Journal of
Marine Science and Engineering

MDPI

Article

Hypersalinity in Coastal Wetlands and Potential Restoration Solutions, Lake Austin and East Matagorda Bay, Texas, USA

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Abstract: When droughts occur, freshwater inputs to coastal wetlands can become scarce and hypersalinity can become a problem. In 2023, a severe drought negatively affected a Texas watershed known as Lake Austin that fed a large expanse of wetlands on East Matagorda Bay. To study the hypersalinity problem in these wetlands, we identified freshwater inflows and mapped vegetation changes over time. We found that from 1943 to 2023, the upper portion of the Lake Austin watershed lost freshwater wetlands to agricultural conversion, and ranged from fresh to brackish, with salinity rapidly rising to a maximum of 31 mS during the summer drought of 2023. The lower portion of the watershed gained saltwater wetlands due to sea level rise, and marshes became hypersaline (64–96 mS) during the 2023 drought, endangering its biota. But after large precipitation events, the entire Lake Austin basin rapidly freshened but then returned to its normal salinities within a week as the tides re-delivered saltwater into its basin. Given current climatic trends, we expect that freshwater inflow will continue to slightly increase for the Lake Austin watershed but also that there will be more extreme periods of episodic drought that negatively affect its wetlands. Accordingly, we assessed several potential restoration actions that would improve freshwater flow and delivery to the Lake Austin coastal wetlands.

Keywords: restoration; inflows; freshwater; drought; wetlands; watershed; estuarine; salinity; precipitation; ecology

Citation: Feagin, R.A.; Lerner, J.E.; Noyola, C.; Huff, T.P.; Madewell, J.; Balboa, B. Hypersalinity in Coastal Wetlands and Potential Restoration Solutions, Lake Austin and East Matagorda Bay, Texas, USA. *J. Mar. Sci. Eng.* **2024**, *12*, 829. https://doi.org/10.3390/jmse12050829

Received: 12 April 2024
Revised: 13 May 2024
Accepted: 14 May 2024
Published: 16 May 2024

1. Introduction

Coastal wetlands provide critical habitat and economic value through their numerous ecosystem services [1]; however, they are vulnerable to a reduction in their inflowing freshwater [2]. Adequate freshwater inflows and hydrologic connectivity are important to sustaining healthy and productive wetland vegetation [3,4], by preventing stagnation that can lead to hypersaline and hypoxic waters [5]. On the Texas Coast, healthy wetlands offer nursery habitat for aquatic invertebrates and commercial and recreational fishery species [6], which attract migrating waterfowl, wading birds, and shorebirds from the Central Flyway to wintering sites along the coast [7].

However, as freshwater inflows are reduced, naturally or anthropogenically, saltwater intrudes further inland into the watershed and can kill or alter wetland and wetland-adjacent vegetation [8]. Wetland losses due to reduced freshwater inflows not only affect the survivability of dependent species [7,9,10], but also have costly economic consequences due to the loss of irreplaceable ecosystem services, including carbon sequestration [11], flood abatement [12], and water quality improvement [13]. From the 1950s to 1990s, 30% of Texas coastal freshwater and intermediate salinity wetlands (<5 ppt) have been lost or degraded [14]. Hypersalinity coinciding with drought is known to cause acute wetland dieback [15], and, moreover, the damage associated with predicted increases in the frequency and intensity of drought may be insurmountable for coastal wetlands vulnerable to sea level rise and reduced freshwater inflows. Coastal Texas wetlands epitomize this risk.

The Colorado River of Texas no longer provides direct freshwater inflow to East Matagorda Bay (EMB). Due to a series of hydrologic modifications, its discharging waters are now split between a flood discharge channel and the Colorado River Navigation Channel (CRNC) that leads into West Matagorda Bay [16]. EMB still receives an indirect input via the Gulf Intracoastal Water Way (GIWW), but this quantity is relatively insignificant. Because of these modifications, the resilience of EMB oyster reefs and recreational fisheries has been an ongoing concern [17,18]. EMB is somewhat hydrologically isolated, its tidal beat is largely driven by wind tides, and it can be hypersaline at times [19]. Sediment transport in EMB has been equally impacted by the diversion of flows into Matagorda Bay and the Gulf of Mexico [20,21], and this has limited the inorganic vertical accretion within wetlands [22,23]. To address these concerns, we developed a multi-phased approach to assess the inflows arriving into EMB from these small basins.

Today, a few small watersheds provide the only inflowing freshwater to EMB, including the Big Boggy Creek watershed [24,25], which is adjacent to the Lake Austin watershed. Previous studies have indicated that EMB may not be receiving adequate freshwater inflows from the Big Boggy Creek watershed, and a simple inflow decision tool was developed to assist resource managers and policymakers in their efforts to set environmental flow standards during the summer months. In the present study, we focused on Lake Austin, which is the largest watershed that currently supplies EMB with freshwater. However, there are no gauged watersheds in the EMB basin, so estimates of freshwater inflows to EMB have historically been limited to monthly intervals obtained from models that lack empirical data inputs [17]. This project validated these existing models of inflow to EMB with empirical data we collected during a period of extreme drought events, interposed with extreme precipitation events, conditions that we show are rapidly becoming more common in this watershed.

Our primary objective was to determine if the lower marshes in the Lake Austin watershed were hypersaline, and, if so, whether restoration would help bring more freshwater into these ecosystems. Our team mapped vegetation and hydrologic network changes over time and incorporated stakeholder knowledge and input to recommend potential restoration actions that would improve freshwater flows and delivery in this region, where freshwater inflow fuels life in these shallow aquatic and mixed-aquatic terrestrial ecosystems.

2. Materials and Methods

2.1. Study Area

The Lake Austin watershed is a drainage basin that flows into EMB (Figure 1a). It encompasses ~560 km^2, and stretches from Bay City on its northern extent, down to the GIWW on its southern extent. Lake Austin itself is a ~13 km^2 water body that collects flows from two main tributaries, Peyton Creek and Live Oak Bayou. Peyton Creek (PC) and Live Oak Bayou have characteristically different vegetation regimes and drainage patterns. Peyton Creek (PC) drains the northern and western portions of the Lake Austin watershed and flows directly into Lake Austin on its northwest side. It is surrounded by a coastal prairie mosaic with farms and pastureland. Upstream near Bay City, many drainage ditches lead into smaller tributaries that themselves lead into PC. These smaller tributaries include Cottonwood Creek, Dry Creek, and Bucks Bayou. Further downstream, many irrigation canals ferry water from the nearby Colorado River across the landscape to rice and crawfish farms. These farms then drain into ditches, which lead to Live Oak Creek and Wadsworth Slough, which then themselves flow to PC.

