TCEQ to develop a guidance document for those water utilities who wish to pursue direct potable reuse of wastewater, potentially an important part of meeting future water supply demands. Another bill, SB 1118 (Johnson/Wilson), authorizes TSSWCB to create an On-the-Ground Conservation Program to facilitate landowners in implementing soil conservation measures that—among other benefits—conserve and manage water resources and prevent and manage flooding.

Unfortunately, another environmentally important bill, Representative Tracy King's HB 4146—known unofficially as the "pristine waters bill"—passed the House but was never considered in the Senate. That bill would have prevented direct wastewater discharges, with some exceptions, into certain streams with extremely low or no levels of phosphorous in order to maintain high water quality in those streams.

CONCLUSION

The Lone Star Chapter of the Sierra Club's review of water legislation in the regular session of the 87th Texas Legislature, though not comprehensive, reinforces the point that even when water is not considered a priority issue in a legislative session, the range of water legislation introduced and water issues debated is extensive. Water remains a fundamental concern of Texas lawmakers. Although water may not be a dominant issue in any one legislative session, water bills are something that legislators have to wade through each session.

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TEXAS WATER INFRASTRUCTURE SUMMARY OF KEY CONSTRUCTION-RELATED LAW FROM 87TH LEGISLATIVE SESSION

By Perry L. Fowler, Executive Director, Texas Water Infrastructure Network, and Jeff Chapman, The Chapman Firm PLLC

The Texas Water Infrastructure Network (TXWIN) is a 501 C6 nonprofit trade association founded in 2013 representing construction companies and related interests involved in the construction of water infrastructure in the state of Texas. The primary focus of TXWIN is the promotion of competition, accountability, and consistent application of sound public contracting and procurement law in addition to supporting funding policy to ensure adequate and consistent investment in Texas water infrastructure.

TXWIN tracked approximately 500 of the 6,927 bills filed in the 87th regular legislative session. Approximately 100 of the bills tracked by TXWIN passed, 41 of which related to the creation or governance of special districts such as municipal utility districts and water control and improvement districts. That passage rate was consistent with the overall bill passage rate of approximately 15%. Ultimately Governor Abbott exercised his veto power on 21 bills. TXWIN does not anticipate any significant legislation impacting the water or infrastructure sector in any special sessions of the 87th Legislature called by Governor Abbott. The following report will attempt to focus on infrastructure-related bills relevant to the water infrastructure construction sector and public owner community.

Very few bills that impact the public works construction industry made it to Governor Abbott's desk to become law. However, three new key pieces of legislation do have an immediate and impending impact on the construction industry. The bills change the law in a way that generally impacts and promotes competition for public work and increases fairness in public contract awards. These new changes will make a meaningful impact on retainage, the procedures by which public works contracts are awarded, and eliminate abuses to the competitive marketplace by clarifying the purposes of particular contracts awarded to promote energy efficiency. TXWIN is willing and available to assist interested parties especially regarding implementation of new and existing contracting law from this legislative session.

HB 692 (Shine/Creighton)

Relating to retainage requirements for certain public works construction projects.

The first piece of legislation was championed by its sponsors and supporters as one of the most significant retainage laws ever passed in Texas. Contractors have long complained about retainage on bonded public projects. The burden of statutory retainage is generally passed from the general contractors through subcontractor agreements that contain contractual retainage provisions, which similarly allows the general contractor to ensure the subcontractor's work is performed in accordance with the contract and completion of such work. Essentially retainage provides the contractor with an incentive to complete the project while also providing the owner with some protection against delays, contractual default, payment claims, and the like.

HB 692 addends Texas Government Code 2252 in several significant respects. First, it requires owners to include a provision within the public works contract that provides conditions for release of a portion of retainage and establishing circumstances under which the project is considered substantially complete or finally complete. The new bill also caps maximum retainage withheld for contracts over $5 million dollars at 5%, including materials and equipment delivered on site to be installed. For contracts under $5 million dollars, the maximum retainage is capped at 10%. Owners of competitively awarded contracts with a value of $10 million dollars or more and contracts awarded using a method other than competitive bidding may also agree with the contractor to deposit the retainage in an interest-bearing account. The key change here from the prior version of the law is that an owner was free from paying interest on retainage as long as the amount withheld did not exceed 5%. Now, all large contracts will be eligible for interest to the contractor even at 5%.

Regarding subcontractor withholding, HB 692 prohibits subcontractor withholding at a greater percentage of retainage than the percentage withheld from the prime contractor. This prohibition also applies to sub-subcontractors. The bill further prohibits withholding of retainage during the warranty period after the completion and acceptance of work, and prohibits the withholding of retainage to compel the contractor to perform work on manufactured systems or goods that were properly installed. Finally, HB 692 contains the right to cure provisions for the parties to agree on reasonable compensation for any noncompliant labor services or materials that cannot properly be cured and preserves the owner's ability to withhold retainage in the event of a bona fide dispute, default, or no performance. One key component of the legislation that allowed it to pass both the House and Senate without opposition from key interest groups is the fact that much of the bill's provisions are permissive and not mandatory. This important distinction must be understood and utilized by contractors and owners while negotiating contract terms on any procurement method that permits post-submission negotiations, such as competitive sealed proposals.

HB 692 was signed by Governor Abbott on June 15, 2021 and took effect immediately. TXWIN strongly encourages all public owners to carefully examine internal procedures and boiler plate documents to ensure compliance. Contractors should also carefully review specifications in bid and solicitation documents for compliance with HB 692. Key features and summary of HB 692 are:

- Sets the maximum amount for retainage at 10% for jobs under $5 million and 5% for jobs over $5 million on all schedules of work and materials delivered on site.
- Requires public works contracts to contain a provision stating when the contract is considered substantially completed and when the governmental entity may release all or a portion of retainage.
- Allows for retainage to be placed in an interest-bearing account for projects that are negotiated and for competitively bid projects for $10 million or more.
- Prohibits subcontractor withholding in excess of the rate of retainage withheld on the general or prime contractor.
- Prohibits withholding of retainage during the warranty period, or to perform work on systems properly installed and accepted by the owner.
- Prohibits withholding of retainage after the completion of work performed under the contract to require the contractor to perform work on manufactured goods or systems that were specified by the designer and properly installed.
- Contains right to cure provisions to secure release of retainage or offer compensation for items with consent of the owner.
- Contains special provisions allowing 10% retainage on dams, certain SWIFT funded projects under contract as of 2019, and wholesale water supplier that supplies water to customers in 10 or more counties and is governed by Chapter 49, Texas Water Code. However, all other provisions of the bill apply, and this provision requires retainage over 5% to be placed in an interest-bearing account.

HB 2581 (Kacal/Hancock)

Relating to civil works projects and other construction projects of governmental entities.

The next piece of legislation passed, HB 2581, reforms the procurement laws contained in the Texas Government Code, Chapter 2269. The bill applies to all procurements conducted pursuant to Chapter 2269. Two of the most significant changes to the existing law involve the disclosure of information in relation to the evaluation of all bidders and offerors, and the weighting of price in requests for proposals for a competitive sealed proposal project.

To improve openness of government and competition for public work, Chapter 2269 enables a contractor who submits a response to a bid or request for proposal for any project issued under Chapter 2269 to request, from the owner, documents related to the evaluation of the offeror's submission. The law requires that the owner supply the documents to the requesting party no later than 30 days after the request.

Specifically, on competitive sealed proposal procurements for civil works projects, HB 2581 requires the weighted value assigned to price be at least 50% of the total weighted value of all selection criteria. An exception to the 50% mandate exists where the governing body of a governmental entity determines that assigning a lower weighted value is in the public interest. In that scenario, a governmental entity may dip below the 50% bottom and assign a weight to price of no less than 36.9%.

The reform further requires CSP scores and evaluations to be made public to all offerors no later than seven business days after the contract is awarded. The language in HB 2581 also modified the older version of the law by adding evaluations to the information required to be made public. Finally, the bill increases the amount of time for a contractor to seek injunctive relief to 15 calendar days (up from 10) after the contract has been awarded.

HB 2581 was signed by Governor Abbott on June 15, 2021 and takes effect on September 1, 2021. All solicitations and contract documents for projects advertised and scheduled for award as of September 1, 2021 should be compliant with changes in HB 2581. Specifically, the owner community should familiarize themselves with provisions applicable to explaining scoring methodologies in requests for qualifications and requests for proposals. Finally, contractors and public owners should ensure that provisions related to price weighing on competitive sealed proposal solicitations are taken into account and contemplate procedures regarding release of scoring on CSP projects to ensure that they are compliant with changes in the law. Key features and summary of HB 2581 are:

- Requires disclosure of scoring methodologies and bid evaluations.
- Requires governmental entities to provide documents related to how an unsuccessful offeror was ranked or scored upon request without requiring open records or public information requests 30 days after request from the contractor.
- Requires that competitive sealed proposals for civil works projects assign a 50% weight to price in scoring proposals and allows for an entity to assign a lower price weighting with the formal approval of its governing body to 36.9%.

- Requires that CSP scores and evaluations be made public and provided to all offerors within 7 days of award.
- Increases the time that a contractor may seek injunctive relief from 10 calendar days to 15 calendar days after the contract has been awarded.

HB 3583 (Paddie/Hinojosa)

Relating to energy savings performance contracts.

The final major piece of legislation to address is HB 3583. This bill reforms the manner in which an energy savings performance contract, commonly referred to as "ESPC," may be awarded and modified. This bill addresses a trend of abuses and misuse of the energy savings ESPC statute by ensuring that energy savings performance contracts are utilized in a transparent manner for the purpose originally intended, and not as a means to bypass statutes relating to the procurement of public works projects to add unrelated scope. The prior version of this law, which is codified in Texas Local Government Code Chapter 302, allowed a provider of services for energy efficiency to be awarded a contract based on the professional services contracting rules. In allowing this type of award, the legislature exempted these contracts from competitive bidding. To promote transparency and competition, this bill now specifically defines what types of water infrastructure projects may be awarded in that manner. The bill also places limits on the amount of change orders allowed on a project. Finally, it provides a means and timeframe for enforcement of the chapter through declaratory or injunctive relief. Both latter changes closely resemble the language that is found in Chapter 2269.

HB 3583 was signed by Governor Abbott on June 14, 2021 and takes effect immediately. Key features and summary of HB 3583 are:

- The bill prohibits the use of ESPC for public works and civil works projects, including "design or new construction of a water supply project, water plant, wastewater plant, water and wastewater distribution or conveyance facility, or drainage project," which are subject to well-established contracting and procurement statutes (HB 3583 2021).
- While the bill specifically prohibits the use of ESPC for the design or construction of major water civil works projects, it does allow the use of ESPC to perform water and energy savings projects, upgrades, system replacements, and water conservation measures such as the installation of advanced metering or smart water metering infrastructure.
- The bill prohibits change orders adding scope unrelated to or ancillary to the original contract and caps change orders at 25% of original project budget. The bill also contains provisions for injunctive relief.

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TEXAS RURAL WATER ASSOCIATION SUMMARY OF THE 87TH LEGISLATIVE SESSION

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

The Texas Rural Water Association (TRWA) is a nonprofit trade association that provides training, technical and legal support, and legislative services for more than 760 water utilities collectively serving more than three million customers across the state. TWRA's members include nonprofit water supply corporations, special utility districts, other types of water districts, small cities, and investor-owned utilities.

Water issues are always a hot topic at the capitol when the Texas Legislature convenes every other year, and the 87th legislative session was no exception. As a statewide trade association serving the interests of more than 750 rural water and wastewater utilities, TRWA tracked more than 450 bills this legislative session that could affect the quality and affordability of water for more than three million Texans. TRWA's membership consists of nonprofit water supply corporations (WSCs), special utility districts (SUDs), other types of districts, small cities, and investor-owned utilities, each with their own unique challenges and regulatory frameworks. While other organizations in this journal will be covering bills with broader impacts on water law and policy in Texas, TRWA has identified the following bills as having the most impact on the rural water industry in Texas.

Response to Winter Storm Uri

SB 3 (Schwertner)

While the bulk of this bill addressed issues with the state's electrical grid that were brought to light during February's freezing weather event, the bill also contains several provisions pertaining to water utilities:

- Water utilities must provide service during an extended power outage as soon as it is safe and practicable to do so following the occurrence of a natural disaster.
- Utilities must also adopt and submit to the TCEQ a plan demonstrating the utility's ability to provide emergency operations. Participation in a statewide mutual aid program counts toward meeting this requirement. The bill also requires TCEQ to develop a template plan for systems to utilize and mandates that the agency provide systems with access to financial, managerial, and technical staff for assistance. TRWA currently provides these services to systems through a contract with TCEQ.
- SB 3 prohibits systems from disconnecting customers for nonpayment and from imposing late fees during an "extreme weather emergency," which is defined as a period when the previous day's high temperature did not exceed 28 degrees Fahrenheit and is predicted to remain at that level for the next 24 hours.
- Utilities are required to work with customers that request a payment schedule for unpaid bills during extreme weather emergencies. Based on the experience this February, most systems were already voluntarily doing this.
- Violations of SB 3's billing provisions could result in fines up to $50,000, though the bill mandates that only extreme cases qualify for fines of more than $5,000.
- Utilities have until November 1, 2021, to submit critical infrastructure and emergency contact information to the PUC, their electric provider(s), their local office of emergency management, and the Texas Division of Emergency Management. They have until March 1, 2022, to submit their emergency preparedness plan to TCEQ and until July 1, 2022 (or later if approved by TCEQ) to implement that plan.

Cybersecurity training for district employees and directors

HB 1118 (Capriglione)

Last legislative session, the Legislature mandated that all district employees and directors must complete an annual cybersecurity training approved by DIR. HB 1118 narrows the scope of the cybersecurity requirement and became effective immediately upon Governor Abbott signing it on May 18, 2021. Under the new law, only employees and board members who use a system computer to perform at least 25% of their required duties must complete the annual cybersecurity training. This should eliminate most board members and some field staff from the requirement.

Water supply corporations were never subject to the cybersecurity training requirement and HB 1118 did impose this obligation upon them, but TRWA recommends that staff of those entities who utilize system computers voluntarily complete the training anyway, as water systems continue to be a target for this type of breach.

Retail rates

SB 387 (Schwertner)

This bill authorizes rate appeals for customers within a city's extraterritorial jurisdiction (ETJ) when their service is taken over by another municipal utility and their rates increase as a result.

HB 3689 (Cortez)

Chapter 13 of the Texas Water Code gives municipal utility customers located outside a city's limits to appeal their rates to the PUC because they are not able to vote in city elections. However, in a recent appeal on the reasonableness of a city's rates outside its limits, the PUC assumed jurisdiction to review not only those rates but also the rates charged to customers within the city limits. HB 3689 clarifies that the PUC's jurisdiction extends only to the rates charged to out-of-city customers, and that the agency may not compare those rates to the rates charged within the city.

HB 1484 (Metcalf)

This bill relates to the rates charged by a utility after it purchases or otherwise acquires another utility. Under the new law, the acquiring utility may charge its newly acquired customers the rates specified in its tariff that are in effect for its current customers without having to go through a new rate proceeding at the PUC.

Certificates of Convenience and Necessity (CCN) issues

HB 837 (Lucio)

Last legislative session, the Legislature changed the manner in which the PUC compensates utilities when their service area is decertified by a landowner or developer. Since then, several utilities have been able to work out compensation with developers who decertify land from their service area. HB 837 simply adds to last session's legislation by requiring the landowner or developer to notify the PUC once the compensation is paid.

HB 3476 (Schofield)

The Texas Water Code requires cities with a population of 500,000 or more to give their consent when a new CCN is requested within the city's boundaries or ETJ. As a condition of giving consent, the city may require that all water and sewer facilities be designed and constructed in accordance with its standards. In general, cities have less authority in their ETJ than they do within their boundaries, and HB 3476 makes a similar distinction in this area. Under the new law, affected cities may no longer require facilities within their ETJ to comply with the city's standards. Instead, those facilities are subject to standards set forth by TCEQ. The bill does not affect cities' ability to require that facilities within their city boundaries be designed and constructed in accordance with their standards.

Direct potable reuse guidance

SB 905 (Perry)

This bill requires TCEQ to develop and make available to the public a regulatory guidance manual to explain its rules applying to direct potable reuse, which is defined as the introduction of treated or reclaimed municipal wastewater directly into a public water system or into a raw water supply immediately before it enters a water treatment plant.

Public Information Act

HB 872 (Bernal)

Section 182.052 of the Utilities Code currently requires utilities to keep confidential the address, phone number, social security number, and usage information of their customers, but only if the customer requests that they do so. HB 872 flips this opt-in confidentiality process to an opt-out structure. Beginning September 1, utilities can automatically withhold this information from Public Information Act requests without express permission from their customers. Instead, customers may request that the information be made available on request. This should make responding to this type of request much easier because systems will no longer need to redact the information of some customers while providing the information of others.

TEXAS DESALINATION ASSOCIATION POST 87TH LEGISLATIVE SESSION REPORT

By Kyle Frazier, Executive Director

Since 2011, the Texas Desalination Association (TXD) and its members have been advocating for the development of brackish, marine, and produced water. The TXD focuses on educating state and local decisionmakers, the public, and industry leaders on the effectiveness and cost benefits of desalination.

The 2021 legislative session has come to a close (87th for those counting). While all legislative sessions are unique, this version may eventually prove to be more unusual than normal. It's necessary to say "prove to be" because the process has probably not quite finished despite the May 31 deadline having come and gone.

There are several unanswered questions (depending on to whom one listens) that might be considered unfinished business for the Texas Legislature. Without question, the Legislature will need to return in a special session early this fall to pass redistricting legislation. The necessary information is still being developed by the federal government, and the Texas Legislature must wait for receipt of that data to complete their work.

In addition, a number of high-profile partisan issues were left unresolved that Governor Abbott could include as issues to be addressed during some future special session. As a reminder, the governor calls a special session and determines the issue(s) to be discussed. A special session lasts no more than 30 days and the governor may call as many as desired. With the June 20 deadline for signing, vetoing, or allowing to become law without signature now passed, there is a more complete picture of this past legislative session and what the future may hold.

On July 8, Governor Abbott called a special session of the Legislature. The second called special session is now under way, with no end in sight due to the inability of the House to make quorum.

TXD

While TXD tracked a number of bills during the legislative session, the main interest was in the passage of SB 601 (Perry/Burrows). SB 601 passed the Senate by a vote of 31-0 and the House by 143-0. It is unusual for water-centric legislation to pass unopposed, but having a great author and sponsor always helps. The bill was amended in the House, but the bill went to conference and the amendment was removed. For the most part the bill passed as originally drafted. Governor Abbott signed SB 601 on June 18, and because of the language and overwhelming support in both House and Senate, the bill went into immediate effect.

Although this was not really a water-centric legislative session—for good or ill—a number of infrastructure bills were filed. While most of these bills did not pass, and many did not even get a hearing, several were possible vehicles for desalination-related legislation. HB 2905 (Morrison), which expanded the use of public-private partnerships, is certainly worthy of consideration in a future legislative session. Another bill, also by Representative Morrison, HB 3040 continued and expanded the use of the Chapter 313 economic development program. Adding desalination projects (among other projects) to this particular part of the tax code has been of interest to various segments of the desalination industry for the past several years. The failure of this bill was not because of the addition of the desalination project language; this particular segment of the tax code has been under fire for the past several legislative sessions. The bill failed because of the ongoing concern about the expansion of these types of "incentives."

Besides SB 601, the only other water-related bills that TXD tracked that were passed and signed were:

- **HB 1322**, requiring agencies to publish brief summary of proposed rules on website.
- **HB 1904**, ensuring that equity that can no longer be used under the water infrastructure fund can be used for other programs in the Texas Water Development Fund II.
- **HB 1905**, relating to relieving regional water planning groups of certain duties.
- **HB 2361**, amending the Texas Health and Safety Code to include projects that reduce flaring emissions and other site emissions among the projects for which TCEQ is required to give preference in awarding grants under the new technology implementation grant program.
- **SB 669**, relating to certain reports created by TWDB.
- **SB 905**, directing TCEQ to create a direct potable reuse document so that entities will understand the process for having such a project. It does not create new rules or permitting.

Unless something dramatic changes, there do not appear to be any possible water issues that would be included in the special sessions. Regardless of the bills that failed this legislative session, the future of desalination looks extremely bright.

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Focused Flows to Maintain Natural Nursery Habitats

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Abstract: Regulatory standards for environmental flows to estuaries are not common, but they are required in Texas. This has led to adoption of complex freshwater inflow regimes that reflect seasonal and yearly fluctuations that vary geographically throughout the state. The flow regimes are based on dilution of saline water with fresh water in whole systems. Because the estuaries are large lagoons, large volumes of fresh water are required to meet standards. However, this volume of water is not available during dry periods. We present a new concept, focused flows, for lower flow volumes that would maintain the ecological health of the upper reaches of estuaries during droughts. The concept is based on maintaining ecological integrity of nursery habitats, which is an important ecological function of estuaries. These focused flows would protect nursery habitats during droughts and allow estuaries to recover more quickly when the hydrology returns to average or higher flow periods. This approach could be applied globally where increasing water infrastructure and deficits are a concern or increasing aridity due to climate change is reducing river flows to coasts.

Keywords: environmental flow, freshwater inflow, focused flows, hydrology, nursery habitats, management, protection

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Terms used in paper

Acronym / Initialism	Descriptive Name
ac-ft	acre-feet
ha	hectare
HB	house bill
m^3	cubic meters
NOAA	National Oceanic and Atmospheric Administration
psu	practical salinity unit
s	second
SAC	Science Advisory Committee
SB	Senate Bill
y	year

INTRODUCTION

While nearly every political jurisdiction on Earth has some kind of laws, rules, or regulations that protect water quality, very few jurisdictions have such protections for water quantity. Yet rivers that do not flow are hardly river habitats at all, and the dilution of sea water with fresh water defines estuary habitats. Scientists and managers of freshwater ecosystems have long recognized the importance of flowing water in the environment to define aquatic habitats, and that management of flow rates is important to protect freshwater species (Ward and Stanford 1979; Postel et al. 1996; Richter et al. 1997). The importance of natural flow regimes, which acknowledge the dynamic nature of the timing and flow of rivers instead of just a minimum flow rate, is now recognized as a critical management approach (Poff et al. 1997). Recently, the field of hydroecology (or ecohydrology) has arisen to examine the relationship among environmental flow regimes, ecological responses, and potential management applications (Wood et al. 2008).

Estuary habitats are different from river and stream habitats. Flow rates in flowing freshwater riverine environments define instream habitats, maintain riparian and floodplain communities, influence habitat quality, and transport matter and materials downstream (Bain et al. 1988). This is not true in estuaries. In estuaries, freshwater inflow from rivers and streams delivers nutrients and sediments and dilutes sea water from the coastal ocean; thus, environmental flow is a driver of estuarine condition and ecological responses to the varying estuarine conditions (Alber 2002). The importance of salinity in defining estuary conditions also has a long history since first described by Pritchard (1952, 1967). The role of nutrients and sediments in shaping estuarine productivity and habitats along salinity gradients from the river to the sea is also well known (Day et al. 1989). Early studies of estuaries demonstrated that they provide nursery habitats, which support fish and shellfish fishery species, and these nurseries are primarily located in marshes and near river mouths (Gunter 1967; Weinstein 1979).

While it has been firmly established that estuaries are complex ecosystems with high spatial and temporal variability (which influences food webs, habitat complexity, and ecosystem productivity characteristics), early attempts to address management of freshwater inflows focused on flow rates alone. This was true in many regions (Adams 2014). For example, in Texas, United States, the primary approach to identifying freshwater inflow needs was a model of fisheries harvest that was driven by freshwater inflow rates (Longley 1994; Powell et al. 2002). In Florida, United States, a percent of flow approach has been used in some estuaries (Flannery et al. 2002). In South Africa, static volumes were used to set inflow criteria (Adams et al. 2002). In other cases, the flow required to maintain a downstream salinity value was used, as in San Francisco Bay, California (Jassby et al. 1995; Kimmerer 2002a), Georgia, United States, estuaries (Alber and Flory 2002), and Swan River Estuary, Western Australia (Kurup et al. 1998). These condition approaches to define inflow needs were replaced by more mechanistic and holistic approaches over time (Adams 2014).

However, one consequence of these whole-estuary approaches to identify inflow needs is that very large volumes of fresh

Table 1. Estuary and river basin characteristics on the Texas coast. Estuary inflow and river flows are in 10^3 acre-feet/year (ac-ft/y), estuary volume is in 10^3 ac-ft, and flushing rate (i.e., volume/surface inflow) is in days.

Estuary characteristics [a]					River basin characteristics [b]			
Estuary	Volume	Surface inflow	Inflow balance	Flushing rate	**River basin**	Naturalized flows at outlet	Regulated flows at outlet	Percent regulated flow
Sabine-Neches	492	13,866	13,919	13	Sabine	6,633	6,192	93%
					Neches	6,224	5,572	90%
Trinity-San Jacinto	2,108	11,120	11,241	69	Trinity	6,630	4,829	73%
					San Jacinto	2270	1,119	49%
Lavaca-Colorado	1,798	3,528	3,242	186	Colorado	3,119	1,908	61%
					Lavaca	860	806	94%
Guadalupe	564	2,455	2,270	84	Guadalupe & San Antonio	2,220	2,063	93%
Mission-Aransas	702	490	280	522				
Nueces	964	587	262	599	Nueces	648	440	68%
Laguna Madre	414	705	-595	215	Rio-Grande	1,100	75	7%

[a] Montagna et al. 2011
[b] Wurbs and Zhang 2014

water are required to dilute salinity in whole-bay and estuary systems or to maintain a salt wedge in the downstream area near the inlet or pass where sea water and fresh water are mixing. These large volumes impose a problem for those resource managers setting inflow standards or others attempting to restore hydrology to ensure estuary functions. The problem is that the large volumes of fresh water may no longer be available. The reality is that there are about 16.7 million reservoirs larger than 0.01 hectare (ha; 0.08 acre-feet [ac-ft]) in the world (Lehner et al. 2011), and one-sixth of the river flow in the world is now captured behind these dams (Hanasaki et al. 2006), which is severely restricting fresh water and sediment flow to the coasts (Tessler et al. 2018). In addition to land-use change, climate change will also alter water availability. Aridity is increasing worldwide because of climate change (Berdugo et al. 2020). This is particularly true in the southwestern region of North America where extreme droughts can extend many years (Seager et al. 2007). So, the problem is: How will we ever hydrologically restore estuaries if large volumes of water are no longer available in rivers and streams or are already allocated?

TEXAS ESTUARIES

There are 10 major river basins and nine coastal basins in Texas that provide freshwater inflow to seven major receiving estuaries, which range from hydrologically positive in the northeast to negative in the southwest (Montagna et al. 2011; Table 1). Water supply diversions are less than natural flows in every Texas river basin except for the Rio Grande in the southwest (Wurbs and Zhang 2014; Table 1). However, on average, regulated flows at the outlet of the river basins to the estuaries is 81% of the naturalized flows at the outlet, meaning that much environmental water is still reaching bays and estuaries. Reduced inflow may already be a problem in the southernmost, hydrologically neutral and negative estuaries, where water is already naturally scarce. An example of this is the Nueces River, where flushing rates are very slow and regulated flows are much reduced from naturalized flows (Table 1).

Since the mid-1980s, the state of Texas has struggled with the issue of how to secure freshwater inflows to estuaries sufficient to keep them healthy and productive while also meeting the myriad of human demands on that limited resource. Because of these legislative mandates (1985 House Bill [HB] 2, 1997 Senate Bill [SB] 1, and 2007 SB 3), Texas has led the world in efforts to characterize environmental water and especially freshwater inflows as the basis of making rational, science-based decisions about water allocation and management to assure healthy and productive bays and estuaries. Much of that early work was synthesized in the seminal book Freshwater Inflows to Texas Bays and Estuaries (Longley 1994). A fundamental tenet of those early studies was a focus on recreationally and commercially important shellfish species (i.e., crabs, shrimp, and oysters), and finfish (i.e., black drum, flounder, red drum, and spotted seatrout). That focus generated two significant constraints on efforts to produce a model that would predict the required inflows, both in quantity and timing to meet the legislative mandate (Powell et al. 2002). The models necessarily had to encompass an entire bay system because of

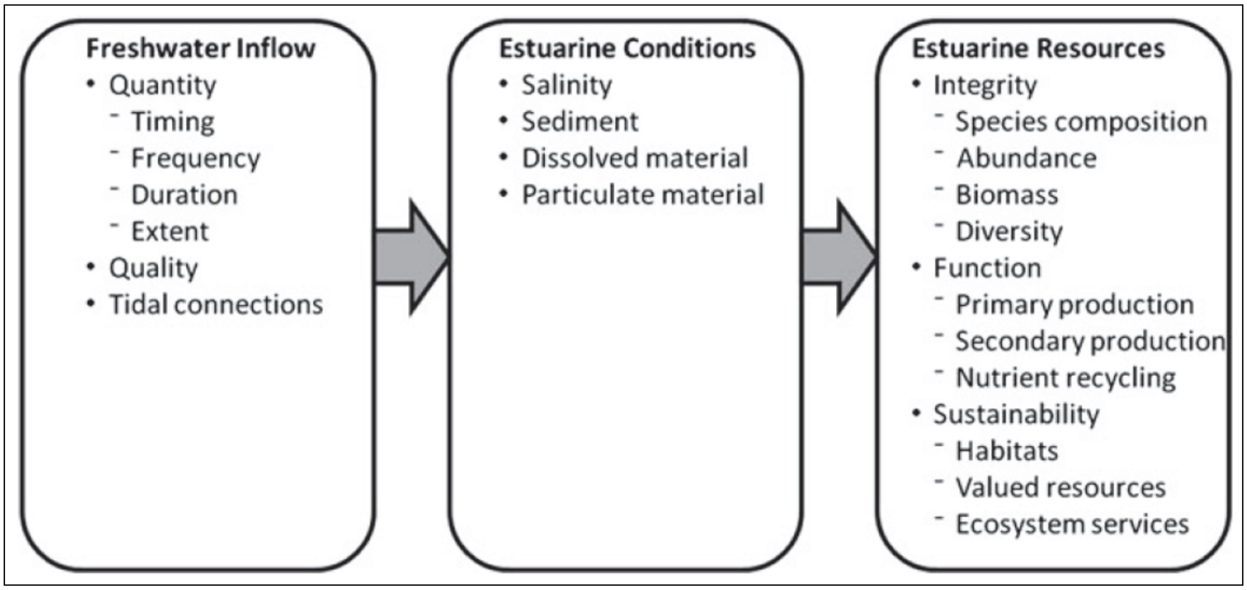

Figure 1. The domino theory conceptual model of freshwater inflow effects on estuary ecosystems (based on Alber 2002; Brandes et al. 2009; Palmer et al. 2011; Montagna et al. 2013).

these species' mobility (only oysters remained a fixed community). The focus on the entire bay meant models had to predict the effect of changing conditions over large areas and relate those changes to the adult stages of the target species. Such complexities made the margins of error in the models large and difficult to resolve.

These scientific constraints created two significant political impediments to securing environmental flows for estuaries. The large margins of error in the models made it necessary to provide a range of inflows with differing biological impacts rather than more specific recommendations. While that may be a scientifically reasonable approach, detractors seized on that as an uncertainty to discredit the recommendations. Second, and more importantly, because the focus of the effort was on entire bay systems, the quantities of water needed to meet legislative mandates was in the hundreds of thousands (even millions) of acre-feet, and that high volume proved to be politically, economically, and hydrologically impossible to secure.

As described above, the state of Texas started with a conceptual model of direct effects of flow on harvestable species (Matsumoto et al. 1994). The conceptual model was that "fisheries' production may be considered a measure of an estuary's overall health," and the mathematical approach was essentially a regression between inflow and harvest (Matsumoto et al. 1994, page 700). The strengths and weaknesses of the method have been described in detail by the Texas Environmental Flows Science Advisory Committee (SAC; Brandes et al. 2009, pages 33-37). The main problem is that harvest is an economic factor driven by pricing and fishery regulation, not an ecological factor, and that finfish and shellfish need food to grow and habitat to live in. There is not a simple harvest = flow relationship. The original idea was a species-based management approach. The problem with species management is related to the problem with the direct relationship approach, in that species live in a complex environmental setting, and what is good for one species may be bad for another. Modern environmental management usually takes an ecosystem-based approach where habitat and environmental quality is managed for the benefit of the full complement of species. The idea that evolved was that inflow has an indirect effect on bays and estuaries and is best managed by an ecosystem-based approach focused on habitats.

Role of fresh water in estuaries

While it is recognized that freshwater inflow has indirect effects in estuaries (i.e., inflow affects water quality conditions, and water condition affects habitat quality), the idea was first formalized into a management strategy by Alber (2002). The Alber conceptual model was based on a quantitative model of the cumulative impacts on ecosystem processes as a function of changes in freshwater, sediment, and nutrient inflows created by Sklar and Browder (1998). The indirect approach was adopted by SAC to provide guidance to all science and stakeholder teams responsible for making inflow recommendations to the Texas Commission on Environmental Quality, the agency responsible for setting environmental flow standards in Texas (Brandes et al. 2009). The conceptual model developed by these earlier efforts was refined by Palmer et al. (2011) and Montagna et al. (2013) and named the domino theory (Figure 1).

The conceptual model is called the domino theory because there is a domino effect where inflow drives water quality conditions, and living estuarine resources respond to the water quality conditions that drive habitat quality. Recent numerical modeling approaches use this idea to integrate the delivery of nutrients to the estuary that drives primary production, which in turn drives secondary production (Montagna and Li 2010; Kim and Montagna 2009, 2012).

Ultimately, biological resources in estuaries are affected more by salinity solely by flow, because salinity is the most important water quality component regulating community structure (Van Diggelen and Montagna 2016). Salinity is affected by inflow, but there are complexities because of the interactions between tides and geomorphology. Consequently, all salinity-flow relationships are characterized by very high variance or scatter, especially in the low flow end of the spectrum. Because of the links among flow, salinity, and biology, all the resource-based approaches are multi-step and essentially run the domino theory backwards. First, the resource to be protected is identified. Second, the salinity range or requirements of that resource are identified in both space and time. Third, the flow regime needed to support the required distribution of salinity is identified.

It is impossible to manage freshwater inflow without a policy framework and an adaptive management process, both of which have evolved over time in Texas. After a drought in the 1950s, the Texas Water Planning Act was passed by the Texas State Legislature in 1957. This act was amended over the next 10 years and led to the creation of a Texas water plan that was adopted in 1969 and called for 13.5 million ac-ft of freshwater inflows annually to Texas bays and estuaries. Estuarine monitoring programs to inform state water planning and permitting decisions were enacted in legislation in 1985 (HB 2) and 1987 (SB 683; Longley 1994; Powell et al. 2002). A major change occurred in 2007 when the Texas Legislature passed SB 3, which requires that new water permits contain, to the extent possible, a set aside for an environmental flow regime (Montagna et al. 2013). Complex inflow regimes were adopted for stream locations throughout Texas river basins that include provision for subsistence, base, and pulse flows during each of the four seasons (winter, spring, summer, and fall; Opdyke et al. 2014). Altogether, these volumes are large (millions of ac-ft/year [y] or billions of cubic meters [m^3]/y) because they are based on diluting whole estuary systems.

