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Santa Elena Canyon, Big Bend National Park, Texas.

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

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

Keywords: Texas, wetlands, climate, wildlife, regulatory

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Terms used in paper

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

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

INTRODUCTION

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

Definition of Wetlands and Factors Contributing to Their Patterns

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

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

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

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

Importance of Wetlands in Texas

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

Wildlife

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

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

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

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

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

Socioeconomic

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

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

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

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

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

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

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

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

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

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

Water Quality

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

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

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

Climate

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

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

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

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

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

CLIMATE CHANGE AND LAND CONVERSION IMPACTS ON TEXAS WETLANDS

Changes in Precipitation and Temperature Patterns

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

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

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

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

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

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

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

Rising Sea Levels and Coastal Wetlands

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

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

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

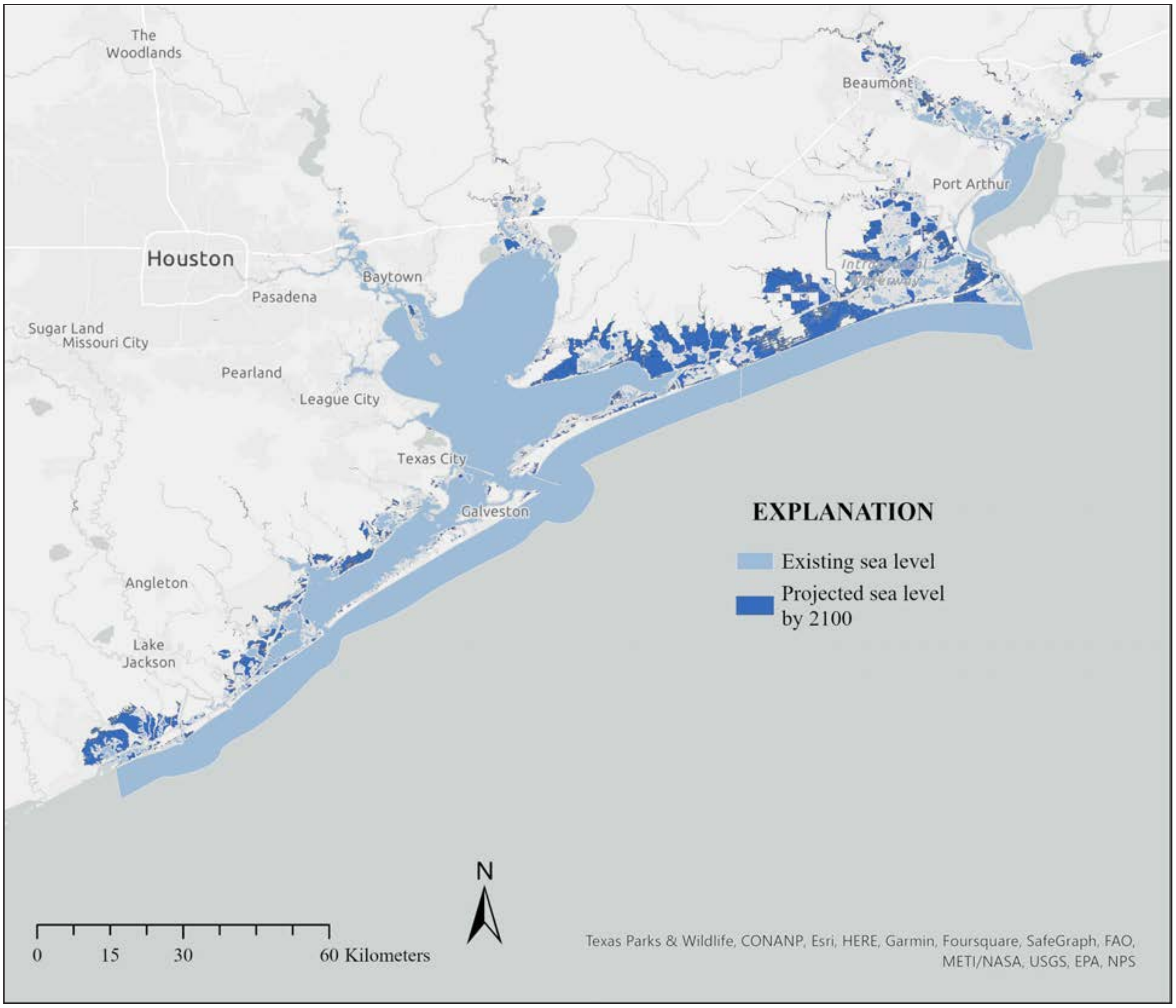

Figure 1. Representation of current and projected sea level rise of 1 foot by 2100 on the upper Texas coast.

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

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

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

Land Conversion

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

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

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

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

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

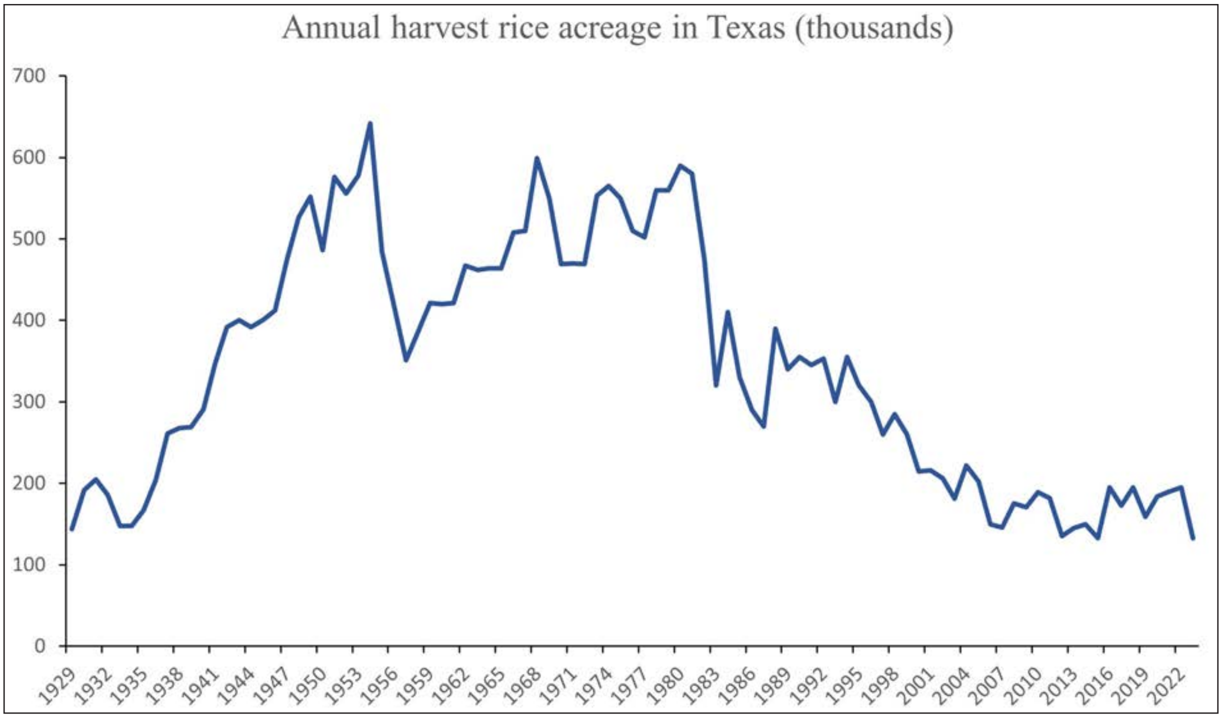

Figure 2. Graph reporting the declines in total harvest rice acreage in Texas 1929–2022 (United States Department of Agriculture [USDA], 2023).