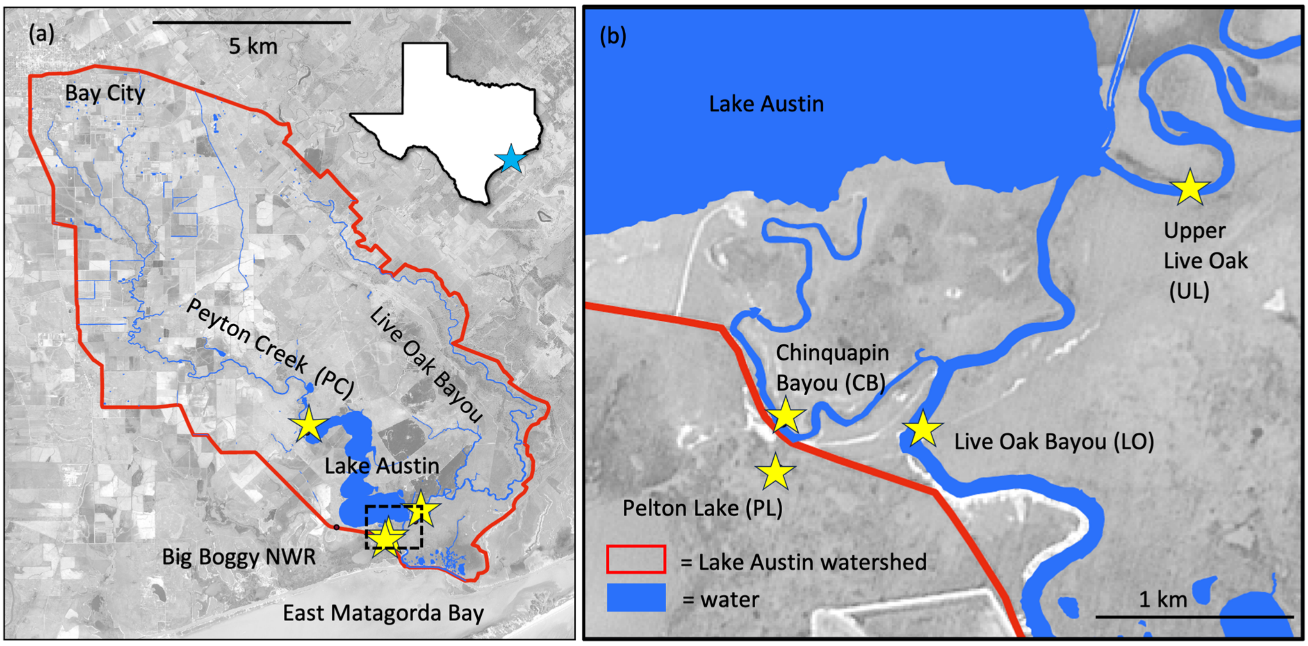

Figure 1. The Lake Austin watershed (**a**) empties its outflowing waters into East Matagorda Bay through a main connecting channel (**b**) known as Live Oak Bayou (LO). CTD sensor stations (stars) were placed at the upper section of Lake Austin, where Peyton Creek (PC) flows into it, as well as at the lower section, where LO is connected to the bay, and at the related channels of Upper Live Oak (UL), Chinquapin Bayou (CB), and Pelton Lake (PL). The black box in (**a**) is shown at higher magnification in (**b**).

Live Oak Bayou drains the eastern portion of the Lake Austin watershed and both flow into and out of Lake Austin on its southeast side (Figure 1b). Upstream of Lake Austin (we refer to this portion as Upper Live Oak—UL), it is primarily surrounded by bottomland hardwood forest. This forested landscape is a part of the extensive Columbia Bottomlands, which stretch further to the east towards Caney Creek, the San Bernard River, and the Brazos River. A portion of UL is in the US Fish & Wildlife (USFWS) San Bernard National Wildlife Refuge (NWR), a vital migratory stopover for hundreds of bird species. Canoe Bayou flows directly into UL, and there are several oxbow lakes surrounding UL that exchange with it intermittently.

Downstream of Lake Austin, the landscape is composed of salt marsh (we refer to this portion of Live Oak Bayou, which passes by a small fishing community, as LO). Chinquapin Bayou (CB) meanders through the marsh on the western side of LO and drains to LO. A gravel road, Chinquapin Road, forms the western boundary of the Lake Austin watershed, near CB and LO. A separate watershed, the Big Boggy Creek watershed, connects through a culvert under this road and across the watershed boundary (Figure 1b). The Big Boggy Creek watershed contains the USFWS Big Boggy NWR and Pelton Lake (PL). A portion of the Big Boggy NWR also lies on the Lake Austin watershed side, in the area immediately surrounding CB.

Big Boggy NWR officials have expressed concern that during periods of drought, PL becomes hydrologically disconnected from CB, LO, and other portions of the refuge. Madewell et al. [24,25] investigated this problem, and we wanted to look for restoration opportunities in the Big Boggy NWR as well as in Lake Austin. USFWS and Texas Parks & Wildlife Department (TPWD) officials have reported that large fish kills do occur in PL, and several state agencies have been involved in trying to rescue fish in the past. The NWR complex also supports more than 100,000 shorebirds annually [26], including threatened and endangered species such as the piping plover (*Charadrius melodus*), reddish egrets (*Egretta rufescens*), northern Aplomado falcon (*Falco femoralis septentrionalis*), and the interior least tern (*Sterna antillarum athalassos*). To better manage the NWR, we need a better understanding of the hydrology in this area.

Still further downstream of Lake Austin and along the eastern side of LO, the salt marsh primarily drains directly to the GIWW via Turkey Island Slough. However, this area of marsh also partially connects to LO through a few small tidal creeks and overland flow.

2.2. Sensors and Data Collection

To better understand the hydrologic connectivity of Lake Austin, we quantified tidal water level and conductivity (as a proxy for salinity) using Conductivity–Temperature–Depth dataloggers (CTDs; Solinst Levelogger 5 LTC, Solinst Canada Ltd., Georgetown, ON, Canada). We placed these CTDs at five stations, PC, LO, UL, CB, and PL, over a series of dates (Figure 1a,b, Table 1).

Table 1. The sensors and gauges placed throughout the study area. CTD = conductivity, temperature, depth sensor. B = barometer. PG = precipitation gauge.

