Final Report:

Freshwater Inflow Standards for East Matagorda Bay Wetlands: Lake Austin

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Texas Coastal Management Program, Texas General Land Office Contract #23-020-006-D600

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. 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.

Executive Summary

The Colorado River no longer provides direct inflow to East Matagorda Bay, and a few small watersheds provide the only inflowing freshwater. One of these watersheds is Lake Austin and its inflowing sources include Peyton Creek and Live Oak Bayou. The central objective of this project was to identify freshwater inflows for the Lake Austin watershed and recommend potential restoration actions to sustain its wetlands. To achieve this objective, we first quantified the water levels, salinities, and flow rates. We then created a water budget. In general, we found that Lake Austin acted as a perched tidal basin that was 0.3 m higher than East Matagorda Bay, followed its own tidal beat, and discharged large volumes of freshwater at times even when tides were incoming. We found that at its northern terminus and connection with Peyton Creek, Lake Austin ranged from fresh to brackish (an average of 9 mS), with salinity rapidly rising up to a maximum of 31 mS during the summer drought of 2023. At its southern terminus and connection with Live Oak Bayou, Lake Austin was primarily saline. During the most extreme portions of the summer drought in August 2023, the lower reaches of Live Oak Bayou, Chinquapin Bayou, and Pelton Lake became hypersaline with peaks of 64, 65, and 96 mS, respectively. 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. Roughly half of the freshwater contributed to East Matagorda Bay from Lake Austin arrived from each of Peyton Creek and Live Oak Bayou. As compared to the nearby Big Boggy Creek watershed, we estimated that the Lake Austin watershed discharged an order of magnitude greater quantity of freshwater. We also mapped the vegetation and hydrologic network changes from 1943 to 2020. We found that the upper portion of the Lake Austin watershed has lost freshwater wetlands to agricultural conversion (particularly in the Peyton Creek sub-watershed), while the lower portion has gained saltwater wetlands due to sea level rise (particularly in the Live Oak Bayou sub-watershed). The differences between the two sub-watersheds were primarily due to their relative elevation and position on the coastal landscape. 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. Finally, we assessed the potential for restoration actions to increase freshwater inflows and restore wetlands. While we found relatively few opportunities for wetland restoration in Lake Austin itself, we found several unique opportunities throughout its watershed. Action is needed to remove marine navigation hazards, repair culverts and damns, supplement environmental flows, and conserve forested bottomlands.

Introduction

Coastal wetlands provide critical habitat and economic value through their numerous ecosystem services (Costanza et al. 2014), however, they are vulnerable to a reduction in their inflowing freshwater (Buzan et al. 2009). Adequate freshwater inflows and hydrologic connectivity are important to sustaining healthy and productive wetland vegetation (Cronk and Mitsch 1994, Tuttle et al. 2008) by preventing stagnation that can lead to hypersaline and hypoxic waters (Baustian et al. 2019). On the Texas Coast, healthy wetlands offer nursery habitat for aquatic invertebrates and commercial and recreational fishery species (Boesch and Turner 1984), which attract migrating waterfowl, wading birds, and shorebirds from the Central Flyway to wintering sites along the coast (Butler et al. 2014).

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 (Feagin et al. 2020). Wetland losses due to reduced freshwater inflows not only affect the survivability of dependent species (Butler et al. 2014, Pugesek et al. 2013.; Stehn and Haralson-Strobel 2016), but also have costly economic consequences due to the loss of irreplaceable ecosystem services, including carbon sequestration (Hinson et al. 2017, 2019), flood abatement (Zedler and Kercher 2005), and water quality improvement (Breaux et al. 1995). From the 1950's to 1990's, 30% of Texas coastal freshwater and intermediate salinity wetlands (<5 ppt) have been lost or degraded (Moulton 1997).

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 CRNC that leads into West Matagorda Bay (Clay, 1949). 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 (Schoenbaechler et al. 2011, Neupane et al. 2023). EMB is somewhat hydrologically isolated, its tidal beat is largely driven by wind tides, and it can be hypersaline at times (Kraus and Militello 1996). Sediment transport in EMB has been equally impacted by the diversion of flows into Matagorda Bay and the Gulf of Mexico (Morton et al. 1976, Wilkinson and Basse 1978), and this has limited the inorganic vertical accretion within wetlands (Colon-Rivera et al. 2012, Feagin et al. 2013, Yeager et al. 2019).

Today, a few small watersheds provide the only inflowing freshwater to EMB. To support the needs of several agencies on the Texas General Land Office (GLO)'s Coastal Coordination Advisory Committee (CCAC), as well as those of a variety of stakeholders, we developed a multi-phased approach to assess the inflows arriving into EMB from these small basins. The first phase of this approach was completed for the Big Boggy Creek watershed in 2020-2021, with funding from the Texas Water Development Board (TWDB) (Madewell et al. 2021, Madewell et al. 2024). In the second and current phase, we have leveraged that work and focused on Lake Austin, which is the largest watershed that currently supplies EMB with freshwater.

The current project focused on Lake Austin and implemented a portion of the Texas Coastal Resiliency Master Plan (Texas General Land Office 2023), 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 (Texas Commission on Environmental Quality 2012).

To better understand the freshwater inflows that arrive in EMB from Lake Austin, our team: (1) Quantified water flow rates into/out of Lake Austin and created a water budget, and (2) mapped vegetation and hydrologic network changes over time, and (3) incorporated stakeholder knowledge and input to help develop volumetric flow rate standards and recommend potential restoration actions.

2. Materials and Methods

2.1 Study Area

The Lake Austin watershed is a drainage basin that flows into EMB (Fig. 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 and Live Oak Bayou have characteristically different vegetation regimes and drainage patterns.