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

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

CONSERVATION AND MANAGEMENT STRATEGIES FOR TEXAS WETLANDS

Policy and Legal Framework

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

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

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

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

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

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

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

Federal and State Conservation Programs

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

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

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

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

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

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

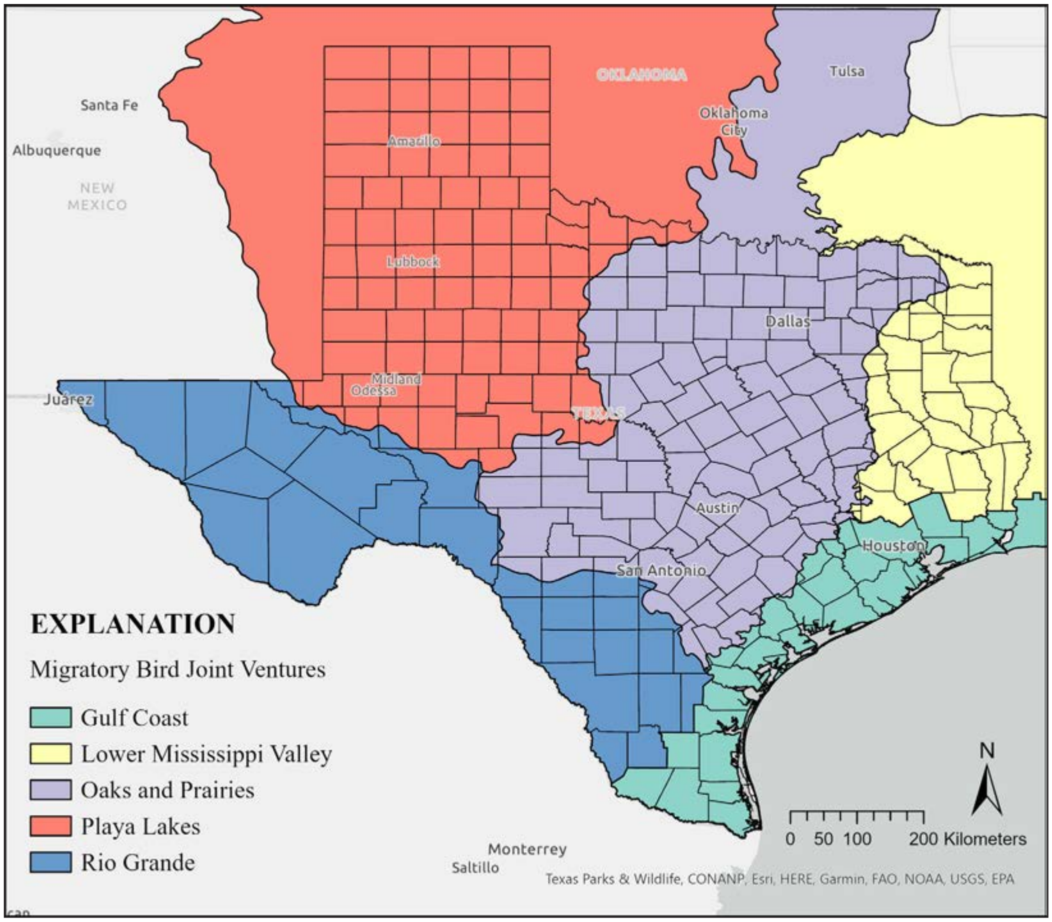

Figure 3. Administrative geographies of joint ventures in Texas as defined by the North American Waterfowl Management Plan.

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

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

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

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

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

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

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

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

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

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

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

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

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

Wetland Loss Mitigation Strategies in Texas

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

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

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

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

CONCLUSIONS

Call to Action for Wetland Conservation and Management in Texas

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

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

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

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

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

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

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

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Appendix I

Characteristics and Distribution of Wetlands in Texas

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

Table 2. Estimated acreage of wetland types in Texas.