Station Name	Sensor Type	Start Date	End Date
Peyton Creek (PC)	CTD	27 February 2023	21 December 2023
Live Oak Bayou (LO)	CTD	23 March 2023	22 December 2023
Upper Live Oak (UL)	CTD	23 March 2023	22 December 2023
Chinquapin Bayou (CB)	CTD	22 March 2023	22 December 2023
Pelton Lake (PL)	CTD	22 March 2023	22 December 2023
Chinquapin Bayou (CB)	B	22 March 2023	22 December 2023
Chinquapin Bayou (CB)	PG	22 March 2023	11 August 2023
near Cedar Lane, TX	PG	24 February 2023	1 March 2023
near Matagorda, TX (LCRA gauge)	PG	1 January 2023	22 December 2023

The CTDs contained a pressure sensor that measured the hydrostatic pressure of the water, as well as a conductivity sensor that measured the specific conductivity of the water in millisiemens (mS). Conductivity is a standard proxy for salinity. The CTDs were set to record measurements hourly. They were deployed in a PVC pipe securely inserted into the bottom of the water body or channel, with slits in the pipe allowing for water to exchange freely.

To calculate water level depth, the raw CTD pressure data were compensated using atmospheric pressure recorded by a datalogger (Solinst Barologger, Solinst Canada Ltd., Georgetown, ON, Canada) located near CB. Atmospheric pressure does not measurably vary in Texas across the scale of the study area, at the hourly time scale, so the use of this single barometer was appropriate. The water level was then vertically referenced into North American Vertical Datum (NAVD88) units, after surveying the CTD position using the survey-grade Global Navigation Satellite System (GNSS), which included Global Positioning System (GPS) and GLONASS satellites. The GNSS average precision was 0.02 m in horizontal and 0.03 m in vertical.

We also set up several precipitation gauges throughout the study area, but only one produced suitable data (it was located next to the barometer near CB). Additional hourly precipitation data were obtained from the Lower Colorado River Authority (LCRA) rain gauge at Matagorda, Texas (Gauge Matagorda 1 S, Quad 912), 10 miles southwest of the study area [27,28]. We found a strong correlation between our field gauge near CB and the LCRA gauge. Thus, for all subsequent analyses and figures, we used this LCRA dataset because it provided a longer time series of historical data.

2.3. Map Vegetation and Hydrologic Networks over Time

To identify historical changes in wetland cover and hydrologic connection across the landscape, we analyzed aerial imagery from 1943, 1978, and 2020. These 1 m horizontal resolution images were chosen based on their image quality and distribution in time. All images were obtained through the Texas Natural Resources Information System [29]. It is important to note that the available 1943 imagery did not provide full coverage of the Lake Austin watershed; its northern portions were missing. Thus, to maintain consistency across the available years, we limited the following analysis to a constrained portion of the overall study area (see Section 3 for more detail).

Four land cover classes were identified in each image: open water, salt marsh, freshwater wetland, and upland. The water class was characterized as areas of standing water with no vegetation present. Salt marshes were intertidal areas dominated primarily by *Spartina alterniflora* but also included halophytes such as *Batis maritima*, *Salicornia virginica*, and *Distichlis spicata*. Freshwater wetlands were typically dominated by either the herbaceous *Phragmites australis*, *Typha latifolia*, and *Alternanthera philoxeroides*, particularly in the Peyton Creek sub-watershed, or by woody trees such as *Salix nigra*, *Quercus nigra*, *Fraxinus pennsylvanica*, and *Ulmus americana*, with an understory of *Sabal minor*, particularly in the Live Oak sub-watershed. The upland class included all non-water and non-wetland classes (variously dominated by *Andropogon glomeratus*, *Prosopis glandulosa*, *Baccharis halimifolia*, *Celtis laevigata*, *Triadica sebifera*, and *Rosa bracteate*), and human structures or impervious surfaces. Infrared bands available in the 2020 imagery facilitated the precise delineation of darker-toned wetland vegetation from lighter-toned upland areas and open water. The infrared band also aided in distinguishing between freshwater and saltwater wetlands, as freshwater wetlands contained more shrubs and trees than herbaceous-dominated salt marshes. In earlier imagery, contrast and texture were manually used to differentiate between wetland and upland and freshwater wetlands and saltwater wetlands.

Each land cover class was digitized using ArcGIS Pro (ESRI, Version 3.2) at a consistent map scale of 1:4000 to mitigate differences in imagery quality from 1943 to 2020. Since imagery from 1943 had the lowest quality and resolution, more recent imagery was constantly referenced during the digitization process to help with orientation and positioning. While most land cover classifications were unambiguous to the digitizer, an additional expert provided assistance in classifying areas of uncertainty and confirming that the final land cover classifications were accurate. In situ sight identification of vegetation from 2022 to 2023 and several hundred geo-tagged photos were used as a reference for the effort by the digitizer to ground truth the aerial and satellite imagery. In addition, the digitization of similar land cover types from previous research [24,25], including from the neighboring Big Boggy Creek watershed, was referenced to assist in land cover classification. The temporal changes among the classified land cover maps were then analyzed with a number of geoprocessing operations to determine the land cover changes from 1943 to 2020. We then summarized the land cover change uniquely for each sub-watershed.

To understand hydrologic changes from 1943 to 2020, we also measured the shoreline position along Lake Austin and the widths of the channels at PC, UL, LO, and CB near where they connected to Lake Austin. We also delineated several distinct sub-watersheds that uniquely contributed freshwater inflows to the PC and LO stations, using the Watershed tool in ArcGIS Pro (ESRI, Version 3.2 and a 1 m Digital Elevation Model (DEM)).

3. Results

3.1. Sensor Datsasets

In terms of hydrologic connectivity, PC and the northern portion of Lake Austin appeared to be relatively unique from the other stations. On average, the water in PC was primarily fresh to brackish, while other stations were salty and at times hypersaline (Table 2). In addition, the water level at PC was perched ~0.3 m above the other stations. The range in water level at PC was also much greater.

Still, the water level and salinity at all five of the stations were affected by both precipitation events and tides (Figure 2). When it rained heavily, the water level rapidly increased and the conductivity dropped at all stations. During a long drought that occurred in the summer, the water level decreased and conductivity greatly increased at all stations.

Table 2. Water level and conductivity at the station.