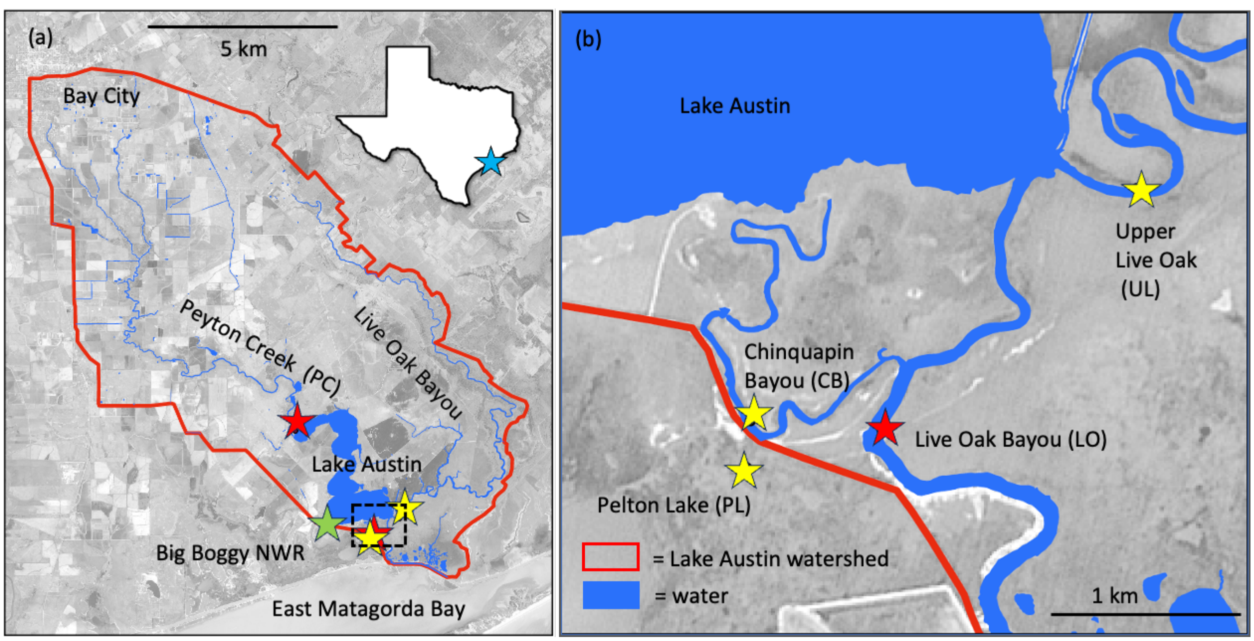

Figure 1. The Lake Austin watershed (a) empties its outflowing waters into East Matagorda Bay through a main connecting channel (b) known as Live Oak Bayou (LO). CTD and ADCP sensor stations (red stars) were placed at the upper section of Lake Austin, where Peyton Creek (PC) flows into it, as well as at the lower section, where LO connected to the bay. CTDs only (yellow stars) were placed at the related channels of Upper Live Oak (UL), Chinquapin Bayou (CB), and Pelton Lake (PL). A rain gauge was placed at the lower end of the watershed (green star).

Peyton Creek (PC) drains the northern and western portions of the Lake Austin watershed and flows directly into Lake Austin on its northwest side (Fig. 2). It is surrounded by a coastal prairie mosaic with farm 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 (Fig. 3). 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.

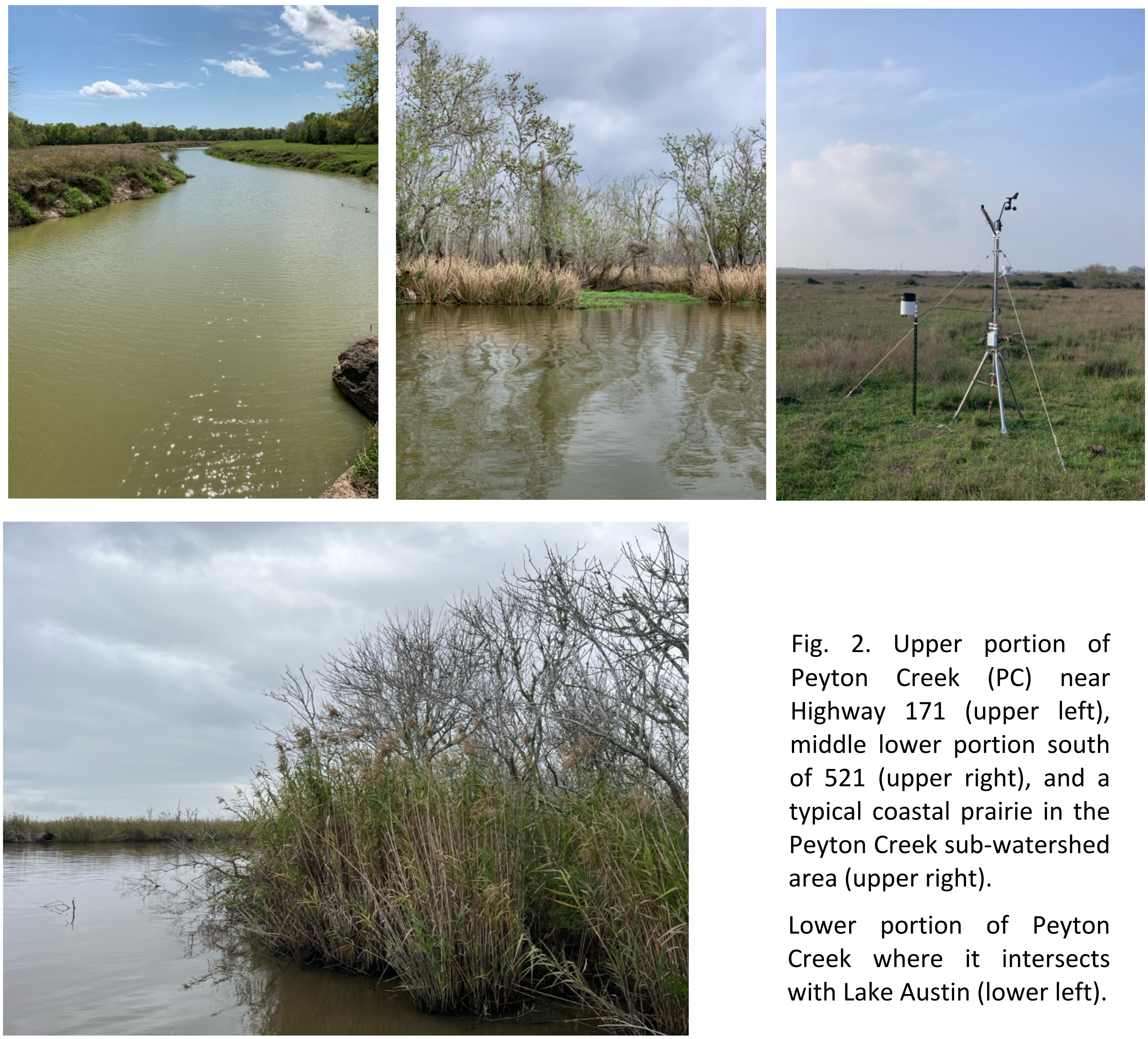

Fig. 2. Upper portion of Peyton Creek (PC) near Highway 171 (upper left), middle lower portion south of 521 (upper right), and a typical coastal prairie in the Peyton Creek sub-watershed area (upper right).