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

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

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

PINEYWOODS

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

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

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

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

Flora and Fauna

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

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

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

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

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

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

COASTAL PRAIRIES AND MARSHES

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

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

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

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

Flora and Fauna

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

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

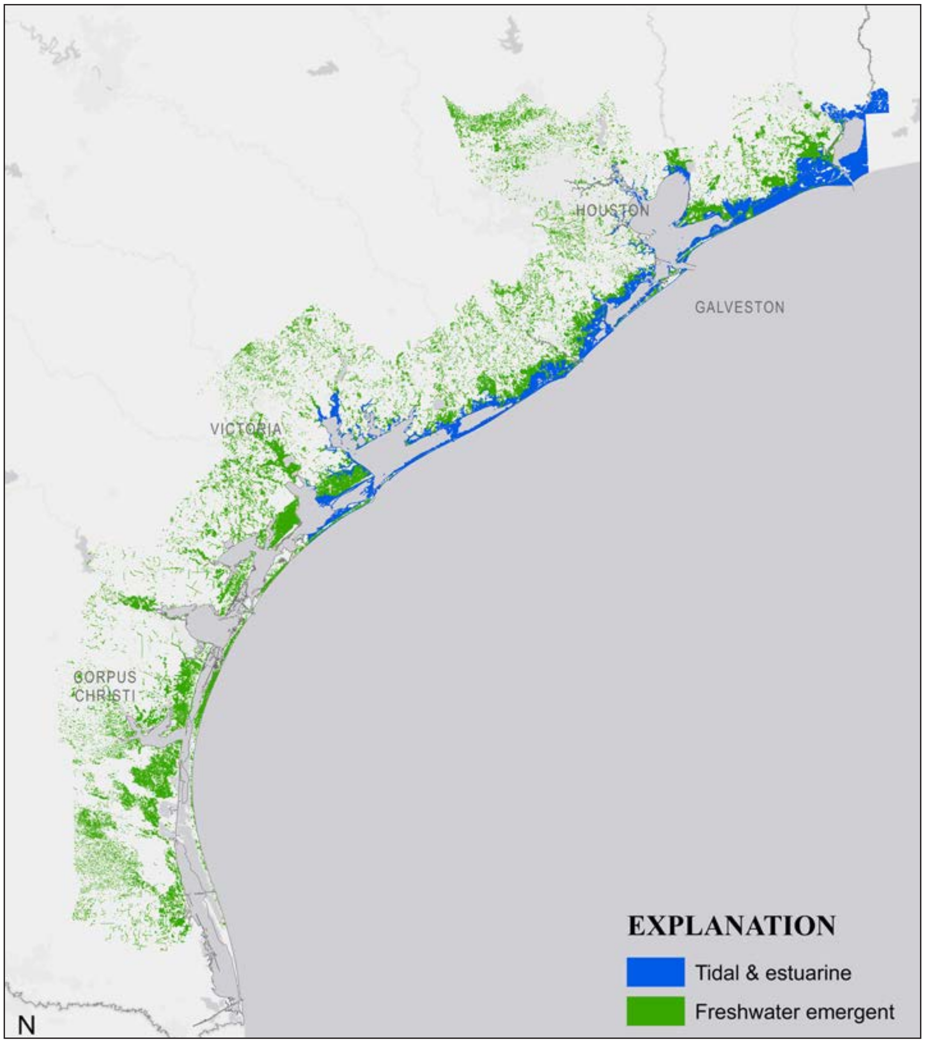

Figure 5. Distribution and extent of coastal freshwater emergent and tidal/estuarine wetlands in Texas (USFWS, 2023b).