	Station				
Water Level (m, NAVD88)	**PC**	**LO**	**UL**	**CB**	**PL**
Average ± Std. Dev. Range	0.50 ± 0.14 0.23 to 1.05	0.23 ± 0.15 −0.02 to 0.74	0.20 ± 0.16 −0.04 to 0.75	0.20 ± 0.15 −0.04 to 0.71	0.19 ± 0.13 −0.05 to 0.66
Conductivity (mS)	PC	LO	UL	CB	PL
Average ± Std. Dev. Range	9 ± 7 0 to 31	37 ± 12 4 to 64	40 ± 14 2 to 67	38 ± 1 0 8 to 65	46 ± 14 9 to 96

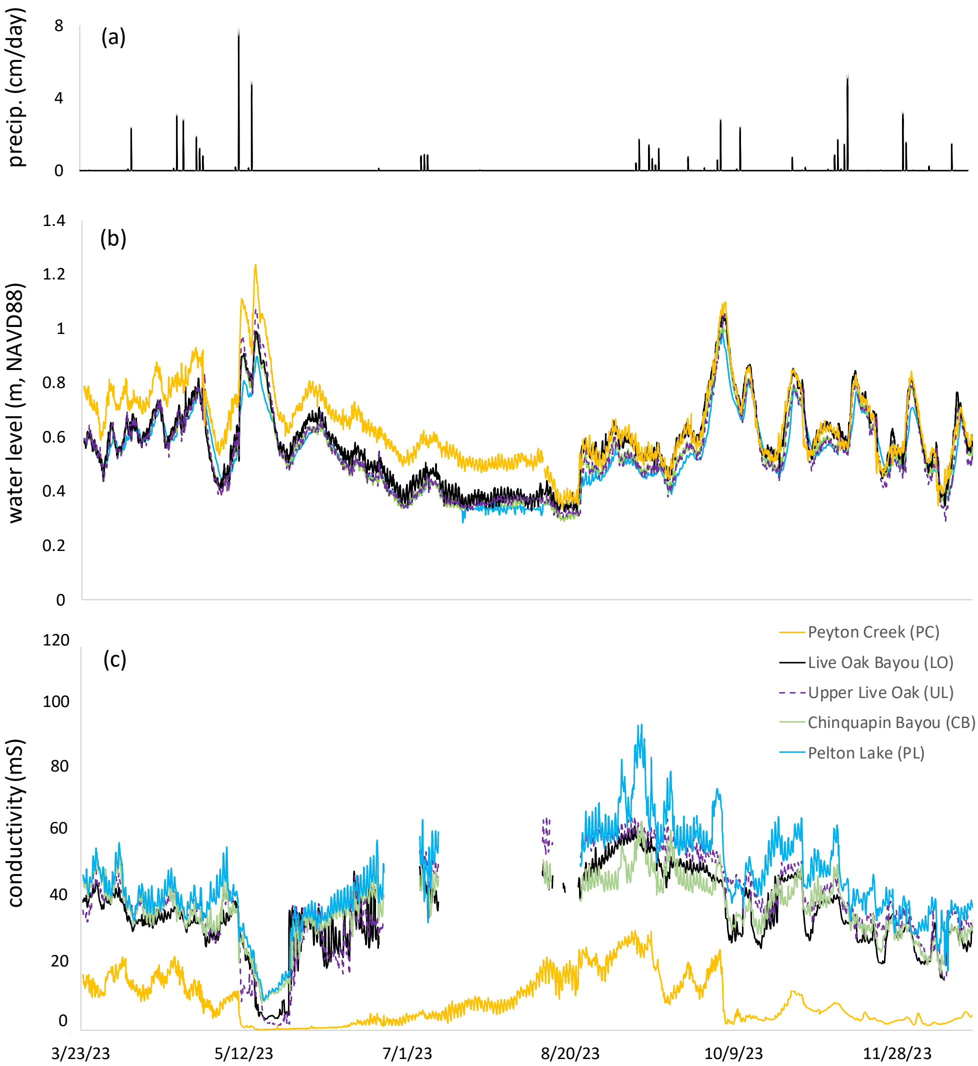

Figure 2. (**a**) Precipitation, (**b**) water level, and (**c**) conductivity from 23 March 2023 to 22 December 2023 at the Lake Austin sensor stations.

Looking more closely at specific precipitation events, when it rained heavily on 11 May 2023 and 14 May 23, the water level rapidly increased and the conductivity dropped at all stations. PC and UL water levels jumped by a factor of 6 (as might be expected of inflowing creeks), LO and CB by 5 (as might be expected in lower receiving channels), and PL by 3 (as might be expected by an isolated area of marsh). Once the freshwater had flushed out of the system, the saline tidal influence first returned on 25 May 23 at LO (lowest receiving channel), 12 h later at CB and PL, and, finally, 24 h later at UL. PC did not return to a similar level of salinity for months after.

After only traces of precipitation during four months over the summer, all stations except for PC experienced hypersalinity. PC and LO showed the most tidal influence (~0.65 m and 0.58 m water level ranges, respectively), while UL, CB, and PL showed only a small influence (all with ranges ~0.04 m). These results suggest that UL, CB, and PL act as minor backwater channels during times of low precipitation, while LO is the main channel with tidal influence from the bay. Surprisingly, PC expressed the largest daily tidal range and strongest semi-diurnal beat, even though it was the furthest from the bay and contained much more freshwater.

3.2. Vegetation and Hydrologic Networks over Time

We found that the DEM elevations throughout the Lake Austin watershed were quite different for the Peyton Creek (PC) and the Live Oak Bayou (LO) sub-watersheds (Figure 3a,b). The PC sub-watershed showed a clearly incised tributary that drained a relatively high coastal plain, whereas the LO sub-watershed showed a deltaic tributary with overflow ridges that had prograded across a much lower basin.