Lower portion of Peyton Creek where it intersects with Lake Austin (lower left).

Fig. 3. Cottonwood Creek (upper left), Dry Creek (upper right), and Bucks Bayou (lower left). All of these tributaries are upstream of Peyton Creek and flow into it.

Live Oak Bayou drains the eastern portion of the Lake Austin watershed and both flows into and out of Lake Austin on its southeast side (Fig. 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). Canoe Bayou flows directly into UL, and there are several oxbow lakes surrounding UL that exchange with it intermittently.

Fig. 4. Upper portion of Live Oak Bayou (UL portion) near 521 (upper right), and middle portion in the San Bernard NWR near Hawkins Road (below and bottom).

Downstream of Lake Austin, the landscape is composed of salt marsh (Fig. 5; we refer to this portion of Live Oak Bayou, that 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 (Fig. 6). 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.

Fig. 5. Salt marsh near the intersection of Live Oak Bayou (LO) and Chinquapin Bayou (CB) (right).

The Lake Austin watershed connects with the adjacent Big Boggy Creek watershed through culverts that go under Chinquapin Road (below). This location connects between our Chinquapin Bayou (CB) and Pelton Lake (PL) stations.

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. 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 (FWS, 2013), 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. Quantify Water Flow Rates Into/out of Lake Austin and Create a Water Budget

2.2.1 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.). We placed these CTDs at five stations, PC, LO, UL, CB, and PL over a series of dates (Fig. 1a-b, Table 1).

Table 1. The sensors and gauges placed throughout the study area.

Station Name	**Sensor Type**	**Start Date**	**End Date**
Peyton Creek (PC)	CTD	2/27/23	12/21/23
Live Oak Bayou (LO)	CTD	3/23/23	12/22/23
Upper Live Oak (UL)	CTD	3/23/23	12/22/23
Chinquapin Bayou (CB)	CTD	3/22/23	12/22/23
Pelton Lake (PL)	CTD	3/22/23	12/22/23
Chinquapin Bayou (CB)	B	3/22/23	12/22/23
Peyton Creek (PC)	ADCP	2/27/23	6/15/23
Live Oak Bayou (LO)	ADCP	3/18/23	4/23/23
Upper Live Oak (UL)	ADCP	3/18/23	UNRECOVERED
Chinquapin Bayou (CB)	PG	3/22/23	8/11/23
near Wadsworth, TX	PG	2/24/23	UNRECOVERED
near Cedar Lane, TX	PG	2/24/23	3/1/23
near Matagorda, TX (LCRA gauge)	PG	1/1/23	12/22/23

CTD = Conductivity, Temperature, Depth sensor. B = Barometer. ADCP = Acoustic Doppler Current Profiler. PG = Precipitation Gauge.

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 (Fig. 6).

Fig. 6. The CTDs were installed inside of PVC pipes and placed into water bodies or channels.

To calculate water level depth, the raw CTD pressure data was compensated using atmospheric pressure recorded by a datalogger (Solinst barologger, Solinst Canada Ltd.) located near CB (as depicted by the green star in Fig. 1b). Atmospheric pressure does not measurably vary in Texas across the scale of the study area, at the hourly time scale, and 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), that included Global Positioning System (GPS) and GLONASS satellites. The GNSS average precision was 0.02 m horizontal and 0.03 m vertical.

To assess the quantity of freshwater flowing through the Lake Austin watershed, we installed Acoustic Doppler Current Profilers (Fig. 7, ADCPs; Nortek Eco, Nortek Group). We placed these sensors and recovered their data at only two primary stations, PC and LO (Fig. 1a-b). We had initially sought to perform this analysis at UL as well, but the ADCP was unable to be recovered (Table 1).

The ADCPs measured the flow speed of the water column. They were tethered to a steel fence post using coated steel cables and placed facing upwards on the stream bed in the center of the stream channels. Hourly stream flow volumes were calculated by multiplying the ADCP-measured, depth-averaged water velocities in a given direction by the cross-sectional area of the channel. The cross-sectional area also varied each hour based on the water level height, and this height was identified by using the accompanying CTD datasets (channel width * hourly water level depth = hourly cross-sectional area). Upstream and downstream flows were determined using the ADCP directional measurements.

Fig. 7. Installing an ADCP (upper left). The ADCP can be seen on the front of the boat hull. Installing a precipitation gauge (upper right). Checking the salinity in UL using a refractometer (lower right).

We also set up several precipitation gauges throughout the study area (Fig. 7), but only one produced suitable data (it was located next to the barometer near CB, as depicted by the green star in Fig. 1b). Additional hourly precipitation data was obtained from the Lower Colorado River Authority (LCRA) rain gauge at Matagorda, Texas (Gauge Matagorda 1 S), 10 miles southwest of the study area (Lower Colorado River Authority 2024, Texas Water Development Board 2024). We found a strong correlation between our field gauge near CB and the LCRA gauge. Thus, for all subsequent analyses, we used this LCRA dataset because it provided a longer time series of historical data.

2.2.2 Water Budget

We next developed a rough water budget to estimate the relative quantity of freshwater inflow arriving into (at PC) and exiting from (at LO) Lake Austin. To create this budget, we first identified the sub-watersheds that uniquely contributed freshwater inflows to the PC and LO stations. These sub-watersheds were delineated using the Watershed tool in ArcGIS Pro (ESRI, Version 3.2 and 1 m Digital Elevation Model (DEM). This process delineated several distinct sub-watersheds, however we only calculated the water budget for PC and LO given the location of the ADCPs (Fig. 8).