Freshwater inflow needs

There are two issues that make identification of freshwater inflow needs problematic: 1) a large amount of fresh water is needed to maintain ecological integrity, which is dependent on salinity gradients from the river to the sea in the entire estuary, and 2) water in the upstream basins can be allocated to a high degree during droughts. Thus, finding water quantities necessary to resolve these problems is going to be a challenge.

The state of Texas creates a new water plan every 5 years (Texas Water Development Board 2017), which provides the following facts. Human water demand in 2017 was 18.4 million ac-ft/y (22 billion m^3/y), but water supply during a drought is only 15.2 million ac-ft (19 billion m^3/y). This data shows that during droughts, there are insufficient supplies to meet human needs, let alone environmental needs. Worse, it is projected that by 2070 annual water demand will increase 17% and annual water supply will decrease by 11%, which will considerably widen the shortfall during droughts. It is obvious that fresh water is currently over-allocated to meet current demands during droughts.

Where will the water come from to meet environmental needs and standards when it is most needed for human uses, i.e., during droughts? With so little water available and such large volumes necessary to maintain estuarine conditions, it appears that Texas estuaries are at great risk. The arid parts of Texas are already characterized by water scarcity, and this risk increases with climate change (Ward 2011).

Inflow creates different salinity zone habitats within bays (Montagna et al. 1996, and thus the critical need is to characterize within bay dynamics, not bay-wide dynamics. In addition, we now know that minimal inflow during dry times would minimize a bay system from degrading during droughts (Palmer and Montagna 2015; Montagna et al. 2017).

Advances in estuarine science have demonstrated that there are zones within bay systems. The critical zones are the estuarine habitats that are the natural nurseries for estuaries (Deegan and Day 1984) that support connectivity with the coastal sea (Vasconcelos et al. 2011). These zones have also been called refuges, or refugia, because this is a place where estuarine-dependent species can seek refuge during times of stress (Boesch and Turner 1984). Often these nursery habitats are associated with edges of vegetated habitats near freshwater sources, such as mangroves (Nagelkerken et al. 2008), marshes (Boesch and Turner 1984), or areas near river mouths (McCambridge and Alden 1984; Zimmerman and Minello 1984; Kimmerer 2002b; Fernández-Delgado et al. 2007). The key paradigms have been that estuaries are nurseries, many species are estuarine dependent, and freshwater inflow influences habitat (Able 2005). Thus, salinity gradients define habitat utilization in Texas estuaries (Zimmerman et al. 1990; Montagna et al. 2013).

Water resources in Texas are driven by spatial and temporal variability, and most flow occurs during floods separated by periods of low to moderate flows (Wurbs 2021). Thus, periods of higher inflow will occur after low-flow periods. So, if we maintain a natural nursery, this will enable the bay to recolonize more rapidly when higher flow periods resume, and we can ensure that we "maintain the productivity, extent, and persistence of key aquatic habitats" over the long-term as required by 2007's SB 3. These two developments (drought regimes and refuges) provide a basis for a new goal: to determine how much fresh water is needed during dry times to maintain natural nurseries (i.e., refugia).

The areas near river mouths are smaller and shallower, and thus have much smaller volumes of water. Therefore, these areas need much less water to maintain an estuarine salinity zone that would maintain these natural nurseries. A model of the Nueces Delta marsh predicts reductions in plant cover in both drought and moderate conditions, and marsh plant coverage increases only during wet conditions (Montagna et al. 2017). The delta marshes near river mouths are typically composed of a community of marsh plants, such as *Batis maritima, Distichlis spicata, Monanthcloe littoralis, Salicornia virginica, Borrichia frutescens,* and *Spartina alterniflora* (Montagna et al. 2017). These marshes are distinct from fringing marshes that are composed of only *Spartina alterniflora* and occur throughout the bay systems, including the primary bays. Focused flows will not affect fringing marsh habitat in primary bays.

ONE POTENTIAL SOLUTION: FOCUSED FLOWS

The issue of adequate freshwater inflows to maintain estuaries was first raised in the 1960s (Copeland 1966). There have been at least four compilations or reviews on this topic since then: Cross and Williams (1981), Dyer and Orth (1994), Montagna et al. (2002a), and Acreman et al. (2014). So there is quite a bit known about the importance of freshwater inflow to estuaries and the science used to identify environmental flow needs of estuaries (Brandes et al. 2011; Montagna et al. 2013; Adams 2014).

Small scale hydrological restoration projects have demonstrated that measurable environmental benefits can be derived from relatively small amounts of water delivered strategically into the upper ends of Texas estuaries. For example, construction of two dams in the Nueces River watershed and an ensuing drought reduced flow to the Nueces Estuary and overbanking from the Nueces River to Rincon Bayou, which feeds the Nueces Delta marsh (Ward et al. 2002). This led to higher salinities and a reverse estuary where salinity was higher at the mouth of the river than downstream in the bay (Palmer et al. 2002). In 1995, an overflow channel was cut into the bank of the Nueces River to increase the frequency of flow into Rincon Bayou and the marsh. This solution led to higher abundance and diversity of intertidal vegetation (Alexander and Dunton 2002) and benthic communities (Montagna et al. 2002b). Additionally, a pipeline was built to move fresh water directly into the marsh in 2009, and the pumping was able to maintain salinities at less than 35 practical salinity units (psu) during droughts (Del Rosario and Montagna 2018). It was also determined that inflow volumes as low 0.41 m^3/second (29 ac-ft/day) would maintain optimal salinity and water depth for infauna and epifauna communities (Montagna et al. 2018). Water depth is an important factor because focused flows would be delivered to shallow upland marshes and bayous. In Rincon Bayou, which is a good example of an area that requires focused flows, maintaining the ecological health of the marsh would require maintaining salinity between 6 and 18 psu and a minimum water depth between 0.2 meters to 0.3 meters (Montagna et al. 2018).

Flows that create and sustain natural nurseries can accelerate recovery of estuaries, perhaps by years, following the end of droughts. A more rapid recovery of these productive systems has both economic and ecological benefits. Thus, a small amount of water delivered to strategic areas of the estuary during droughts can have great ecosystem and human benefits. These areas are nursery habitats, which are also of lower overall volumes and thus require less fresh water to dilute salt water. Therefore only thousands, rather than hundreds of thousands, of acre-feet of fresh water would be necessary. Small volumes of freshwater inflow could be focused on these nursery habitats at critical times, hence the name of this strategy is "focused flows."

Focused flows are likely not adequate to sustain ecosystem health and productivity for whole estuarine systems, and they cannot substitute for environmental flows that sustain fisheries or ecosystem services beyond drought mitigation. However, focused flows do provide significantly more ecosystem value than a requirement to meet minimum water quality standards, and it has been shown that the public places high value on the impact of freshwater inflow (Yoskowitz and Montagna 2009).

The concept of focused flows could be a more palatable political goal for securing environmental water than what has been attempted in the past. It is a strategy that many stakeholders would likely agree to because it does not force the false choice between securing water to serve people versus the environment. These focused flows may be the only viable option in systems where water is mostly allocated, or restoration is a desirable environmental goal.

The focused flows concept also has economic benefits. Payment for conservation and restoration activities that have public benefits can be provided from the public sector, public-private partnerships, or private social impact investing (Alix-Garcia et al. 2018; Holl and Howarth 2000; Pascal et al. 2018). Also, focused flows could be secured through market-based approaches (i.e., purchasing permanent rights, spot market transactions, or options contracts) because smaller volumes of water are more likely to be available than larger volumes. It has been suggested that a water market in Texas could encourage water conservation (Vaca et al. 2019). Focused flows from water transactions could also be created by mitigation or restoration actions, or a permanent water right. Part of the economic value generated by a more rapid recovery from extreme droughts using a focused flow regime—where natural nurseries are maintained—can be calculated by the increase in the rate of recovery of habitat and infauna and epifauna communities (Montagna et al. 2018; Montagna et al. 2017) and commercially and recreationally important fish recovery (Lellis-Dibble et al. 2008; Brown et al. 2018). Thus, focused flows is an economically useful strategy for restoration projects.

Should a focused flows program be adopted, there will be many new questions that will need to be answered with research, as well as engineering challenges to be met. To design a focused flow regime, it will be necessary to know details about the species present at a specific location, their seasonal dynamics, and the optimal salinity and depth ranges to support the habitat requirements of the species present. It will be necessary to identify valued ecosystem components that would benefit from the focused flows. Mechanisms to deliver water will also have to be resolved. For example, a pipeline was built to transport water around the saltwater barrier (i.e., the Calallen Dam) on the Nueces River to deliver water directly to Rincon Bayou (Montagna et al. 2009). So some kind of conveyance, such as a pipeline or ditch, may be required to deliver water directly to where it might provide the most benefits. Water might be required from storage, return flows, or aquifer storage and recovery, which will provide additional engineering challenges.

Additionally, a focused flow program will likely require some monitoring to determine if the project is working as designed. While the benefit is primarily for maintaining nursery habitat function for biological resources, it will be expensive to monitor the target species utilizing the habitat. However, a minimal monitoring program is inexpensive and should measure habitat characteristics, such as salinity and water elevation, to ensure the habitat design requirements are being met.

The general public expects environmental programs to benefit society (Kulin et al. 2019) and will support them when they are perceived as fair and effective. The focused flows concept provides a science-based approach that meets this desire and in doing so facilitates governmental agencies in meeting regulatory requirements related to water allocations. A focused flow program could also be a means to engage non-governmental organizations more productively (Bennett et al. 2018) to create projects and apply for funding to restore hydrological functioning of estuaries. Water markets have successfully been used to address conservation issues in freshwater systems (Garrick et al. 2009). Focused flows expand those market possibilities to estuarine systems, providing both government agencies and conservation organizations with new cost-effective means to meet both regulatory and environmental needs.

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Estimating statistical power for detecting long term trends in surface water *Escherichia coli* concentrations

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Abstract: Water quality monitoring programs commonly use the Mann-Kendall test or linear regression to identify statistically significant monotonic trends in fecal indicator bacteria concentrations (typically *Escherichia coli* [*E. coli*]). The statistical power of these tests to detect trends of different magnitudes (effect size) is rarely communicated to stakeholders, and it is unlikely they are considered when designing monitoring schedules. The statistical power for detecting trends in surface water *E. coli* bacteria concentrations using Mann-Kendall and linear regression at water quality monitoring sites across Texas was estimated using Monte Carlo simulation. The probability that an individual water quality monitoring site in Texas had adequate statistical power was also estimated using logistic regression.

Mann-Kendall and linear regression trend tests show similar statistical power. Both tests are unlikely to achieve adequate statis-tical power when *E. coli* concentrations decrease by 20% or less over 7 years under most sampling frequencies. To adequately detect concentration decreases of 30% to 40% over 7 years, monthly sampling is required. Because many sites across Texas are sampled quarterly, monotonic trends tests will not be powerful enough to detect trends of moderate magnitudes. To better facil-itate stakeholder decision-making, it is important to communicate the relative power of statistical tests and detectible magnitudes of changes. I suggest data analysts conduct power analyses to improve monitoring program designs and improve communication of trend test limitations. Software and training for water quality analysts could facilitate communication of power and effect sizes. Alternative trend assessment methods may be more reliable for describing changes in fecal indicator bacteria concentrations.

Keywords: trend detection, *E. coli,* statistical power

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Terms used in paper

Acronym / Initialism	Descriptive Name
CV	coefficient of variation
EPA	U.S. Environmental Protection Agency
E. coli	*Escherichia coli*
GLM	generalized linear model
LOADEST	Load Estimator
mL	milliliter
MPN	most probable number
SWAT	Soil and Water Assessment Tool
SWQM	Surface Water Quality Monitoring
TCEQ	Texas Commission on Environmental Quality
TMDL	Total Maximum Daily Load
WRTDS	Weighted Regressions on Time, Discharge, and Season

INTRODUCTION

Excessive concentrations of fecal indicator bacteria are one of the primary sources of surface water quality impairment in the state of Texas. Fecal indicator bacteria trends are often assessed for significant downward or upward trends using statistical tests. The number of samples and the statistical variance directly impact the magnitude (or effect size) that a statistical test can reliably detect. This is typically referred to as statistical power. Because fecal indicator bacteria concentrations are often characterized by high variance, there is considerable likelihood that common trend tests are not powerful enough to detect trends with the magnitude of interest to stakeholders or decision-makers under typical monitoring frequencies. The primary purpose of this article is to provide an improved understanding of and guidance for determining monitoring frequencies for trend analyses of fecal indicator bacteria in Texas.

Fecal indicator bacteria are used to assess the sanitary quality of water for recreational and water supply purposes. Fecal indicator bacteria themselves are not dangerous but are utilized as an indicator of potential health risks associated with exposure to pathogens associated with fecal matter. *Escherichia coli (E. coli)* is a non-host specific bacteria found in the gut of warm-blooded animals and used as a fecal indicator bacteria in Texas to assess if streams and other freshwater bodies meet numeric water quality criteria for contact recreation. The numeric criterion for *E. coli* concentrations is based on U.S. Environmental Protection Agency (EPA) epidemiological studies correlating risks of illness with concentrations of *E. coli* at recreational beaches with point source sewage discharges (Dufour 1984; Fujioka et al. 2015). Typical sources of *E. coli* include sewage, domestic livestock, wildlife, and pets, although *E. coli* has also been documented to naturalize in sediment and algae (Ishii and Sadowsky 2008).

The Texas Commission on Environmental Quality (TCEQ) biennially assesses water quality across the state as part of the requirements with the federal Clean Water Act. Water bodies that exceed water quality standards are placed on the 303(d) list that is provided to EPA. The state is required to develop total maximum daily loads (TMDLs) that calculate allowable pollutant loads and allocate the loads between different sources that discharge to a water body when a water body fails to achieve improved water quality and removal or delisting from the 303(d) list.

In-stream fecal indicator bacteria concentrations typically follow a log-normal distribution (Novotny 2004). As a result, TCEQ biennially evaluates compliance with the in-stream criterion of 126 most probable number (MPN)/100 milliliters (mL) using the geometric mean over a 7-year assessment period. The geometric mean is simply a measure of central tendency calculated as the exponential of the arithmetic mean of logarithms:

$$\left(\prod_{i=1}^{n} y_i\right)^{\frac{1}{n}} = \exp\left[\frac{1}{n}\sum_{i=1}^{n} \log y_i\right], \quad \text{when} \quad y_1, y_2, \ldots, y_n > 0 \quad (1)$$

Simplified, the geometric mean computes the arithmetic mean of *log(y)* and exponentiation returns the mean to the original scale. An alternative approach is to take the *n*th root of the product of y_i. The current assessment approach requires a minimum sample size of 20 over a 7-year assessment period with an 80% confidence interval that exceeds the 126 MPN/100 mL criterion at the lower bound for a stream to be considered impaired and added to the 303(d) list of impaired water bodies (TCEQ 2019a). Delisting requires 20 samples and a geometric mean below the 126/100 mL criterion. TCEQ (2019a) does not specify how the confidence interval should be calculated. Traditional methods multiply a critical value (obtained from the standard normal distribution or Student's t-distribution) by the standard error. Confidence intervals can also be obtained by parametric bootstrap methods (Wilcox 2013).

As of 2018, TCEQ identified 237 impaired water bodies based on elevated fecal indicator bacteria (TCEQ 2019b). TMDLs and implementation plans or watershed protection plans are developed for these impaired water bodies to address potential fecal indicator bacteria sources. As part of these plans, trend analysis is typically conducted to assess if bacterial concentrations have increased or decreased over time. Two common methods for assessing statistical significance of monotonic trends are the Mann-Kendall test and linear regression on fecal indicator bacteria concentration values (Helsel and Hirsch 2002; Yue and Wang 2002).

Yue and Wang (2002) described the calculation of the Mann-Kendall test and the modifications for correlated data. In short, when the Mann-Kendall test statistic, *S*, is negative, newer values tend to be smaller than older values and indicate a downward trend. A small absolute value of *S* indicates no trend. The *P* value of the test statistic is estimated using the normal cumulative distribution function. The null hypothesis of the Mann-Kendall test is that there is no trend.

Simple linear regressions on log-transformed *E. coli* concentrations are also suitable for identifying trends. In order to assess presence of a trend, the following linear regression is used:

$$\log(y) = \beta_0 + \beta_1 x + \varepsilon \quad (2)$$

where y is *E. coli* concentration, β_0 is the intercept, β_1 is the coefficient of time variable x, and ε is the error term assumed normally distributed around mean zero. If linear regressions are utilized to assess *E. coli* trends, the analyst should assess model residuals to ensure the regression model meets assumptions of heterogeneity and normal distribution.

Both the Mann-Kendall test and linear regression are straight forward methods for water quality analysts to apply and assess trends in *E. coli* concentrations. They are well accepted and have routines available in most statistical software. However, general guidance is not available for the number of samples required to detect given effect sizes. Current assessment guidance for attainment of the water quality criterion (20 samples over 7 years) is adequate given the ability to estimate confidence intervals for the geometric mean calculation. As a result, many monitoring programs across the state utilize quarterly sampling regimes, which equate to approximately four samples per year or 28 samples over a 7-year assessment period.

Often, the results of trends tests are simply communicated as, "the Mann-Kendall trend test detected a significant trend ($p < 0.05$)." On its own, the presence or lack of statistical significance does not provide meaningful information for decision-making. The p-value is simply a threshold for the researcher to reject the null hypothesis. More bluntly, the researcher infers that an effect exists from the p-value, but the p-value does not communicate the magnitude of the effect or whether it is meaningful. Reporting a model coefficient or Sen slope with the p-value provides context of effect size. For water quality, this is typically described in units of total change or more commonly percent change over the time period of interest, such as by saying "a statistically significant 35% decrease in fecal indicator bacteria was observed." Such reporting of effect sizes to stakeholders is important because it provides context of environmental change that is useful for decision-making.

Reporting the results of a trend detection test implies the test has the statistical power to detect trends of certain magnitudes or effect size. However, that information is rarely reported, and it is unlikely that it is routinely calculated by water quality analysts. Therefore, there is considerable uncertainty if monitoring schedules (especially those designed around quarterly monitoring) used across the state are adequate for detecting trends in fecal indicator bacteria.

Statistical power refers to the probability that a statistical test rejects the null hypothesis when the alternative hypothesis is true. In the case of the discussed trend tests, power is the probability that the null hypothesis (that no trend is present) is rejected when there is in fact a trend in the data. Statistical power is a function of pre-assigned significance level (α), effect size, sample size, and variance within the time series (Yue et al. 2002). First, a meaningful effect size must be determined. The effect size might be biologically meaningful or informed by stakeholder input. Statistical power can be determined for a range of sample size, significance levels, effect sizes and sample variance. Using this information, a monitoring program can be designed that balances sample size and ability to detect meaningful effect sizes with a trend test.

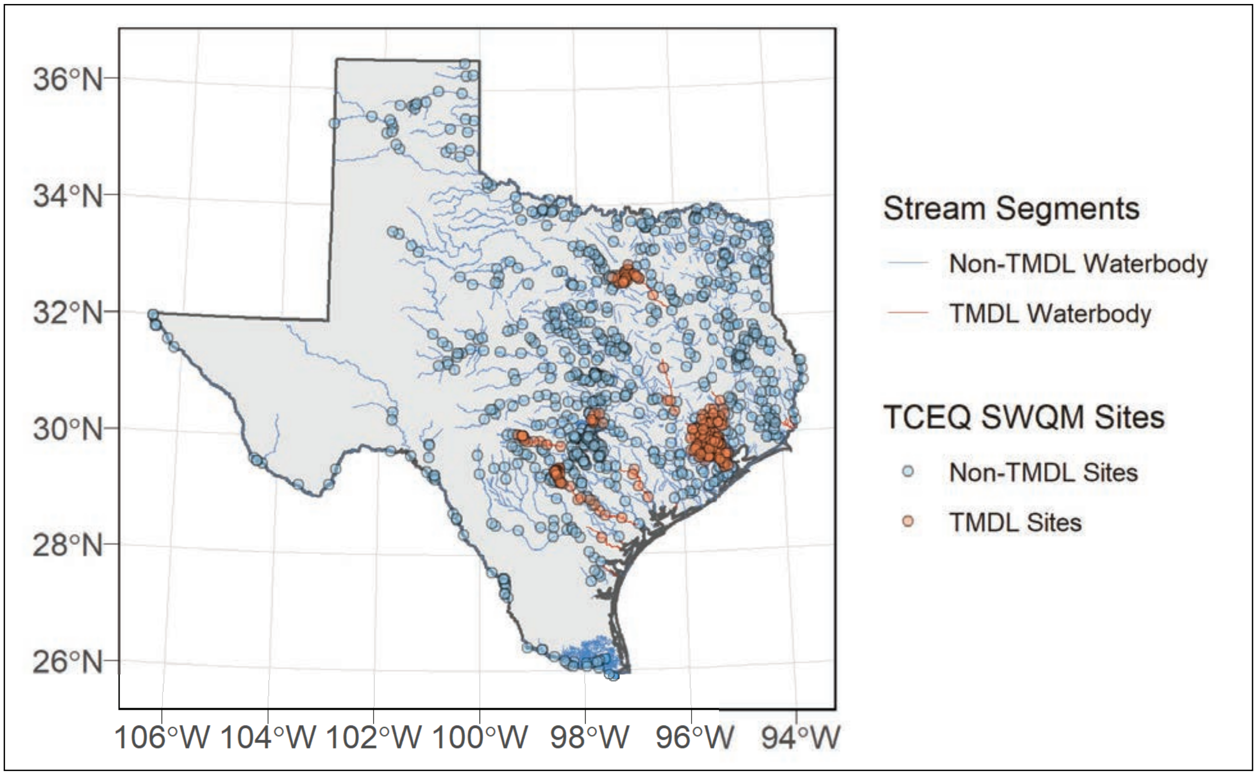

Figure 1. Map of TMDL and non-TMDL stream and SWQM site locations.

Two examples are described to provide practical context of statistical power and effect sizes. In the first scenario, a watershed group is interested in monitoring *E. coli* concentration trends following the installation of a large best management practice in the watershed. The best management practice is expected to result in a 10% reduction in bacteria concentrations over 5 years. The monitoring plan will need to determine how many samples are needed annually to confidently detect the hypothesized trend. If too few samples are collected, a 10% change may never be detected by the hypothesis test. If too many samples are collected, trends of smaller effect size can be detected. However, the group is not interested in detecting a small effect and the money could be better used elsewhere by the group.

In the second scenario, a watershed group is analyzing *E. coli* data collected over the last 7 years. In this case, the number of samples is already established. The hypothesis test fails to reject the null hypothesis that there is no trend in the bacteria data. The watershed group is disappointed because they worked hard to address bacteria sources and expected at least a small improvement in bacteria concentrations. In this case, a post-hoc power analysis indicates that the statistical power is 0.80 when there is an 40% change in bacteria concentrations over 7 years. Power analysis also indicates that the statistical power drops to 0.40 if there is only a 30% change in bacteria concentrations. In this case, it is important to tell the group that based on the number of samples, it was unlikely that a trend could be detected at a given significance level. Using different experimental design (such as pre-, post-testing) or improved sampling procedures would provide more meaningful insight for the stakeholders.

The purpose of this article is to provide some guidance and context in determining monitoring frequency for trend analysis of fecal indicator bacteria, specifically *E. coli*. First, I estimate the statistical power of Mann-Kendall and linear regression trend tests at sampling sites across the state using Monte Carlo simulation. Second, I provide statistical power plots at different effect sizes for a range of observed variance values. Finally, I model the likelihood of adequate statistical power for *E. coli* trend detection at sampling sites across Texas.

METHODS

Data

TCEQ Surface Water Quality Monitoring (SWQM) site information and associated *E. coli* samples collected during the 7-year period from January 2012 through December 2019 were obtained from the Water Quality Portal using the "dataRetrieval" package in R (De Cicco et al. 2018; R Core Team 2019). Data was restricted to river or stream sampling sites, and SWQM sites with fewer than one sample per year were removed from analysis. In total, *E. coli* data was assessed from 984 SWQM sites (Figure 1). Stations were also divided into groups based on the presence or absence of an indicator bacteria TMDL. Water body locations and TMDL classification were spatially linked to a SWQM station location layer to classify SWQM stations as located within or outside a TMDL water body (TCEQ 2020). Although stations could have been split by a number of different variables (for example, watershed protection plans, impairment status, or region), TMDLs were used due to the simplified association with specific water bodies and relatively high number of indicator bacteria TMDLs to ease interpretation of results.

Statistical power computation

The significance level, α, is the probability of rejecting the null hypothesis when it is true (Type I error). The probability of accepting the null hypothesis when it is false is a Type II error (β). The statistical power of a test is the probability of rejecting the null hypothesis when the alternative hypothesis is true and is equal to 1 - β. A power of 0.80 is typically considered appropriate, which equates to a 20% chance of encountering a Type II error. If sampling from a population where the null hypothesis is false, power is calculated as:

$$Power = \frac{N_{rejected}}{N} \quad (3)$$

where N is the total number of tests and $N_{rejected}$ are the total number of times the test rejected the null hypothesis.

For each SWQM site, Monte Carlo simulation was used to observe the statistical power of the Mann-Kendall and linear regression test for detecting trends (Sigal and Chalmers 2016). The simulation generates 1,000 independent log-normal distributed time series samples per evaluated effect size for each SWQM site using the site-specific log-transformed mean and standard deviation. Effect sizes were induced by reducing the annual log-transformed mean over the 7-year sampling period by 10%, 20%, 40%, and 80%. Over 3.93 million simulations were run per trend detection method. Significance level, α, was set at 0.10. The Mann-Kendall test and linear regression were applied to each simulation sample and the number of times the tests correctly rejected the null hypothesis ($N_{rejected}$) were tabulated. Statistical power plots were also generated using Monte Carlo simulation on sample datasets generated using the quartiles (lower, median, and upper) of the observed coefficient of variation (CV) of *E. coli* from SWQM sites. CV is a method of measuring the spread of a distribution relative to the size of the mean; specifically, it is ratio of the standard deviation to the mean. These power plots provide a general idea of the expected statistical power of characteristic *E. coli* datasets in the state using typical sampling intervals. They are not intended to be a replacement for conducting a statistical power test using site-specific data.

Likelihood of adequate statistical power

I modeled the likelihood that a SWQM site would have adequate statistical power (≥ 0.80) as a function of sample size, variance, and effect size using generalized linear models (GLMs). GLMs are an extension of linear regression that allows for response variable with non-normal error distributions through the use of a link function. GLMs were setup as a logistic regression model of form:

$$\log\left[\frac{P(Y)}{1-P(Y)}\right] = \quad (4)$$

$$\beta_0 + \beta_1 cv + \beta_2 sample\ size + \beta_3 effect\ size + \varepsilon$$

where the probability of adequate statistical power is response on the right-hand side of the equation and is a function of the sum of the dependent variables with their corresponding coefficients (β) and random errors (ε). GLMs were fit using the “glm” function in R with the binomial family and logit link function.

RESULTS

Monitoring frequency

Out of the 987 evaluated SWQM sites, 329 were located in water bodies with a TMDL. A total of 22,766 samples were collected at the 658 non-TMDL SWQM sites compared to 13,008 collected at the 329 TMDL SWQM sites. SWQM sites located on water bodies without a TMDL were generally sampled three to four times per year (Figure 2). SWQM sites with a TMDL skewed higher, with a peak at nine times per year and smaller peaks at four and six times per year. This suggests that increased monitoring efforts are targeted towards sites with TMDLs. Similarly, the *E. coli* geometric mean skewed higher at sites with a TMDL (Figure 3). This is expected as TMDL sites are impaired for bacteria, although there are non-TMDL sites that are also impaired and a TMDL has not been developed yet.

Estimated statistical power at SWQM sites

At current annual sampling frequencies, all SWQM sites fell below 0.80 power for detecting effect sizes of 10% (Figure 4). At 20% effect size, all non-TMDL sites had less than 0.80 power. The majority of TMDL SWQM sites fail to detect a 20% change. However, there is large observed variance in statistical power for TMDL sites at 20% effect size. At 40% and 80% effect sizes, the majority of TMDL SWQM sites had power above 0.80. Non-TMDL SWQM sites exhibit high variance at 40% effect sizes and sufficient statistical power at most sites

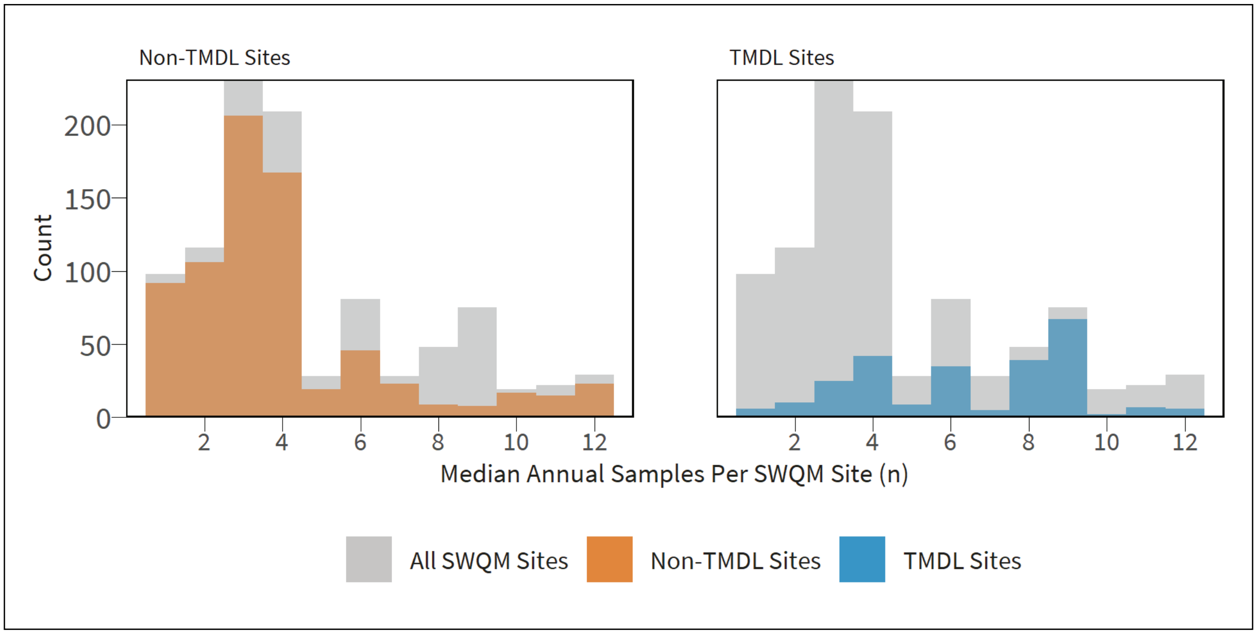

Figure 2. Histograms of annual *E. coli* sampling distribution for TMDL and non-TMDL SWQM sites across Texas (January 2012 through December 2019).

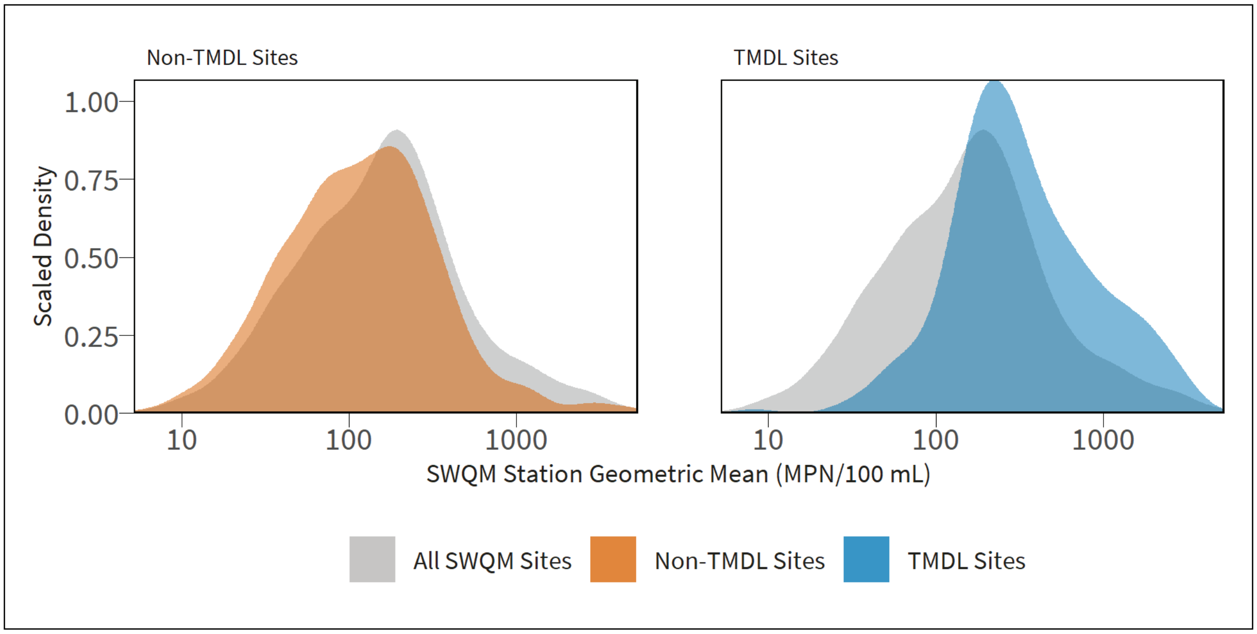

Figure 3. Scaled density plots of *E. coli* geometric mean distribution for TMDL and non-TMDL SWQM sites across Texas.