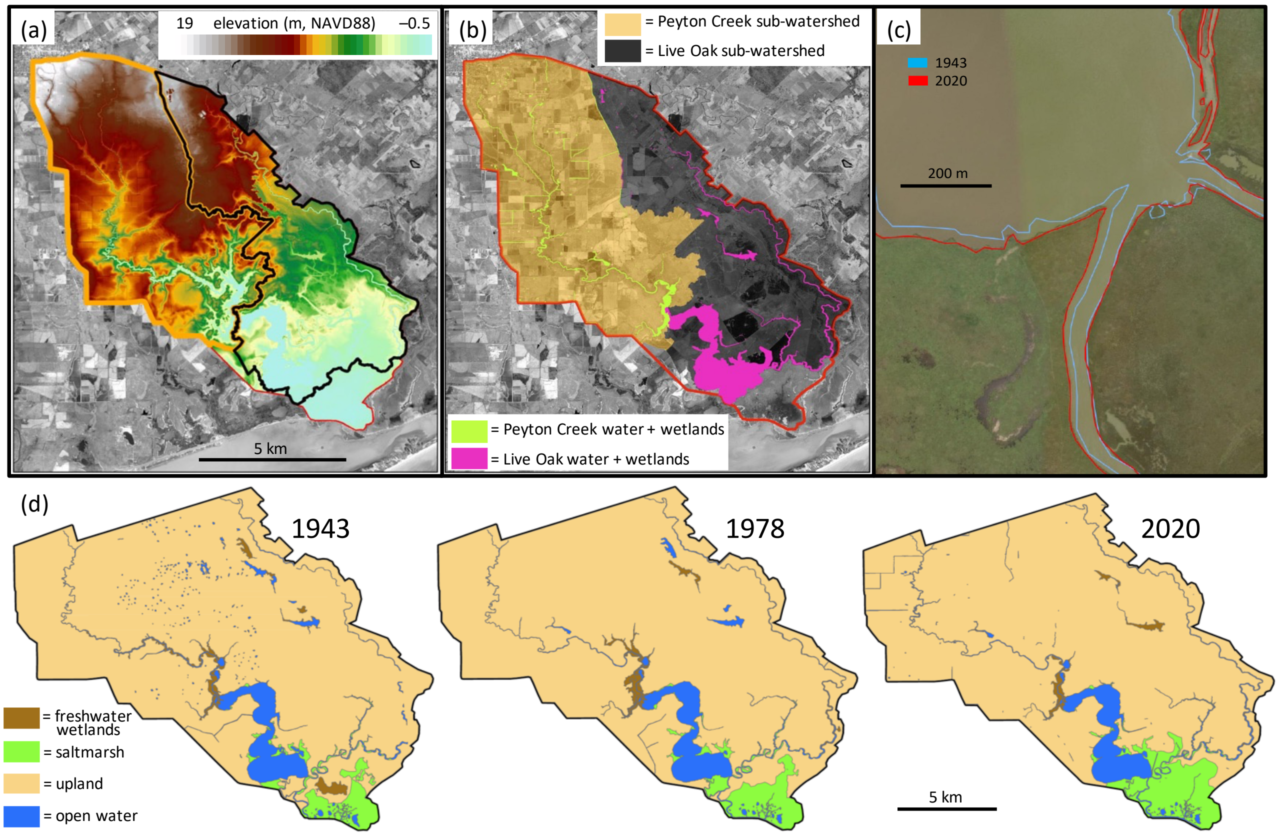

Figure 3. The DEM elevations (**a**) in the Peyton Creek (PC) and the Live Oak Bayou (LO) sub-watersheds, as defined by the orange versus black lines, respectively. (**b**) Wetlands in the PC sub-watershed (yellow) are highlighted in green, and wetlands in the LO sub-watershed (black) are highlighted in pink. (**c**) Shoreline locations in Lake Austin near Live Oak Bayou, from 1943 to 2020. (**d**) Land cover change over time, from 1943 to 1978 to 2020.

We also found that the shoreline generally eroded along Lake Austin (Figure 3c), while the widths of the nearby channels at UL and LO expanded (Table 3). Both PC and CB channels contracted in width. Of particular note, the Lake Austin shoreline eroded considerably at the location immediately adjacent to its connection with UL. Extrapolating the shoreline positions backward in time suggests that Lake Austin and LO likely merged in the 1800s.

Table 3. Channel width expansion and contraction at station locations near Lake Austin, 1943 to 2020. Five widths were measured for each channel and then averaged.

	Station			
	PC	**LO**	**UL**	**CB**
Average change in width (m)	−0.4	15.5	11.5	−8.0
Average change in width, as proportion of original width (%)	−1	41	31	−25

Overall, the upper portions of the Lake Austin area lost freshwater wetlands to agricultural conversion, while the lower portions gained saltwater wetlands due to sea level rise (Figure 3d). From 1943 to 2020, salt marsh increased (+896 hectares), freshwater wetlands decreased (−97 ha), upland areas decreased (−752 ha), and water decreased (−44 ha).

The loss of freshwater wetlands was most prominent in the Turkey Island and Chinquapin (−107 ha) and the Peyton Creek (−56 ha) sub-watersheds (Figure 4). Interestingly, a large number of small "pothole" open water bodies in the Peyton Creek sub-watershed were present in 1943, but they had disappeared by 1978 (Figure 3d). These water bodies appeared to have been drained and converted into rice farms or rangelands. By 2020, an increasing number of drainage channels had been constructed in the upper portions of the Peyton Creek sub-watershed.

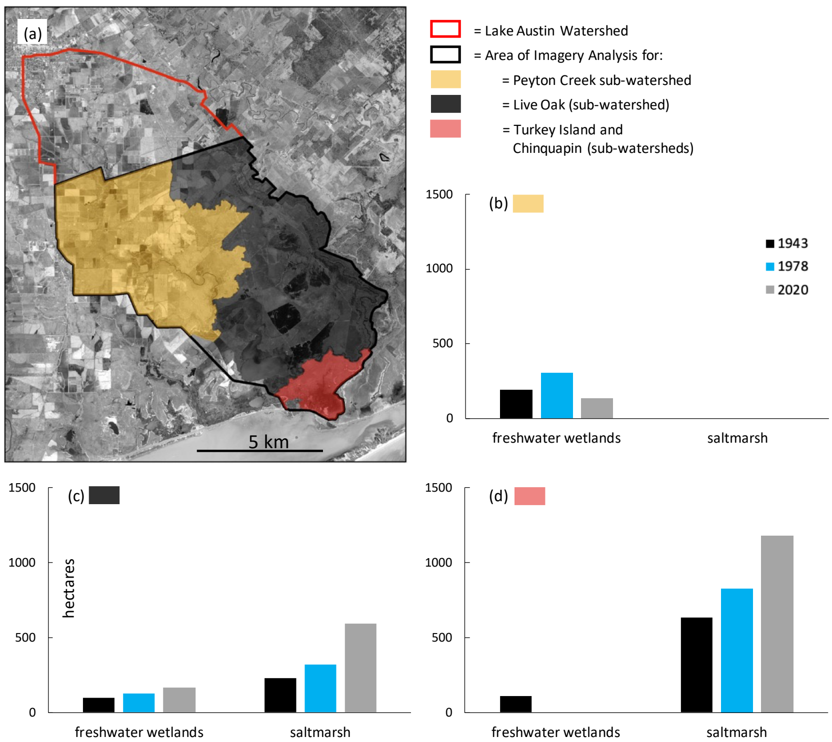

Figure 4. Land cover change analysis from 1943 to 1978 to 2020, sub-divided among (**a**) three sub-watersheds. Land cover change for wetland cover only, over time in (**b**) Peyton Creek sub-watershed, (**c**) Live Oak sub-watershed, and (**d**) Turkey Island and Chinquapin Bayou sub-watersheds.

The increase in salt marsh occurred primarily in the lower portions of the Lake Austin area, particularly in the Turkey Island and Chinquapin (+547 ha) and Live Oak Bayou (+364 ha) sub-watersheds (Figure 4). Large areas of former uplands in 1943, mostly composed of coastal prairie, had flooded and converted either into wetlands or open water by 2020, for these two watersheds (−443 and −381 ha, respectively).