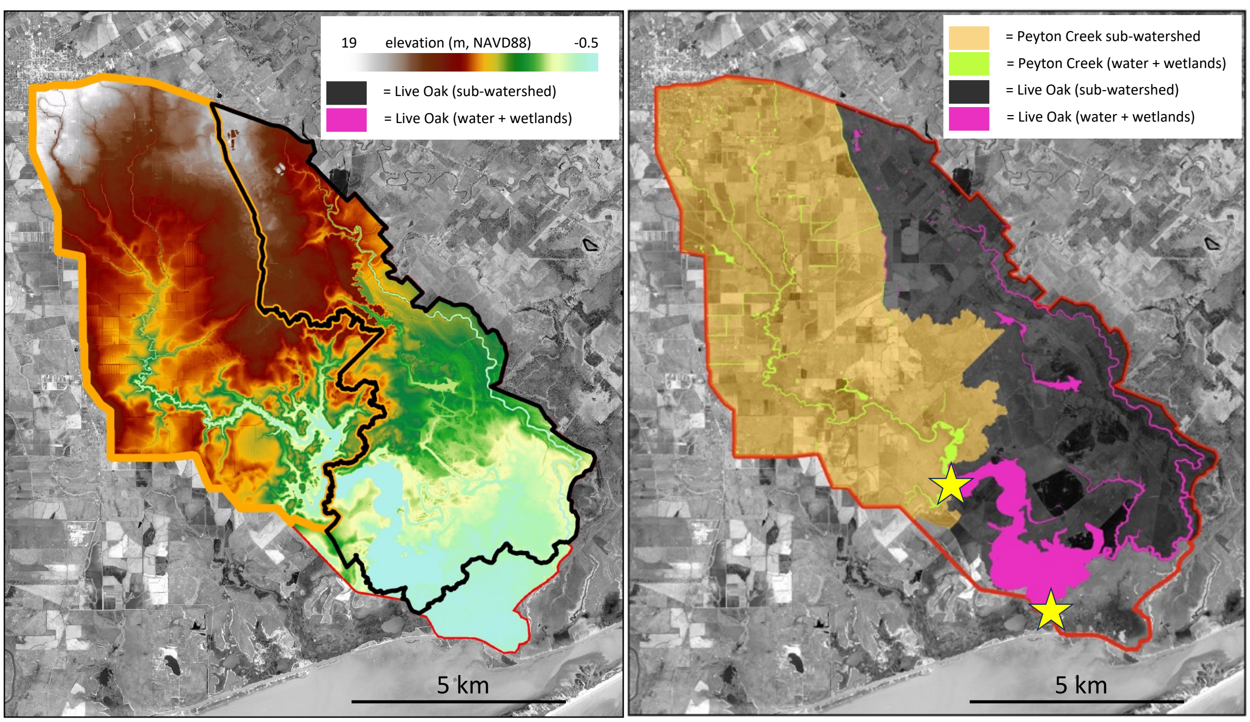

Fig. 8. The DEM elevations throughout the Lake Austin watershed (a) were quite different for the Peyton Creek and the Live Oak Bayou sub-watersheds that were defined (b). The PC sub-watershed showed a clearly incised tributary that drained a relatively high coastal plain, whereas the LO sub-watershed showed a deltaic tributary with overflow ridges that had prograded across a much lower basin.

For the PC and LO sub-watersheds only, we next brought together a variety of datasets including the CTDs, ADCPs, LCRA precipitation gauge, MOD16 evapotranspiration datasets (Google Earth Engine 2024, as sourced from the Numerical Terradynamic Simulation Group), and TWDB surface water evaporation estimates (Texas Water Development Board 2024). The net freshwater inflow at each station was calculated as the change in storage (Δ S):

$$\Delta S = P - ET - E \pm SW \pm GW \qquad \text{Eq. 1}$$

where P is the total precipitation volume in the sub-watershed above the station, ET is the total evapotranspiration volume in the terrestrial vegetated areas, E is the total evaporation volume in the water body areas, SW is the net water flow through the channel where the ADCP was located, and GW is the net groundwater exchange. All quantities were calculated in m^3 per time units.

We chose to calculate this budget only for a limited time period ranging from 3/18/23 to 4/23/23 to ensure data consistency between the PC and LO stations. We aggregated the data for each variable in Eq. 1 over this entire time frame, based on an initial investigation into the hourly timing of the relationship between measured precipitation and perceived flow at the stations. We concluded that the time series were not sufficiently long enough for us to quantitatively account for timing delays caused by complex watershed effects and antecedent conditions. Similarly, there may be limitations in the dataset due to the relatively short period of record. Still, during this time range the measured precipitation balance (4.7 in at the LCRA gauge for April) was above the mean but within the expected standard deviation for the period over the past since 1940 (3.0 ± 2.0 in at the same gauge, see Results for more). Over the entirety of 2023 through the end of April, it was a relatively dry year but again not falling outside of the expected standard deviation (7.1 in versus 11.4 ± 4.7). Nevertheless, it is likely that flows during our period of record do not match flow patterns for other periods throughout the year, and so one must be careful in making overly broad conclusions from this analysis.

The P that fell on the sub-watershed above each station was calculated by multiplying the precipitation quantity that fell during the time period by the total sub-watershed area that was found upstream from each station.

The ET in each of these two sub-watersheds was obtained from NASA's MODIS satellite 8 day ET product (referred to here as MOD16). The MOD16 product has a 500 m spatial resolution and is based on the Penman-Monteith equation for ET using daily meteorological reanalysis data and 8 day remotely sensed vegetation properties. We averaged the data from each 500 m pixel to arrive at a single value for the sub-watershed. MOD16 provided ET values only for the terrestrial surface of each sub-watershed. For this reason, we also obtained E data from Texas Water Development Board (2024), specifically from Quad 912. The ET for the time period was then multiplied by the area of the terrestrial land cover and the E was multiplied by the area of the water bodies, within the sub-watersheds above each station.

At each station, we found the SW as the imbalance between upstream and downstream flow volume using the ADCP data. Upstream flows could include both incoming tides and storm surges. Downstream flows could include outgoing tides and freshwater flows from upstream reaches of the sub-watershed. The difference in up versus down volume was assumed to be freshwater inflow. We did not explicitly estimate GW, and instead discuss this below in the Results section as a potential source of error.

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-meter 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 (TNRIS 2023). 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 Results 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. In-situ sight identification of vegetation from 2022 to 2023, and several hundred geo-tagged photos, were used as a reference for the effort.

Each land cover class was digitized using ArcGIS Pro (ESRI, Version 3.2) at a consistent map scale of 1:4,000. 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 of the sub-watersheds. 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 to where they connected to Lake Austin.

3. Results

3.1. Water Flow Rates Into/out of Lake Austin and Water Budget

3.1.1. Sensor Datasets

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.

Table 2. Water level and conductivity at the stations.

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

Still, the water level and salinity at all five of the stations were affected by both precipitation events and by tides (Fig. 9). 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.

Looking more closely at specific precipitation events (Fig. 10), when it rained heavily on 05/11/23 and 05/14/23, 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 05/25/23 at LO (lowest receiving channel), 12 hours later at CB and PL, and finally 24 hours later at UL. PC did not return to a similar level of salinity for months later.

After only traces of precipitation during four months over the summer (Fig. 11), 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.