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

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

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

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

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

HIGH PLAINS

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

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

Flora and Fauna

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

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

WEST AND CENTRAL REGIONS

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

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

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

Flora and Fauna

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

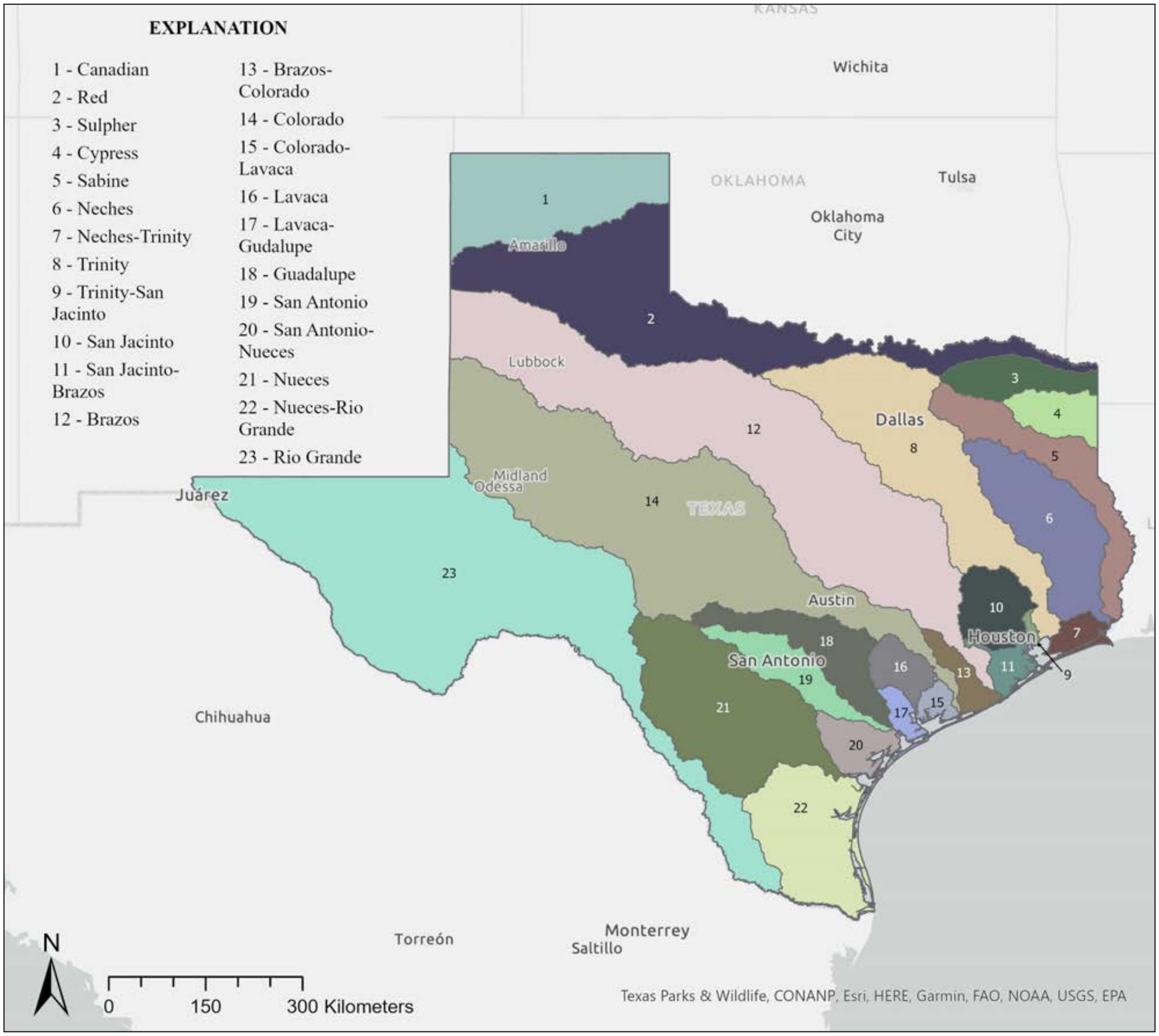

Figure 6. Representation of the 23 major watersheds in Texas.

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

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

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