3.3. Climatic Trends

Within the broad historical context from 1940 through to today, the amount of precipitation in the Lake Austin watershed has been slowly increasing at a rate of 0.2% per year, on average, and to a 30% increase for 160 years (Figure 5a). At the same time, the oscillatory nature of wet versus dry months of precipitation has been becoming more extreme (Figure 5b). Over the last eighty years, maximum monthly precipitation has been increasing, while monthly rainfall minimums have been decreasing. In the past 25 years especially, drought has become commonplace, punctuated by months with high rainfall amounts unprecedented in the last eighty years.

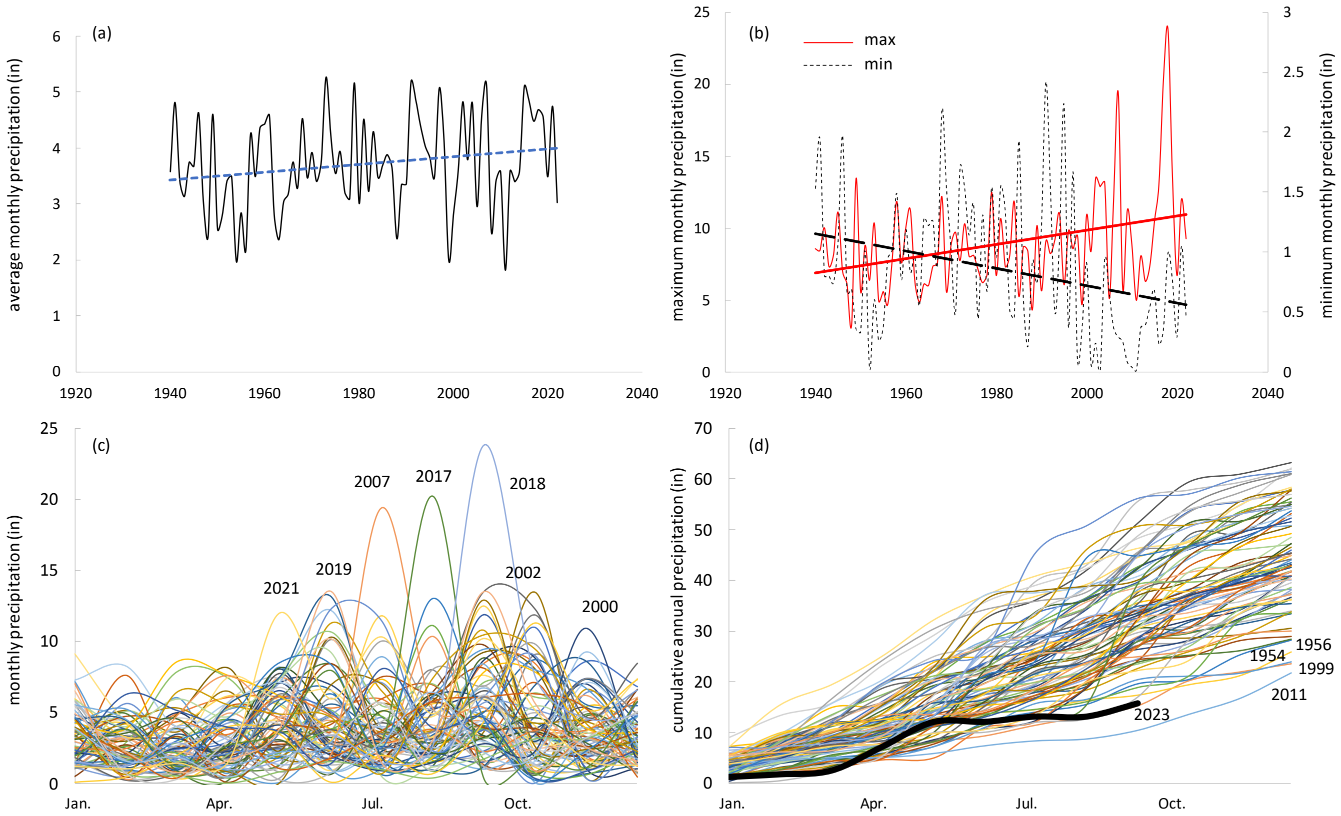

Figure 5. (**a**) Average monthly precipitation at Lake Austin from 1940 to 2023 (black), fit with a linear regression (y = 0.007x − 10.22; blue dashed line). (**b**) Maximum monthly precipitation (red) and minimum monthly precipitation (black), from 1940 to today, fit with linear regressions (y = 0.049x − 88.66 for maximum monthly precipitation; y = −0.007x + 15.28 for minimum monthly precipitation). (**c**) Monthly average precipitation across the years, from 1940 to today. (**d**) Cumulative annual precipitation across the years, from 1940 to today. The year of our field datasets, 2023 (black line), was in an extreme drought. All precipitation data were obtained from the LCRA rain gauge in Matagorda, Texas [28].

Lake Austin is experiencing the potential for both greater flooding and worse droughts at the same time. The likelihood of an extreme precipitation event is increasing for the Lake Austin watershed, and the past two decades have seen some of the largest flooding events since 1940 (Figure 5c). The likelihood of an extreme drought event is increasing for the Lake Austin watershed as well. The past 25 years have seen three of the worst five droughts on record (Figure 5d).

4. Discussion

This study occurred during a particularly dry summer in 2023, and the water level and conductivity data showed that under such conditions, the connectivity to freshwater sources greatly declined. Hypersalinity occurred and even the salt marsh plants suffered under conditions that were not suitable for growth.

4.1. Historical and Future Context for Lake Austin Watershed Restoration and Conservation

The evidence that we collected (the relative water level and salinity at the stations, the land cover and shoreline change over time, and the channel widening and contraction over time) suggests that the following sequence of events likely occurred in the past.

Prior to the 1800s, Lake Austin was an inland freshwater lake with only minimal tidal connection. Water primarily flowed down Peyton Creek, accumulated in this freshwater lake, exited down Chinquapin Bayou, and emptied into EMB. Prior to this time, Live Oak Bayou was not connected to Lake Austin and, though it was likely tidal, it was less so than today.

As the sea level slowly rose, Live Oak Bayou became increasingly tidal and its channel widened. At the same time, wind-driven wave erosion along the southern shoreline of Lake Austin reduced the quantity of land between its shoreline and that of Live Oak Bayou.