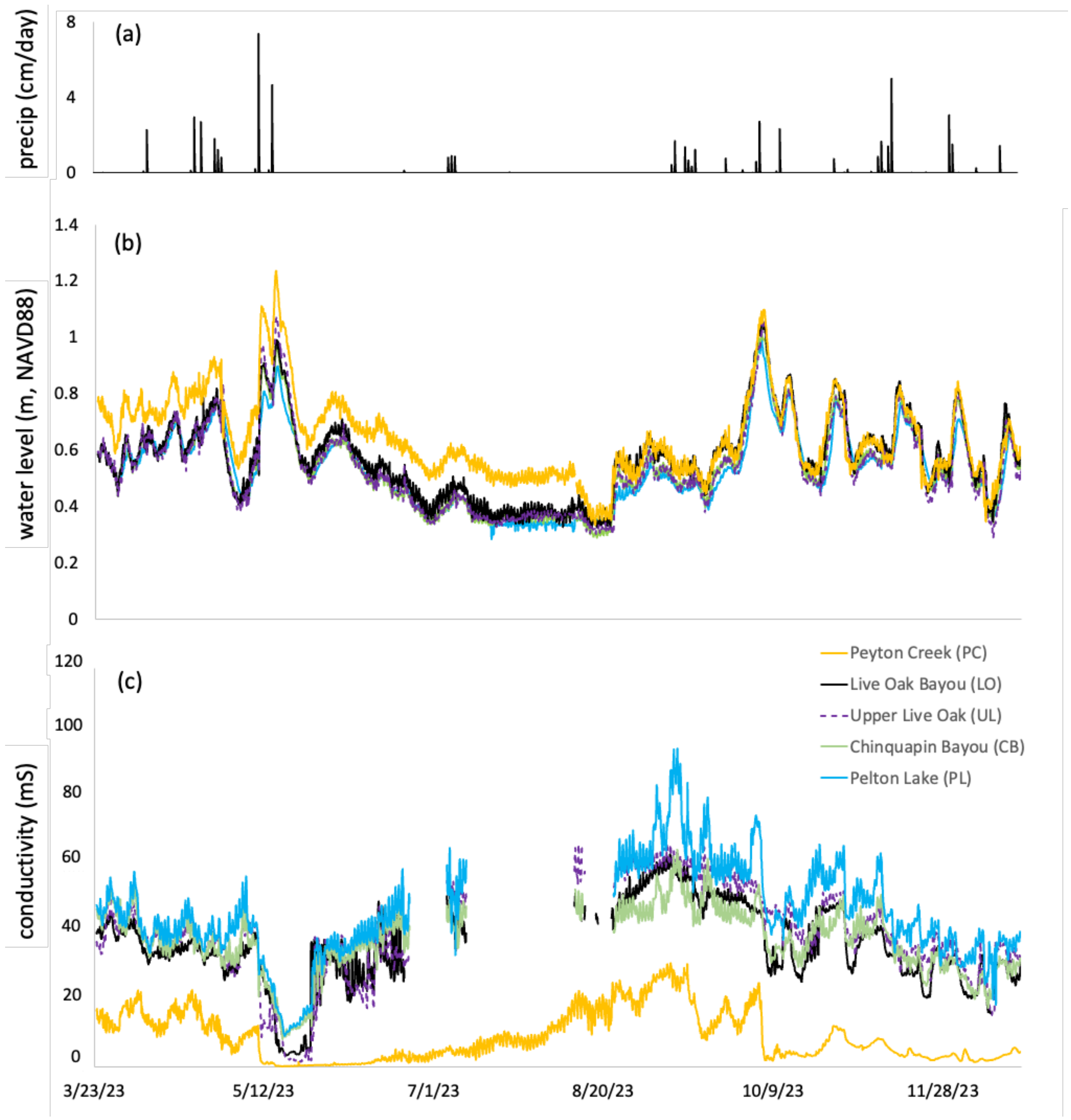

Fig. 9. (a) Precipitation, (b) water level, and (c) conductivity from 03/23/23 to 12/22/23 at the Lake Austin sensor stations.