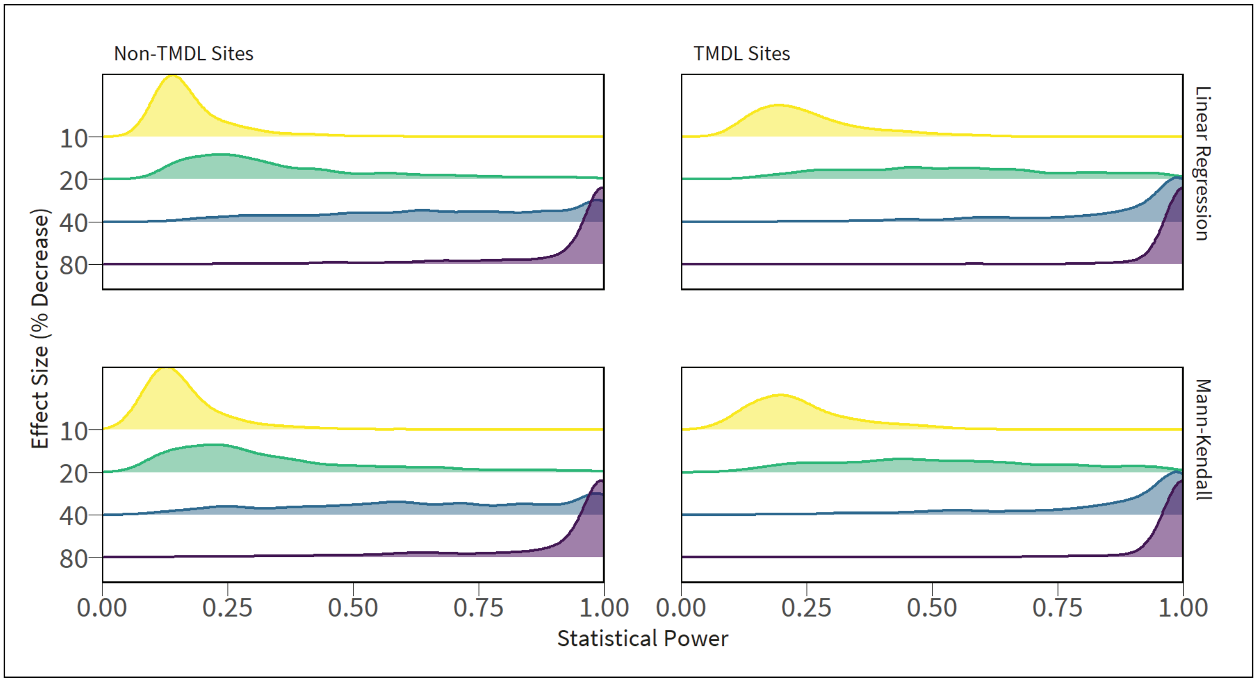

Figure 4. Scaled density plots of Mann-Kendall and linear regression statistical power distribution for TMDL and non-TMDL SWQM sites as a function of effect size at α = 0.1. Individual curves represent the scaled density estimate of statistical power values calculated for SWQM sites at a given effect size (y-axis values).

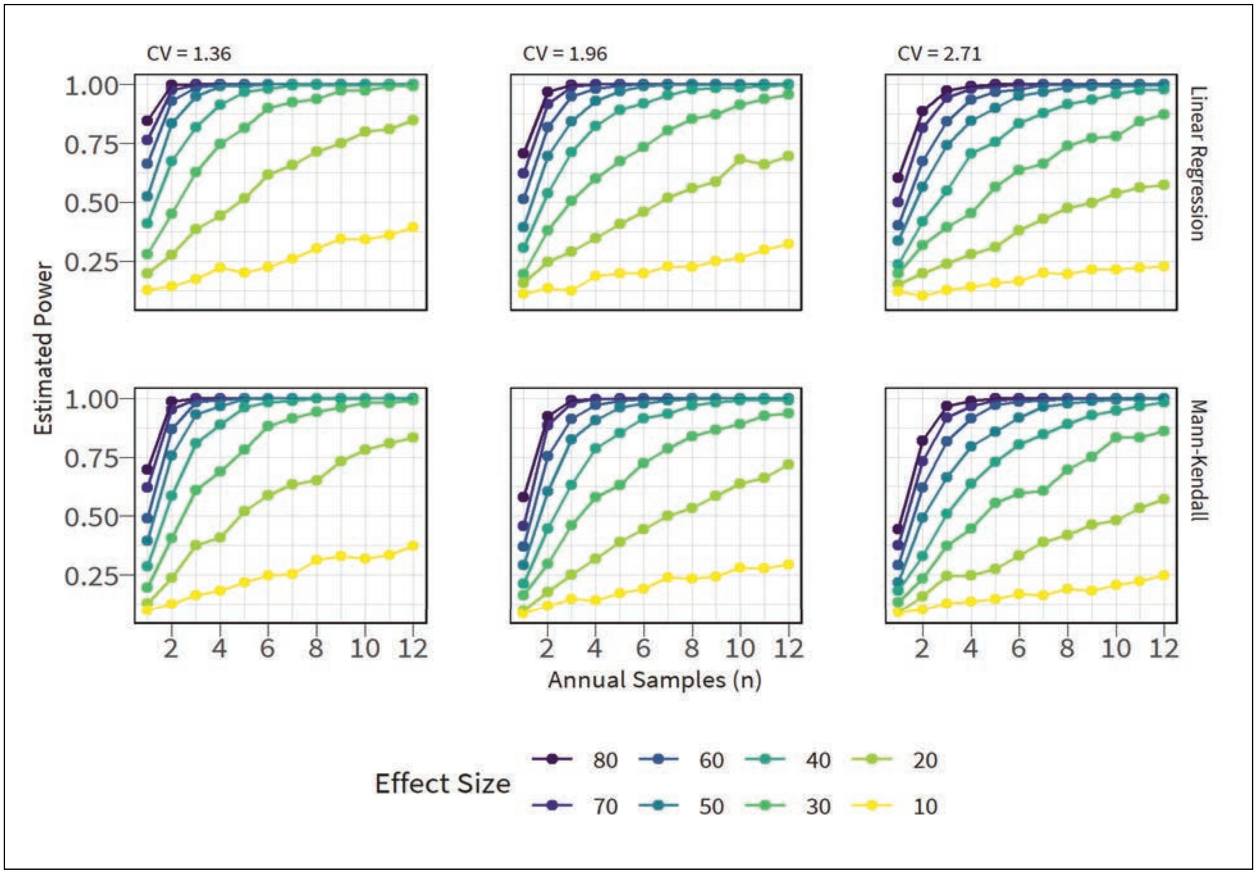

Figure 5. Estimated statistical power of Mann-Kendall and linear regression trend tests at upper, middle, and lower quartiles of observed station *E. coli* variance.

Table 1. GLMs for probability of adequate statistical power.

	Mann-Kendall			Linear regression		
Variable	OR[1]	95% CI[1]	p-value	OR[1]	95% CI[1]	p-value
CV	0.39	0.34, 0.45	<0.001	0.38	0.33, 0.43	<0.001
Sample size	1.74	1.66, 1.83	<0.001	1.72	1.63, 1.80	<0.001
Effect size	0.90	0.89, 0.90	<0.001	0.89	0.89, 0.90	<0.001

[1] OR = odds ratio, CI = confidence interval

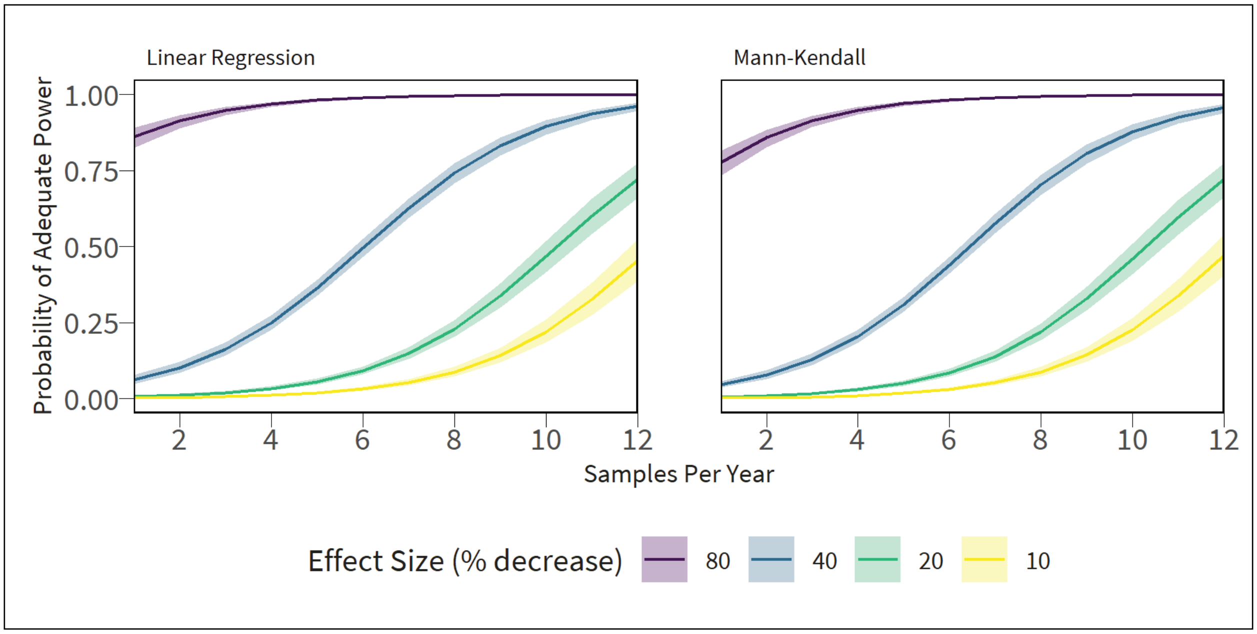

Figure 6. GLM marginal effects plots show the likelihood that a SWQM site has adequate statistical power for detecting trends as a function of the number of samples and desired detected effect size. CV is held constant at the mean.

at 80% effect size. These differences coincide with the higher sampling efforts devoted to TMDL SWQM sites.

The upper, middle, and lower quartiles of the CV across all sites was 2.71, 1.96, and 1.36. The CV values indicate the relatively high variance in *E. coli* concentrations within SWQM sites. Statistical power calculated for the Mann-Kendall and linear regression tests on simulated *E. coli* datasets at the identified CV quartiles is displayed in Figure 5. For each test, as CV increases, statistical power decreases at each given effect size. Overall, both methods show similar statistical power.

Neither method has adequate power to detect trends at 10% effect size. At median variance, both tests have marginal power to detect trends of 30% with 12 samples per year. At 40% effect size, Mann-Kendall and linear regression require five and four samples per year respectively to achieve greater than 0.8 power. At 50% and greater effect size, three or fewer samples per year are required to achieve adequate power. It is important to note that these figures are developed for typically expected *E. coli* distributions at SWQM sites. A site-specific power analysis conducted using existing sample sets would provide a more accurate assessment of the expected sample distribution and estimated statistical power.

Likelihood of obtaining statistical power

Variance, sample size, and effect size are significant and substantial predictors of the probability that a SWQM site will have adequate power for detecting trends using linear regression or Mann-Kendall test methods (Table 1). Figure 6 displays the estimated effect of sample size and effect size on probability of adequate statistical power being obtained at a SWQM site. At mean variance values and large effect sizes, it is likely that adequate power will be obtained regardless of sample size. Probability decreases substantially as effect size and sample size decrease. Even with monthly sampling, there is only 0.5 probability that a SWQM site will obtain 0.80 power for detecting a 10% effect size.

The GLM models demonstrate the implications of sample design for identifying trends at SWQM sites. Non-TMDL sites often have four or fewer samples per year (Figure 2). The likelihood of detecting all but the largest of changes in *E. coli* concentrations at non-TMDL sites are small. TMDL sites generally implement more sampling effort through the year and are more likely to obtain adequate power for identifying trends of smaller magnitude. In either case, the relative detectable effect size might seem high to stakeholders given the sampling effort expended.

DISCUSSION

The primary objective of this exploratory analysis is to communicate the importance of considering effect sizes when utilizing hypothesis tests to identify trends in fecal indicator bacteria datasets. Given the high variance observed in *E. coli* samples, I observed relatively low power for detecting trends of 20% or less in magnitude. Logistic regression demonstrates there is low likelihood that SWQM sites will have the desired power for detecting up to a 20% change in *E. coli*. At 40% and larger effect sizes, various sampling regimes can be developed with sufficient power for detecting trends. The paper focuses on statistical power and effect size because effect size is a more useful metric than p-values and provides environmental or decision-making relevance (Nakagawa and Cuthill 2007; Hanel and Mehler 2019). While statistical significance provides a metric to infer the presence of an effect, statistical power and effect sizes provide information about detectable magnitudes that can be used to make decisions.

Power calculations prior to development of monitoring schedules would allow improved estimation of the number of samples required for trend detection. Given the number of ongoing monitoring programs across the state, a more likely scenario is a post-hoc analysis to identify the minimum effect size that is likely to be detected by a trend test. The basis of identifiable effect sizes requires communication with stakeholders to determine meaningful changes in water quality. Conversely, power can be calculated after the data are collected to identify the statistical power achieved. Water quality management is an inherently stakeholder-driven process that requires substantial communication, trust, and knowledge-sharing (Leach and Pelkey 2001). Power analysis could be useful for communicating the anticipated or achieved statistical power of trend tests to stakeholders. By focusing discussion on effect sizes and not statistical significance, there is increased opportunity for communicating understandable results.

Although the Mann-Kendall and linear regression trend tests are relatively easy to conduct, statistical power tests are likely to be outside the expertise of a typical water quality analyst. Communication with a statistician is often recommended before sample design. Additionally, for such routinely designed water quality monitoring projects, an accessible software package for water quality analysts would be useful. For example, the "emon" package in R provides accessible functions for estimating the statistical power of various hypothesis tests on environmental data sets (Barry et al. 2017). However, it does not include functions for evaluating typically log-normal data such as fecal indicator bacteria. There is an opportunity to provide simplified interfaces for routine power tests. For example, the Soil and Water Assessment Tool (SWAT) is now available online with a simplified user interface (Yen et al. 2016). SWAT is a fairly complex deterministic model used to simulate physical watershed processes such as streamflow and pollutant loading. Although it is used by hydrologists and researchers around the world, it requires substantial user investment to develop skills to properly use it. The simplified online interface provides calibrated SWAT model outputs that are much more accessible to watershed planners and non-modelers. With the increased availability of low-cost cloud computing and cloud based statistical platforms, similar implementation of simplified targeted statistical services should be feasible.

Alternative methods for evaluating indicator bacteria trends can also be utilized. Statistical models, such as generalized additive models, Load Estimator (LOADEST), or Weighted Regressions on Time, Discharge, and Season (WRTDS), can estimate monthly or annual average fecal indicator concentrations (Runkel et al. 2004; Hirsch et al. 2010; Wood 2011). Aggregated modeled values typically have less variance than sampled measurements, allowing for improved comparisons of year-to-year variations and trends. Furthermore, the marginal effect of the temporal component of these models can be assessed for periods of significant change using confidence intervals or decomposed to assess trends under different flow conditions (Zhang et al. 2020). It is likely that monthly sampling for at least several years is required to build an accurate statistical model. For example, WRTDS recommends 10 to 20 years of data and at least 100 samples to identify temporal trends with confidence. Even this recommendation might be low for log-normal data with such high variance. A second drawback is the difficulty fitting these models. Generalized additive models and WRTDS both rely on the R statistical software and an analyst who is proficient in statistical modeling and programming in R. LOADEST is available as a stand-alone executable; however, the program still requires some specified training.

Monotonic (and non-linear) trend analysis is not the only method to evaluate water quality. A plethora of statistical methods are available to analysts, and the appropriateness of those methods will vary based on the questions that stakeholders and decision-makers need answered. It is outside the scope of this article to discuss each method and scenario. Underlying the effective use of any empirical method is an understanding of appropriate sample sizes required to make informed decisions. In some cases, exact formulas are available to calculate required sample sizes to achieve adequate statistical power. In other cases, as shown here, Monte Carlo simulation provides an effective way to estimate statistical power under various scenarios.

It is worth noting that despite the numerous TMDLs and watershed-based plans developed in Texas based on fecal indicator bacteria-based assessments, effort is being made toward developing risk-based assessments using quantitative microbial risk assessment and microbial source tracking (Goodwin et al. 2017). It is well established that pathogen sources (wildlife, raw sewage, or treated effluent for example) influence the infectivity of fecal pathogens, which directly influence the risk of infection associated with exposure to water with fecal contamination (Schoen and Ashbolt 2010; Soller et al. 2010; Gitter et al. 2020). Management based only on fecal indicator bacteria concentrations and not the makeup of the contributing sources results in overestimates of human health risk. As methods to assess water body compliance with potential future-risk-based pathogen exposure criteria develop, the methods to estimate and communicate trends and effect sizes with stakeholders will also need to evolve.

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Groundwater Withdrawals Associated with Oil and Gas Production from Water Supply Aquifers in Texas: Implications for Water Management Practices

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Kristine Uhlman[3], Chris Vickers[1,2]

Abstract: The demand for water in Texas is continuing to increase as population and industry grow. The Natural Resources Defense Council has indicated that Texas is at "extreme risk" and will require implementation of sustainable water management practices, particularly since groundwater supplies much of the state's freshwater demands. This study evaluated the occurrence and extent of produced water discharge with low total dissolved solids associated with oil and gas production from the Carrizo-Wilcox formation in Texas. We conducted analyses of produced water discharge permits from the Railroad Commission of Texas, which included limited water quality data of permitted discharges, the groundwater quality in the Carrizo-Wilcox formation from which the producing wells extract, and the potential conflicts between state permitted discharge quantities and ongoing aquifer conservation programs in the area. Our findings show that the Railroad Commission of Texas, the governing agency for Texas oil and gas development, permits produced water to be discharged into surface waters if the discharged water quality meets Texas Surface Water Quality Standards set by the Texas Commission on Environmental Quality for the specific receiving water body. Nearly 5,331,975 cubic meters (4,323 acre-feet) of groundwater each year is discharged as produced water from the Carrizo-Wilcox Aquifer to surface waters through discharge permits designated as "agricultural". Based on an evaluation of the reported Whole Effluent Toxicity test data, 69 discharges of water from the Carrizo-Wilcox formation amount to total dissolved solids levels of less than 1,000 milligrams per liter, 35 of the discharges have total dissolved solids levels of 1,000–1,500 milligrams per liter, and 20 of the discharges have total dissolved solids levels of 1,500–4,000 milligrams per liter. Forty four percent of the referenced discharges exceed the Texas Commission on Environmental Quality's secondary drinking water standard for total dissolved solids (1,000 milligrams per liter), and there is potential that water quality changes are under-reported, as permit values are stagnant but produced water quality generally degrades over time. However, the water quality of the discharges complies with general requirements for several water uses associated with agricultural and industrial practices, although it is understood water quality would need further characterization prior to use. Evidence found in this study suggests that the lack of communication regarding the identified discharges and the associated water quality could lead to conflicting groundwater practices that, at least on a local level, could have negative impacts, such as contributing to aquifer overexploitation. This overextraction in turn is expected to negatively impact existing groundwater conservation efforts and the future of water supply of Texas.
Keywords: low total dissolved solids produced water, shallow oil and gas production, water supply aquifers, Texas

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Terms used in paper

Acronym / Initialism	Descriptive Name
ac-ft	acre-feet
API	American Petroleum Institute
ASR	aquifer storage and recovery
bbl	billion barrels
bgs	below ground surface
BUQW	base of usable quality water
CFR	Code of Federal Regulations
CWA	Clean Water Act
EPA	U.S. Environmental Protection Agency
ft	feet
GCD	groundwater conservation district
m^3	cubic meters
MAL	minimum analytical limit
MDD	maximum daily discharge
mg L^{-1}	milligrams per liter
NPDES	National Pollutant Effluent Discharge System
POTW	publicly owned treatment works
ppm	parts per million
PWA	produced water analysis
RRC	Railroad Commission of Texas
SAWS	San Antonio Water System
SI	supplementary information
TCEQ	Texas Commission on Environmental Quality
TDS	total dissolved solids
TOC	total organic carbon
TSWQS	Texas Surface Water Quality Standards
TWDB	Texas Water Development Board
WET	Whole Effluent Toxicity

INTRODUCTION

Increased study of groundwater conservation has become critical as the demand for freshwater is continuing to increase with population and development growth. As engineering technologies have improved over the last 100 years, extraction rates of groundwater, the single largest resource of freshwater in the world, have increased substantially to accommodate the needs of a growing population (USGS 2015). In addition, inconsistent use of the term freshwater since the formation of the Texas Board of Water Engineers in 1913, and later the 1957 Texas Water Development Board (TWDB), has resulted in confusion in characterization of water quality. For example, attributing freshwater as being < 3,000 parts per million (ppm) was common until the formation of the TWDB Groundwater Advisory Unit (GAU), which specified the base of usable quality water (BUQW) as < 3,000 ppm of total dissolved solids (TDS) and superior quality water ("good tasting") as < 1,000 ppm (RRC 2020). Early TWDB data tabulations of produced water generically characterized as freshwater (< 3,000 ppm) led to confusion (RRC 2021). To avoid confusion, in this paper we use the TCEQ water quality standard definition. Further, poor management leads to the overexploitation of freshwater from aquifers and detrimental impacts including but not limited to resource depletion, land subsidence, and water quality degradation (Ponce 2006).

Although water demand across the United States has declined due to conservation efforts in the last decade, based on current trends of population and development growth in Texas, total water demand is projected to increase by 12.3% between 2000 and 2050. Additionally, comparing groundwater extraction to precipitation and aquifer recharge, groundwater overdraft rates are greater than 25%, pointing to our society's current and growing unsustainable use of aquifers (Spencer and Altman 2010). In Texas, while water demand has decreased in the last decade, the water supply is still overextended from both groundwater and surface water (Schwabe et al. 2020). The significant population growth coupled with climate change and other factors contributing to drought, including increased evaporation, present significant challenges to Texas in its efforts to confront water scarcity. Challenges include an estimated water shortage of 8.9 million acre-feet (ac-ft) annually by 2070, caused by current supply allocation problems (Brun et al. 2017).

In 2014, Texas aquifers supplied 62% of the 16.9 billion cubic meters (m^3; 13.7 ac-ft) of water used in the state, making aquifers a critical source of water for Texas (TWDB 2016). In 2010, the Natural Resources Defense Council deemed that Texas and other surrounding states are at "extreme risk" and require implementation of sustainable water management tools, and if extraction rates continue to exceed supply, Texas is likely to experience increasing limitations on water availability in the near future (Spencer and Altman 2010). As though lack of adequate groundwater management is not reason enough for concern, hydrologists and water managers have long recognized that large quantities of water in Texas surface reservoirs are subject to evaporation (Wurbs and Ayala 2014) and seasonal variation due to periods of precipitation and drought, indicating that groundwater is the most reliable source of freshwater available to the state.

Texas has historically been and continues to be the United States' leading state in oil production (Kim and Ruppel 2005; EIA 2020). Additionally, oil and gas production is one of the main driving factors of the Texas economy, which is ranked second largest in the United States, with a value of $1.6 trillion (Forbes 2016). The oil and gas sector produces mainly from source formations, primarily producing non-potable water as a byproduct of oil and gas production (Veil et al. 2004). Produced water from these formations is considered to be a large source of waste that contains relatively elevated levels of hydrocarbons, heavy metals, and other pollutants (Al-Ghouti et al. 2019). Not as common are instances where the produced water may be of low TDS when oil and gas production occurs in shallow geologic strata that host water of low salinities, such as water supply aquifers as discussed in this study. To our knowledge there are two other locations in the United States where water of low TDS is extracted as a product of conventional oil and gas explorations: the Pavilion site in Wyoming (Degenhardt 2012) and California, where conventional extraction of oil and gas has been producing water of lower salinity (Kondash et al. 2020). Although most produced waters are salty (brine), some produced waters can be low TDS as demonstrated in this study (RRC 2016a). In Texas, when produced waters meet the standards set by the Texas Commission on Environmental Quality (TCEQ; RRC 2016b), the operator can discharge the produced water directly into surface waters. Most of the produced water, however, is not of a usable water quality (TDS < 1,000 milligrams per liter [mg L^{-1}]) but is instead salty/brine (TDS > 35,000 mg L^{-1}) and is disposed of via injection wells regulated by the Railroad Commission of Texas (RRC 2016b).

Produced water is generally brine and is disposed of via injection wells (EPA 2012a). However, to our knowledge, no research has addressed the discharge of produced water originating from formations also known to be hosting potable water resources in Texas. An unusual occurrence, the disposal of low-TDS produced water was investigated in this study. More specifically, the aim of this study was to determine the existence and extent of low-TDS produced water discharge associated with oil and gas production practices in an area in Texas that overlaps the Eagle Ford Shale Play. In addition, the quality of permitted produced water discharges was evaluated in the context of potential reuse for different needs in the near area. This information was attained through analyses of produced water discharge permits from RRC, which included the gener-

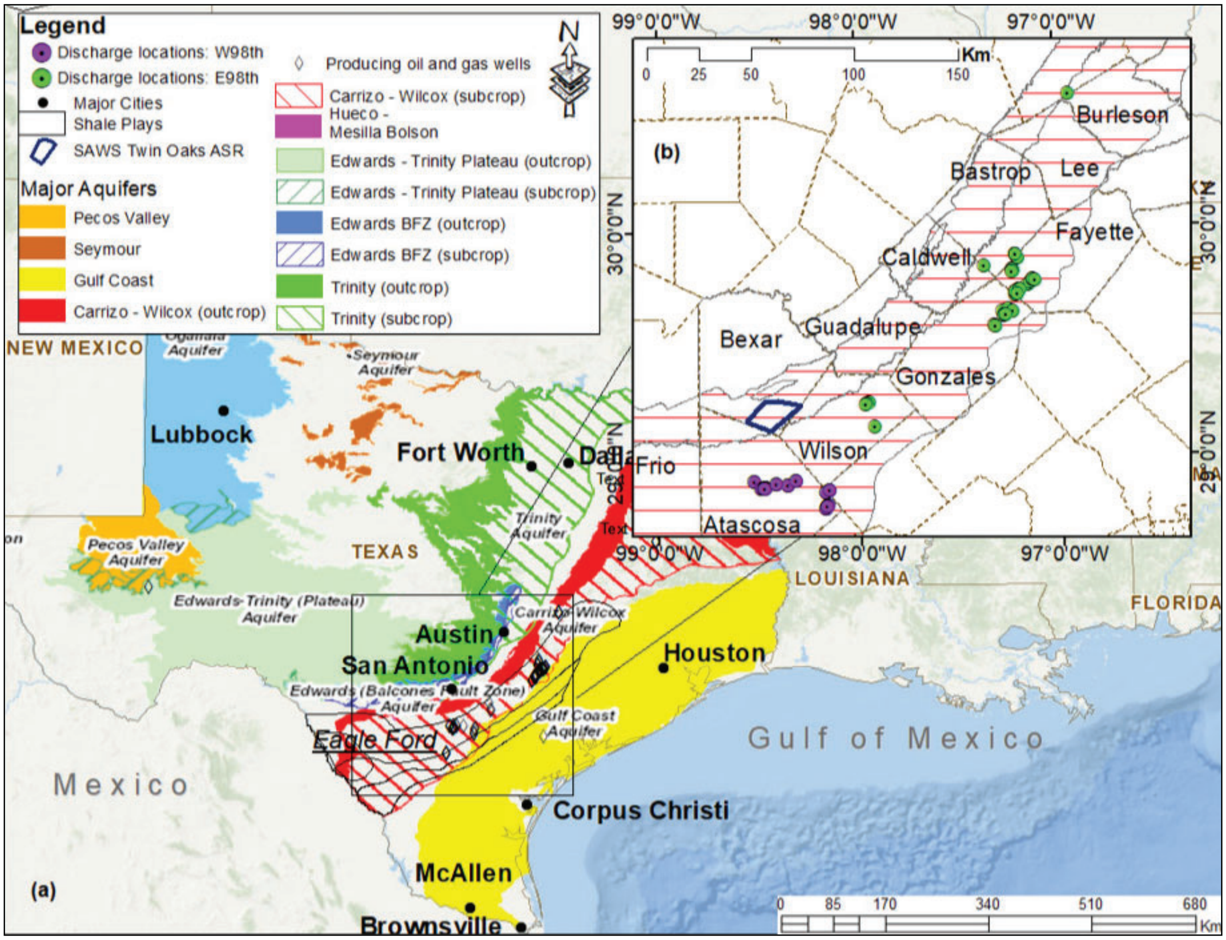

Figure 1. Location map of the study area including location of oil and gas wells (a) associated with surface discharge permits for low total dissolved solids produced water (b). In (b), the location of Carrizo-Wilcox Aquifer outcrop and subcrop are identified by the red line filed region. In (a), the San Antonio Water System aquifer storage and recovery area includes the injection and recovery wellfield.

al information about the water quality of permitted discharges, the groundwater quality in the Carrizo-Wilcox formation from which the producing wells extract, and potential conflicts between state permitted discharge quantities and ongoing aquifer conservation programs in the area. These discharge data were gathered by individual oil and gas companies and submitted to RRC as criteria to maintain operating permits.

MATERIALS AND METHODS

Study area

One of the most extensive water-producing formations in Texas, the Carrizo-Wilcox Aquifer stretches, within the Gulf of Mexico Coastal Plain, from the Rio Grande to the Texas/Louisiana/Arkansas border (Figure 1). Because the Carrizo and Wilcox sands are not easily distinguishable and they are often hydrologically interconnected, the term "Carrizo-Wilcox Aquifer" is frequently used. The massive formation that makes up the Paleocene-age Carrizo Sand is overlaid by the Wilcox Group, a Tertiary-age formation interbedded with sands, clays, silts, and some discontinuous lignite beds. This hydrologically connected area makes up the Carrizo-Wilcox Aquifer that is overlaid by confining shales and clays of the Reklaw and Bigford Formations in East and Central Texas and South Texas, respectively. The thickness of the Carrizo-Wilcox Aquifer varies widely across the state. The saturated thicknesses of the outcrops vary from less than 100 feet (ft) in South Texas to 700 ft in South Central Texas. In down-dip sections, the Carrizo-Wilcox Aquifer reaches only a maximum of 500 ft in South Texas and up to 2,000 ft in South Central Texas. In Central and East Texas, the Carrizo-Wilcox Aquifer thins somewhat, with outcrop saturated thickness of less than 500 ft and down-dip thickness of 1,000 to 1,500 ft and no more than 1,000 ft, respectively (Figure 2). Four general cross sections for the Carrizo-Wilcox Aquifer are shown in Supplementary Information (SI) I.

In South Texas, the Carrizo Sand is the preferred source of groundwater with only minor amounts of water being with-

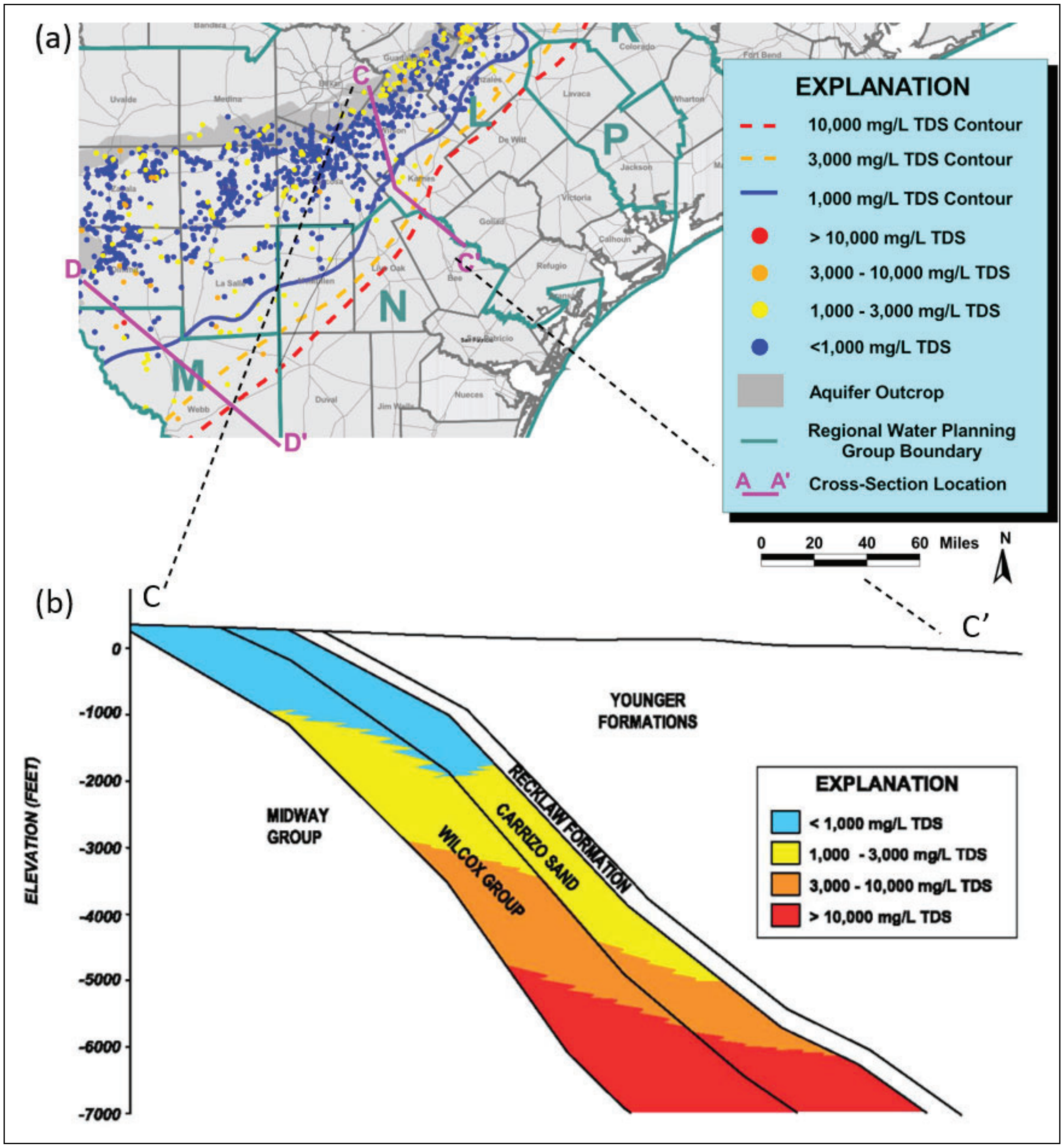

Figure 2. (a) Visual representation of groundwater quality in the Carrizo-Wilcox Aquifer, accompanied by cross section views including formation total dissolved solids (TDS) and depth and (b) simplified cross section C-C' of the Carrizo-Wilcox Aquifer with generalized water quality ranges (LBG-Guyton Associates 2003).

drawn from the sand and clays of the underlying Wilcox formation. A significant amount of freshwater is withdrawn from the Carrizo-Wilcox Aquifer for irrigation, industrial, and public water supply uses. Low-TDS water is found in the outcrop areas and up to 40 miles down-dip from the outcrop areas throughout much of the extent of Carrizo-Wilcox Aquifer in the state. Only in South Texas is low-TDS water not found in the outcrop areas of Carrizo-Wilcox Aquifer. In general, salinities increase farther down-dip, with low-TDS water generally being found in outcrop areas and at shallow depths, while slightly saline water is found at depths ranging from about 3,000 to 4,000 ft and moderately saline water at depths ranging from about 3,000 to 6,000 ft.

Data types, sources, and analyses

TThe data presented in the results and discussion section of this study was provided by RRC through an open records request between 2017 and 2019. This information was processed, and locations were inputted into ArcMap, along with daily discharge levels, for visual data representation. Upon receipt of the requested information, a thorough analysis of data was conducted, and permits were separated based on "active" and "inactive" status (see SI III, IV). Discharge quantity levels were only provided by RRC with the active permits; however, some of the values for active permits were not provided despite the status (see SI IV). It is understood that with age of the producing well, the volume of produced water is expected to increase. The permits are named and listed numerically, although there is some confusion based on the indicated information that some permits with higher numbers have earlier initiation dates and others do not. It is possible that the discharge permit records through RRC may not have been maintained, as many of the original permit dates given are not categorized as "new" but rather as "transfer(ed)" or "renew(ed)" (see SI III). Additionally, several discharge permits that were categorized as "discharging" were not listed on the active permit list (see SI IV).