During the 1800s, the shoreline of Lake Austin eroded into Live Oak Bayou, or vice versa, and the two water bodies merged. After this tipping point in time, the volume of Lake Austin was captured by Live Oak Bayou and the lake suddenly became more tidal and saltier. Chinquapin Bayou was no longer an efficient exit route for water leaving Lake Austin because it was still relatively small and shallow; it thus silted up at its connection with Lake Austin and its width contracted. Since this tipping point occurred and as the sea level has continued to rise, the existing shoreline along the main channel of Live Oak Bayou at the LO location has been eroding and widening in order to move an increasingly large volume of water.

In the future, as sea level continues to rise, the shorelines of Lake Austin and Live Oak Bayou will continue to erode and widen. Because Lake Austin is today slightly perched above the main channel at LO, it continues to act semi-independently with respect to tidal beat. Eventually, likely within the next 100 years, the entirety of Lake Austin will become fully saline and its upper portion at PC will also become fully saline like LO, UL, CB, and PL are today. Moreover, salt marsh vegetation will continue to replace freshwater wetlands in Peyton Creek and Live Oak Bayou.

4.2. Potential Restoration Opportunities

While natural resource management can address both past environmental damages and future landscape change, we found relatively few areas with obvious restoration potential in the Lake Austin watershed. Lake Austin itself has relatively few wetlands along its immediate shorelines and instead is composed of a relatively steep edge ~1–2 m in height with an adjacent coastal prairie dominated by *Spartina spartinae*. Moreover, as compared to the adjacent Big Boggy Creek watershed [24,25], there were also fewer possibilities to remove hydrologic barriers upstream. Nevertheless, we have identified two high-priority restoration opportunities that would alleviate hypersaline waters and marshes around Lake Austin (Figure 6): (1) installing a small bridge or larger culverts at Chinquapin Road and (2) modifying the existing canal infrastructure in the area to divert freshwater from the Colorado River to Lake Austin. We also suggest conserving the Columbia Bottomlands ecosystem along Live Oak Bayou and increasing advocacy for protecting the watershed.

The current project implemented a portion of the Texas Coastal Resiliency Master Plan [30], specifically the need for a Matagorda Bay Regional Inflow Study (Project #R2-18 in earlier versions of the document, and #9070 in 2023). It also implemented the Texas Water Development Board (TWDB) Colorado and Lavaca Basin and Bay Area Stakeholder Committee (BBASC) Adaptive Management Work Plan by identifying baseline conditions and providing flow regime recommendations and Texas Commission on Environmental Quality (TCEQ) Environmental Flow Standards for the Colorado River and Matagorda Bay [31].

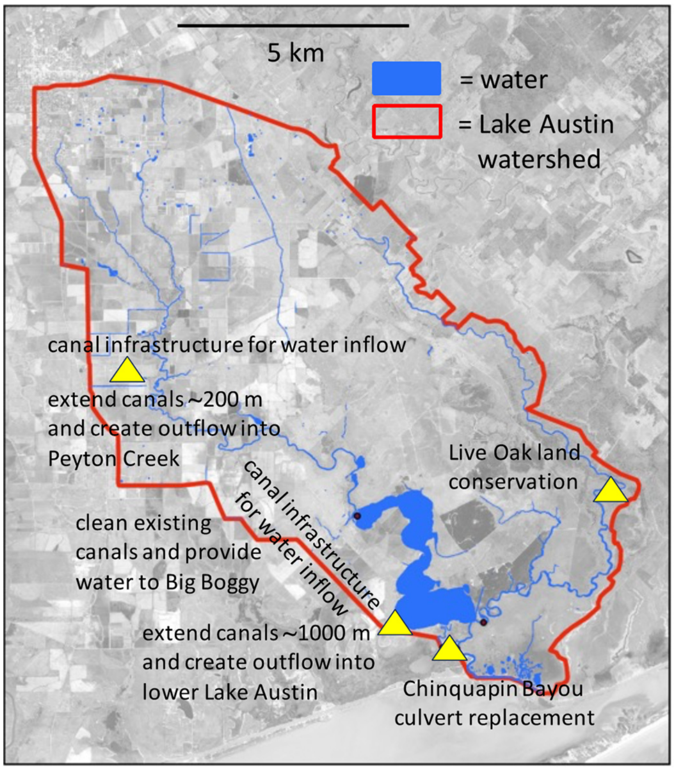

Figure 6. Map of potential restoration and conservation opportunities (yellow). Chinquapin Bayou culvert replacement and modifying existing canal infrastructure for water inflow are two opportunities to alleviate hypersalinity. A tract of the Columbia Bottomlands could be conserved and access trails could be constructed to allow the public to visit this unique ecosystem.

4.2.1. Chinquapin Bayou Flow Passage

USFWS and TPWD have expressed concern that the hydrologic connection between the Lake Austin watershed and the Big Boggy watershed may be interrupted by Chinquapin Road. There are currently two culverts at this location, but it has long been a question about whether they provide sufficient flow. Madewell et al. [24,25] were unable to fully address this question due to sensor failure.

The present study shows that the culverts appear to provide adequate flow (as shown by the data from the CB and PL stations) even during extreme summer drought conditions. The water level was still relatively high during the drought. Still, Pelton Lake at the PL station, and likely the eastern side of the large marsh complex in the Big Boggy NWR, suffered from hypersalinity during this time period. Thus, the problem is larger than this one set of culverts. To reduce hypersalinity at PL, restoration would likely need to more directly reconnect that area to the GIWW.

Chinquapin Road also floods with very high tides and this creates evacuation issues for the residents of the small fishing community along Live Oak Bayou. Thus, there is likely still some benefit to be gained by installing a small bridge or larger culverts at this location.

4.2.2. Canal Infrastructure for Water Inflow

The ability to purchase freshwater during extreme drought conditions, for example, from the LCRA, is likely to be difficult and expensive because other users also need these resources. In addition, the volumes required to make an impact on the Lake Austin watershed are likely to be unattainable. For the Live Oak Bayou sub-watershed, its relatively low elevation, geomorphic landform, existing salinity, and lack of connectivity to existing water infrastructure, such as canals, make this area still more difficult for enhancing flows.

Peyton Creek could be more feasibly and predictably sustained with an inflow standard. Our preliminary calculations suggest filling a need for ~3700 to 17,000 ML per month (or ~3000 to 14,000 acre feet per month), for a drought equivalent to that in the summer of 2011 or 2023 (~USD 200,000 to USD 1,000,000 per month, at 2021 prices). This volume seems reasonable compared to the estimates made by [17,18] for the entirety of EMB over the course of a year, considering that the upper-end values cover the lowest periods of flow during a typical year (similarly, it also coincides with [32]). However, this volume would be ~13–25 times larger than the standard recommended in [25] for Big Boggy Creek during such a drought: ~269 to 675 ML per month (or ~218 to 547 acre feet of water per month). At such a scale and cost, the effort would be better spent on putting the purchased inflows towards the Big Boggy Creek watershed, due to its high concentration of wetlands and relatively lower water demands needed to sustain them.