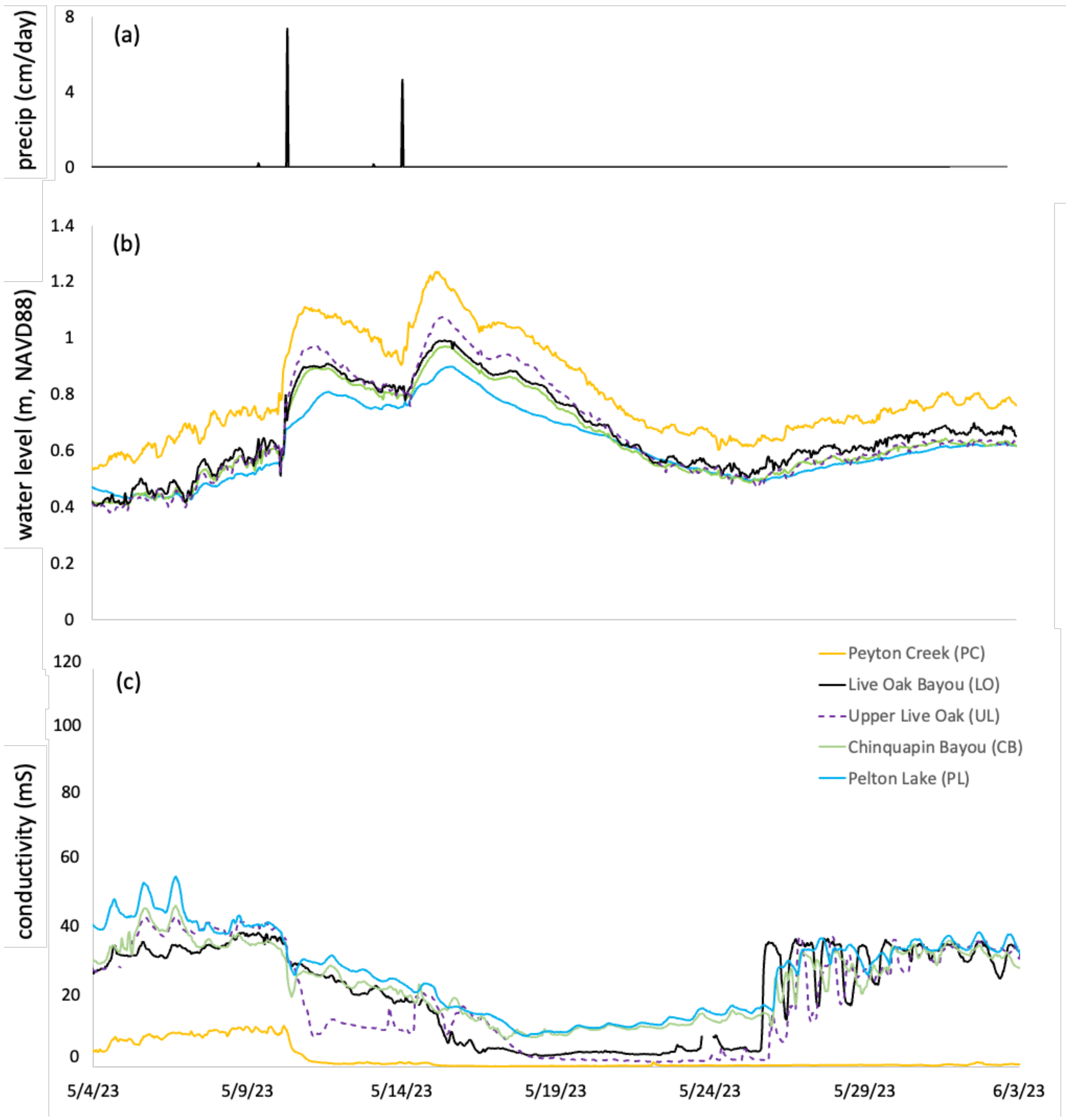

Fig. 10. (a) Precipitation, (b) water level, and (c) conductivity from 05/04/23 to 05/19/23 at the Lake Austin sensor stations.

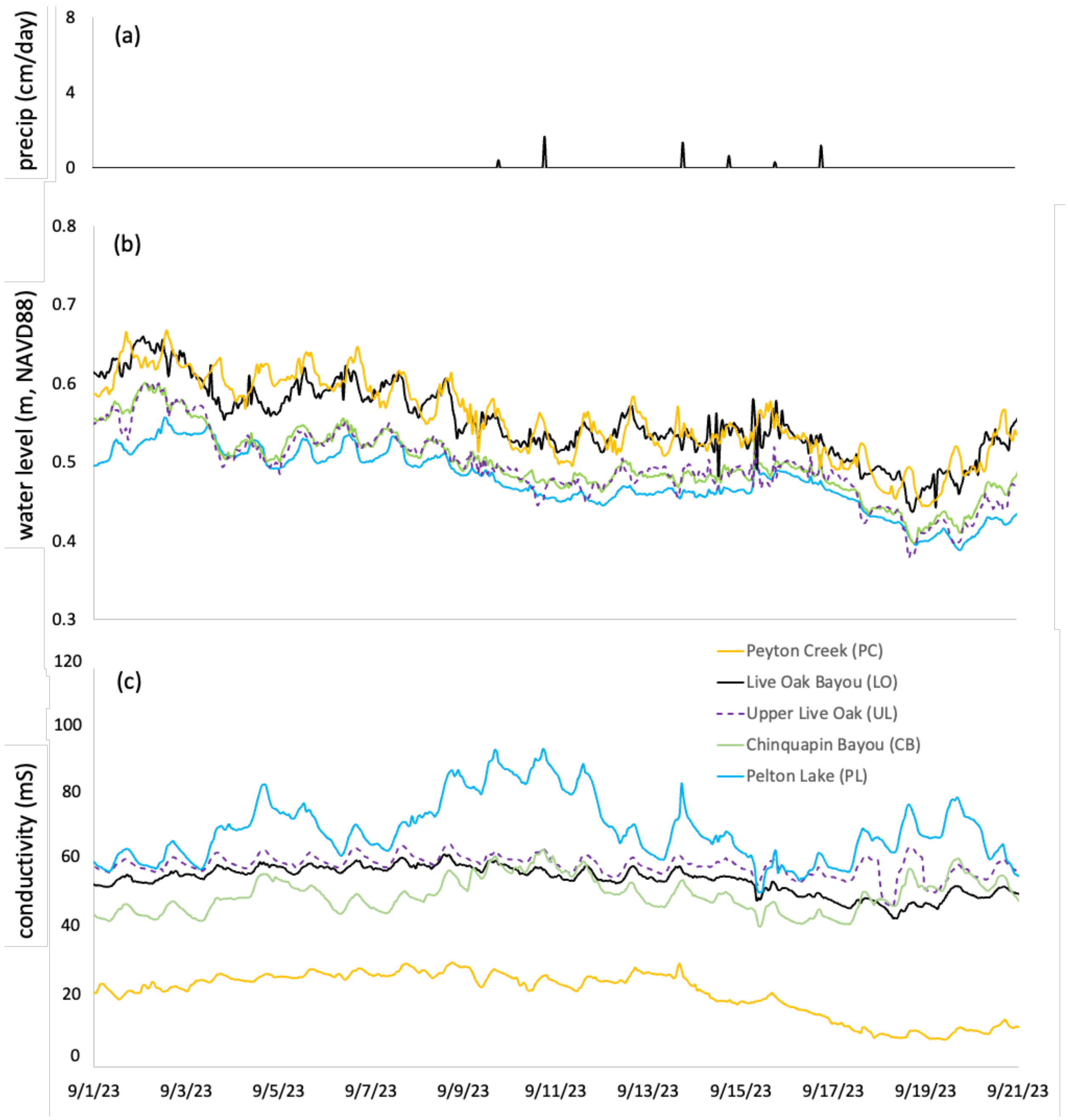

Fig. 11. (a) Precipitation, (b) water level, and (c) conductivity from 09/01/23 to 09/21/at the Lake Austin sensor stations.