In addition, a search for the oil and gas wells by American Petroleum Institute (API) commission number (API, drilling permit number, oil lease number, and/or gas identification number) associated with the permitted discharges was conducted to determine producing depths and the associated water-bearing formation and water quality. The data were also obtained from RRC via open record requests and the RRC geographic information systems viewer. Depth of production for each well was compared with TWDB groundwater chemistry data for water wells in the immediate area to the identified APIs. The TWDB groundwater chemistry data were compared to that from the reported National Pollutant Effluent Discharge System (NPDES) permit Whole Effluent Toxicity (WET) tests filed with U.S. Environmental Protection Agency (EPA) for those sites where produced water was being discharged under a NPDES permit. An evaluation of existing water resource management programs and potential for produced water reuses in Texas was conducted, and the information was compared to the data findings.

RESULTS AND DISCUSSION

For reporting and discussion, EPA guidelines for water quality were used in this paper (EPA 2020). The 1,000 mg L^{-1} limit is the secondary drinking water standard set by TCEQ (Young and Ronayne 2011). Slightly saline water, with TDS values between 1,000 and 3,000 mg L^{-1}, is generally used for livestock and agriculture, while water with levels above 3,000 mg L^{-1} must be treated to reduce salinity prior to use. Water with TDS exceeding 3,000 mg L^{-1} and less than 10,000 mg L^{-1} is considered moderately saline. Water with more than 10,000 mg L^{-1} to less than or equal to 35,000 mg L^{-1} is very saline. When TDS levels are greater than seawater (approximately 35,000 mg L^{-1}), the water is considered brine (WHO 1996; Young and Ronayne 2011; Godsey 2017).

Permitted discharge process and requirements

An evaluation of surface water discharge permits for the South Texas area presented in this study shows when low-salinity or low-TDS water is produced as a byproduct of oil and gas development, the operator of the producing well can file for a produced water discharge permit. This permit, acquired from RRC, classifies all the low TDS discharges as "agricultural," and the information of discharge quantity and quality is not shared with local groundwater conservation districts (GDCs).

Texas is separated into four NPDES discharge zones: two offshore zones within 9 nautical miles of the shore and two inshore zones, east of the 98th meridian and west of the 98th meridian (Figure 1). The 98th meridian is an arbitrary line established by EPA and followed by RRC to structure monitoring of inland discharge permits (Humberson 2016). All Texas inland discharge locations, regardless of zone, are subject to the RRC application. Discharge permits allow for produced water to be separated and discharged into a creek or other waterway as long as the quality of the discharged water meets the Texas Surface Water Quality Standards (TSWQS) set by TCEQ for the specific receiving body. Along with a produced water analysis (PWA), the permit application must meet several other criteria, including permission from the surface owner of the producing property (see SI II.2).

Based on surface water quality standards set by TCEQ, RRC compares each PWA to the standards of the affected receiving water body, listed as "segments" in the TSWQS. The TSWQS for and location of all segments actively receiving produced water from locations with permits issued by the RRC is provided in SI IV. Maximum allowable TDS levels and the daily discharge in barrels at that maximum TDS level for each segment are depicted in Figure 3. RRC's Statewide Rule 8(d)(6) states that an oil and gas operator may submit a permit application to RRC for authority to operate settling pits. Settling pits function as the last stage of water and oil/grease separation after the standard facility separation process. Along with the permit application, the operator may submit a written letter for request of landfarming or produced water discharge. The operator must notify the surface owner of the land where the pit will be located and submit a written letter of approval by the surface owner to RRC along with the written pit permit application. If the land where the pit will be located is within municipal corporate limits, the operator must also notify the city clerk or other appropriate city official. If water disposal is by discharge into a watercourse, Rule 8(d)(6)(C) requires that an applicant for a discharge permit must give proper notice to the surface owner of each waterfront tract between the discharge point and 0.5 miles downstream of the discharge point. Notification is only necessary during the initial permitting process and not during permit renewal, which occurs every 5 years, per Rule 8(d)(6).

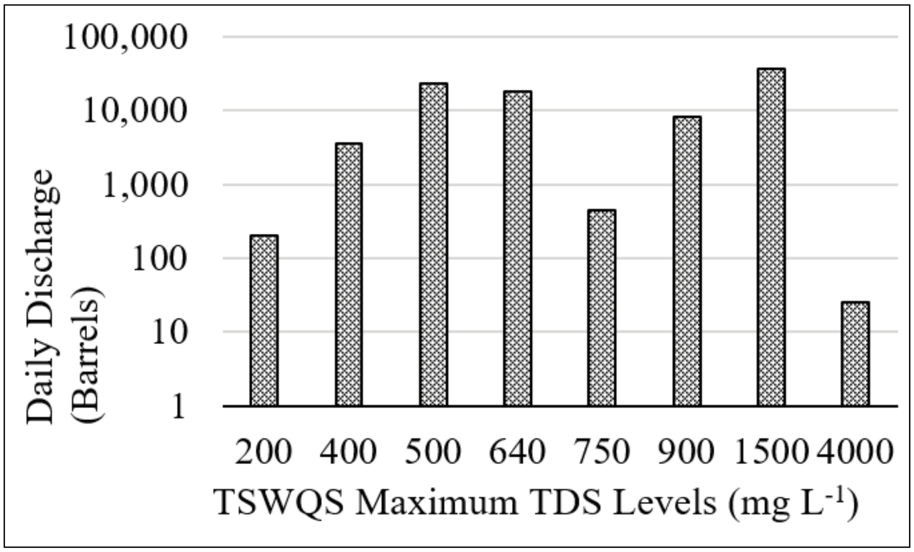

Figure 3. Permitted volumes of water discharged into various segments, as shown in Supplementary Information III by maximum allowable total dissolved solids levels.

Landowners affected by the drilling can oppose the permit and request a hearing. The RRC director of environmental services may also request a hearing if they feel it is in the public's interest. A permit may be modified, suspended, and/or terminated at any point after RRC issues it if a request for hearing is attained for good cause, which constitutes the following six options: (1) Water pollution is occurring or is likely to occur; (2) Waste is occurring or is likely to occur; (3) Permit or rule violation; (4) Factual misrepresentation in application; (5) Failure to give notice; and/or (6) Material change of conditions (RRC 2016a).

When a permit application is approved by RRC, the operator must then apply for a NPDES permit. In the past, the application requirements and permits were slightly different based on the inshore discharge zone in which the applicant was located (separated by the 98th meridian, Figure 1). EPA has drafted a permit, the TXG350000, intended to apply to all inshore produced-water discharge locations regardless of their location. In conclusion, when applying for a produced water discharge permit, an applicant must meet all TSWQS as well as pass the NPDES WET test. According to EPA, the WET test is a vital component to implementing federal water quality standards under the Clean Water Act (CWA) 402. The test is intended to replicate the total effect of environmental exposure of aquatic life to the toxic pollutants in an effluent without requiring a lab analysis and identification of the specific pollutants. If the exposed aquatic life survives the effluent, the test is passed. An applicant or permit holder must submit a WET test to EPA on an annual basis so long as the discharge point is active (EPA 2017).

Through RRC permits, the well operators are only required to notify landowners and EPA of water discharge, and any potential issue with the discharge permits focuses predominantly on water quality and potential toxicity. There is no attention placed on the amount of low-TDS water being removed and discharged under NPDES, and as a result, there is no legal requirement that the relevant GCDs be notified of the discharge locations or quantities. To our knowledge, at the time this study was conducted, there was no communication with GCDs regarding these discharges.

The data obtained from RRC are incomplete in certain permit representations. The daily discharge levels are based on the submitted maximum daily discharge (MDD) segment of each permit, at the discretion of each individual well operator. The water discharged after the separation process must meet TSWQ standards for the respective segment. According to RRC, the MDD levels are supplied every 5 years at the time of permit renewals and are not monitored further, although a well operator is supposed to notify RRC if discharge levels increase (SI II.1). The listed MDD levels are for current permits only. Therefore, any well re-completion that may have occurred in the past such that a permitted well might produce more oil, and therefore more water, has not been considered in the current analysis. This lapse in data recording suggests that the actual amount of low-TDS produced water maybe unknown. It is also important to note that according to an article published by the U.S. Geological Survey, as a well ages, the amount of water produced increases exponentially (Veil et al. 2004). Thus, older conventional oil and gas wells could be abandoned, no longer bringing low-TDS water to the surface. It is also expected that the water quality will degrade with time. Lastly, to highlight the lack of available discharge data, the actual age of many of the discharge permits is unknown, as many of the first records classify a permit as "transfer" or "renew" (see SI IV).

Table 1. Water volumes. The numbers indicated in bold font are numbers taken from researched data. All other numbers are converted through standard conversion rates.

Water practice	Cubic meters	Acre-feet	Gallons	Barrels
Removed through oil and gas shallow formation exploration discharge permits/year	5,331,975	4,323	1,408,547,775	**32,756,925**
Injected into SAWS ASR/year (2004–2011)	17,715,865	14,362	**4,680,000,000**	108,837,209
Injected into SAWS ASR/year (2015–2020)	29,603,520	24,00	**7,820,420,000**	181,870,233
NPDES discharges in Atascosa County	2,152,515	1,745	568,629,850	**13,223,950**
NPDES discharges Atascosa, Wilson, and Karnes counties/year	2,725,845	2,210	720,086,600	**16,746,200**
2014: amount of water used in Texas	**16,900,000,000**	13,700,946	4,464,473,000,000	103,824,953,488

* There may be an option to use low total dissolved solids produced water based on physical location in counties such as Atascosa. Acronyms: San Antonio Water System (SAWS) Aquifer Storage and Recovery (ASR); National Pollutant Discharge Elimination System (NPDES).

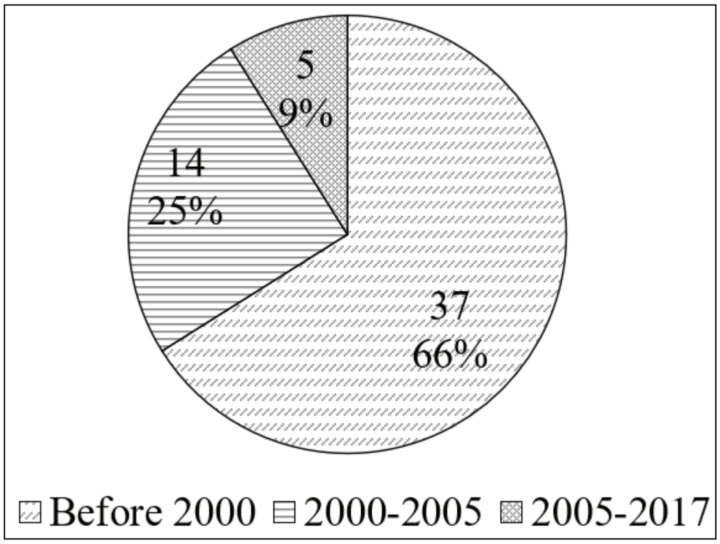

Figure 4. Ages of active discharge permits found in SI IV and the number of active discharge points that have been running since the dates provided by the Railroad Commission of Texas.

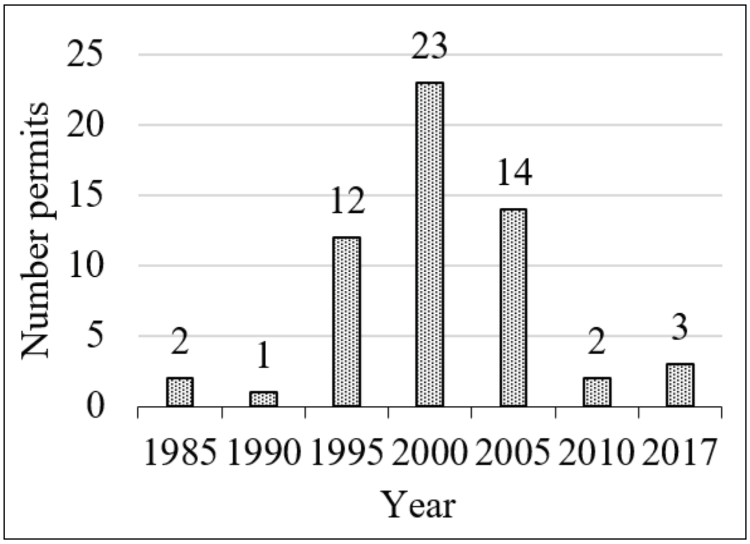

Figure 5. Number of new permits issued between each 5-year sequence.

Occurrence and disposal of low-TDS produced water discharges

According to the data identified in this study from RRC, there are 57 active permits for low-TDS water discharge in the state of Texas (SI IV.2). One of these permits is in northwest Texas, thus not associated with the area of interest. When compared to the data provided on discharge quantity and location, four permits are listed as currently discharging but are not included in the active permit list. Simultaneously, there are seven active permits for which no discharge data were provided (see SI IV). As a result, the following discussion is derived from an assessment of both active and non-active permits. Of the 56 permits, two-thirds (37) of the locations have been discharging low-TDS water since before the year 2000 (Figure 4); some of those locations appear to have been active since 1984. The largest number of new permits (e.g., 49) were in 1995 and 2005 (Figure 5). The number of new permits decreased drastically by 2017. Fifty-three of the discharge locations provided are in proximity to the Carrizo-Wilcox formation (Figure 1). Excluding several of the active permits for which discharge data were not reported, the permitted produced water discharge volume was a significant 5,331,975 m³ (4,323 ac-ft) per year (Table 1) with TDS ranging from 36 to 3,892 mg L^{-1} (average 960 mg L^{-1}).

Another limitation on the data available from RRC is related to the depth from which the water is removed through the oil and gas extraction process. To fill this gap, API drilling permits were compiled. Available information indicates that roughly 157 oil and gas wells are associated with the 56 permits discharging in proximity to the Carrizo-Wilcox Aquifer (SI IV.1). The well records indicate oil and gas producing depths ranging from 570 to 6,025 ft below ground surface (bgs). Out of the total number of wells, 138 produce from depths ranging from 570 to 2,570 ft bgs (Figure 6a), corresponding to the Carrizo-Wilcox Aquifer. Another 15 wells produce from depths between 2,570 and 4,570 ft bgs and are also associated with this formation, though these depths correspond more with the lower Wilcox formation (SI I.2). Two wells with production depth between 5,570 and 6,570 ft bgs were not clearly correlated with the Wilcox formation.

Data collected from water wells located near these producing wells indicate that 73 of the producing wells extract from aquifer depths ranging from 1,355 to 3,800 ft, where groundwater TDS is less than or close to 500 mg L^{-1}. Another 74 wells produce from aquifer depths ranging between 1,350 to 2,800 ft, where nearby groundwater TDS levels are between 1,000 and 1,500 mg L^{-1}. At most, eight wells produce from aquifer depths between 3,500 and 4,500 ft, where groundwater TDS is around 1,650 mg L^{-1}. Furthermore, two of the wells that produce from aquifer depths between 5,700 and 6,025 ft could not be correlated with any groundwater quality data. These wells, however, were associated with the higher TDS NPDS discharge (average 2,050 mg L^{-1} TDS) for permit 00768 (see SI I.1). Unfortunately, no information was found related to the volumes of produced water by wells associated with each permit.

The groundwater quality assessment shows good agreement with the reported water quality data per permitted discharge as presented in Figure 6b. Based on this evaluation, most NPDES discharges (~83%) do not exceed 1,500 mg L^{-1} TDS. Receiving basins (segments) that have adopted environmental inflow standards (Figures 7 and 8) are Atascosa River (segment 2107), Colorado Cummins Creek (segment 1402), Martinez Creek (segment 1902), Somerville Lake (segment 1212), Frio River (above Choke Canyon Reservoir; segment 2117), Cienegas Creek to Rio Grande (segment 1748), and Guadalupe River below San Marcos River (segment 1803; Figure 8). The average reported TDS concentrations per TSWQS 307 segment criteria (e.g., water quality standards for each water body or segment) was found to exceed the established limit for segments 2304, 1902, and 2117 (Figures 7b, 8). Other parameters such as total organic carbon (TOC) and oil and grease (Figure 6c) were evaluated; however, there is no set maximum limit for the water body by the TSWQS 307 segment criteria for comparison.

The only existing regulation governing oil and grease discharge is related to EPA pretreatment discharge, regulation 40 Code of Federal Regulations (CFR) 403.5(b)(6). These criteria prohibit the discharge of "petroleum oil, non-biodegradable cutting oil, or products of mineral oil origin in amounts that will cause interference or pass through" when water is distributed to a publicly owned treatment works (POTW; EPA 2004). Most POTWs have adopted 100 mg L^{-1} as their local limit for petroleum-based oil and grease. Nevertheless, recommendations are for concentrations less than or equal to 75 mg L^{-1} and preferably less than 50 mg L^{-1} of oil and grease from mineral or petroleum origin to prevent water quality degradation (Costle et al. 1979). The identified permitted discharges were on average oil and grease concentrations below 20 mg L^{-1} (Figure 6c).

Alternative beneficial use of TDS produced water

With the demand for freshwater increasing rapidly, the need to preserve and reuse water is becoming more urgent. Texas is experiencing declining groundwater levels and intermittent water flows, and the capture and storage of water when it is available is critical to sustainable water management for the state (Nicot et al. 2011). Yet based on this evaluation, thousands of acre-feet of produced low-TDS water have been discharged to surface water bodies in Texas annually. As also indicated in this study, the amount of low-TDS produced water

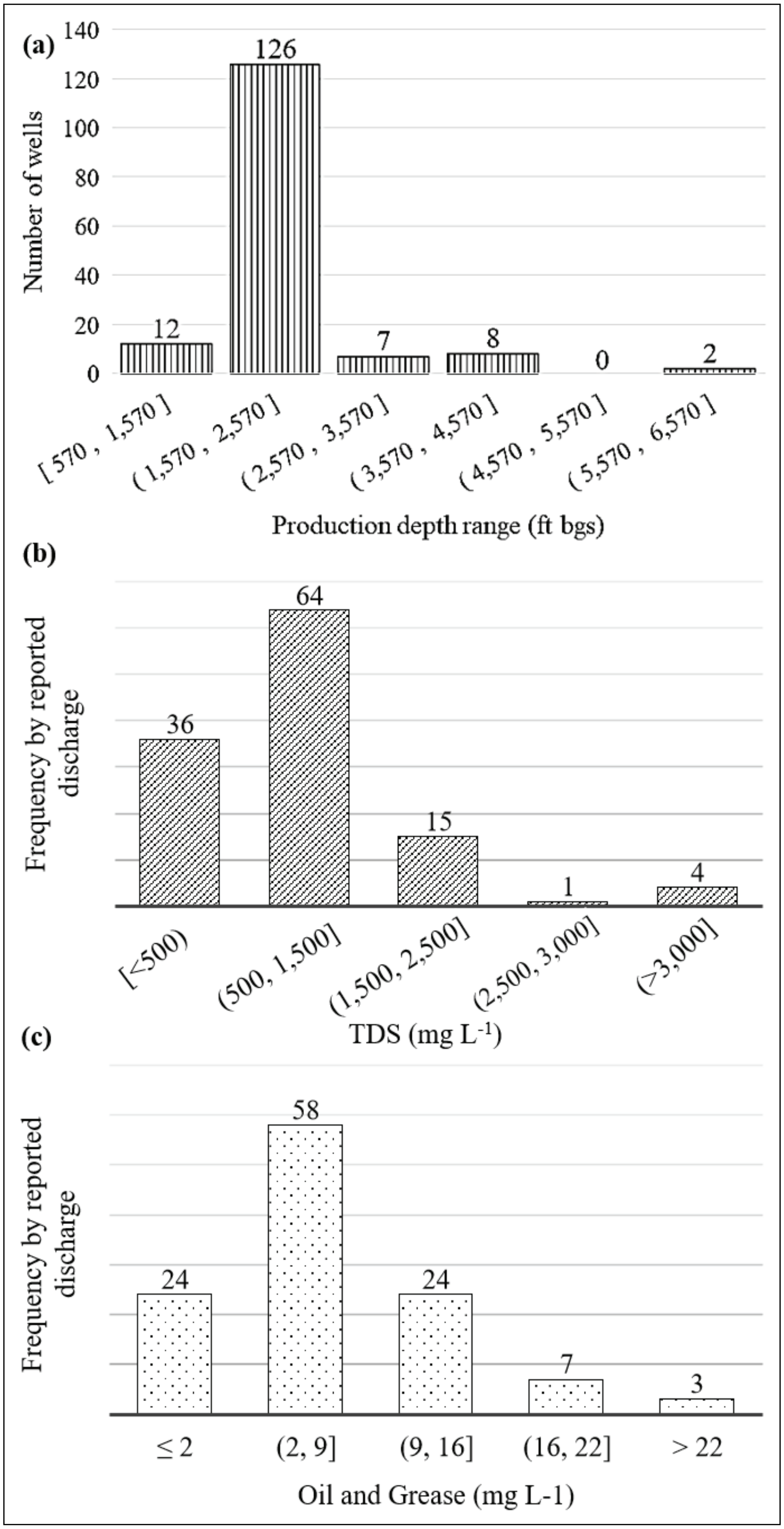

Figure 6. Frequency of occurrence of (a) wells per producing depth range, (b) total dissolved solids (TDS) level distribution based on reported water quality data per year, and (c) oil and grease level distribution based on reported water quality data per year.

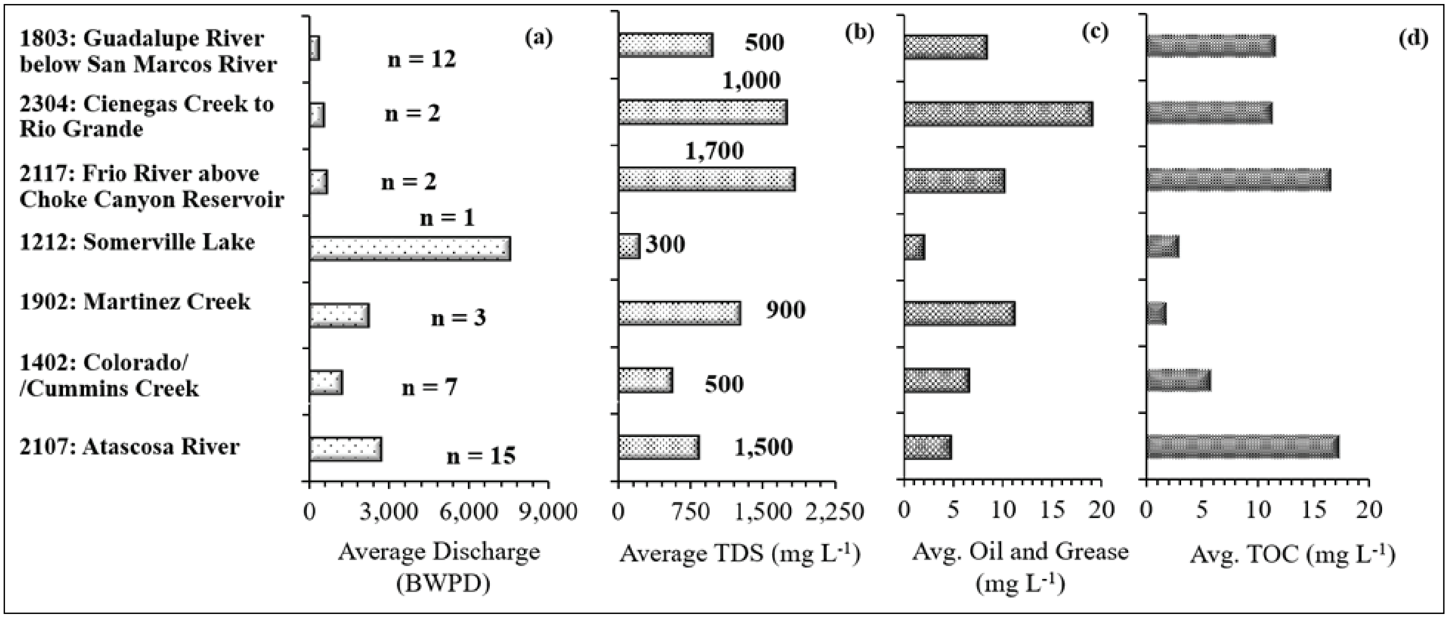

Figure 7. Average reported discharge volumes (a) and laboratory analyses levels of total dissolved solids (TDS) (b), oil and grease (c), and total organic carbon (TOC) (d) by segment. These data are based on the number of permitted discharges (i.e., n in (a)) reporting water quality data and discharge volumes from the Railroad Commission of Texas. The Texas Surface Water Quality Standard 307 segment criteria for TDS (in milligrams per liter [mg L^{-1}]) is included next to the average measured TDS for each segment as shown on Figure 8.

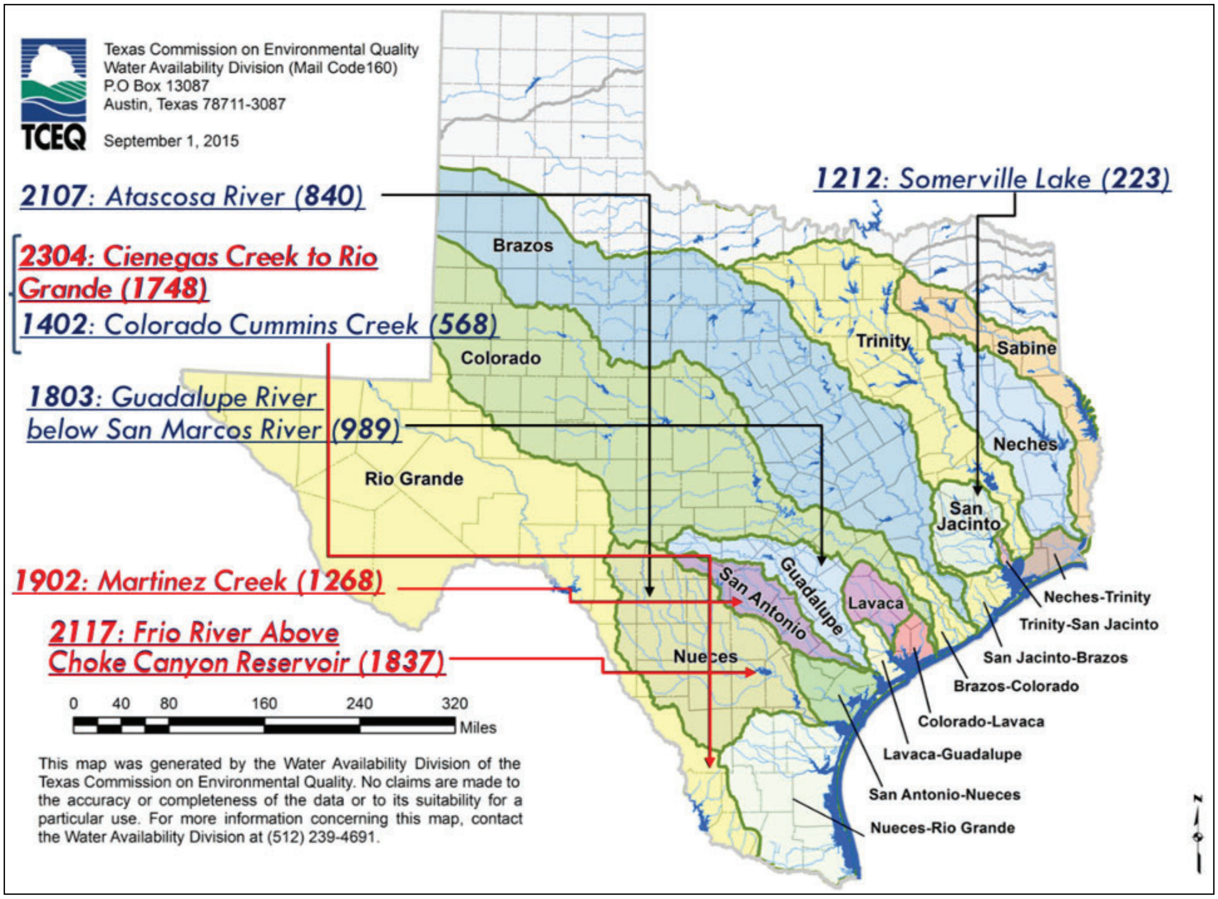

Figure 8. Map showing the produced water receiving basins which have adopted environmental inflow standards. The average reported total dissolved solids concentrations per Texas Surface Water Quality Standard 307 segments is also included with 2304, 1902, and 2117 exceeding the established segment criteria.

through oil and gas production has been inaccurately recorded and documented.

Reported NPDES discharges of produced water from oil and gas operations associated with shallow water-producing formations are filed as agricultural use by landowners surrounding the discharge point. The produced water, once extracted, is discharged to a surface waterway (Figures 7, 8). Once in the watershed, water supplies are exposed to climatic influences and evapotranspiration. It appears, based on the findings of this study (see SI IV), that most of the water discharged from RRC-permitted locations is flowing away from the Carrizo-Wilcox recharge zone.

As presented by Veil (2015), there are a variety of water management technologies and strategies that could optimize beneficial use of the low-TDS produced water. Practices that involve reuse or recycling of produced water for different purposes include reinjection for later use (e.g., aquifer storage and recovery or ASR) and hydrologic maintenance purposes (e.g., preventing land subsidence). Depending on specific water quality, reuse can also benefit agricultural and industrial use as well as treatment for drinking purposes (Veil 2015). In the absence of reuse/recycle options, methods for disposal of produced water include direct discharge (common for offshore production), underground injection (including enhanced recovery and common for onshore production), evaporation, and offsite commercial disposal. Discharge to receiving streams may also benefit stream ecology and in that sense may not be considered disposal. The more common management of produced water is disposal via Class II injection wells into formations that are not connected with underground drinking water sources (EPA 2012a).

In the short term, it is more economical and less labor-intensive for oil and gas operators to discharge low-salinity water into TCEQ segments than to dispose of the produced water via injection wells. As a result, when produced water, such as that in this study, has been determined to be of low TDS overall, water disposal practices such as disposal via deep injection are not discussed.

Aquifer storage and recovery of low-TDS produced water

There are currently three active ASR programs in Texas, among which is the San Antonio Water System (SAWS) program. The SAWS ASR program, located south of San Antonio in Bexar, Atascosa, and Wilson counties (Figure 1), is the third largest in the country. Today it costs SAWS approximately \$9.5 million per year to administer and maintain the program, which is funded by SAWS customers through the water supply fee (Eckhardt 2016).

Based on the SAWS 2019 statistics report, the SAWS program annually recharged or injected on average 17,715,865 m^3 (14,362 ac-ft) between 2004 and 2011 and 29,603,520 m^3 (24,000 ac-ft) between 2015 and 2020 of groundwater into the Carrizo-Wilcox Aquifer. In comparison, based on data collected during this study, at least an annual volume of 2,725,845 m^3 (2,210 ac-ft) of low-TDS water may be available for ASR, although costs have not been taken into consideration. In a white paper by the Argonne National Laboratory for the U.S. Department of Energy, Veil et al. (2004) indicated that the cost of managing produced water before disposal can range anywhere from less than \$0.01 to at least \$7 per barrel. Several examples of costs provided in the study include produced water from different type of oil or gas operations. Produced water from an operation in the Kern River Oil Field, California, has been mixed with treated groundwater and, after filtration, sent to the local water district for use in irrigation and aquifer storage and recharge (Martel-Valles et al. 2016).

Low-TDS produced water could be used to enhance oil and gas recovery in the area, benefiting the operator in the long term. The TDS guidelines for oil and gas injection are lenient. Fluids consisting of brine, freshwater, steam, polymers, or carbon dioxide are injected into oil-bearing formations to recover residual oil and, in limited applications, natural gas (EPA 2012a). Since there is an abundance of oil activity in the area, produced water could also be used in drilling fluids. This practice is allowable in the area under the GCD's rules that allow groundwater export outside of the districts; thus, the produced water from conventional exploration in the Carrizo-Wilcox Aquifer currently discharged to surface water bodies could be exported for use for hydraulic fracturing, even to other areas of the state (Cook et al. 2015). Given that water used as a drilling fluid is normally purchased, reusing the low TDS produced water available nearby may be a proactive way for local oil and gas companies to either save or increase revenue.

Low-TDS produced water may also be used for industrial cooling, agriculture, and/or solution mining of uranium. There are five uranium deposits in South Texas (Sass 2011), with several nearby low-TDS produced water discharge locations. Although little water overall is used by the uranium extraction industry, the mine site reclamation and restoration require more water. Nicot et al. (2011) used an average value of 250 gallons per pound of uranium as an overall representation of water consumption, which is the equivalent of 3,785 m^3 or 840 ac-ft of water consumed for all producing uranium mines in Texas. The known annual removal of low-TDS groundwater discussed in this study is five times larger than the total freshwater removed in Texas for uranium mining purposes (i.e., 5,331,975 m^3 or 4,323 ac-ft). Thus, given the proximity, use of produced water from water supply formations could help reduce the strain on groundwater sources, both short- and long-term.

Recommendations

A relatively large volume of water (5,331,975 m³ or 4,323 ac-ft), which meets TSWQS, has been removed by the oil and gas sector and filed under agricultural use each year between 1983 and 2017. This practice has been implemented without the knowledge of GCDs in the affected areas, as the wells are oil producing and not primarily water wells." This groundwater removal may not seem significant but may exacerbate groundwater depletion when compounded by other uses. In addition to revealing the existence of low-TDS water extraction associated with oil and gas production and the surface discharge, this study has emphasized the lack of and the need for communication between separate state entities. Efforts should be directed toward a sustainable water management plan for the state of Texas that contains involvement from all state regulatory agencies, including RRC, TCEQ, and GCDs. Better communication and regulation could help prevent unsustainable water practices and increase water security, which could have significant impacts on a local level and which includes beneficial use of low-TDS produced water.

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Conflict of interest

None.