Austin et al. [33] identified a handful of water delivery options to supplement EMB with freshwater from the Colorado River. One such option is to purchase and deliver water through a series of old canals to Big Boggy or Lake Austin. The Texas Water Trade (TWT) is currently investigating such purchases to place them into Moist Soil Units (MSUs) in Big Boggy NWR, immediately adjacent to the PL station at Pelton Lake.

The existing canal infrastructure in Matagorda County could be used to route freshwater inflow into both the Lake Austin and Big Boggy Creek watersheds (Figure 6). In particular, water could be deposited directly into Peyton Creek by extending the infrastructure ~200 m from an area that is currently under rice farming. The canal infrastructure upstream of this location is in suitable shape.

Water could also be routed further down the canals, but the canals would need to be cleaned at their lower ends. There is an existing outflow location and canal infrastructure that leads to the MSUs in Big Boggy NWR. These could be cleaned out and water routed through them. Another option would be to route the water down the same pathway but create a new canal of ~1000 m in length for this water to lead into the lower portion of Lake Austin. Such a project could be accomplished on existing land owned by the NWR.

A relevant question is whether water should need to be purchased from the LCRA. This water would source from the Colorado River and run down the canal infrastructure network. However, prior to the early 1900s, this river's environmental flows were delivered to both EMB and West Matagorda Bay. Today, they do not reach EMB. Thus, perhaps some of this water should be re-routed to EMB without the need for purchasing it. The benefit would be larger than any one user.

4.2.3. Live Oak Land Conservation

Live Oak Bayou contains a broad expanse of relatively isolated bottomland forest, which constitutes a portion of the Columbia Bottomlands. The Columbia Bottomlands contains nearly all of the remnant coastal bottomland forest in Texas and is a critical biodiversity hotspot. Conservation initiatives are underway for these lands and other lands in the nearby Big Boggy Creek watershed [27], and the landowners are interested in managing the natural resources for the maximum benefit of all ecosystem services. However, more efforts by conservation groups could help these efforts. Access trails could be constructed in the San Bernard NWR to allow the public to visit this unique ecosystem. Such access would only increase advocacy for conserving the environmental flows in the Lake Austin watershed.

4.2.4. Dataset Limitations

As with most field studies, more data, namely a longer time series in this case, could have helped improve the accuracy and interpretation of our sensor datasets. Salinity, water level, and water temperature datasets were collected from late March through December and excluded the winter months of January, February, and early March. A longer multiyear dataset that included a wider range of extremes, antecedent conditions, and different seasons could have addressed concerns that the nine-month study period did not adequately represent the variability at this site. However, our aim was to address the hypersaline conditions that developed during the summer when evaporation rates were at their highest, so additional data collected during the winter when conditions were not hypersaline would not have significantly influenced our interpretations of the results.

More notably, there were data dropouts in the CTD conductivity readings during periods of summer drought when water levels dropped and the sensor was no longer fully submerged underwater and able to make accurate conductivity measurements. These readings were subsequently flagged and removed from the final conductivity dataset, so, unfortunately, we were unable to precisely measure the extent of hypersalinity when water levels were low at times in July and August. However, we still captured the steady increase in salinity during late spring into early summer, as well as the peak of hypersalinity later in August and September. Thus, while the conductivity dataset was somewhat incomplete, this limitation did not significantly alter our findings as the missing data could be inferred to be between the values recorded in June and those recorded later during peak hypersalinity in August.

5. Conclusions

This study provided the first empirical measures of salinity, water temperature, water level, and land cover change in the Lake Austin watershed, the largest watershed supplying freshwater to East Matagorda Bay in Texas. Lake Austin is experiencing the potential for both severe droughts and floods at the same time, as the last two decades have seen some of the most extreme droughts and floods on record since the 1940s. Already, the watershed has lost about 97 ha of freshwater wetlands and 752 ha of upland since 1943. Hypersaline conditions, such as those observed throughout the watershed in 2023, further imperil its wetlands. Although salt marsh wetlands increased by 893 ha since 1943 due to sea level rise, these areas were also particularly vulnerable to drought-associated hypersalinity causing marsh dieback and hypoxia-induced fish mortality.

We assessed several restoration actions that would potentially benefit wetland conservation in the region by alleviating hypersalinity via improved delivery and flow of freshwater. One such action would be the installation of a small bridge or larger culverts at Chinquapin Road to allow for greater exchange between the Live Oak, Turkey Island, and Chinquapin sub-watersheds. Also, the existing canal infrastructure in Matagorda County could be used to route freshwater into both the Lake Austin and Big Boggy Creek watersheds during drought. Since average monthly precipitation has been steadily increasing since the 1940s, cleaning and maintaining these canals may also improve flood abatement and freshwater flows during extreme precipitation events, which, like drought, have also been increasing in frequency and intensity throughout the region. Further advocacy for the conservation of environmental flows in the EMB region is needed to protect the future of these valuable ecosystems from increasingly extreme droughts and floods.

Author Contributions: Conceptualization, R.A.F. and J.M.; methodology, R.A.F., J.M., T.P.H., C.N. and J.E.L.; software, J.M., T.P.H. and J.E.L.; formal analysis, R.A.F., J.M., C.N. and J.E.L.; data curation, J.M., C.N., and J.E.L.; writing—original draft preparation, R.A.F.; writing—review and editing, J.E.L. and B.B.; visualization, R.A.F., C.N. and J.E.L.; project administration, R.A.F. and B.B.; funding acquisition, R.A.F. and B.B. All authors have read and agreed to the published version of the manuscript.

Funding: This report was funded in part by a Texas Coastal Management Program grant approved by the Texas Land Commissioner, providing financial assistance under the Coastal Zone Management Act of 1972, as amended, awarded by the National Oceanic and Atmospheric Administration (NOAA), Office for Coastal Management, pursuant to NOAA Award No. NA22NOS4190148, Texas Coastal Management Program, Texas General Land Office Contract #23-020-006-D600. This report also was funded in part by a grant from Phillips 66 to the Matagorda Bay Foundation. The views expressed herein are those of the author(s) and do not necessarily reflect the views of NOAA, the U.S. Department of Commerce, or any of their subagencies.

Data Availability Statement: Data are contained within the article.

Acknowledgments: The authors would like to thank the U.S. Fish & Wildlife Service for their cooperation in allowing access to the Big Boggy National Wildlife Refuge.

Conflicts of Interest: The authors declare no conflicts of interest.

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