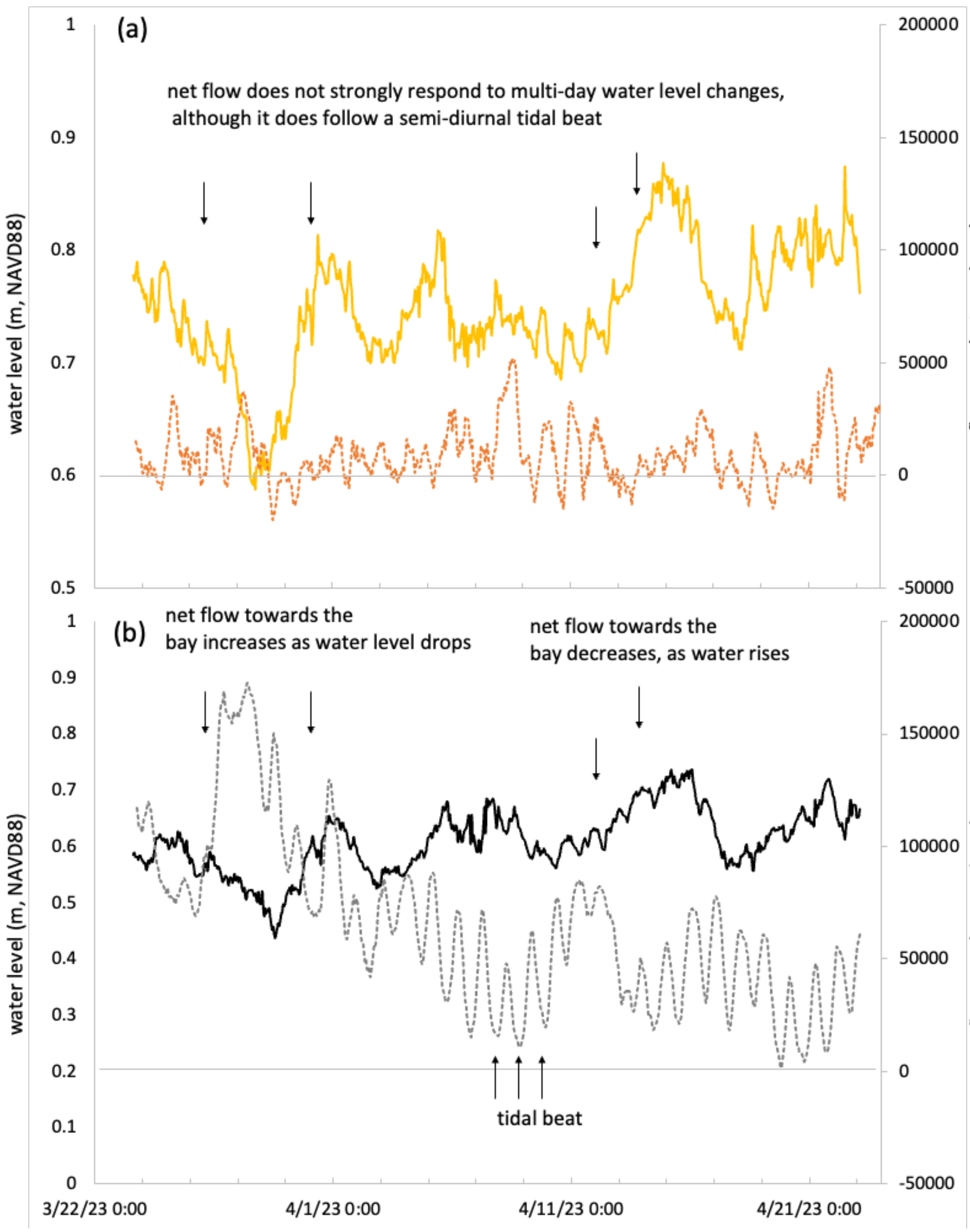

Fig. 12. Water flow rate and water level from 03/23/23 to 04/23/23 at (a) Peyton Creek (PC), and (b) Live Oak Bayou (LO). Positive flow rate indicates downstream movement, negative indicates upstream.

In terms of the freshwater volumes flowing into and out of Lake Austin, PC was relatively low while LO was much higher (Fig. 12). Interestingly, the PC water level and flow rate followed a semi-diurnal tidal beat and flowed both upstream and downstream, but it did not follow multi-day wind tides (e.g., 03/23/23 to 03/21/23). Still, its flow spiked after large precipitation events on 05/11/23 and 05/14/23 (Fig. 13). Strangely and in opposition, the LO water flow rate followed both a semi-diurnal and multi-day wind tidal beat, yet its flow direction was always going downstream towards the bay during the period of record.

Lake Austin appears to be acting as a perched basin that follows its own tidal beat. The results show that the northern portion of Lake Austin (at PC) experiences a larger semi-diurnal tide range than the lower portions (LO). And yet, the upper portion of Lake Austin (at PC) is the freshest in terms of salinity and most strongly affected by precipitation. Even more strange, while this northern portion is fully tidal, it does not follow irregular wind tides as strongly as the southern portion of Lake Austin (at LO).

A unique aspect of Lake Austin is that the tide may be coming up vertically (water level rising) even as the net flow is exiting towards EMB. This phenomenon is likely due to the perched nature of the basin, with a base elevation ~0.3 m higher at its upper portion compared with its exit channel that connects to EMB. In an extreme sense, there may be a subtle form of a “waterfall” located where the exiting channel from Lake Austin flows past the LO station into EMB.

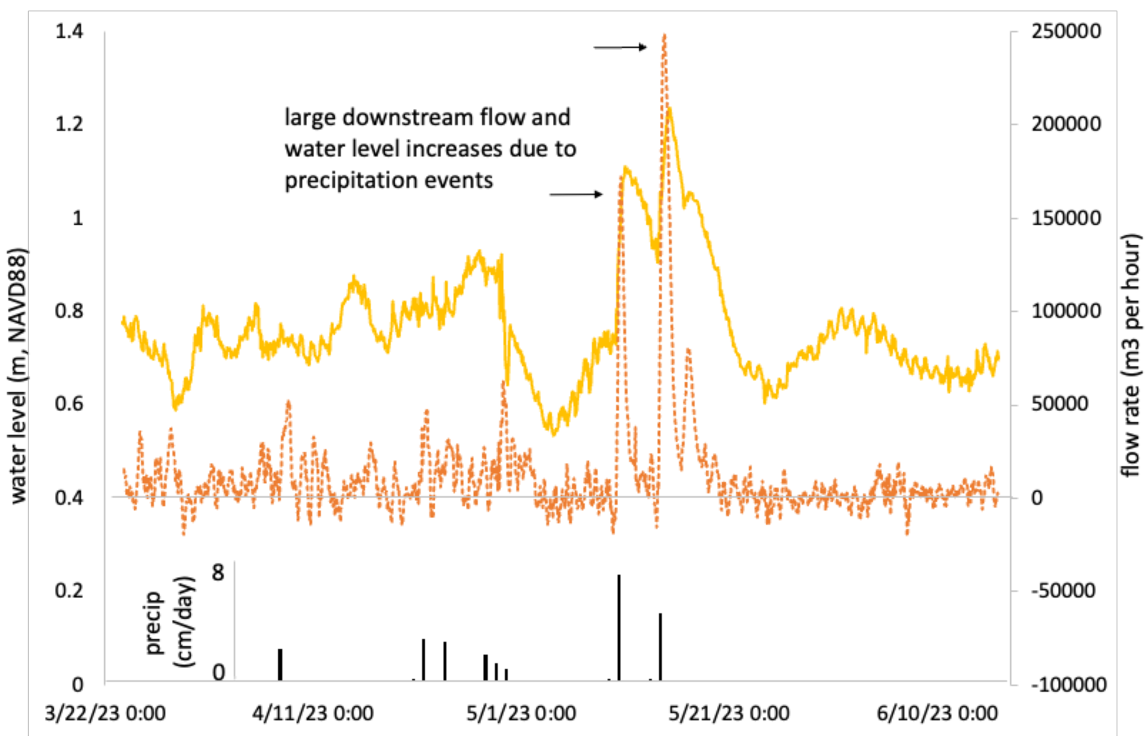

Fig. 13. Water flow rate, water level, and precipitation from 03/23/23 to 06/15/23 at Peyton Creek (PC). Positive flow rate indicates downstream movement, negative indicates upstream.