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Supplementary Information

SUPPLEMENTARY INFORMATION (SI) I

SI I.1 Water quality by surface water permit discharge number and the associated oil and gas production wells

County	Segment	Permit number	Year	TDS mg L^{-1}	Chloride mg L^{-1}	Sulfates mg L^{-1}	Selenium mg L^{-1}	pH	Oil and grease mg L^{-1}	Barrels per day	Temperature (°F)	API	Well name	Depth (ft)	Latitude	Longitude
Atascosa	2107	01048	2005	1010	77	<1	<0.003	7.6	19.2	530		013-30391	5	1880	28.903846	-98.425163
			2013	1190	181	80	<0.01	7.6	6.7	-	57.4	013-34644	9	1876	28.904001	-98.430203
		01011	1993	567	80	6	0.004	7.9	2	-		013-31525	6	1575	28.911745	-98.531122
			2004	37.5	77	45	<0.05	7.8	<28.5	1500		013-31367	7	1556	28.916214	-98.525404
												013-32104	9	1575	28.914461	-98.528617
												013-32103	10	1575	28.915603	-98.527040
												013-31076	5	1575	28.916160	-98.526325
		00900	1998	1670	232	8	0.005	7.8	5	3500		013-00729	6	3779	28.803409	-98.166279
			2003	180	89	1	<0.0003	7.7	2.1	5870		013-34241	12	3739	28.804927	-98.163891
			2008	78	19.6	<1	<0.01	6.97	7.3	15700						
		00869	1998	1670	232	8	0.005	7.8	5	1500		013-00748	5	3787	28.795996	-98.172033
			2003	180	89	1	<0.003	7.7	2.1	1500						
			2008	46	11.5	<1	<0.01	7.45	9.1	1500						
		00832	1997	399	36.2	4	<0.002	7	12.2	365		013-03077	1	2161	28.917646	-98.318602
			2003	420	35	20	<0.003	7	<2	500						
		00828	1993	500	16	-	<0.01	8.1	2	-		013-35013	15	1772	28.885391	-98.470848
			2003	390	56	11	<0.003	6.4	2	1347		013-35012	14	1765	28.887384	-98.467885
			2009	390	14.2	7.09	<0.01	7.07	-	1347		013-34148	5R	1790	28.886025	-98.472033
												013-34799	12	1760	28.886291	-98.470880
												013-01185	9	1831	28.879099	-98.480694
Karnes		00759	1998	1504	200	3	<0.002	8.7	2	900		255-31192	1	3450	28.863706	-98.169386
			2004	3892	825	4	0.008	8.5	2	900						
			2009	3230	810	<1	<0.01	8.5	<5	700						
Jefferson	2107	00065	2003	794	7	0	<0.005	7	7	5000						
			2009	802	46	0		7.65	5.4	4000		149-33197	23	2278	29.756021	97.149523
												149-32085	16	2269	29.755369	-97.147785
												149-32087	17	2209	29.753227	-97.150296

County	Segment	Permit number	Year	TDS mg L^{-1}	Chloride mg L^{-1}	Sulfates mg L^{-1}	Selenium mg L^{-1}	pH	Oil and grease mg L^{-1}	Barrels per day	Temperature (°F)	API	Well name	Depth (ft)	Latitude	Longitude
												149-32165	18	2191	29.754102	-97.151369
												149-32194	19	2282	29.754102	-97.151369
												149-00150	9	3508	28.754736	-97.150897
												149-00153	5	2271	29.755127	-97.148493
												149-00367	12	2300	29.755257	-97.149609
												149-00391	11	2270	29.756468	-97.147292
												149-00415	13	2303	29.753003	-97.152914
												149-30039	14	2236	29.753394	-97.152613
												149-32221	12	2352	29.758055	-97.159126
												149-32222	13	2266	29.751908	-97.154684
												149-32225	11	2192	29.747772	-97.155306
												149-00416	2A	2225	29.751405	-97.154405
	1402	00889	1997	618	16	6	<0.002	7	10	200		149-32171	4	2377	29.777557	-97.116468
			2003	561	8	0	<0.005	7.1	1.2	300		149-32168	5	2365	29.778935	-97.113292
			2011	606	23		0.02	7.63	7.6	314						
			2016	189	20		0.002	7.8	1.4	715						
		00808	1997	821	38	2	<0.002	8.51	7	1000		149-32283	1A	2352	29.773590	-97.121918
			2003	776	7	0	<0.005	7.1	6.2	1000		149-32698	3B	2402	29.776812	-97.118463
			2009	632	21	4	<0.02	7.6	3.6			149-32284	2 B	2383	29.776923	-97.117176
		00777	2009	1083	292	263	<0.002	7.1	6.8	650		149-32422	4A	1347	29.817349	-97.222383
			2014	586	162	104		7.5	8							
		00778	2000	760	15	3	<0.005	8.3	<5	1750		149-32795	7	2380	29.773012	-97.122519
			2012	564	157	9		8.5	9.2			149-00197	3	2333	29.772342	-97.123249
		00786	2001	1100	192	44	<0.005	8.3	<5	5000		493-00975	7	1604	29.253140	-97.954010
			2006	980	173	80	<0.05	7.9	12.4	5000						
			2012	1120	269	79	<0.01	8.6	8.8		84.9					
Milam	1212	00823	1996	215	26	11	<0.005	8.4	3.8			331-33473	12	1980	30.582512	-96.921003
			2001	230	27	8	<0.005	8	0.48	7500		331-35005	15	1975	30.583177	-96.924350
												331-35008	16	1980	30.582918	-96.923728
												331-33068	2	2887	30.582364	-96.922676
												331-33289	4	1987	30.583805	-96.920638
												331-33328	5	1902	30.581865	-96.922998
												331-33718	13	2006	30.581404	-96.923535

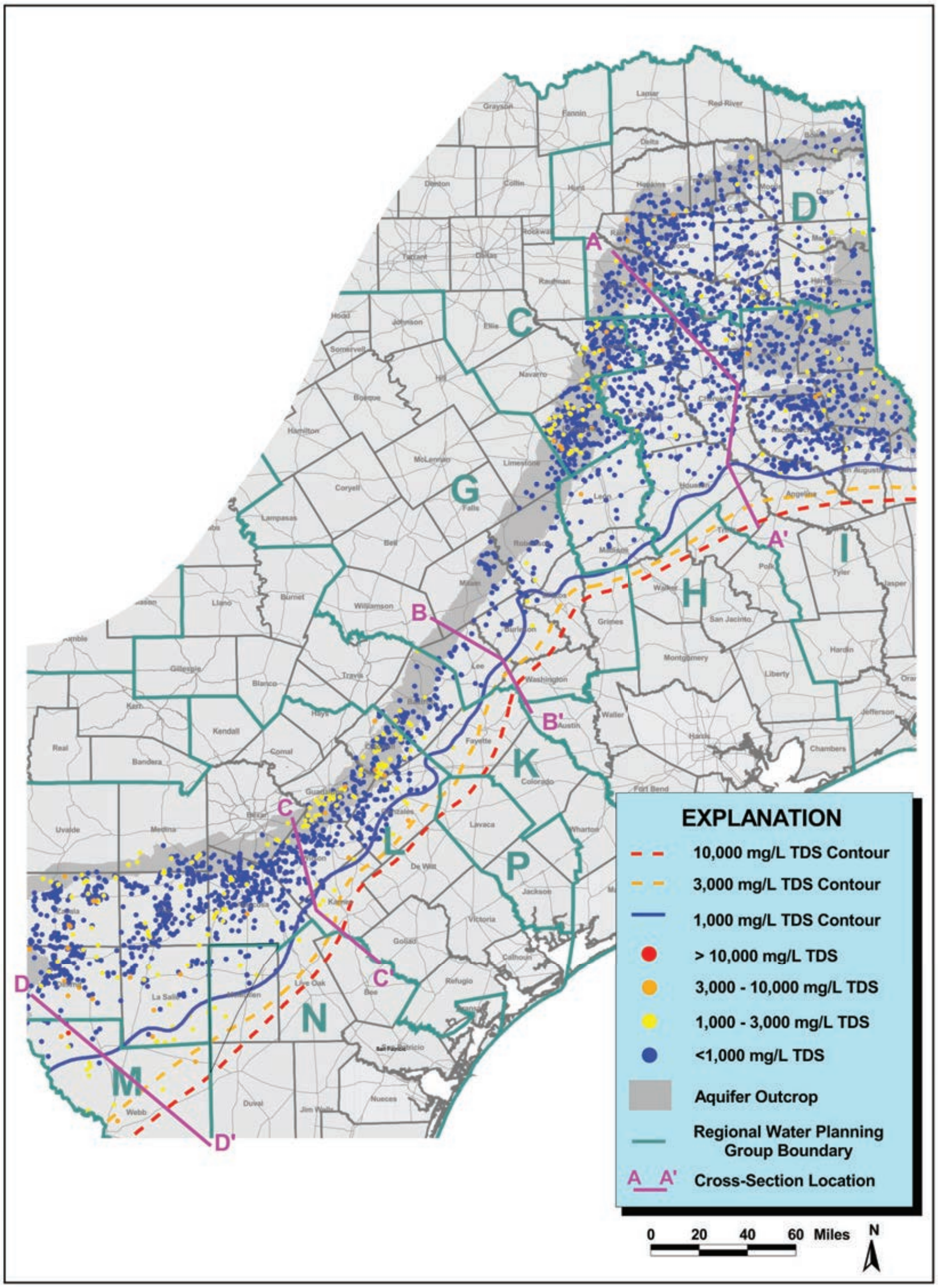
County	Segment	Permit number	Year	TDS mg L^{-1}	Chloride mg L^{-1}	Sulfates mg L^{-1}	Selenium mg L^{-1}	pH	Oil and grease mg L^{-1}	Barrels per day	Temperature (°F)	API	Well name	Depth (ft)	Latitude	Longitude
												331-33409	7	1916	30.581071	-96.923213
												331-33442	8	1932	30.582678	-96.922161
												331-33443	9	1940	30.583306	-96.923320
												331-33474	10	2000	30.582844	-96.924178
												331-33559	11	1980	30.582253	-96.919887
												331-33644	14	2025	30.581810	-96.923470
												331-33344	6	1914	30.581736	-96.921754
												331-34981	7	1998	30.581237	-96.922226
												331-33212	1	2007	30.579686	-96.921711
												331-33326	2	1907	30.580443	-96.922912
												331-33524	6	2021	30.579649	-96.921303
												331-33430	4	1966	30.579538	-96.922440
												331-33449	5	2000	30.581071	-96.920874
												331-33353	3	1965	30.580831	-96.921754
McMullen	2117	00768	1967	3321	122	17						311-00123	2	3720	28.506021	-98.583194
			1997	1506	108	4	<0.002	8	20	1000		311-00127	5	3700	28.509149	-98.588061
			2003	1320	89	1	<0.003	8.3	13.8			311-32925	6	5700	28.507078	-98.586835
												311-00129	7	6025	28.504145	-98.587415
												311-00122	8	3700	28.510029	-98.583033
Gonzales	1803	00995	1997	1084	23	2	0.002	8.5	1	50		177-32008	1	2264	29.626523	-97.262327
			2003	1072	24	7	<0.003	8.2	28	75		177-32025	2	2271	29.627680	-97.260395
			2009	973	21		0.002	8.3	1	75						
		00966	1995	1310	29	<5	<0.005	8.3	<5	400		177-20029	1	2280	29.624378	-97.266939
			2001	1280	85	10	<0.005	8.3	9	500		177-00653	2	2300	29.623277	-97.266939
			2006	1038	288	260	<0.002	6.8	8.6	200		177-31791	4	2200	29.623072	-97.268570
			2012	1621	235	16		8.6	<1	-		177-31848	5	2190	29.622624	-97.268548
												177-31974	6	2215	29.623576	-97.267819
												177-32029	7	2204	29.624940	-97.270007
		00760	2006	837	227	205	<0.002	6.9	3	650		177-32599	107	1985	29.580998	-97.316235
			2012	1126	312		0.002	8.1	24.3	650		177-31578	1	1998	29.579617	-97.316922
												177-32058	2A	1995	29.578479	-97.316857
												177-32055	3	2079	29.577826	-97.317673
												177-32049	2	1998	29.579767	-97.317930

County	Segment	Permit number	Year	TDS mg L^{-1}	Chloride mg L^{-1}	Sulfates mg L^{-1}	Selenium mg L^{-1}	pH	Oil and grease mg L^{-1}	Barrels per day	Temperature (°F)	API	Well name	Depth (ft)	Latitude	Longitude
												177-33974	7A	2050	29.578255	-97.319454
												177-30563	1	8470	29.579468	-97.318381
												177-31323	1A	2130	29.579934	-97.318424
												177-32055	6A	2079	29.577826	-97.317673
												177-31758	3A	2045	29.580812	-97.318252
												177-31986	4A	2050	29.577210	-97.318939
												177-32049	5A	1998	29.579841	-97.317801
												177-31411	2A	2133	29.576538	-97.318445
		00775	1999	1219	14.2	0.74	<0.001	8.07	5.8	100		177-30223	1	2068	29.636164	-97.278809
			2004	1092	18.4	<1	<0.002	8.2	3.7	200		177-30476	2	2138	29.636612	-97.279517
			2014	3650	30	<20		8.75	5.8	-		177-31740	7	2141	29.638626	-97.278466
												177-31733	6	2140	29.638831	-97.278273
												177-31515	5	2155	29.636295	-97.280891
		00782	1988	1555	20	2	0.003	8.4	18	-		177-33841	102	2170	29.647093	-97.255335
			2000	1141	21	<10	<0.01	8.4	10.3	320		177-33987	104	2196	29.650636	-97.243683
			2006	2186	63	5.8	<0.002	8.6	10	350		177-32070	101	2150	29.646291	-97.257137
			2011	315	88	10.7		8.7	8.2	-		177-30099	1	2036	29.652202	-97.245765
Fayette		00965	2006	550	153	138	<0.002	6.6	18.2	800		149-32931	1	1357	29.809213	-97.226996
			2014	441	122		0.002	7.7	5.7	800		149-32944	3	1393	29.808524	-97.228348
												149-32986	6	1390	29.808468	-97.228520
												149-32960	4	1355	29.808990	-97.229679
												149-32989	7	1405	29.807854	-97.229829
		00906	2001	1067	300	25	<0.005	8.15	20	250		149-31473	1A	1975	29.737040	-97.188544
			2006	1108	302	278	<0.002	6.9	4.2	400		149-31472	2B	1981	29.737283	-97.188888
			2009	1108	302	279		6.9	4.2	-						
			2014	377	19	16		8.4	<5	-						
		00891	1997	676	17	2	<0.002	7.4	15	600		149-31473	1A	1975	29.737040	-97.188544
			2003	586	9	0	<0.005	7.2	2.6	800		149-31472	2B	1981	29.737283	-97.188888
			2009	805	26		0.02	7.9	8.6	800						
			2016	213	<20	<20			<1.4	-						
		00890	1997	622	14	5	<0.002	7.1	13	150		149-00401	1	2103	29.721556	-97.208414
			2003	792	8	0	<0.01	7	7.8	200						
			2009	1381	27	<1.0		7.96	6.4	-						

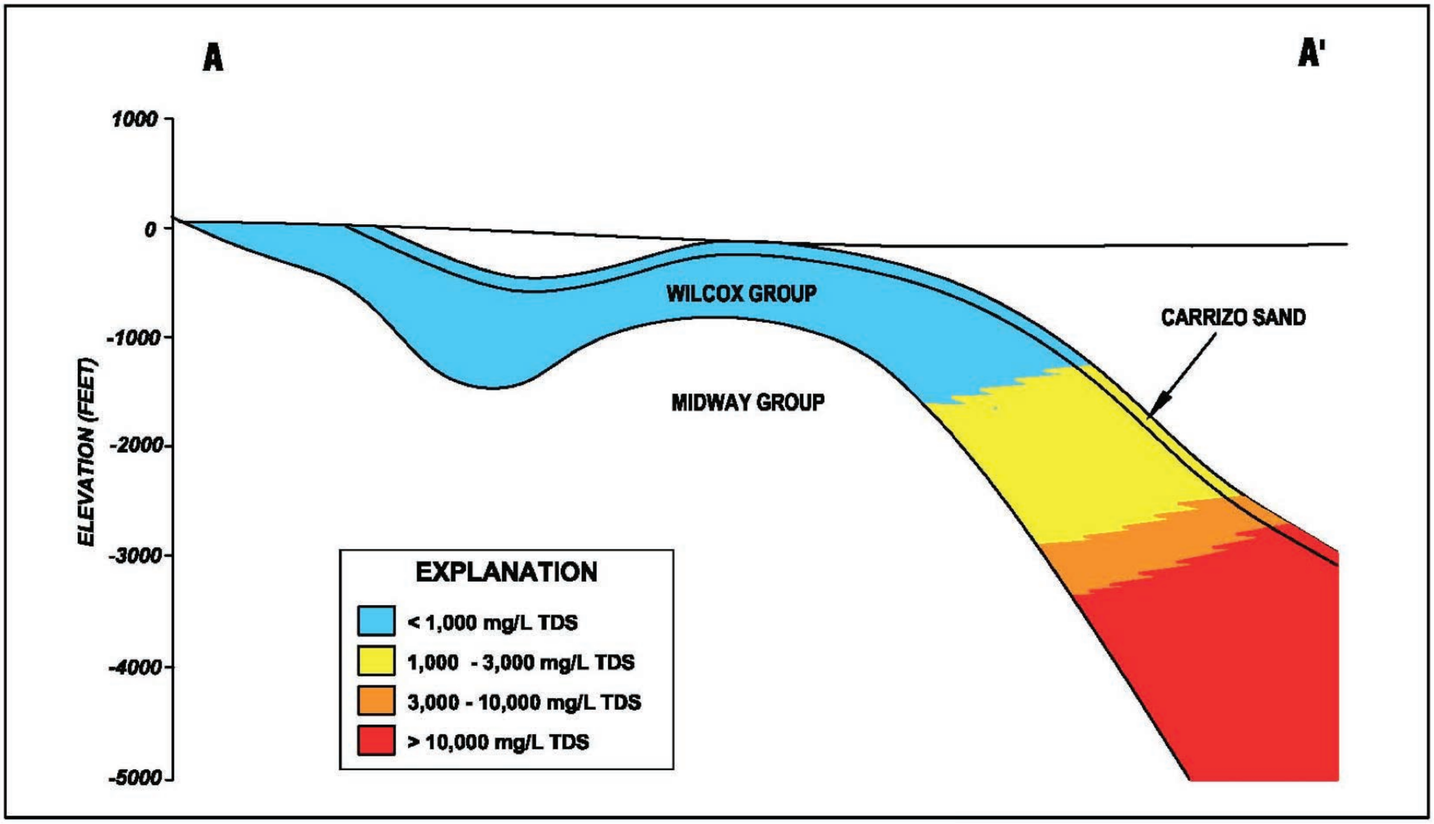
County	Segment	Permit number	Year	TDS mg L^{-1}	Chloride mg L^{-1}	Sulfates mg L^{-1}	Selenium mg L^{-1}	pH	Oil and grease mg L^{-1}	Barrels per day	Temperature (°F)	API	Well name	Depth (ft)	Latitude	Longitude
			2011	1381	27		0.02	7.96	6.4	200						
			2016	370	20		0.002	-	1.4	260						
		00887	1997	701	14	3	<0.002	7.3	11	315		149-33283	5	1967	29.722506	-97.212555
			2003	789	6	0	<0.005	7.1	18.9	315		149-32814	3	1980	29.720270	-97.215517
			2009	1384	21		0.02	8.1	7	215		149-30097	2	2004	29.721426	-97.213650
			2016	130			<0.002			-						
		00859	1997	613	16	<1	<0.002	7.2	12	325		177-31984	2	2135	29.640547	-97.275741
			2009	1015	23		0.02	8.2	3.8	360						
			2016	210	74	<20			<5	-						
		00763	2001	788	90	<1	<0.004	8.98	6	200		149-32549	5	1955	29.732364	-97.196248
			2006	742	137	152	<0.002	7.3	<1	200		149-31319	1	2290	29.733202	-97.194660
			2011	1191	330		0.002	8.2	8.25	200						

*Total dissolved solids (TDS), milligram per liter (mg L-1), API (American Petroleum Institute), Fahrenheit (°F), feet (ft)

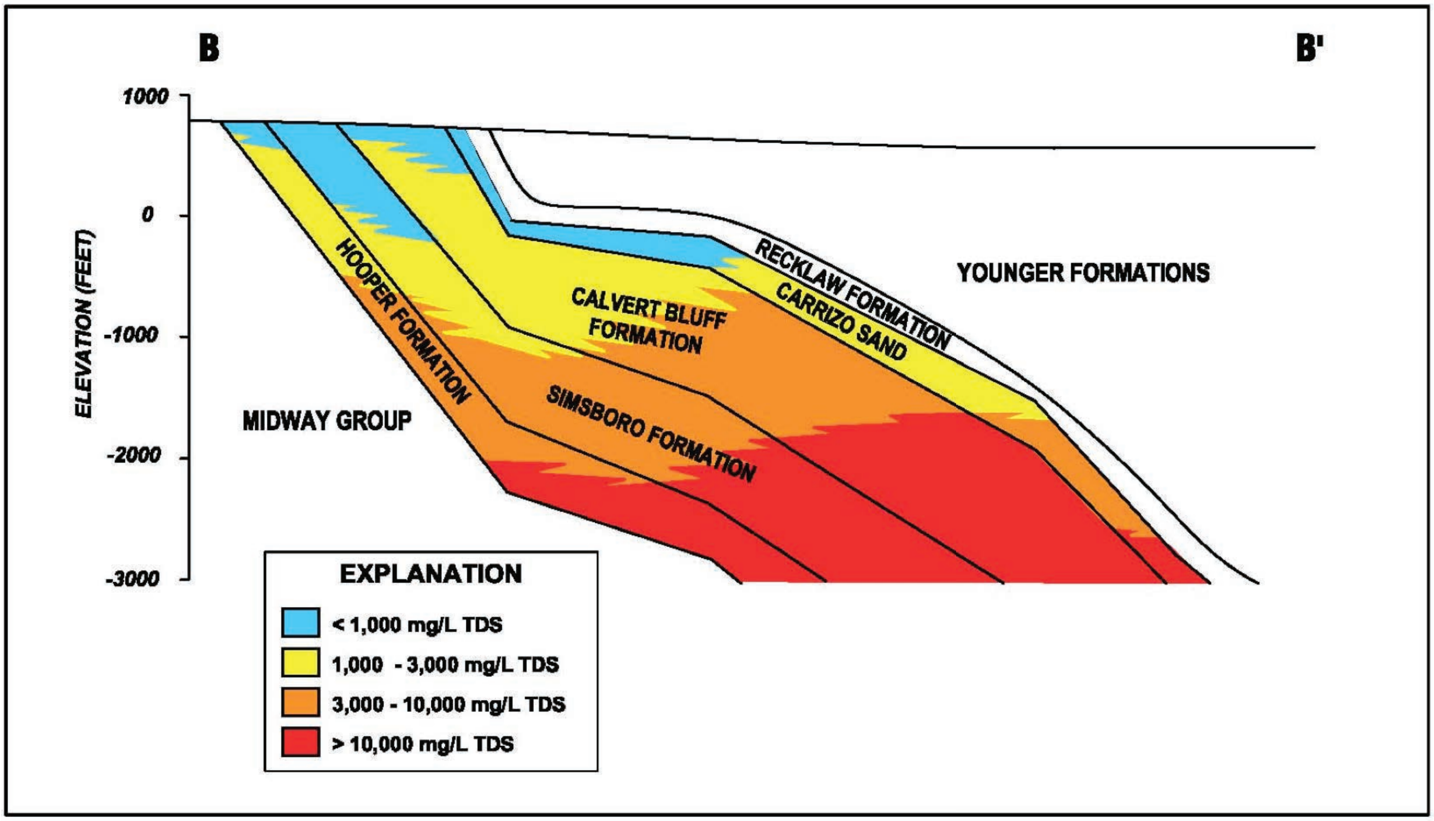
SI I.2 Groundwater quality of the Carrizo-Wilcox Aquifer



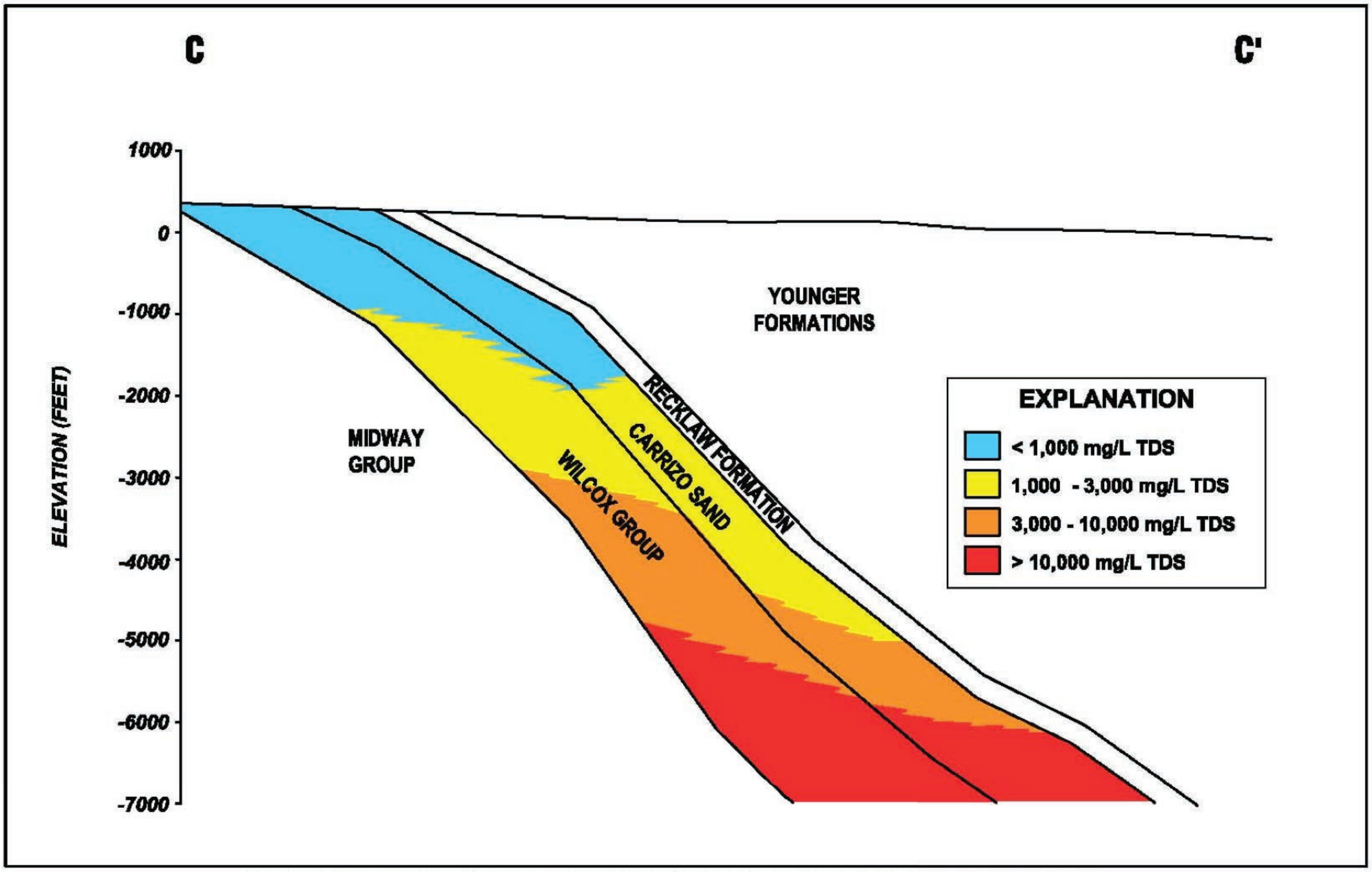
Visual representation of groundwater quality in the Carrizo-Wilcox Aquifer, accompanied by cross section views including formation total dissolved solids (TDS) and depth (LBG-Guyton Associates 2003).



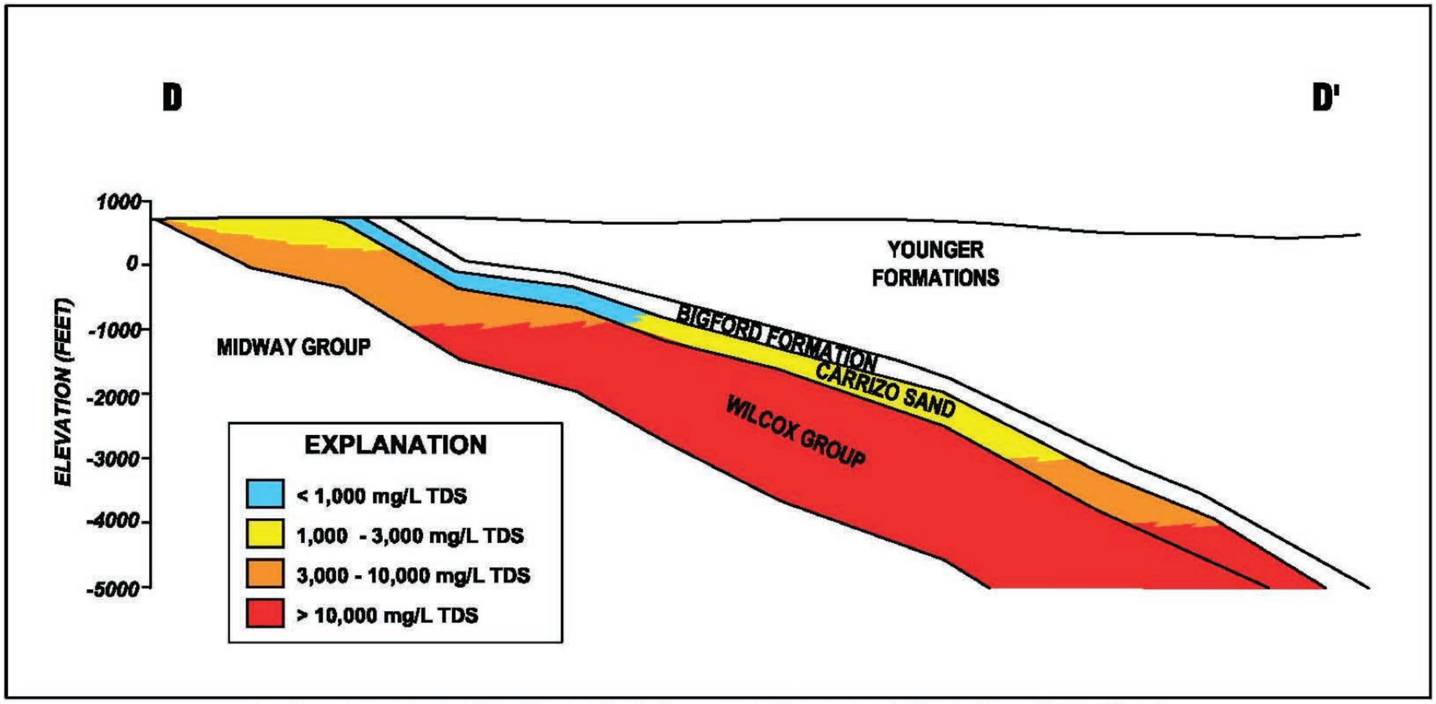
Simplified Cross Section A-A' of the Carrizo-Wilcox Aquifer with generalized water quality ranges (LBG-Guyton Associates 2003).



Simplified Cross Section B-B' of the Carrizo-Wilcox Aquifer with generalized water quality ranges (LBG-Guyton Associates 2003).



Simplified Cross Section C-C' of the Carrizo-Wilcox Aquifer with generalized water quality ranges (LBG-Guyton Associates 2003).



Simplified Cross Section D-D' of the Carrizo-Wilcox Aquifer with generalized water quality ranges (LBG-Guyton Associates 2003).

SI II

SI II.1 Surface waste management manual (RRC 2015)

Application for a permit to discharge produced water to inland waters

Application should be made by letter of request; there is no application form. You may number your responses to correspond to the requests for information outlined below. The application must contain this information before it can be processed.

1. Operator name, address, and telephone number. Note that unless otherwise specified in an application, the permit and correspondence will only be mailed to the operator's P5 address.
2. Identify the county, field(s), lease name(s), lease number(s), and well number(s) producing the water to be discharged. Include any wells that are currently shut in but may contribute to the discharge sometime in the future.
3. Include a list of the average and estimated maximum water production rates (billion barrels/day) on a wellbywell basis. Also indicate whether you believe the maximum produced water rate will increase, and if so, to what rate. Any discharge permit issued may contain a discharge rate restriction.
4. Include a drawing and description of the treatment the produced water will receive before being discharged. Indicate the size of tanks and/or pits and show any special piping, baffles, weirs, etc. inside tanks or pits to minimize turbulence, control oil carry over, control water level, etc. Include a copy of any technical data available from the manufacturer on any equipment used to treat the water.
5. Pits associated with oil and gas activities are required to be permitted unless they are authorized by Statewide Rule 8(d)(4). If any pits are used to treat or contain the water prior to discharge, please advise of the use and size of each pit. Include permit numbers for all permitted pits.
6. List any chemicals that are in use or will be used to treat the water or oil, the purpose for using the chemicals, and the concentrations used. Attach a copy of the manufacturer's brochure and the material safety data sheets for each chemical.
7. A representative sample of the produced water you wish to discharge must be analyzed as outlined in the attached document entitled "Produced Water Analysis." If you have any reason to believe any analyzed contaminant will increase or decrease in concentration during the time you wish to discharge, you must advise us of which contaminant, whether the concentration of the contaminant will increase or decrease, and the extent, if known, of the expected increase or decrease.
8. Please indicate the latitude longitude coordinates to the nearest second for the discharge point, the treatment facility, and each wellhead associated with this discharge. If the latitude longitude coordinates are not readily available, a complete original U.S. Geological Survey 7 1/2-minute quadrangle map of the area may be submitted with the exact location of each well, the treatment facility, and the discharge point clearly marked.
9. Indicate on a county highway map, or include on the USGS map above, the location of the treatment facility, the proposed discharge point, and the route the discharged water will take to the nearest watercourse (creek or river). If the water is to be used for livestock or irrigation, indicate how the water will reach the ultimate point of disposal. A letter from the surface owner must be included stating he wants and has a need for the water or that he does not object to the water being disposed of on his property.
10. If disposal is by discharge into a watercourse, Rule 8(d)(6)(C) requires an applicant for a discharge permit must give proper notice to the surface owner at the point of discharge and to the surface owner of each waterfront tract between the discharge point and 1/2 mile downstream of the discharge point. If any of these waterfront tracts are within an incorporated city, town, or village, then notice shall be given to the city clerk. Notice of the permit application shall consist of a copy of the application together with a statement that any protest to the application should be filed with the Commission within 15 days of the date the application is filed with the Commission. The applicant shall mail or deliver the required notice to the surface owners on or before the date the application is mailed or delivered to the Commission in Austin. After giving the required notice, you must file with the Commission a statement setting out the names and addresses of persons notified and the dates they were notified, and stating the listed persons are all the persons required by Rule 8 to be notified.

11. In the event produced water is delivered into a flood control ditch or similar waterway, written permission must be filed with the Commission from the authority having jurisdiction.
12. There is a $300 nonrefundable application fee for a permit to discharge oil and gas waste to surface waters of the state. EFFCTIVE MAY 1, 2012, A SURCHARGE OF 150% HAS BEEN IMPOSED ON THE APPLICATION FEE to implement the provisions of Senate Bill 1 (82nd Legislature, First Called Session, 2011), which mandated the Commission to impose reasonable surcharges on Commission fees. Accordingly, for applications received on or after May 1, 2012, the total application fee will now be $750. If the discharged water will not reach surface waters of the State or the discharge point is west of the 98th meridian and the water is for agriculture or wildlife use, the fee is not required. If the fee is applicable, checks or money orders should be made payable to "Railroad Commission of Texas." Please do not send cash through the mail. This fee is an application fee and is not refundable even if your application is returned, withdrawn, or denied. If the fee is not applicable, a statement indicating the reason the fee does not apply to your application must be provided.
13. Please provide a statement as to whether the water is for agricultural or wildlife use.
14. You must certify the application as follows:

    "I certify that I am authorized to make this application, that this application was prepared by me or under my supervision and direction, and that the data and facts stated herein are true, correct, and complete to the best of my knowledge."

The application and any attachments should be mailed to:

Railroad Commission of Texas
Oil and Gas Division
Technical Permitting
P. O. Box 12967
Austin, TX 787112967

Send a copy of the application and any attachments to the appropriate District Office.

Before any permit may be issued, the operator must have an Organization (Form P5) on file with the Austin Office of the Commission.

If your facility is east of the 98th meridian, a permit from the U.S. Environmental Protection Agency (EPA) may be required for a discharge to surface waters under the National Pollutant Discharge Elimination System (NPDES). Contact EPA Region 6 (http://www.epa.gov/region6/) in Dallas for more information.

SI II.2 Produced Water Analysis

An application for a permit to discharge produced water must contain an analysis of the water to be discharged. The parameters listed below must be reported. Samples must be representative of the discharged water. Analysis must be performed according to procedures approved by EPA as part of the 40 CFR Part 136 – Guidelines establishing test procedures for the analysis of pollutants (EPA 2021), and, where applicable, samples must be preserved as specified by these procedures. The procedures used to preserve the samples and the analytical methods used must be reported. All parameters should be reported in milligrams per liter unless otherwise specified.

General parameters	Toxic pollutants***	MAL (mg L^{-1})
Temperature (°F)	Aluminum	0.03
pH (standard units)	Arsenic	0.01
Dissolved oxygen	Barium	0.01
Hardness (mg L^{-1} as CaCO3)	Benzene	0.01
Total suspended solids	Cadmium	0.001
Total dissolved solids	Chromium	0.01
Chlorides	Hexavalent Chromium	0.01
Sulfates	Copper	0.01
Sulfides	Cyanide	0.02
Ammonia nitrogen	Lead	0.005
Calcium	Mercury	0.0002
Magnesium	Nickel	0.01
Sodium	Selenium	0.01
Potassium	Silver	0.002
Iron	Zinc	0.005
Manganese		
Oil and grease		
Total organic carbon		
Phenols		
Naphthalene		

***These toxic pollutants have numerical criteria specified in the Texas Surface Water Quality Standards and may be present in some gas plant wastewater. Toxic pollutant concentrations in milligram per liter (mg L^{-1}) above the specified minimum analytical limit (MAL) must be reported. If the laboratory, using acceptable analytical practices, cannot report concentrations down to the specified level due to reasons such as matrix interference, a statement to that effect from the laboratory must be submitted with the results. Also, the MAL achieved by the laboratory for each toxic pollutant must be reported. Temperature is in Fahrenheit (°F).

Last Updated: 3/1/2018

The information above is available from the Railroad Commission of Texas (RRC 2018).

SI III

SI III.1 Discharges west of the 98th meridian

Tiffany Humberson
Environmental Permitting and Support
Texas Railroad Commission

The Agricultural and Wildlife Water Use Subcategory **(40 Code of Federal Regulations [CFR] 435.50)** applies to facilities located in the continental United States west of the 98th meridian for which produced water is clean enough to be used for wildlife and livestock watering or other agricultural uses. The 98th meridian extends from near the eastern edge of the Dakotas through central Nebraska, Kansas, Oklahoma, and Texas. Produced water may be discharged from such sites with limits placed on oil and grease. Note that regulations for reuse of reclaimed water vary from state to state, and not all states have developed water reuse guidelines or regulations (EPA 2012b).

Subpart E—Agricultural and Wildlife Water Use Subcategory

§435.50

Applicability; description of the beneficial use subcategory.

The provisions of this subpart are applicable to those onshore facilities located in the continental United States and west of the 98th meridian for which the produced water has a use in agriculture or wildlife propagation when discharged into navigable waters. These facilities are engaged in the production, drilling, well completion, and well treatment in the oil and gas extraction industry.

§ 435.51

Specialized definitions.

For the purpose of this subpart:

(a) Except as provided below, the general definitions, abbreviations, and methods of analysis set forth in 40 CFR part 401 shall apply to this subpart.

(b) The term "onshore" shall mean all land areas landward of the territorial seas as defined in 40 CFR 125.1(gg).

(c) The term "use in agricultural or wildlife propagation" means that the produced water is of good enough quality to be used for wildlife or livestock watering or other agricultural uses and that the produced water is put to such use during periods of discharge.

Effluent characteristics: Effluent limitation* (mg L^{-1}) *oil and grease: 35

Discharge cannot violate Texas Surface Water Quality Standards (TSWQS). These parameters change depending on the receiving surface water. Some may be impaired, and limits would be strict, or the discharge may be denied.

TSWQS used for permitting can be found at https://www.tceq.texas.gov/assets/public/waterquality/standards/TSWQS2010/TSWQS2010_rule.pdf.

Recommendations for livestock water

TDS less than 1,000 mg L^{-1} is best for all
TDS less than 3,000 mg L^{-1} is still safe to use

Refer to Texas Agricultural Extension Service published paper on water quality found at http://publications.tamu.edu/WATER/PUB_water_Water%20Quality%20Guide%20for%20Livestock%20and%20Poultry.pdf.

All discharges west of the 98th meridian require individual NPDES permits from EPA Region 6 if discharged into navigable surface waters or impaired water bodies.

SI IV

SI IV.1 Water uses and supporting numerical criteria for each of the state's classified segments

The following tables identify the water uses and supporting numerical criteria for each of the state's classified segments. The tables are ordered by segment number correlating with the standards set by the Texas Commission on Environmental Quality. The following descriptions denote how each numerical criterion is used subject to the provisions in §307.7 of the Texas Surface Water Quality Standards title (relating to Site-Specific Uses and Criteria), §307.8 of the title (relating to Application of Standards), and §307.9 of the title (relating to Determination of Standards Attainment).

The criteria for Cl^{-1} (chloride), SO_4^{-2} (sulfate), and TDS (total dissolved solids) are listed as maximum annual averages for the segment.

Dissolved oxygen criteria are listed as minimum 24-hour means at any site within the segment. Absolute minima and seasonal criteria are listed in §307.7 of the title.

The pH criteria are listed as minimum and maximum values expressed in standard units at any site within the segment.

The freshwater indicator for bacteria for recreation is *E. coli*.

The criteria for temperature are listed as maximum values at any site within the segment.

Number of segments	Segment number	Cl^{-1} mg L^{-1}	SO_4^{-2} mg L^{-1}	TDS mg L^{-1}	Dissolved oxygen (mg L^{-1})	pH range	Indicator bacteria #/100 ml	Temperature (°F)
1	0604	50	50	200	5.0	6.0-8.5	126	91
1	1211	140	130	640	5.0	6.5-9.0	126	91
30	1803	100	100	500	5.0	6.5-9.0	126	93
3	1902	17	275	900	5.0	6.5-9.0	126	90
1	1911	150	150	750	5.0	6.5-9.0	126	90
16	2107	600	500	1500	5.0	6.5-9.0	126	90
1	2113	50	50	400	5.0	6.5-9.0	126	90
1	2310	1700	1000	4000	5.0	6.5-9.0	126	90

*Miligram per liter (mg L^{-1}), mililiters (ml), Fahrenheit (°F)
Segment 0604 is in the Neches/Trinity River basin and represents a discharge point into the Neches River.
Segment 1211 is in the Brazos River Basin and represents a discharge point into the Yegua Creek.
Segment 1803 is in the Guadalupe River Basin and represents discharge points into the Guadalupe River.
Segment 1902 is in the San Antonio River Basin and represents discharge points into the Cibolo Creek.
Segment 1911 is in the San Antonio River Basin and represents a discharge point into the San Antonio River.
Segment 2107 is in the San Antonio and Nueces river basins and represents discharge points into the Atascosa River.
Segment 2113 is in the Nueces River basin and represents a discharge point into the Frio River.
Segment 2310 is in the Rio Grande basin and represents a discharge point into the Pecos River.

SI IV.2 Active freshwater discharge permits in Texas

Active freshwater discharge permits in Texas, derived from an evaluation of discharge locations and active permits.

Type	Date received	Permit designation	Permit / application number	Action status	Final action date	Permit expire date	bbls day^{-1}	m^3 day^{-1}
Renew		Discharge	00005	Approved	6/7/2001	none	960	152.63
Renew	6/14/2006	Discharge	00005	Approved	12/17/2012	12/16/2017		
Transfer	5/10/1993	Discharge	00065	Approved	9/8/1993	9/8/1998	4,975	790.96
Renew	4/19/2000	Discharge	00065	Approved	3/27/2002	3/26/2003		
Transfer	10/16/2003	Discharge	00065	Approved	4/5/2004	4/4/2009		
Renew	8/13/2009	Discharge	00065	Approved	8/3/2012	8/2/2017		
Amend	8/13/2009	Discharge	00065	Approved	8/3/2012	8/2/2017		
Transfer	5/10/1993	Discharge	00066	Approved	9/8/1993	9/8/1998	6,100	969.82
Renew	4/19/2000	Discharge	00066	Approved	3/27/2002	3/26/2003		
Transfer	9/19/2003	Discharge	00066	Approved	4/5/2004	4/4/2009		
Renew	9/19/2003	Discharge	00066	Approved	4/5/2004	4/4/2009		
Renew	8/13/2009	Discharge	00066	Approved	8/3/2012	8/2/2017		
Amend	8/13/2009	Discharge	00066	Approved	8/3/2012	8/2/2017		
Renew	4/12/1996	Discharge	00268	Approved	2/16/2000	2/15/2005	N/A	N/A
Transfer	11/1/2000	Discharge	00268	Approved	11/16/2000	2/15/2005		
Transfer	12/14/2000	Discharge	00268	Approved	1/23/2001	2/15/2005		
Amend	8/7/2002	Discharge	00268	Approved	9/4/2002	2/15/2005		
Amend	7/14/2003	Discharge	00268	Approved	7/29/2003	2/15/2005		
Transfer	7/23/2004	Discharge	00268	Approved	9/20/2004	9/19/2009		
Renew	9/18/2009	Discharge	00268	Approved	11/24/2009	11/23/2014		
Transfer	1/25/2011	Discharge	00268	Approved	3/28/2012	3/27/2017		
Amend		Discharge	00268	Approved				
Renew	5/8/1998	Discharge	00759	Approved	3/23/1999	3/22/2004	700	111.29
Renew	2/17/2004	Discharge	00759	Approved	4/2/2004	4/1/2009		
Renew	4/28/2009	Discharge	00759	Approved	10/30/2009	10/29/2014		
Renew	8/28/2009	Discharge	00759	Approved	10/30/2009			
Renew	10/22/2014	Discharge	00759	Approved	12/16/2016	12/15/2021		

Type	Date received	Permit designation	Permit / application number	Action status	Final action date	Permit expire date	bbls day^{-1}	m^3 day^{-1}
Transfer	8/7/1995	Discharge	00760	Approved	1/22/1996	1/22/2001	650	103.34
Renew	12/5/2006	Discharge	00760	Approved	4/18/2007	4/17/2012		
Renew	3/27/2012	Discharge	00760	Approved	3/2/2015	3/2/2020		
Amend	7/5/2016	Discharge	00760	Approved	8/25/2016	3/2/2020		
Amend	9/1/2016	Discharge	00760	Approved	9/30/2016	3/2/2020		
Renew	5/4/1987	Discharge	00762	Approved	10/30/2009	10/29/2014	200	31.80
Renew	5/8/1998	Discharge	00762	Approved	3/23/1999	3/22/2004		
Renew	2/17/2004	Discharge	00762	Approved	4/6/2004	4/5/2009		
Renew	10/22/2014	Discharge	00762	Approved	12/16/2016	12/15/2021		
Renew	3/19/2001	Discharge	00763	Approved	5/10/2001	5/9/2006	200	31.80
Transfer	12/9/2002	Discharge	00763	Approved	4/17/2003	5/9/2006		
Renew	5/24/2006	Discharge	00763	Approved	7/11/2006	7/10/2011		
Renew	7/13/2011	Discharge	00763	Approved	7/10/2013	7/10/2018		
Amend	6/23/2014	Discharge	00763	Approved	6/4/2015	7/10/2018		
Transfer	12/9/2002	Discharge	00764	Approved	4/17/2003	5/9/2006	665	105.73
Renew	5/26/2006	Discharge	00764	Approved	7/11/2006	7/10/2011		
Renew	7/15/2011	Discharge	00764	Approved	3/30/2012	7/10/2011		
Amend	9/11/2014	Discharge	00764	Approved	1/5/2015	3/29/2017		
Amend	9/11/2014	Discharge	00764	Approved	1/20/2015	3/29/2017		
Renew	3/16/2017	Discharge	00764	Approved	6/16/2017	6/15/2022		
Renew	8/28/2003	Discharge	00765	Approved	3/9/2004	3/8/2009	1,200	190.79
Renew	3/12/2009	Discharge	00765	Approved	6/19/2009	6/18/2014		
Renew	6/23/2014	Discharge	00765	Approved	7/1/2014	7/1/2019		
Amend	1/20/2015	Discharge	00765	Approved	2/9/2015	7/1/2019		
Renew	8/26/2003	Discharge	00768	Approved	4/2/2004	4/1/2009	3,600	572.36
Renew	5/8/2009	Discharge	00768	Approved	10/2/2009	10/1/2014		
New	2/19/1999	Discharge	00775	Approved	5/24/1999	5/23/2004	200	31.80
Transfer	5/25/2004	Discharge	00775	Approved	7/27/2004	7/26/2009		
Renew	1/16/2009	Discharge	00775	Approved	3/31/2009	3/30/2014		
Renew	10/3/2014	Discharge	00775	Approved	2/24/2015	2/24/2020		

Type	Date received	Permit designation	Permit/application number	Action status	Final action date	Permit expire date	bbls day^{-1}	m^3 day^{-1}
New	8/30/1983	Discharge	00777	Approved	11/1/1983	none	250	39.75
Amend	5/12/2009	Discharge	00777	Approved	6/4/2009	6/3/2014		
Transfer	5/12/2009	Discharge	00777	Approved	6/4/2009	6/3/2014		
Renew	6/18/2014	Discharge	00777	Approved	6/25/2014	6/25/2019		
Amend	9/11/2014	Discharge	00777	Approved	1/2/2015	6/25/2019		
Amend	9/11/2014	Discharge	00777	Approved	1/5/2015	6/25/2019		
Amend	9/11/2014	Discharge	00777	Approved	1/20/2015	6/25/2019		
Amend	8/16/1993	Discharge	00778	Approved	12/28/1993	7/23/1998	1,500	238.48
Renew	11/17/2000	Discharge	00778	Approved	10/10/2001	10/9/2006		
Renew	6/25/2007	Discharge	00778	Approved	1/10/2013	1/10/2018		
Amend	6/23/2014	Discharge	00778	Approved		1/10/2018		
Amend	9/11/2014	Discharge	00778	Approved	2/3/2015	1/10/2018		
New	8/3/1995	Discharge	00782	Approved	10/31/1995	10/31/2000	665	105.73
Renew	9/11/2000	Discharge	00782	Approved	3/6/2001	3/5/2006		
Renew	3/28/2006	Discharge	00782	Approved	6/26/2006	6/25/2011		
Amend	7/29/2008	Discharge	00782	Approved	11/18/2008	6/25/2011		
Renew	7/6/2011	Discharge	00782	Approved	2/3/2012	2/2/2017		
Amend	9/11/2014	Discharge	00782	Approved	2/3/2015	2/2/2017		
Amend	9/10/2015	Discharge	00782	Approved	2/3/2015	2/2/2017		
Renew	2/24/2017	Discharge	00782	Approved	3/20/2017	3/19/2022		
New	6/2/1983	Discharge	00783	Approved	6/2/1983	none	400	63.60
Amend	9/11/2014	Discharge	00783	Approved	1/2/2015	1/2/2020		
Amend	9/11/2014	Discharge	00783	Approved	1/5/2015	1/2/2020		
Amend	9/11/2014	Discharge	00783	Approved	2/17/2015	1/2/2020		
New	3/1/2001	Discharge	00786	Approved	6/13/2001	6/12/2006	6,850	1,089.06
Renew	7/18/2006	Discharge	00786	Approved	8/22/2006	8/21/2011		
Renew	8/16/2011	Discharge	00786	Approved	7/11/2012	7/11/2017		
Amend	8/16/2011	Discharge	00786	Approved	1/2/2015	7/11/2017		
Amend	8/16/2011	Discharge	00786	Approved	1/5/2015	7/11/2017		
New	1/23/1998	Discharge	00808	Approved	8/24/1998	8/24/2003	1,200	190.79
Renew	9/19/2003	Discharge	00808	Approved	4/5/2004	4/4/2009		
Renew	5/8/2009	Discharge	00808	Approved	8/3/2012	8/2/2017		
Transfer	2/11/1991	Discharge	00814	Approved	3/9/1991		375	59.62
Renew	9/11/2014	Discharge	00814	Approved	7/15/2015	7/15/2020		

Type	Date received	Permit designation	Permit/application number	Action status	Final action date	Permit expire date	bbls day^{-1}	m^3 day^{-1}
Renew	3/1/2001	Discharge	00821	Approved	6/13/2001	6/12/2006	1,000	158.99
Renew	7/18/2006	Discharge	00821	Approved	8/22/2006	8/21/2011		
Renew	8/16/2011	Discharge	00821	Approved	7/11/2012	7/11/2017		
Amend	5/27/2016	Discharge	00821	Approved	6/17/2016	7/11/2017		
Transfer	12/11/1995	Discharge	00823	Approved	4/3/1996	4/3/2001	18,000	2,861.78
Amend	11/26/2001	Discharge	00823	Approved	3/7/2006	1/17/2007		
Renew	12/4/2009	Discharge	00823	Approved	6/20/2013	6/19/2018		
Amend	6/23/2014	Discharge	00823	Approved	5/21/2015	6/19/2018		
Renew	9/2/2003	Discharge	00828	Approved	3/9/2004	3/8/2009	900	143.09
Renew	3/2/2009	Discharge	00828	Approved	6/19/2009	6/18/2014		
Renew	6/23/2014	Discharge	00828	Approved	9/5/2014	9/4/2019		
Transfer	6/23/2014	Discharge	00828	Approved	9/5/2014	9/4/2019		
Amend	6/23/2014	Discharge	00828	Approved	5/20/2015	9/4/2019		
Renew	8/28/2003	Discharge	00832	Approved	3/9/2004	3/8/2009	500	79.49
Renew	6/23/2014	Discharge	00832	Approved	7/28/2014	7/27/2019		
Renew	6/12/1997	Discharge	00845	Approved	6/25/1997	6/25/2002	100	15.90
Renew	8/18/2003	Discharge	00845	Approved	4/26/2004	4/25/2009		
Renew	5/21/2012	Discharge	00845	Approved	5/25/2012	5/24/2017		
New	4/25/1991	Discharge	00858	Approved	5/7/1991		175	27.82
Amend	9/11/2014	Discharge	00858	Approved	5/1/2015	5/1/2020		
New	1/23/1998	Discharge	00859	Approved	8/24/1998	8/24/2003	350	55.65
Renew	9/19/2003	Discharge	00859	Approved	4/5/2004	4/4/2009		
Renew	5/19/2009	Discharge	00859	Approved	6/13/2011	6/12/2016		
Transfer	4/23/2015	Discharge	00859	Approved	6/17/2015	6/12/2016		
Renew	7/5/2016	Discharge	00859	Approved	9/14/2016	9/13/2021		
Transfer	6/4/1996	Discharge	00869	Approved	2/26/1998	2/26/2003	1,500	238.48
Transfer	4/19/2002	Discharge	00869	Approved	5/15/2002	2/26/2003		
Renew	2/27/2003	Discharge	00869	Approved	5/9/2003	4/24/2008		
Renew	7/9/2009	Discharge	00869	Approved	10/6/2009	10/5/2014		
Renew	9/11/2014	Discharge	00869	Approved	3/23/2015	3/23/2020		

Type	Date received	Permit designation	Permit / application number	Action status	Final action date	Permit expire date	bbls day^{-1}	m^3 day^{-1}
Transfer	6/4/1996	Discharge	00870	Approved	2/26/1998	2/26/2003	5,000	794.94
Transfer	4/19/2002	Discharge	00870	Approved	5/15/2002	2/26/2003		
Renew	2/27/2003	Discharge	00870	Approved	5/9/2003	4/24/2008		
Renew	7/9/2009	Discharge	00870	Approved	10/6/2009	10/5/2014		
Renew	9/11/2014	Discharge	00870	Approved	3/23/2015	3/23/2020		
Transfer	6/4/1996	Discharge	00871	Approved	2/26/1998	2/26/2003	N/A	N/A
Transfer	4/19/2002	Discharge	00871	Approved	5/15/2002	2/26/2003		
Renew	2/27/2003	Discharge	00871	Approved	5/9/2003	4/24/2008		
Renew	10/20/2008	Discharge	00871	Approved	10/2/2009	10/1/2014		
Renew	9/11/2014	Discharge	00871	Approved	3/23/2015	3/23/2020		
Transfer	6/4/1996	Discharge	00872	Approved	2/26/1998	2/26/2003	N/A	N/A
Transfer	4/19/2002	Discharge	00872	Approved	5/15/2002	2/26/2003		
Renew	2/27/2003	Discharge	00872	Approved	5/9/2003	4/24/2008		
Renew	7/21/2008	Discharge	00872	Approved	5/7/2013	5/6/2018		
Renew	5/29/1997	Discharge	00886	Approved	8/24/1998	8/24/2003	600	95.39
Renew	11/7/2003	Discharge	00886	Approved	4/5/2004	4/4/2009		
Renew	5/19/2009	Discharge	00886	Approved	8/3/2012	8/15/2017		
Amend	5/29/1997	Discharge	00887	Approved	8/24/1998	8/24/2003	225	35.77
Renew	9/19/2003	Discharge	00887	Approved	4/4/2009	4/4/2009		
Amend	9/11/2014	Discharge	00887	Approved	5/1/2015	6/12/2016		
Renew	6/20/2016	Discharge	00887	Approved	8/16/2016	8/17/2021		
Renew		Discharge	00887	Approved	6/13/2011	6/12/2016		
Renew	5/29/1997	Discharge	00889	Approved	8/24/1998	8/24/2003	600	95.39
Renew	8/29/2003	Discharge	00889	Approved	4/5/2004	4/4/2009		
Renew	1/27/2011	Discharge	00889	Approved	6/13/2011	6/12/2016		
Amend	9/11/2014	Discharge	00889	Approved	5/1/2015	6/12/2016		
Renew	6/20/2016	Discharge	00889	Approved	8/2/2016	8/1/2021		
Amend	2/1/2017	Discharge	00889	Approved	2/21/2017	8/1/2021		
Renew	5/29/1997	Discharge	00890	Approved	8/24/1998	8/24/2003	150	23.85
Renew	8/29/2003	Discharge	00890	Approved	4/5/2004	4/4/2009		
Renew	1/27/2011	Discharge	00890	Approved	6/13/2011	6/12/2016		
Amend	9/11/2014	Discharge	00890	Approved	5/1/2015	6/12/2016		
Renew	6/20/2016	Discharge	00890	Approved	8/2/2016	8/1/2021		
Amend	2/1/2017	Discharge	00890	Approved	2/21/2017	8/1/2021		

Type	Date received	Permit designation	Permit/application number	Action status	Final action date	Permit expire date	bbls day^{-1}	m^3 day^{-1}
Renew	5/29/1997	Discharge	00891	Approved	8/24/1998	8/24/2003	775	123.22
Renew	10/16/2003	Discharge	00891	Approved	4/5/2004	4/4/2009		
Renew	1/27/2011	Discharge	00891	Approved	6/13/2011	6/12/2016		
Amend	9/11/2014	Discharge	00891	Approved	6/1/2015	6/12/2016		
Renew	6/20/2016	Discharge	00891	Approved	8/18/2016	8/17/2021		
Renew	5/29/1997	Discharge	00895	Approved	8/24/1998	8/24/2003	310	49.29
Renew	8/29/2003	Discharge	00895	Approved	4/5/2004	4/4/2009		
Transfer	4/23/2015	Discharge	00895	Approved	12/16/2015	6/12/2016		
Renew	7/5/2016	Discharge	00895	Approved	12/6/2016	12/5/2021		
Renew	1/23/1998	Discharge	00897	Approved	8/24/1998	8/24/2003	250	39.75
Renew	8/29/2003	Discharge	00897	Approved	4/5/2004	4/4/2009		
Renew	5/19/2009	Discharge	00897	Approved	11/17/2009	11/16/2014		
Renew	8/24/2015	Discharge	00897	Approved	4/27/2016	4/26/2021		
Transfer	6/4/1996	Discharge	00899	Approved	2/26/1998	2/26/2003	3,000	476.96
Transfer	4/19/2002	Discharge	00899	Approved	5/15/2002	2/26/2003		
Renew	2/27/2003	Discharge	00899	Approved	5/9/2003	4/24/2008		
Renew	7/9/2009	Discharge	00899	Approved	10/6/2009	10/5/2014		
Transfer	4/30/1996	Discharge	00900	Approved	2/26/1998	2/26/2003	15,700	2,496.10
Transfer	4/19/2002	Discharge	00900	Approved	5/15/2002	2/26/2003		
Renew	2/27/2003	Discharge	00900	Approved	5/9/2003	4/24/2008		
Renew	7/9/2009	Discharge	00900	Approved	10/6/2009	10/5/2014		
New	6/1/2001	Discharge	00906	Approved	8/3/2001	8/2/2006	500	79.49
Renew	5/4/2009	Discharge	00906	Approved	10/27/2009	10/26/2014		
Amend	11/3/2014	Discharge	00906	Approved	8/4/2016	8/3/2021		
New	12/4/2000	Discharge	00907	Approved	3/19/2001	3/18/2006	375	59.62
Renew	3/28/2006	Discharge	00907	Approved	5/1/2006	4/30/2011		
Amend	7/29/2008	Discharge	00907	Approved	11/18/2008	4/30/2011		
Renew	4/26/2011	Discharge	00907	Approved	7/11/2011	7/10/2016		
Amend	6/20/2014	Discharge	00907	Approved	11/7/2014	7/10/2016		
Renew	4/26/2006	Discharge	00936	Approved	10/11/2006	10/10/2011	250	39.75
Renew	10/7/2011	Discharge	00936	Approved	7/10/2013	7/10/2018		
Amend	7/1/2016	Discharge	00936	Approved	7/29/2016	7/10/2018		

Type	Date received	Permit designation	Permit/application number	Action status	Final action date	Permit expire date	bbls day^{-1}	m^3 day^{-1}
Renew	7/9/1999	Discharge	00943	Approved	8/18/2000	8/17/2005	200	31.80
Transfer	6/7/2004	Discharge	00943	Approved	9/15/2004	9/14/2009		
Renew	12/22/2009	Discharge	00943	Approved	1/19/2012	1/17/2017		
Renew	9/21/1993	Discharge	00944	Approved	7/8/1994	7/8/1999	375	59.62
Renew	3/9/2001	Discharge	00944	Approved	1/15/2002	1/14/2007		
Renew	3/25/2008	Discharge	00944	Approved	6/12/2009	6/11/2014		
Amend	6/11/2014	Discharge	00944	Approved	5/22/2015	5/21/2020		
Renew	6/11/2014	Discharge	00944	Approved	5/22/2015	5/21/2020		
New	3/1/2001	Discharge	00947	Approved	6/13/2001	6/12/2006	450	71.54
Renew	7/18/2006	Discharge	00947	Approved	8/22/2006	8/21/2011		
Renew	8/16/2011	Discharge	00947	Approved	7/11/2012	7/11/2017		
Amend	5/27/2016	Discharge	00947	Approved	6/17/2016	7/11/2017		
New	5/16/1995	Discharge	00965	Approved	6/27/1995	6/27/2000	595	94.60
Renew	4/5/2001	Discharge	00965	Approved	7/26/2001	7/25/2006		
Amend	6/10/2005	Discharge	00965	Approved	7/6/2005	7/25/2006		
Renew	9/5/2006	Discharge	00965	Approved	6/17/2013	6/17/2018		
Amend	6/23/2014	Discharge	00965	Approved	3/19/2015	6/17/2018		
Renew	4/5/2001	Discharge	00966	Approved	7/26/2001	7/25/2006	155	24.64
Renew	11/21/2006	Discharge	00966	Approved	1/11/2013	1/11/2018		
Renew	4/1/2016	Discharge	00966	Approved	4/29/2016	1/11/2018		
New	11/2/1995	Discharge	00973	Approved	1/22/1996	1/22/2001	200	31.80
Renew	4/5/2001	Discharge	00973	Approved	7/26/2001	7/25/2006		
Renew	11/3/2006	Discharge	00973	Approved	1/10/2013	1/10/2018		
Amend	6/23/2014	Discharge	00973	Approved	3/2/2015	1/10/2018		
New	5/20/1997	Discharge	00995	Approved	1/13/1998	1/13/2003	75	11.92
Renew	8/19/2003	Discharge	00995	Approved	3/26/2004	3/25/2009		
Renew	11/18/2009	Discharge	00995	Approved	1/19/2012	1/19/2017		
Amend	9/11/2014	Discharge	00995	Approved	8/28/2015	1/19/2017		
Renew	1/19/2017	Discharge	00995	Approved	3/31/2017	3/30/2022		
New	8/11/1998	Discharge	01004	Approved	9/11/1998	9/11/2003	N/A	N/A
Renew	8/12/2003	Discharge	01004	Approved	7/1/2004	6/30/2009		
Renew	10/27/2009	Discharge	01004	Approved	11/14/2012	11/15/2017		

Type	Date received	Permit designation	Permit / application number	Action status	Final action date	Permit expire date	bbls day^{-1}	m^3 day^{-1}
New	6/25/1999	Discharge	01011	Approved	11/12/1999	11/11/2004	1,500	238.48
Renew	11/8/2004	Discharge	01011	Approved	1/20/2005	1/19/2010		
Renew	4/13/2010	Discharge	01011	Approved	12/14/2012	12/14/2017		
Amend	10/12/2015	Discharge	01011	Approved	1/22/2016	1/21/2021		
New	10/30/2002	Discharge	01031	Approved	1/15/2003	1/14/2008	N/A	N/A
Transfer	4/16/2004	Discharge	01031	Approved	9/14/2004	1/14/2008		
Renew	3/19/2008	Discharge	01031	Approved	5/23/2008	5/22/2013		
Renew	5/4/2009	Discharge	01031	Approved	8/13/2013	8/12/2018		
New	10/30/2002	Discharge	01032	Approved	1/15/2003	1/14/2008	N/A	N/A
Transfer	5/24/2004	Discharge	01032	Approved	8/25/2004	1/14/2008		
Amend	3/6/2007	Discharge	01032	Approved	2/19/2008	1/14/2008		
Renew	5/6/2008	Discharge	01032	Approved	8/13/2013	8/12/2018		
New	7/25/2005	Discharge	01048	Approved	9/21/2005	9/20/2010	4,770	758.37
Amend	9/28/2005	Discharge	01048	Approved	10/4/2005	9/20/2010		
Renew	12/1/2008	Discharge	01048	Approved	6/28/2013	6/27/2018		
New	1/7/2013	Discharge	01107	Approved	7/18/2013	7/17/2018	450	71.54
Amend	9/11/2014	Discharge	01107	Approved	7/6/2015	7/17/2018		
New	8/15/2016	Discharge	01120	Approved	9/26/2016	9/25/2021	25	3.97
New	9/6/2016	Discharge	01121	Approved	5/19/2017	5/18/2022	N/A	N/A
						Total	**9,745**	**14,268**

Billion barrels per day (bbls day^{-1}) represents the number of barrels of water permitted to discharge per day, m^3 day^{-1} represents the quantity in cubic meters, and N/A represents information not available. These data do not include the four discharge locations that were not displayed as “active” in the open records request. For the complete list of data received, including all permits both active and inactive, as well as renewal dates and locations, please see SI IV.5.

SI IV.3 Permit status information

The following information is based off data provided by a Railroad Commission of Texas open records request. Permits in red indicate inactive permits; permits in grey indicate the first registered date for the respective active permit.

Type	Date received	Permit / app number	Operator	Action status	Final action date	Permit expire date
Renew		**00005**	Bay Rock Operating Company	Approved	6/7/2001	none
Renew	6/14/2006	**00005**	Bay Rock Operating Company	Approved	12/17/2012	12/16/2017
Renew	6/23/1998	**00006**	Bay Rock Corp.	Approved	4/27/2000	
Renew	1/4/2001	**00009**	Bay Rock Operating Company	Approved	6/7/2001	6/6/2006
Transfer		**00014**	Duke Energy Field Services, Inc.	Approved	2/18/1999	2/17/2004
Transfer	11/20/2000	**00017**	Pueblo Midstream Gas Corporation	Approved	5/8/2002	5/7/2007
Renew	2/19/2004	**00030**	Ray Jr. Co., Inc.	Approved	8/23/2004	8/22/2009
Renew	12/15/2009	**00030**	Ray Jr. Co., Inc.	Approved	10/5/2010	9/29/2015
Renew		**00053**	Vastar Resources, Inc.	Approved	3/13/1998	3/13/2003
Renew		**00054**	Vastar Resources, Inc.	Approved	3/13/1998	3/13/2003
Transfer	5/10/1993	**00065**	Enex Resources Corp.	Approved	9/8/1993	9/8/1998
Renew	4/19/2000	**00065**	3TEC Energy Corp.	Approved	3/27/2002	3/26/2003
Transfer	10/16/2003	**00065**	MCA Petroleum Corporation	Approved	4/5/2004	4/4/2009
Renew	8/13/2009	**00065**	MCA Petroleum Corporation	Approved	8/3/2012	8/2/2017
Amend	8/13/2009	**00065**	MCA Petroleum Corporation	Approved	8/3/2012	8/2/2017
Transfer	5/10/1993	**00066**	Enex Resources Corp.	Approved	9/8/1993	9/8/1998
Renew	4/19/2000	**00066**	3TEC Energy Corp.	Approved	3/27/2002	3/26/2003
Transfer	9/19/2003	**00066**	MCA Petroleum Corporation	Approved	4/5/2004	4/4/2009
Renew	9/19/2003	**00066**	MCA Petroleum Corporation	Approved	4/5/2004	4/4/2009
Renew	8/13/2009	**00066**	MCA Petroleum Corporation	Approved	8/3/2012	8/2/2017
Amend	8/13/2009	**00066**	MCA Petroleum Corporation	Approved	8/3/2012	8/2/2017
Transfer	11/7/1996	**00116**	Bellwether Exploration Company	Approved	8/13/1997	8/13/2002
Transfer	4/3/2001	**00116**	RSEC II, LLC	Approved	5/14/2001	8/13/2002
Renew	8/14/2002	**00116**	RSEC II, LLC	Approved	9/10/2002	9/9/2007
Transfer	10/20/1997	**00130**	Louis Dreyfus Natural Gas Corp.	Approved	6/20/2000	6/19/2005
Renew	2/25/1999	**00190**	GPM Gas Corporation	Approved	4/30/1999	4/30/2004
Transfer	2/25/2000	**00190**	GPM Gas Company LLC	Approved	8/18/2000	4/30/2004
Renew	2/25/1999	**00206**	GPM Gas Corporation	Approved	4/30/1999	4/30/2004
Transfer	2/25/2000	**00206**	GPM Gas Company LLC	Approved	8/18/2000	4/30/2004
Renew	8/20/2003	**00236**	Sabco Operating Company	Approved	5/7/2004	5/6/2009

Type	Date received	Permit/app number	Operator	Action status	Final action date	Permit expire date
Renew	9/17/2007	**00236**	Sabco Operating Company	Approved	10/27/2009	10/26/2014
Amend	2/29/2012	**00236**	Sabco Operating Company	Approved	5/8/2012	10/26/2014
Renew	4/12/1996	**00268**	National Energy Group, Inc.	Approved	2/16/2000	2/15/2005
Transfer	11/1/2000	**00268**	Orient Petroleum Offshore, LLC	Approved	11/16/2000	2/15/2005
Transfer	12/14/2000	**00268**	Osprey Petroleum Company, Inc.	Approved	1/23/2001	2/15/2005
Amend	8/7/2002	**00268**	Osprey Petroleum Company, Inc.	Approved	9/4/2002	2/15/2005
Amend	7/14/2003	**00268**	Osprey Petroleum Company, Inc.	Approved	7/29/2003	2/15/2005
Transfer	7/23/2004	**00268**	Sterling Energy, Inc.	Approved	9/20/2004	9/19/2009
Renew	9/18/2009	**00268**	Sterling Energy, Inc.	Approved	11/24/2009	11/23/2014
Transfer	1/25/2011	**00268**	Atinum Energy, Inc.	Approved	3/28/2012	3/27/2017
Amend		**00268**	Sterling Energy, Inc.	Approved		
Renew	2/25/1999	**00269**	GPM Gas Company LLC	Approved	11/6/2000	11/6/2005
Transfer	10/29/1997	**00687**	Sharpe Energy Company	Approved	1/7/2000	1/6/2005
Transfer	7/19/2001	**00687**	Vamos Oil & Gas, LLC	Approved	8/30/2001	1/6/2005
Amend	1/28/1999	**00692**	Tri-Union Development Corp.	Approved	1/29/1999	9/30/2003
Transfer	12/16/1997	**00695**	Xplor Energy Operating Co.	Approved	7/31/1998	8/4/2003
Transfer	12/5/2001	**00695**	Enfield Operating, L.L.C.	Approved	1/4/2002	8/4/2003
New	3/8/1999	**00697**	Whiting Petroleum Corporation	Approved	6/18/1999	6/17/2004
Amend	3/9/2001	**00697**	Whiting Petroleum Corporation	Approved	3/26/2001	6/17/2004
Transfer	2/20/2004	**00697**	Whiting Oil and Gas Corporation	Approved	6/8/2004	6/7/2009
Transfer	4/9/1998	**00707**	Forcenergy, Inc.	Approved	5/21/1999	6/22/2000
Renew	5/23/2000	**00707**	Forcenergy, Inc.	Approved	10/24/2000	10/23/2005
Transfer	1/16/2001	**00707**	Forest Oil Corp.	Approved	1/30/2001	10/23/2005
Renew	3/5/1997	**00731**	Rutherford Oil Corporation	Approved	10/13/1998	10/13/2003
New	8/14/1986	**00732**	Rutherford Oil Corporation	Approved	8/26/1986	
Amend	1/7/1991	**00733**	Rutherford Oil Corporation	Approved	2/11/1991	none
Transfer	8/3/1995	**00741**	National Energy Group, Inc.	Approved	8/18/1995	8/18/2000
Transfer	4/11/2006	**00741**	Chaparral Energy, L.L.C.	Approved	5/9/2006	5/8/2011
Renew	5/8/1998	**00759**	Delray Oil, Inc.	Approved	3/23/1999	3/22/2004
Renew	2/17/2004	**00759**	Delray Oil, Inc.	Approved	4/2/2004	4/1/2009
Renew	4/28/2009	**00759**	Delray Oil, Inc.	Approved	10/30/2009	10/29/2014
Renew	8/28/2009	**00759**	Delray Oil, Inc.	Approved	10/30/2009	
Renew	10/22/2014	**00759**	Delray Oil, Inc.	Approved	12/16/2016	12/15/2021
Transfer	8/7/1995	**00760**	Sellers Lease Service, Inc.	Approved	1/22/1996	1/22/2001

Type	Date received	Permit/app number	Operator	Action status	Final action date	Permit expire date
Renew	12/5/2006	**00760**	Sellers Lease Service, Inc.	Approved	4/18/2007	4/17/2012
Renew	3/27/2012	**00760**	Sellers Lease Service, Inc.	Approved	3/2/2015	3/2/2020
Amend	7/5/2016	**00760**	Sellers Lease Service, Inc.	Approved	8/25/2016	3/2/2020
Amend	9/1/2016	**00760**	Sellers Lease Service, Inc.	Approved	9/30/2016	3/2/2020
Renew	5/4/1987	**00762**	Delray Oil, Inc.	Approved	10/30/2009	10/29/2014
Renew	5/8/1998	**00762**	Delray Oil, Inc.	Approved	3/23/1999	3/22/2004
Renew	2/17/2004	**00762**	Delray Oil, Inc.	Approved	4/6/2004	4/5/2009
Renew	10/22/2014	**00762**	Delray Oil, Inc.	Approved	12/16/2016	12/15/2021
Renew	3/19/2001	**00763**	Vomela Resources, Inc.	Approved	5/10/2001	5/9/2006
Transfer	12/9/2002	**00763**	Sellers Lease Service, Inc.	Approved	4/17/2003	5/9/2006
Renew	5/24/2006	**00763**	Sellers Lease Service, Inc.	Approved	7/11/2006	7/10/2011
Renew	7/13/2011	**00763**	Sellers Lease Service, Inc.	Approved	7/10/2013	7/10/2018
Amend	6/23/2014	**00763**	Sellers Lease Service, Inc.	Approved	6/4/2015	7/10/2018
Transfer	12/9/2002	**00764**	Sellers Lease Service, Inc.	Approved	4/17/2003	5/9/2006
Renew	5/26/2006	**00764**	Sellers Lease Service, Inc.	Approved	7/11/2006	7/10/2011
Renew	7/15/2011	**00764**	Sellers Lease Service, Inc.	Approved	3/30/2012	7/10/2011
Amend	9/11/2014	**00764**	Sellers Lease Service, Inc.	Approved	1/5/2015	3/29/2017
Amend	9/11/2014	**00764**	Sellers Lease Service, Inc.	Approved	1/20/2015	3/29/2017
Renew	3/16/2017	**00764**	Sellers Lease Service, Inc.	Approved	6/16/2017	6/15/2022
Renew	8/28/2003	**00765**	Guinn Operating Company	Approved	3/9/2004	3/8/2009
Renew	3/12/2009	**00765**	Guinn Operating Company	Approved	6/19/2009	6/18/2014
Renew	6/23/2014	**00765**	Guinn Operating Company	Approved	7/1/2014	7/1/2019
Amend	1/20/2015	**00765**	Guinn Operating Company	Approved	2/9/2015	7/1/2019
Renew	8/26/2003	**00768**	Acock/Anaqua Operating Co., LC	Approved	4/2/2004	4/1/2009
Renew	5/8/2009	**00768**	Acock/Anaqua Operating Co., LC	Approved	10/2/2009	10/1/2014
New	2/19/1999	**00775**	B J P Operating	Approved	5/24/1999	5/23/2004
Transfer	5/25/2004	**00775**	Harrier Holdings, LTD	Approved	7/27/2004	7/26/2009
Renew	1/16/2009	**00775**	Harrier Holdings, LTD	Approved	3/31/2009	3/30/2014
Renew	10/3/2014	**00775**	Harrier Holdings, LTD	Approved	2/24/2015	2/24/2020
New	8/30/1983	**00777**	Hardin Oil Enterprises	Approved	11/1/1983	none
Amend	5/12/2009	**00777**	Sellers Lease Service, Inc.	Approved	6/4/2009	6/3/2014
Transfer	5/12/2009	**00777**	Sellers Lease Service, Inc.	Approved	6/4/2009	6/3/2014
Renew	6/18/2014	**00777**	Sellers Lease Service, Inc.	Approved	6/25/2014	6/25/2019
Amend	9/11/2014	**00777**	Sellers Lease Service, Inc.	Approved	1/2/2015	6/25/2019

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Amend	9/11/2014	**00777**	Sellers Lease Service, Inc.	Approved	1/5/2015	6/25/2019
Amend	9/11/2014	**00777**	Sellers Lease Service, Inc.	Approved	1/20/2015	6/25/2019
Amend	8/16/1993	**00778**	Sellers Lease Service, Inc.	Approved	12/28/1993	7/23/1998
Renew	11/17/2000	**00778**	Sellers Lease Service, Inc.	Approved	10/10/2001	10/9/2006
Renew	6/25/2007	**00778**	Sellers Lease Service, Inc.	Approved	1/10/2013	1/10/2018
Amend	6/23/2014	**00778**	Sellers Lease Service, Inc.	Approved		1/10/2018
Amend	9/11/2014	**00778**	Sellers Lease Service, Inc.	Approved	2/3/2015	1/10/2018
New	8/3/1995	**00782**	O. Neathery III	Approved	10/31/1995	10/31/2000
Renew	9/11/2000	**00782**	O. Neathery III	Approved	3/6/2001	3/5/2006
Renew	3/28/2006	**00782**	Sellers Lease Service, Inc.	Approved	6/26/2006	6/25/2011
Amend	7/29/2008	**00782**	Sellers Lease Service, Inc.	Approved	11/18/2008	6/25/2011
Renew	7/6/2011	**00782**	Sellers Lease Service, Inc.	Approved	2/3/2012	2/2/2017
Amend	9/11/2014	**00782**	Sellers Lease Service, Inc.	Approved	2/3/2015	2/2/2017
Amend	9/10/2015	**00782**	Sellers Lease Service, Inc.	Approved	2/3/2015	2/2/2017
Renew	2/24/2017	**00782**	Sellers Lease Service, Inc.	Approved	3/20/2017	3/19/2022
New	6/2/1983	**00783**	Somont Oil Co Inc	Approved	6/2/1983	none
Amend	9/11/2014	**00783**	Somont Oil Co Inc	Approved	1/2/2015	1/2/2020
Amend	9/11/2014	**00783**	Somont Oil Co Inc	Approved	1/5/2015	1/2/2020
Amend	9/11/2014	**00783**	Somont Oil Co Inc	Approved	2/17/2015	1/2/2020
New	3/1/2001	**00786**	REC Well Service, Inc.	Approved	6/13/2001	6/12/2006
Renew	7/18/2006	**00786**	REC Well Service, Inc.	Approved	8/22/2006	8/21/2011
Renew	8/16/2011	**00786**	Rickaway Energy, Corp.	Approved	7/11/2012	7/11/2017
Amend	8/16/2011	**00786**	Rickaway Energy, Corp.	Approved	1/2/2015	7/11/2017
Amend	8/16/2011	**00786**	Rickaway Energy, Corp.	Approved	1/5/2015	7/11/2017
New	5/22/1997	**00787**	Guinn Operating Company	Approved	2/17/1998	2/17/2003
Renew	8/28/2003	**00787**	Guinn Operating Company	Approved	7/20/2004	3/8/2009
Renew	3/2/2009	**00787**	Guinn Operating Company	Approved	6/19/2009	6/18/2014
Transfer	10/26/1995	**00791**	Wen-Be	Approved	11/8/1995	11/8/2000
Renew	9/8/2003	**00791**	Wen-Be	Approved	6/8/2004	6/7/2009
Renew	11/3/1997	**00805**	Brymer Contracting Incorporated	Approved	4/10/1998	4/10/2003
Renew	7/31/2002	**00805**	Brymer Contracting Incorporated	Approved	10/16/2002	10/15/2007
Renew	3/25/2009	**00805**	Brymer Contracting Incorporated	Approved	9/29/2009	9/28/2014
New	1/23/1998	**00808**	MCA Petroleum Corporation	Approved	8/24/1998	8/24/2003
Renew	9/19/2003	**00808**	MCA Petroleum Corporation	Approved	4/5/2004	4/4/2009

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Renew	5/8/2009	**00808**	MCA Petroleum Corporation	Approved	8/3/2012	8/2/2017
New	5/10/1988	**00809**	Davenport Oil Company	Approved	1/23/1989	1/23/1994
Renew	9/8/1994	**00809**	Davenport Oil Company	Approved	5/23/1995	5/23/2000
Transfer	2/5/1997	**00809**	JAD Oil, Inc.	Approved	7/23/1999	5/23/2000
Renew	11/29/1995	**00811**	Ray Jr. Co., Inc.	Approved	1/22/1996	1/22/2001
Renew	2/19/2004	**00811**	Ray Jr. Co., Inc.	Approved	4/7/2004	4/6/2009
Transfer	2/11/1991	**00814**	MCA Petroleum Corporation	Approved	3/9/1991	
Renew	9/11/2014	**00814**	MCA Petroleum Corporation	Approved	7/15/2015	7/15/2020
Transfer		**00817**	W. C. Miller Operating Company	Approved	4/17/1989	
Renew	3/1/2001	**00821**	REC Well Service, Inc.	Approved	6/13/2001	6/12/2006
Renew	7/18/2006	**00821**	REC Well Service, Inc.	Approved	8/22/2006	8/21/2011
Renew	8/16/2011	**00821**	Rickaway Energy, Corp.	Approved	7/11/2012	7/11/2017
Amend	5/27/2016	**00821**	Rickaway Energy, Corp.	Approved	6/17/2016	7/11/2017
Transfer	12/11/1995	**00823**	Heartland Resources, Inc.	Approved	4/3/1996	4/3/2001
Amend	11/26/2001	**00823**	Heartland Resources, Inc.	Approved	3/7/2006	1/17/2007
Renew	12/4/2009	**00823**	Three Forks Operating Co LLC	Approved	6/20/2013	6/19/2018
Amend	6/23/2014	**00823**	Three Forks Operating Co LLC	Approved	5/21/2015	6/19/2018
Renew	9/2/2003	**00828**	Guinn Operating Company	Approved	3/9/2004	3/8/2009
Renew	3/2/2009	**00828**	Guinn Operating Company	Approved	6/19/2009	6/18/2014
Renew	6/23/2014	**00828**	Guinn Operating Company	Approved	9/5/2014	9/4/2019
Transfer	6/23/2014	**00828**	Guinn Operating Company LLC	Approved	9/5/2014	9/4/2019
Amend	6/23/2014	**00828**	Guinn Operating Company LLC	Approved	5/20/2015	9/4/2019
Renew	8/28/2003	**00832**	Guinn Operating Company	Approved	3/9/2004	3/8/2009
Renew	6/23/2014	**00832**	Guinn Operating Company	Approved	7/28/2014	7/27/2019
Renew	6/30/2004	**00835**	Bay Rock Operating Company	Approved	9/20/2004	9/19/2009
Renew	6/12/1997	**00845**	Warrior Resources, Inc.	Approved	6/25/1997	6/25/2002
Renew	8/18/2003	**00845**	Warrior Resources, Inc.	Approved	4/26/2004	4/25/2009
Renew	5/21/2012	**00845**	Warrior Resources, Inc.	Approved	5/25/2012	5/24/2017
New	3/27/1995	**00849**	LMN Oil & Gas, Inc.	Approved	6/27/1995	6/27/2000
Renew	1/11/2001	**00849**	Wen-Be	Approved	5/16/2001	5/15/2006
New	1/15/1990	**00850**	Energy Development Corp.	Approved	5/24/1990	none
New	5/4/1998	**00852**	Santos USA Corp.	Approved	7/13/1998	7/13/2003
Transfer	2/14/2001	**00852**	Sterling Exploration & Production Co, LLC	Approved	2/28/2001	7/13/2003
New	4/25/1991	**00858**	MCA Petroleum Corporation	Approved	5/7/1991	

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Amend	9/11/2014	**00858**	MCA Petroleum Corporation	Approved	5/1/2015	5/1/2020
New	1/23/1998	**00859**	MCA Petroleum Corporation	Approved	8/24/1998	8/24/2003
Renew	9/19/2003	**00859**	MCA Petroleum Corporation	Approved	4/5/2004	4/4/2009
Renew	5/19/2009	**00859**	MCA Petroleum Corporation	Approved	6/13/2011	6/12/2016
Transfer	4/23/2015	**00859**	Sellers Lease Service, Inc.	Approved	6/17/2015	6/12/2016
Renew	7/5/2016	**00859**	Sellers Lease Service, Inc.	Approved	9/14/2016	9/13/2021
Transfer	6/4/1996	**00869**	Somex Energy Company	Approved	2/26/1998	2/26/2003
Transfer	4/19/2002	**00869**	Acock Engineering & Assoc., Inc.	Approved	5/15/2002	2/26/2003
Renew	2/27/2003	**00869**	Acock/Anaqua Operating Co., LC	Approved	5/9/2003	4/24/2008
Renew	7/9/2009	**00869**	Acock/Anaqua Operating Co., LC	Approved	10/6/2009	10/5/2014
Renew	9/11/2014	**00869**	Acock/Anaqua Operating Co., LC	Approved	3/23/2015	3/23/2020
Transfer	6/4/1996	**00870**	Somex Energy Company	Approved	2/26/1998	2/26/2003
Transfer	4/19/2002	**00870**	Acock Engineering & Assoc., Inc.	Approved	5/15/2002	2/26/2003
Renew	2/27/2003	**00870**	Acock/Anaqua Operating Co., LC	Approved	5/9/2003	4/24/2008
Renew	7/9/2009	**00870**	Acock/Anaqua Operating Co., LC	Approved	10/6/2009	10/5/2014
Renew	9/11/2014	**00870**	Acock/Anaqua Operating Co., LC	Approved	3/23/2015	3/23/2020
Transfer	6/4/1996	**00871**	Somex Energy Company	Approved	2/26/1998	2/26/2003
Transfer	4/19/2002	**00871**	Acock Engineering & Assoc., Inc.	Approved	5/15/2002	2/26/2003
Renew	2/27/2003	**00871**	Acock/Anaqua Operating Co., LC	Approved	5/9/2003	4/24/2008
Renew	10/20/2008	**00871**	Acock/Anaqua Operating Co., LC	Approved	10/2/2009	10/1/2014
Renew	9/11/2014	**00871**	Acock/Anaqua Operating Co., LC	Approved	3/23/2015	3/23/2020
Transfer	6/4/1996	**00872**	Somex Energy Company	Approved	2/26/1998	2/26/2003
Transfer	4/19/2002	**00872**	Acock Engineering & Assoc., Inc.	Approved	5/15/2002	2/26/2003
Renew	2/27/2003	**00872**	Acock/Anaqua Operating Co., LC	Approved	5/9/2003	4/24/2008
Renew	7/21/2008	**00872**	Acock/Anaqua Operating Co., LC	Approved	5/7/2013	5/6/2018
Transfer	2/2/1998	**00885**	Seagull Energy E&P, Inc.	Approved	4/28/1999	4/27/2004
Renew	5/29/1997	**00886**	MCA Petroleum Corporation	Approved	8/24/1998	8/24/2003
Renew	11/7/2003	**00886**	MCA Petroleum Corporation	Approved	4/5/2004	4/4/2009
Renew	5/19/2009	**00886**	MCA Petroleum Corporation	Approved	8/3/2012	8/15/2017
Amend	5/29/1997	**00887**	MCA Petroleum Corporation	Approved	8/24/1998	8/24/2003
Renew	9/19/2003	**00887**	MCA Petroleum Corporation	Approved	4/4/2009	4/4/2009
Amend	9/11/2014	**00887**	MCA Petroleum Corporation	Approved	5/1/2015	6/12/2016
Renew	6/20/2016	**00887**	MCA Petroleum Corporation	Approved	8/16/2016	8/17/2021
Renew		**00887**	MCA Petroleum Corporation	Approved	6/13/2011	6/12/2016

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Renew	5/29/1997	**00889**	MCA Petroleum Corporation	Approved	8/24/1998	8/24/2003
Renew	8/29/2003	**00889**	MCA Petroleum Corporation	Approved	4/5/2004	4/4/2009
Renew	1/27/2011	**00889**	MCA Petroleum Corporation	Approved	6/13/2011	6/12/2016
Amend	9/11/2014	**00889**	MCA Petroleum Corporation	Approved	5/1/2015	6/12/2016
Renew	6/20/2016	**00889**	MCA Petroleum Corporation	Approved	8/2/2016	8/1/2021
Amend	2/1/2017	**00889**	MCA Petroleum Corporation	Approved	2/21/2017	8/1/2021
Renew	5/29/1997	**00890**	MCA Petroleum Corporation	Approved	8/24/1998	8/24/2003
Renew	8/29/2003	**00890**	MCA Petroleum Corporation	Approved	4/5/2004	4/4/2009
Renew	1/27/2011	**00890**	MCA Petroleum Corporation	Approved	6/13/2011	6/12/2016
Amend	9/11/2014	**00890**	MCA Petroleum Corporation	Approved	5/1/2015	6/12/2016
Renew	6/20/2016	**00890**	MCA Petroleum Corporation	Approved	8/2/2016	8/1/2021
Amend	2/1/2017	**00890**	MCA Petroleum Corporation	Approved	2/21/2017	8/1/2021
Renew	5/29/1997	**00891**	MCA Petroleum Corporation	Approved	8/24/1998	8/24/2003
Renew	10/16/2003	**00891**	MCA Petroleum Corporation	Approved	4/5/2004	4/4/2009
Renew	1/27/2011	**00891**	MCA Petroleum Corporation	Approved	6/13/2011	6/12/2016
Amend	9/11/2014	**00891**	MCA Petroleum Corporation	Approved	6/1/2015	6/12/2016
Renew	6/20/2016	**00891**	MCA Petroleum Corporation	Approved	8/18/2016	8/17/2021
Renew	5/29/1997	**00892**	MCA Petroleum Corporation	Approved	8/24/1998	8/24/2003
Renew	11/7/2003	**00892**	MCA Petroleum Corporation	Approved	4/5/2004	4/4/2009
Transfer	9/16/2004	**00892**	Sellers Lease Service, Inc.	Approved	12/23/2004	12/22/2009
Renew	11/8/2010	**00892**	MCA Petroleum Corporation	Approved	1/9/2012	1/9/2017
Renew	5/15/1998	**00893**	Sellers Lease Service, Inc.	Approved	3/22/1999	3/21/2004
Renew	5/29/1997	**00894**	MCA Petroleum Corporation	Approved	8/24/1998	8/24/2003
Renew	5/29/1997	**00895**	MCA Petroleum Corporation	Approved	8/24/1998	8/24/2003
Renew	8/29/2003	**00895**	MCA Petroleum Corporation	Approved	4/5/2004	4/4/2009
Transfer	4/23/2015	**00895**	Sellers Lease Service, Inc.	Approved	12/16/2015	6/12/2016
Renew	7/5/2016	**00895**	Sellers Lease Service, Inc.	Approved	12/6/2016	12/5/2021
Renew	1/23/1998	**00897**	MCA Petroleum Corporation	Approved	8/24/1998	8/24/2003
Renew	8/29/2003	**00897**	MCA Petroleum Corporation	Approved	4/5/2004	4/4/2009
Renew	5/19/2009	**00897**	MCA Petroleum Corporation	Approved	11/17/2009	11/16/2014
Renew	8/24/2015	**00897**	MCA Petroleum Corporation	Approved	4/27/2016	4/26/2021
Renew	3/9/1998	**00898**	Amoco Production Company	Approved	3/17/1999	3/16/2004
Transfer	6/4/1996	**00899**	Somex Energy Company	Approved	2/26/1998	2/26/2003
Transfer	4/19/2002	**00899**	Acock Engineering & Assoc., Inc.	Approved	5/15/2002	2/26/2003

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Renew	2/27/2003	**00899**	Acock/Anaqua Operating Co., LC	Approved	5/9/2003	4/24/2008
Renew	7/9/2009	**00899**	Acock/Anaqua Operating Co., LC	Approved	10/6/2009	10/5/2014
Transfer	4/30/1996	**00900**	Somex Energy Company	Approved	2/26/1998	2/26/2003
Transfer	4/19/2002	**00900**	Acock Engineering & Assoc., Inc.	Approved	5/15/2002	2/26/2003
Renew	2/27/2003	**00900**	Acock/Anaqua Operating Co., LC	Approved	5/9/2003	4/24/2008
Renew	7/9/2009	**00900**	Acock/Anaqua Operating Co., LC	Approved	10/6/2009	10/5/2014
Renew	1/23/1998	**00902**	MCA Petroleum Corporation	Approved	8/24/1998	8/24/2003
Renew	9/19/2003	**00902**	MCA Petroleum Corporation	Approved	4/5/2004	4/4/2009
Transfer	9/14/2011	**00902**	Acock Operating Limited	Approved	1/19/2012	4/14/2016
New	6/1/2001	**00906**	C. R. Devine, Inc.	Approved	8/3/2001	8/2/2006
Renew	5/4/2009	**00906**	C. R. Devine, Inc.	Approved	10/27/2009	10/26/2014
Amend	11/3/2014	**00906**	C. R. Devine, Inc.	Approved	8/4/2016	8/3/2021
New	12/4/2000	**00907**	Sellers Lease Service, Inc.	Approved	3/19/2001	3/18/2006
Renew	3/28/2006	**00907**	Sellers Lease Service, Inc.	Approved	5/1/2006	4/30/2011
Amend	7/29/2008	**00907**	Sellers Lease Service, Inc.	Approved	11/18/2008	4/30/2011
Renew	4/26/2011	**00907**	Sellers Lease Service, Inc.	Approved	7/11/2011	7/10/2016
Amend	6/20/2014	**00907**	Sellers Lease Service, Inc.	Approved	11/7/2014	7/10/2016
Transfer	10/20/1997	**00910**	Louis Dreyfus Natural Gas Corp.	Approved	6/20/2000	6/19/2005
Transfer	9/14/1995	**00916**	R. K. Bledsoe Trust Oil Operator	Approved	2/14/1996	2/14/2001
Transfer	8/30/1996	**00930**	Tenex Corporation	Approved	2/17/1998	2/17/2003
Renew	4/26/1993	**00935**	W. C. Miller Operating Company	Approved	8/25/1993	8/25/1998
Amend	5/23/1995	**00935**	W. C. Miller Operating Company	Approved	6/27/1995	8/25/1998
Renew	4/26/2006	**00936**	Warrior Resources, Inc.	Approved	10/11/2006	10/10/2011
Renew	10/7/2011	**00936**	Warrior Resources, Inc.	Approved	7/10/2013	7/10/2018
Amend	7/1/2016	**00936**	Warrior Resources, Inc.	Approved	7/29/2016	7/10/2018
Renew	7/9/1999	**00943**	Means Oil Co.	Approved	8/18/2000	8/17/2005
Transfer	6/7/2004	**00943**	EES Oil Company, LLC	Approved	9/15/2004	9/14/2009
Renew	12/22/2009	**00943**	EES Oil Company, LLC	Approved	1/19/2012	1/17/2017
Renew	9/21/1993	**00944**	Warrior Resources, Inc.	Approved	7/8/1994	7/8/1999
Renew	3/9/2001	**00944**	Warrior Resources, Inc.	Approved	1/15/2002	1/14/2007
Renew	3/25/2008	**00944**	Warrior Resources, Inc.	Approved	6/12/2009	6/11/2014
Amend	6/11/2014	**00944**	Warrior Resources, Inc.	Approved	5/22/2015	5/21/2020
Renew	6/11/2014	**00944**	Warrior Resources, Inc.	Approved	5/22/2015	5/21/2020
Transfer	12/23/1996	**00945**	J. W. Lacey, Jr.	Approved	10/2/1998	10/2/2003

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New	3/1/2001	**00947**	REC Well Service, Inc.	Approved	6/13/2001	6/12/2006
Renew	7/18/2006	**00947**	REC Well Service, Inc.	Approved	8/22/2006	8/21/2011
Renew	8/16/2011	**00947**	Rickaway Energy, Corp.	Approved	7/11/2012	7/11/2017
Amend	5/27/2016	**00947**	Rickaway Energy, Corp.	Approved	6/17/2016	7/11/2017
Transfer	2/4/1997	**00955**	Forcenergy, Inc.	Approved	6/9/1997	2/8/2000
Renew	5/16/2000	**00955**	Forcenergy, Inc.	Approved	10/24/2000	10/23/2005
Transfer	1/16/2001	**00955**	Forest Oil Corp.	Approved	1/30/2001	10/23/2005
Transfer	2/4/1997	**00956**	Forcenergy, Inc.	Approved	6/9/1997	2/8/2000
Renew	4/9/1998	**00959**	Forcenergy, Inc.	Approved	1/20/2000	1/19/2005
Renew	4/9/1998	**00960**	Forcenergy, Inc.	Approved	1/20/2000	1/19/2005
Amend	10/14/1999	**00960**	Forcenergy, Inc.	Approved	1/20/2000	1/19/2005
New	5/16/1995	**00965**	Sellers Lease Service, Inc.	Approved	6/27/1995	6/27/2000
Renew	4/5/2001	**00965**	Sellers Lease Service, Inc.	Approved	7/26/2001	7/25/2006
Amend	6/10/2005	**00965**	Sellers Lease Service, Inc.	Approved	7/6/2005	7/25/2006
Renew	9/5/2006	**00965**	Sellers Lease Service, Inc.	Approved	6/17/2013	6/17/2018
Amend	6/23/2014	**00965**	Sellers Lease Service, Inc.	Approved	3/19/2015	6/17/2018
Renew	4/5/2001	**00966**	Sellers Lease Service, Inc.	Approved	7/26/2001	7/25/2006
Renew	11/21/2006	**00966**	Sellers Lease Service, Inc.	Approved	1/11/2013	1/11/2018
Renew	4/1/2016	**00966**	Sellers Lease Service, Inc.	Approved	4/29/2016	1/11/2018
New	10/23/1995	**00971**	The Rollert Co., Inc.	Approved	12/19/1995	12/19/2000
Transfer	8/4/2003	**00971**	RBR Operating, Inc.	Approved	2/26/2004	2/25/2009
Renew	1/21/2009	**00971**	RBR Operating, Inc.	Approved	3/20/009	3/20/2014
New	11/2/1995	**00973**	Sellers Lease Service, Inc.	Approved	1/22/1996	1/22/2001
Renew	4/5/2001	**00973**	Sellers Lease Service, Inc.	Approved	7/26/2001	7/25/2006
Renew	11/3/2006	**00973**	Sellers Lease Service, Inc.	Approved	1/10/2013	1/10/2018
Amend	6/23/2014	**00973**	Sellers Lease Service, Inc.	Approved	3/2/2015	1/10/2018
Renew	11/12/1998	**00976**	Koch Gateway Pipeline Co.	Approved	9/5/2000	9/4/2005
Renew	3/10/1997	**00979**	Mid-Gulf, Inc.	Approved	11/18/1998	11/17/2003
New	9/23/1996	**00989**	Swift Energy Company	Approved	1/27/1998	1/27/2003
New	9/23/1996	**00990**	Swift Energy Company	Approved	1/27/1998	1/27/2003
Renew	2/2/2004	**00990**	Whiting Oil and Gas Corporation	Approved	6/8/2004	5/26/2009
Renew	10/5/2009	**00990**	Whiting Oil and Gas Corporation	Approved	3/9/2012	8/24/2015
Amend	10/5/2009	**00990**	Whiting Oil and Gas Corporation	Approved	3/9/2012	8/24/2015
Renew	9/23/1996	**00991**	Swift Energy Company	Approved	1/29/1998	1/29/2003

Type	Date received	Permit/app number	Operator	Action status	Final action date	Permit expire date
New	1/27/1997	**00993**	Maple Energy Inc.	Approved	10/15/1997	10/15/2002
New	5/20/1997	**00995**	Bastrop Energy Group	Approved	1/13/1998	1/13/2003
Renew	8/19/2003	**00995**	Bastrop Energy Group	Approved	3/26/2004	3/25/2009
Renew	11/18/2009	**00995**	Bastrop Energy Group	Approved	1/19/2012	1/19/2017
Amend	9/11/2014	**00995**	Bastrop Energy Group	Approved	8/28/2015	1/19/2017
Renew	1/19/2017	**00995**	Bastrop Energy Group	Approved	3/31/2017	3/30/2022
New	10/20/1997	**00997**	Louis Dreyfus Natural Gas Corp.	Approved	2/10/1999	2/10/2004
New	3/27/1998	**01001**	MCA Petroleum Corporation	Approved	6/5/1998	6/5/2003
Renew	8/29/2003	**01001**	MCA Petroleum Corporation	Approved	4/5/2004	4/4/2009
New	8/11/1998	**01004**	Dan A. Hughes Company	Approved	9/11/1998	9/11/2003
Renew	8/12/2003	**01004**	Dan A. Hughes Company	Approved	7/1/2004	6/30/2009
Renew	10/27/2009	**01004**	Dan A. Hughes Company	Approved	11/14/2012	11/15/2017
New	8/12/1998	**01005**	Samedan Oil Corp. - Offshore Div.	Approved	2/10/1999	2/10/2004
Amend	3/22/2000	**01005**	Samedan Oil Corp. - Offshore Div.	Approved	4/21/2000	2/10/2004
Renew	7/16/1998	**01006**	Sellers Lease Service, Inc.	Approved	3/17/1999	3/16/2004
New	7/6/1998	**01007**	Louis Dreyfus Natural Gas Corp.	Approved	4/14/2000	4/13/2005
New	3/27/1998	**01009**	MCA Petroleum Corporation	Approved	4/23/1999	4/22/2004
New	1/26/1999	**01010**	Transwestern Pipeline Company	Approved	9/7/1999	9/6/2000
Renew	11/14/2000	**01010**	Transwestern Pipeline Company	Approved	5/9/2001	5/8/2006
New	6/25/1999	**01011**	Pressly Oil Interest, Inc.	Approved	11/12/1999	11/11/2004
Renew	11/8/2004	**01011**	Pressly Oil Interest, Inc.	Approved	1/20/2005	1/19/2010
Renew	4/13/2010	**01011**	Pressly Oil Interest, Inc.	Approved	12/14/2012	12/14/2017
Amend	10/12/2015	**01011**	Pressly Oil Interest, Inc.	Approved	1/22/2016	1/21/2021
New	7/18/2001	**01012**	Amerada Hess Corporation	Approved	2/6/2002	2/5/2007
Transfer	6/30/2003	**01012**	Anadarko Petroleum Corp.	Approved	7/21/2003	2/5/2007
Transfer	12/7/2004	**01012**	Apache Corporation	Approved	12/30/2004	2/5/2007
Transfer	7/25/2000	**01013**	Coastal Field Services Company	Approved	10/27/2000	10/26/2005
Transfer	2/10/2004	**01013**	El Paso Field Services, L.P.	Approved	8/9/2004	8/8/2009
Transfer	11/8/2004	**01013**	Enterprise Products Operating, L.P.	Approved	1/28/2005	8/8/2009
New	8/7/2000	**01016**	Duke Energy Field Services, LLC	Approved	10/23/2000	10/22/2001
Renew	11/26/2001	**01016**	Duke Energy Field Services, LP	Approved	12/5/2001	12/4/2002
New	9/11/2000	**01017**	Spinnaker Exploration Co., LLC	Approved	11/26/2001	11/25/2006
New	8/30/2001	**01018**	Osprey Petroleum Company, Inc.	Approved	2/6/2002	2/5/2007
New	1/23/2002	**01021**	Amerada Hess Corporation	Approved	3/7/2002	3/6/2007

Type	Date received	Permit/app number	Operator	Action status	Final action date	Permit expire date
Transfer	6/30/2003	**01021**	Anadarko Petroleum Corp.	Approved	7/21/2003	3/6/2007
Transfer	10/11/2004	**01021**	Maritech Resources, Inc	Approved	11/1/2004	3/6/2007
New	7/31/2002	**01024**	Brymer Contracting Incorporated	Approved	10/16/2002	10/15/2007
Renew	3/25/2009	**01024**	Brymer Contracting Incorporated	Approved	9/26/2009	9/28/2014
Amend	3/25/2009	**01024**	Brymer Contracting Incorporated	Approved	3/9/2012	9/28/2014
New	7/31/2002	**01025**	Brymer Contracting Incorporated	Approved	10/16/2002	10/15/2007
Renew	3/25/2009	**01025**	Brymer Contracting Incorporated	Approved	9/29/2009	9/28/2014
New	7/31/2002	**01026**	Brymer Contracting Incorporated	Approved	10/16/2002	10/15/2007
Renew	3/25/2009	**01026**	Brymer Contracting Incorporated	Approved	9/29/2009	9/28/2014
New	7/31/2002	**01027**	Brymer Contracting Incorporated	Approved	10/16/2002	10/15/2007
Renew	3/25/2009	**01027**	Brymer Contracting Incorporated	Approved	9/29/2009	9/28/2014
New	9/4/2002	**01028**	LLOG Exploration Offshore, Inc.	Approved	11/8/2002	11/7/2007
New	10/30/2002	**01031**	Saxet Energy, LTD	Approved	1/15/2003	1/14/2008
Transfer	4/16/2004	**01031**	CMR Energy, LP	Approved	9/14/2004	1/14/2008
Renew	3/19/2008	**01031**	CMR Energy, LP	Approved	5/23/2008	5/22/2013
Renew	5/4/2009	**01031**	CMR Energy, LP	Approved	8/13/2013	8/12/2018
New	10/30/2002	**01032**	Saxet Energy, LTD	Approved	1/15/2003	1/14/2008
Transfer	5/24/2004	**01032**	CMR Energy, LP	Approved	8/25/2004	1/14/2008
Amend	3/6/2007	**01032**	CMR Energy, LP	Approved	2/19/2008	1/14/2008
Renew	5/6/2008	**01032**	CMR Energy, LP	Approved	8/13/2013	8/12/2018
New-Amend	7/16/2003	**01033**	Saxet Energy, LTD	Approved	10/2/2003	10/2/2008
Transfer	8/17/2004	**01033**	CMR Energy, LP	Approved	9/15/2004	10/2/2008
Amend	5/17/2006	**01033**	CMR Energy, LP	Approved	9/7/2006	10/2/2008
Renew	5/12/2009	**01033**	CMR Energy, LP	Approved	11/24/2009	11/23/2014
Amend	10/30/2002	**01034**	Saxet Energy, LTD	Approved	1/15/2003	1/14/2008
Renew		**01034**	CMR Energy, LP	Approved	5/23/2008	5/22/2013
Amend	7/16/2003	**01036**	Saxet Energy, LTD	Approved	10/2/2003	10/2/2008
Transfer	8/17/2004	**01036**	CMR Energy, LP	Approved	9/15/2004	10/2/2008
New-Amend	9/12/2005	**01037**	Roma Oil & Gas, Inc	Approved	10/11/2005	10/10/2010
Transfer	7/25/2011	**01037**	Atascosa Exploration, LLC	Approved	8/15/2011	8/14/2016
New	3/18/2004	**01040**	CMR Energy, LP	Approved	9/15/2004	9/14/2009
Renew	7/31/2009	**01040**	CMR Energy, LP	Approved	10/27/2009	10/26/2014
New	3/18/2004	**01041**	CMR Energy, LP	Approved	8/25/2004	8/24/2009
Renew	6/16/2009	**01041**	CMR Energy, LP	Approved	12/31/2009	12/31/2014

Type	Date received	Permit / app number	Operator	Action status	Final action date	Permit expire date
New	5/20/2004	**01043**	CMR Energy, LP	Approved	9/14/2004	9/13/2009
Renew	6/15/2009	**01043**	CMR Energy, LP	Approved	2/24/2012	2/23/2017
New	3/16/2004	**01044**	CMR Energy, LP	Approved	8/25/2004	8/24/2009
Amend	5/25/2006	**01044**	CMR Energy, LP	Approved	9/7/2006	8/24/2009
Renew	6/15/2009	**01044**	CMR Energy, LP	Approved	1/4/2010	1/3/2015
New	7/25/2005	**01048**	REC Well Service, Inc.	Approved	9/21/2005	9/20/2010
Amend	9/28/2005	**01048**	REC Well Service, Inc.	Approved	10/4/2005	9/20/2010
Renew	12/1/2008	**01048**	Rickaway Energy, Corp.	Approved	6/28/2013	6/27/2018
Amend	3/22/2006	**01051**	CMR Energy, LP	Approved	6/3/2009	8/15/2011
Renew	1/21/2011	**01051**	CMR Energy, LP	Approved	2/3/2011	2/2/2017
Renew	5/10/2006	**01052**	Genesis Gas & Oil, LLC	Approved	3/2/2012	3/1/2017
New	5/8/2006	**01053**	CMR Energy, LP	Approved	6/26/2006	6/25/2011
New	11/13/2006	**01054**	Apex Oil & Gas Inc.	Approved	12/6/2006	12/5/2011
New	12/13/2006	**01056**	Black Pool Energy, LP	Approved	3/14/2007	3/13/2012
New	12/20/2006	**01057**	REC Well Service, Inc.	Approved	3/7/2007	3/6/2012
Transfer	12/1/2008	**01057**	Rickaway Energy, Corp.	Approved	12/15/2008	3/6/2012
New	2/6/2007	**01058**	The Exploration Company	Approved	5/23/2007	5/22/2012
Transfer	5/31/2007	**01058**	TXCO Resources, Inc.	Approved	7/11/2007	5/22/2012
Amend	4/24/2008	**01058**	TXCO Resources, Inc.	Approved	12/19/2008	5/22/2012
Renew	1/22/2009	**01058**	TXCO Resources, Inc.	Approved	3/24/2009	5/22/2012
New	3/5/2007	**01059**	CMR Energy, LP	Approved	5/22/2007	5/22/2012
Renew	3/5/2007	**01059**	CMR Energy, LP	Approved	6/7/2013	6/6/2018
New	9/24/2008	**01063**	Rio-Tex, Inc	Approved	6/1/2009	5/31/2014
New	12/8/2008	**01064**	Magellan E&P Holdings, Inc	Approved	3/28/2012	3/29/2017
New	1/16/2009	**01066**	Hawthorn Energy Partners	Approved	3/16/2009	3/16/2014
New	8/6/2009	**01072**	CMR Energy, LP	Approved	2/24/2012	2/23/2017
New	8/10/2009	**01073**	CMR Energy, LP	Approved	11/13/2009	11/12/2014
New	8/12/2009	**01074**	CMR Energy, LP	Approved	1/5/2010	1/4/2015
New	8/12/2009	**01075**	CMR Energy, LP	Approved	2/3/2012	2/2/2017
Amend	8/13/2009	**01076**	CMR Energy, LP	Approved	6/7/2013	11/12/2014
New	8/13/2009	**01077**	CMR Energy, LP	Approved	12/1/2009	11/30/2014
New	8/24/2009	**01078**	CMR Energy, LP	Approved	7/11/2011	7/10/2016

Type	Date received	Permit / app number	Operator	Action status	Final action date	Permit expire date
Type	Date received	**Permit / app number**	Operator	Action status	Final action date	Permit expire date
New	8/31/2009	**01079**	CMR Energy, LP	Approved	2/3/2012	2/2/2017
Amend	8/31/2009	**01080**	CMR Energy, LP	Approved	6/7/2013	11/12/2014
New	8/31/2009	**01081**	CMR Energy, LP	Approved	12/1/2009	11/30/2014
New	11/9/2009	**01083**	CMR Energy, LP	Approved	1/4/2010	1/3/2015
New	11/13/2009	**01084**	Anloc LLC	Approved	12/15/2009	12/14/2014
Transfer	10/26/2010	**01090**	Patterson Energy Corporation	Approved	7/1/2013	2/17/2016
New	1/13/2012	**01097**	Hall Houston Exploration	Approved	3/9/2012	3/8/2017
New	2/27/2012	**01099**	Rickaway Energy, Corp.	Approved	11/20/2012	11/19/2017
New	1/7/2013	**01107**	Rickaway Energy, Corp.	Approved	7/18/2013	7/17/2018
Amend	9/11/2014	**01107**	Rickaway Energy, Corp.	Approved	7/6/2015	7/17/2018
New	8/15/2016	**01120**	Cimarex Energy Co.	Approved	9/26/2016	9/25/2021
New	9/6/2016	**01121**	Enbridge G & P (East Texas) L.P.	Approved	5/19/2017	5/18/2022

SI IV.4 Discharge coordinates and values per permit number

The following are the discharge coordinates and values per permit number provided by the Railroad Commission of Texas via the Open records Requests. The coordinates of the below listed permits are displayed in SI II.

Latitude	Longitude	Permit number	Statue	Quantity	Discharge	Segment
29.754917	-97.148783	**00065**	E98th	4975	Unnamed tributary to West Brook Creek to Big Fivemile Creek to Peach Creek	1803
29.7614	-97.137183	**00066**	E98th	6100	Unnamed tributary to Pin Oak Creek to Buckners Creek	1803
29.581188	-97.318022	**00760**	E98th	650	Unnamed tributary to Sandy Fork Creek to Peach Creek	1803
29.73294	-97.19422	**00763**	E98th	200	Little Fivemile Creek to Big Fivemile Creek to Peach Creek	1803
29.820924	-97.220394	**00764**	E98th	665	Stock Pond to unnamed tributary to Live Oak Creek to Buckners Creek	1803
29.63783	-97.27832	**00775**	E98th	200	Pin Oak Creek to Peach Creek	1803
29.814537	-97.221743	**00777**	E98th	250	Surface to unnamed tributary to Live Oak Creek to Buckners Creek	1803
29.77315	-97.12133	**00778**	E98th	1500	Unnamed tributary to Live Oak Creek to Buckners Creek	1803
29.651685	-97.24666	**00782**	E98th	665	Unnamed tributary to Baldridge Creek to Peach Creek	1803
29.821394	-97.224442	**00783**	E98th	400	Tributary of Live Oak Creek/Buckners Creek	1803
29.254241	-97.953046	**00786**	E98th	6850	Stock Pond to Clifton Branch of Cibolo Creek	1902
29.778611	-97.121944	**00808**	E98th	1200	unnamed tributary to Live Oak Creek to Buckners Creek	1803
29.8705964	-97.196096	**00814**	E98th	375	Little Fivemile Creek to Big Fivemile Creek to Peach Creek	1803
29.247264	-97.964041	**00821**	E98th	1000	Clifton Branch of Cibolo Creek	1902
30.581997	-96.921988	**00823**	E98th	18000	Stockpond to unnamed tributary of Hills Branch to East Yegua Creek	1211
29.88676	-97.20735	**00845**	E98th	100	Stock pond to Buckners Creek	1803
29.710124	-97.211913	**00858**	E98th	175	Surface to Little Fivemile Creek to Big Fivemile Creek to Peach Creek	1803
29.63823	-97.227828	**00859**	E98th	350	Surface to Pin Oak Creek to Peach Creek	1803
29.728232	-97.195378	**00886**	E98th	600	Little Fivemile Creek to Big Fivemile Creek to Peach Creek	1803
29.720336	-97.212819	**00887**	E98th	225	Stock pond to Little Fivemile Creek to Big Fivemile Creek to Peach Creek	1803
29.773783	-97.108933	**00889**	E98th	600	Stock pond to Live Oak Creek to Buck-ners Creek	1803
29.725185	-97.209147	**00890**	E98th	150	Stock pond to Little Fivemile Creek to Big Fivemile Creek to Peach Creek	1803
29.73627	-97.18936	**00891**	E98th	775	Little Fivemile Creek to Big Fivemile Creek to Peach Creek	1803
29.887912	-97.208301	**00895**	E98th	310	Buckners Creek	1803
29.84028	-97.36667	**00897**	E98th	250	Unnamed tributary to Peach Creek	1803
29.71254	-97.20256	**00906**	E98th	500	Surface to Little Fivemile Creek to Big Fivemile Creek to Peach Creek	1803
29.62057	-97.27102	**00907**	E98th	375	Pin Oak Creek to Peach Creek	1803
29.886384	-97.209444	**00936**	E98th	250	East Fork of Live Oak Creek to Buckners Creek	1803
31.62638	-95.47916	**00943**	E98th	200	Surface to unnamed tributary to Squirrel Creek to Ioni Creek to Neches River	0604
29.886384	-97.20944	**00944**	E98th	375	Buckners Creek	1803

Latitude	Longitude	Permit number	Statue	Quantity	Discharge	Segment
29.244476	-97.966051	**00947**	E98th	450	Stock pond to Clifton Branch of Cibolo Creek	1902
29.810139	-97.226944	**00965**	E98th	595	Unnamed tributary Peach Creek	1803
29.624442	-97.267285	**00966**	E98th	150	Pin Oak Creek	1803
29.5775	-97.31527	**00973**	E98th	200	Unnamed tributary to Sandy Fork Creek to Peach Creek	1803
29.626162	-97.261365	**00995**	E98th	75	Unnamed tributary to Baldridge Creek to Peach Creek	1803
29.1459159	-97.9250013	**01107**	E98th	450	Cibola Creek, thence to San Antonio River (Water Body Segement No. 1901)	1911
28.897778	98.364722	**00005**	W98th	960	Atascosa River	2107
28.8645	-98.169806	**00759**	W98th	700	Stock Pond to Tordilla Creek to Borrego Creek	2107
28.872667	-98.15225	**00762**	W98th	200	Tordilla Creek to Borrego Creek	2107
28.898099	-98.36304	**00765**	W98th	1200	Atascosa River	2107
28.50875	-98.584167	**00768**	W98th	3600	Unnamed tributary to Leoncita Creek	2113
28.88689	-98.472111	**00828**	W98th	900	Unnamed tributary to East Metate Creek to Atascosa River	2107
28.91732	-98.31886	**00832**	W98th	500	Unnamed creek to Atascosa River	2107
28.794705	-98.171535	**00869**	W98th	1500	Tordillo Creek to Lipan Creek	2107
28.806944	-98.1625	**00870**	W98th	5000	Tordillo Creek to Lipan Creek	2107
28.799722	-98.165	**00899**	W98th	3000	Tordillo Creek to Lipan Creek	2107
28.802516	-98.166469	**00900**	W98th	15700	Tordillo Creek to Lipan Creek	2107
28.911389	-98.526667	**01011**	W98th	1500	Natural drainage to stock pond to tribu-tary to La Parita Creek to Atascosa River	2107
28.88156	-98.49078	**01024**	W98th	600	Unnamed tributary to East Metate Creek	2107
28.88279	-98.47969	**01025**	W98th	100	Unnamed tributary to East Metate Creek	2107
28.88595	-98.47391	**01026**	W98th	100	Unnamed tributary to East Metate Creek	2107
28.88317	-98.47417	**01027**	W98th	400	Unnamed tributary to East Metate Creek	2107
28.9	-98.416667	**01048**	W98th	4770	Unnamed tributary of East Metate Creek	2107
30.96424	-102.97500	**01120**	W98th	25		2310

SI IV.5 Listed active discharge permits

The following information is an evaluation of the permits provided by the Railroad Commission of Texas. It is a comparison of permits that were listed as "active" and the permits for which discharge locations were provided.

Active permits	Listed discharges	Listed discharge but not dated active
00005	00005	01024
00065	00065	01025
00066	00066	01026
00268	N/A	01027
00759	00759	
00760	00760	
00762	00762	
00763	00763	
00764	00764	
00765	00765	
00768	00768	
00775	00775	
00777	00777	
00778	00778	
00782	00782	
00783	00783	
00786	00786	
00808	00808	
00814	00814	
00821	00821	
00823	00823	
00828	00828	
00832	00832	
00845	00845	
00858	00858	
00859	00859	
00869	00869	
00870	00870	
00871	N/A	

Active permits	Listed discharges	Listed discharge but not dated active
00872	N/A	
00886	00886	
00887	00887	
00889	00889	
00890	00890	
00891	00891	
00895	00895	
00897	00897	
00899	00899	
00900	00900	
00906	00906	
00907	00907	
00936	00936	
00943	00943	
00944	00944	
00947	00947	
00965	00965	
00966	00966	
00973	00973	
00995	00995	
01004	N/A	
01011	01011	
01031	N/A	
01032	N/A	
01048	01048	
01107	01107	
01120	01120	
01121	N/A	

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Comment on "Exploring Groundwater Recoverability in Texas: Maximum Economically Recoverable Storage," published in the Texas Water Journal (2020) 11(1):152-171, by Justin C. Thompson, Charles W. Kreitler, and Michael H. Young

Robert E. Mace[1]*

Editor-in-Chief's Note: The Texas Water Journal accepted a request by Robert E. Mace, Executive Director and Chief Water Policy Officer at The Meadows Center for Water and the Environment, to share his thoughts on the article, Exploring Groundwater Recoverability in Texas: Maximum Economically Recoverable Storage," published in the Texas Water Journal (2020) 11(1):152-171, by Justin C. Thompson, Charles W. Kreitler, and Michael H. Young. 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.

Keywords: groundwater availability, groundwater recoverability, pumping costs, total estimated recoverable storage, TERS, maximum economically recoverable storage, MERS

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Terms used in paper

Acronym / Initialism	Descriptive Name
TERS	total estimated recoverable storage
TWDB	Texas Water Development Board

I applaud Thompson et al. (2021) for investigating the economic limitations of total estimated recoverable storage (TERS). While the concept of TERS may make practical sense when mining an unconfined aquifer such as the Ogallala, it does not make practical sense in many confined aquifers due to issues of hydraulics and, as the paper analyzes, economics.

Unfortunately, the definition of groundwater availability the authors used in the paper is incorrect. This incorrect definition does not impact the results of the study, but the confusion over the definition is important enough to discuss and clarify for the record. Many fierce policy discussions occur across Texas on desired future conditions, modeled available groundwater, total estimated recoverable groundwater, and groundwater availability, so a correct technical definition is critical.

The term “groundwater availability” is not defined in statute, but it has been used as a concept since Texas published its first water plan in 1961 (TBWE 1961). Initially, state agencies estimated groundwater availability with assumptions on what management goals could or should be. In other words, state agencies recognized that there was a policy component to groundwater availability. When Senate Bill 1 (75th Legislature [1997]) moved planning decisions from the Texas Water Development Board (TWDB) to the newly created regional water planning groups, so went planning decisions on groundwater availability. After conflicts arose between the groundwater availability amounts developed and used by regional water planning groups and those developed and used by groundwater conservation districts, who regulate the resource, the Texas Legislature assigned groundwater availability decisions solely to groundwater conservation districts working collectively in groundwater management areas through House Bill 1763 (79th Legislature [2005]), which is where those decisions remain today.

Thompson et al. (2021) quote TWDB (2016, p. 61) as defining availability as “…the maximum volume of raw water that could be withdrawn annually from each source (such as a reservoir or aquifer). Availability does not account for whether the supply is connected to or legally authorized for use by a specific water user group.” [emphasis added by Thompson et al. (2021)]. Later, Thompson et al. (2021) state that “…[modeled available groundwater] volumes derived from [desired future conditions] do not strictly adhere to the definition of availability given by the plan,” noting that the plan defines modeled available groundwater numbers as the (annual) volume that is “legally authorized for use.” Later, they state that “the total storage component of TERS is the state’s closest approximation of groundwater availability…” This is not correct.

I believe that the misinterpretation of the emphasized sentence in the previous paragraph is what confused Thompson et al. (2021). That sentence is intended to contrast water supplies for a water user group (based on existing infrastructure and an existing permit to use the water) with water availability (which is not necessarily constrained by existing infrastructure or existing permits but is constrained by policy, law, and the physical ability to produce water). This is explained a few pages later in the 2017 state water plan (TWDB 2016, p. 65), where the plan states that “groundwater availability is estimated through a combination of policy decisions, made primarily by groundwater conservation districts, and the ability of an aquifer to transmit water to wells.” The plan then goes on to describe how groundwater availability is determined, namely through policy decisions encompassed by the desired future condition and the number that estimates how much water is available for use, the modeled available groundwater.

Mace et al. (2008), which Thompson et al. (2021) reference, also discusses how managed (now modeled) available groundwater is the groundwater availability that is used by groundwater conservation districts and regional water planning groups based on the policy decisions encompassed by the desired future condition. Even in areas without groundwater conservation districts, regional water planning groups may not include existing and planned-for use that exceeds the modeled available groundwater amount.

As mentioned by Thompson et al. (2021), TERS is one of the nine factors that groundwater conservation districts must consider when establishing their desired future conditions. In other words, TERS informs decisions on groundwater availability but does not define them. For example, TERS is relevant for much of the Ogallala Aquifer, where districts plan for the depletion of the saturated zone (50% of water left in storage after 50 years), and irrelevant for the Barton Springs Segment of the Edwards Aquifer, where the aquifer is managed sustainably to maintain springflow. In fact, and in practice, groundwater availability is equal to the modeled available groundwater amount.

Thompson et al. (2021) note that they were unaware of any rationale in the public record for why TWDB used 25% and 75% to represent the limits of TERS. Because I was working at TWDB at the time and was involved in discussions and decisions related to TERS, I can add some background, at least based on my files and perspective.

House Bill 1763 (79th Legislature [2005]) not only introduced the terms desired future condition and managed (now modeled) available groundwater, but it also introduced the term “total aquifer storage,” defined as “the total calculated volume of groundwater that an aquifer is capable of producing.” Although introduced, the Legislature did not assign anyone to calculate total aquifer storage or assign it to be used for anything.

In early 2009, toward the end of the first round of districts defining desired future conditions and TWDB staff providing managed (now modeled) available groundwater numbers, the board members requested briefings at their public meetings on the results of staff calculations of managed available groundwater (Mace and Ridgeway 2009). Mace and Ridgeway (2009) presented managed available groundwater numbers in the context of total groundwater supplies (groundwater availability) in the 2007 state water plan, existing groundwater supplies in the plan, existing groundwater supplies plus groundwater strategies in the plan, and groundwater use estimates. Later that year, the board requested that staff include an estimate of groundwater in storage (for example, Hutchison 2009). Staff included an estimate of the total amount of water in storage as well as an estimate of recharge or some approximation of sustainable yield.

TERS, TWDB’s role in calculating it, and groundwater conservation districts’ role in considering it arrived with the passage of Senate Bill 660 (82nd Legislature [2011]). The bill did not define the term, leaving TWDB to define it.

As Thompson et al. (2021) note, TWDB’s definition of TERS did not consider the economics, although we considered it. However, considering economics opened up a number of policy questions. Economic for who? At what level? At what time? Thompson et al. (2021) used an irrigator in the central Carrizo-Wilcox Aquifer in their analysis; however, farmers generally need inexpensive water to compete in the marketplace. A city can afford to pay a great deal more for water for municipal, institutional, and industrial needs. But what is the most that a city is willing to pay for water? And at what point in the future? And wouldn’t stakeholders need to be involved in assessing economic viability? Furthermore, Senate Bill 660 did not have a fiscal note, so whatever TWDB did, it had to be done with existing resources.

Ultimately, TWDB staff, with board approval, returned to the plain English interpretation of the phrase “total estimated recoverable storage” and set economics, as well as other technical issues, aside. That led staff to calculate TERS the way it is presently calculated with the 25% to 75% range and the disclaimer as expressions of the general uncertainty of this number.

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Editor-in-Chief's Note: The Texas Water Journal accepted a request by authors, Justin C. Thompson, Charles W. Kreitler, and Michael H. Young, to reply to the commentary by Robert E. Mace on their article published in the Texas Water Journal (2021) 12(1):202-205, regarding "Exploring Groundwater Recoverability in Texas: Maximum Economically Recoverable Storage," published in the Texas Water Journal (2020) 11(1):152-171, by Justin C. Thompson, Charles W. Kreitler, and Michael H. Young. The opinions expressed in this commentary are the opinions of the individual authors and not the opinion of the Texas Water Journal or the Texas Water Resources Institute.

Keywords: groundwater availability, groundwater recoverability, pumping costs, total estimated recoverable storage, TERS, maximum economically recoverable storage, MERS

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Terms used in paper

Acronym / Initialism	Descriptive Name
MERS	maximum economically recoverable storage
TERS	total estimated recoverable storage
TWDB	Texas Water Development Board

We appreciate Dr. Robert E. Mace for taking the time to read our paper and for his commentary. We understand Mace (2021) to be composed of two principal elements: (1) the term "groundwater availability" and (2) the implementation of total estimated recoverable storage (TERS) by the Texas Water Development Board (TWDB).

GROUNDWATER AVAILABILITY

Mace (2021) asserts "the definition of groundwater availability the authors used in the paper is incorrect." While he notes that the term "groundwater availability" is not defined by statute and recognizes that the alleged mischaracterization "does not impact the results of the study," he finds sufficient cause to provide clarity and specificity.

We generally acknowledge and accept Mace's (2021) analysis of the term "groundwater availability." We concur that common usage and application in Texas water planning and management have ascribed to this term a specific meaning, rooted in policy, which equates to the modeled available groundwater (Texas Water Code, Chapter 36 §001(25)) volume developed by TWDB pursuant to the desired future conditions adopted by groundwater conservation districts (Texas Water Code, Chapter 36 §1084). This definition of the term "groundwater availability" was explicitly acknowledged at the 9-minute mark of the webinar associated with the Thompson et al. (2020) paper and presented for the Texas Water Journal on February 11, 2021 (Thompson et al. 2021).

At no point in our 2020 paper did we intend to attempt to redefine the term "groundwater availability" as an established term. On the contrary, we were clear that our study sought to expand and enhance the information available to groundwater managers and stakeholders related to groundwater recoverability, as it is one of many important considerations to the groundwater availability assessments embodied by the desired future condition adoption process (Texas Water Code, Chapter 36 § 108(d)). This distinction is made thematically throughout our 2020 paper, in large part with the use of terms such as "recoverability," "feasibility," and "maximum economically recoverable storage" (MERS), and particularly by the following passages:

- "While recoverability data is crucial to groundwater planning and management, particularly with respect to availability assessments, Texas' best estimates of recoverable groundwater volumes reflect only the volume in storage and take no account of well design or economic constraints" (Thompson et al. 2020, p. 153).
- "While not designed to be economically efficient, MERS is intended to establish clear and rational limits to groundwater recoverability for the purpose of evaluating groundwater availability under variable uses and infrastructure" (Thompson et al. 2020, p. 153).
- "The limitations of this MERS analysis are akin to those applied to TERS; no consideration is given to subsidence, surface water interaction, or water quality. These are all clearly important issues for groundwater managers and must be considered when adopting [desired future conditions] pursuant to Chapter 36 §108(d) of the [Texas Water Code]" (Thompson et al. 2020, p. 160).
- "The methods developed here define MERS as a simplified simulation of the physical and economic limitations to groundwater recoverability; key elements of availability common to all human groundwater demand absent from total storage and TERS" (Thompson et al. 2020, p. 167).
- "We suggest that groundwater policymakers, managers, and producers consider including MERS (or a similar metric) along with TERS and the other considerations of Chapter 36 §108(d) of the [Texas Water Code], especially in jurisdictions operating under a depth-to-water based [desired future condition]" (Thompson et al. 2020, p. 168).

We are aware that TERS, or a similarly limited metric such as the MERS term we developed, "informs decisions on groundwater availability but does not define them" (Mace 2021). Even so, we understand how certain passages of our paper could precipitate Mace's commentary.

For instance, in the section of our paper entitled "2017 State Water Plan: Water for Texas," we discuss definitions of "availability" and "supply" given by the state water plan (TWDB 2016). Mace (2021) asserts that we misinterpret these definitions. As noted above, we acknowledge and accept Mace's analysis of the term "groundwater availability," including the relevant passages he notes from the 2017 state water plan that discuss this term. However, we maintain that there appears to be some disconnect between the general definition of "availability" provided by the plan and the definition of "groundwater availability" as described by Mace (2021). Indeed, one key purpose in providing the discussion of the state water plan in our paper was to draw attention to this apparent information gap and the need for analyses like MERS to address it. To explain further, let us revisit the relevant passage of the plan quoted by our 2020 paper:

> "Water availability refers to the maximum volume of raw water that could be withdrawn annually from each source (such as a reservoir or aquifer) during a repeat of the drought of record. Availability does not account for whether the supply is connected to or legally authorized for use by a specific water user group. Water availability is analyzed from the perspective of the source and answers the question: How much water from this source could be delivered to water users as either an existing water supply or, in the future, as part of a water management strategy?" (TWDB 2016, p. 61 in Thompson et al. 2020, p. 154).

First, we ask, how does one understand the phrase: "the maximum volume of raw water that could be withdrawn" (TWDB 2016, p. 61)? Mace (2021) asserts that, for groundwater, this is equivalent to the modeled available groundwater volume developed by TWDB, pursuant to relevant desired future conditions policies, which is what has been practiced in Texas groundwater planning. However, we suggest that a layperson might understand the term "availability" broadly to have a "plain English" (Mace 2021) meaning of (a) the physical limitations on "the ability of an aquifer to transmit water to wells" (TWDB 2016, p. 65) and perhaps also (b) the relevant economic constraints thereto. Such an interpretation of the term "availability" might then be synonymous with the terms "feasibility" or "recoverability" and is clearly separate and distinct from the term "groundwater availability" as discussed by Mace (2021). In our 2020 paper and in subsequent studies, we develop methods and tools to quantify this particular lens on the term "availability," which is not currently addressed by any metric other than TERS.

Secondly, we ask, how does one understand the statement that "availability does not account for whether the supply is connected to or legally authorized for use by a specific water user group" (TWDB 2016, p. 61)? We appreciate Mace's (2021) assertion that the "legally authorized" element of this sentence is intended to describe whether or not a permit has been issued for extraction. However, we suggest that the term "groundwater availability" as discussed by Mace is, by definition, a volume that is constrained by the legal permissibility of extraction, given that it is limited by desired future condition policy (i.e., law) and is therefore separate and distinct from an "available" volume that takes no account of legal permissibility (such as TERS and MERS).

Thirdly, we ask, what does it mean that "availability" answers the question of "how much water from this source could be delivered to water users as either an existing water supply or, in the future, as part of a water management strategy?" (TWDB 2016, p. 61) Here we suggest that the limitations and assumptions of modeled available groundwater, being "the volume of groundwater production, on an average annual basis, that will achieve the desired future condition" (TWDB 2016, p. 66), are important. Consider, for example, a location that implements an enhanced recharge or aquifer storage and recovery project "as part of a water management strategy" (TWDB 2016, p. 61). In such a case, tools like MERS, which can quantify groundwater recoverability at any depth-to-water for any economic purpose, would provide critical, timely groundwater "availability" information for water managers, whereas modeled available groundwater (unless updated to reflect such changes) could not. Further, consider a location that experiences drought-of-record conditions wherein a decision is made to increase groundwater extraction on a temporary basis. As above, unlike MERS, the business-as-usual assumptions of modeled available groundwater would be insufficient to provide timely information on groundwater "availability" to water managers. This last potentiality and the limitations of modeled available groundwater are at least tacitly acknowledged in the 2022 state water plan (TWDB 2021), as it incorporates "a modeled available groundwater peak factor" (TWDB 2021, p. A-72) which "accommodates short-term pumping above the modeled available groundwater value" (TWDB 2021, p. A-72) and recognizes the existence of "potential groundwater that could be available for pumping" (TWDB 2021, p. A-73).

Similarly, in the section of our 2020 paper entitled "Total Estimated Recoverable Storage," we state: "The total storage component of TERS is the state's closest approximation of groundwater availability, or 'the maximum volume of raw water that could be withdrawn' (TWDB 2016, p. 61), as it incorporates depth-to-water and spatially variable aquifer characteristics" (Thompson et al. 2020, p. 156). Here the contiguous use of the words "groundwater" and "availability" is regrettable, as it is understandably conflated with the "groundwater availability" term described by Mace (2021). The phrase "potentially available groundwater" or similar may have been optimal. That said, we also find it unfortunate that Mace (2021) did not provide the full quotation; the latter part of that passage, the verbiage quoted from the state water plan that "the maximum volume of raw water that could be withdrawn" (TWDB 2016, p. 61 in Thompson et al. 2020, emphasis added), was very deliberately provided to help illuminate our intended meaning.

Ultimately, we hope that (a) the overarching themes and the full content of our 2020 paper, together with (b) Mace (2021) and (c) this response will allay any uncertainty or concern regarding the term "groundwater availability."

TOTAL ESTIMATED RECOVERABLE STORAGE

We appreciate Mace's (2021) unique insights into the evolution of TERS and how TWDB implemented it, particularly given that as we noted in our 2020 paper, very little information is available in the public record on this issue, nor is background information on why TWDB elected to represent TERS as 25% and 75% of "total aquifer storage" (Texas Water Code, Chapter 36 §001(24)). We respect that TWDB was given the latitude to define TERS as well as the difficulties and limitations associated with an unfunded mandate to do so.

However, we respectfully disagree with Mace's (2021) assertion that TERS (or perhaps a similar metric such as MERS) is "irrelevant" to any particular groundwater management jurisdiction. Even if a groundwater conservation district elects, as is their prerogative, to give precedence to another desired future condition consideration, such as spring flows or land surface subsidence, we suggest that TERS (or a similar metric such as MERS) provides important information on one key aspect of groundwater management. Moreover, by virtue of its inclusion in Chapter 36 §108(d) of the Texas Water Code, the Legislature has definitively determined that such information is fundamentally relevant to groundwater management in Texas.

On the other hand, we completely agree with Mace's (2021) assessment of the difficulties and complexities associated with quantifying groundwater recoverability. As we demonstrated in our 2020 paper, groundwater recoverability, as constrained by either physical or economic constraints, varies significantly with "use, aquifer characteristics, and well infrastructure" (Thompson et al. 2020, p. 167). Thus, there is no universal, one-size-fits-all solution for groundwater yields constrained by recoverability. While this reality poses challenges for the statutory requirements placed upon TWDB, we propose that the MERS model developed in our 2020 paper (or a similar analysis) could provide useful, timely information for Texas groundwater managers as it "may be applied to any aquifer and any use to estimate groundwater recoverability" (Thompson et al. 2020, p. 168) at any potential depth-to-water, thus ensuring a scientifically informed, sustainable, and prosperous future for Texas water resources.

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