3.1.2 Water Budget

In terms of the water budget for Lake Austin (Fig. 14), the Peyton Creek sub-watershed (at PC) provided moderate freshwater inflow into Lake Austin (5,618 megaliters, or ML). This value was calculated solely as SW using the net downstream and upstream flow using the ADCP dataset (9,222 downstream – 3,604 upstream). This value was roughly 52% of the relative difference between P and $E + ET$ that was calculated upstream from PC (i.e., 26,744 – 15,896 = 10,849 ML), suggesting that a fair portion of the terrestrial landscape does not directly or immediately provide freshwater that flows through the PC channel.

The discharge from Lake Austin into EMB (at LO) was a much larger volume of water (48,392 ML). Unfortunately, we did not obtain recoverable data from the ADCP at UL and so the inflow volume arriving from the upper portions of the Live Oak Bayou sub-watershed were not uniquely identifiable. However, if we follow the same logic as above for PC, we obtain a rough value for the freshwater inflow arriving from the combination of UL and the surface area of Lake Austin itself (22,389 – 13,603) * 52% = 4,568 ML). This freshwater coming down UL along with freshwater falling on the surface of Lake Austin itself, plus the empirical freshwater inflow of SW from PC, add up to 10,186 ML. The difference from this estimate and the empirical of SW all water exiting LO is relatively large (48,392 - 35 - 10,186 = 38,171 ML), implying that a large source of water is missing.

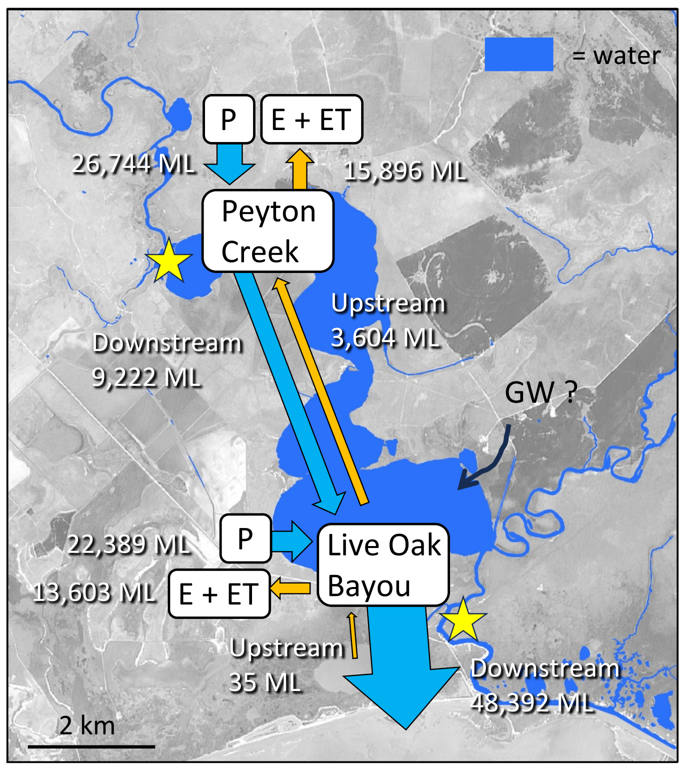

Fig. 14. The water budget flowing through the Peyton Creek (PC) and the Live Oak Bayou (LO) sub-watersheds for March to April 2023. The thickness of the arrows is representative of the volume of flow. Units are in megaliters (ML).

In theory, this missing source of water could be freshwater, but we consider it less likely for several reasons. The missing source was not likely due to groundwater, because we found that the Peyton Creek sub-watershed (at PC) balanced reasonably well (within empirical observed as a factor of roughly 52% of estimated), assuming that GW was zero. This sub-watershed was much more likely to have a groundwater contribution given the nature of its incised drainage network leading from relatively high elevational uplands, compared to the upper portions of the Live Oak sub-watershed (running down through UL with a relatively deltaic drainage network from low elevational bottomlands). It was also not likely due to a missing source of freshwater inflow running through UL, because the water level and salinity datasets showed that this drainage was relatively salty and similar to LO at all times. Based on the available evidence, the UL portion of the Live Oak sub-watershed provided slightly less freshwater than the Peyton Creek sub-watershed.

We consider it more likely that the missing source was salt water. Given that Lake Austin appears to be acting as a perched tidal basin, it is quite possible that this missing quantity of water had been held up in Lake Austin prior to the time period of the water budget and was now exiting due to gravity-induced flow. This possibility aligns with the findings of the water level gauges and ADCP analysis detailed above. Note: This missing source was not likely salt water entering from CB and PL through the culvert from the adjacent Big Boggy Creek watershed, because this water would have entered downstream of LO into EMB.

In summary, the budget suggests that freshwater portion of the downstream flow into EMB from the Lake Austin watershed through the LO station was on the order of 10,186 ML during the time period of study (though we cannot definitively rule out a value as high as 48,492 ML).

3.2 Vegetation and Hydrologic Networks Over Time

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 (Fig. 15-17). From 1943 to 2020, salt marsh increased (+ 896 hectares), freshwater wetlands decreased (- 97), upland areas decreased (-752), and water decreased (-44).

The loss of freshwater wetlands was most prominent in the Turkey Island and Chinquapin (- 107 hectares) and in the Peyton Creek (- 56) sub-watersheds. 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 (Fig. 15). 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.

The increase in salt marsh occurred primarily in the lower portions of the Lake Austin area, particularly in the Turkey Island and Chinquapin (+ 547 hectares) and Live Oak Bayou (+ 364) sub-watersheds. 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, respectively).

The shoreline generally eroded along Lake Austin (Fig. 18), 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 backwards in time suggests that Lake Austin and LO likely merged in the 1800's.

Fig. 15. Land cover change over time, from 1943 to 1978 to 2020.

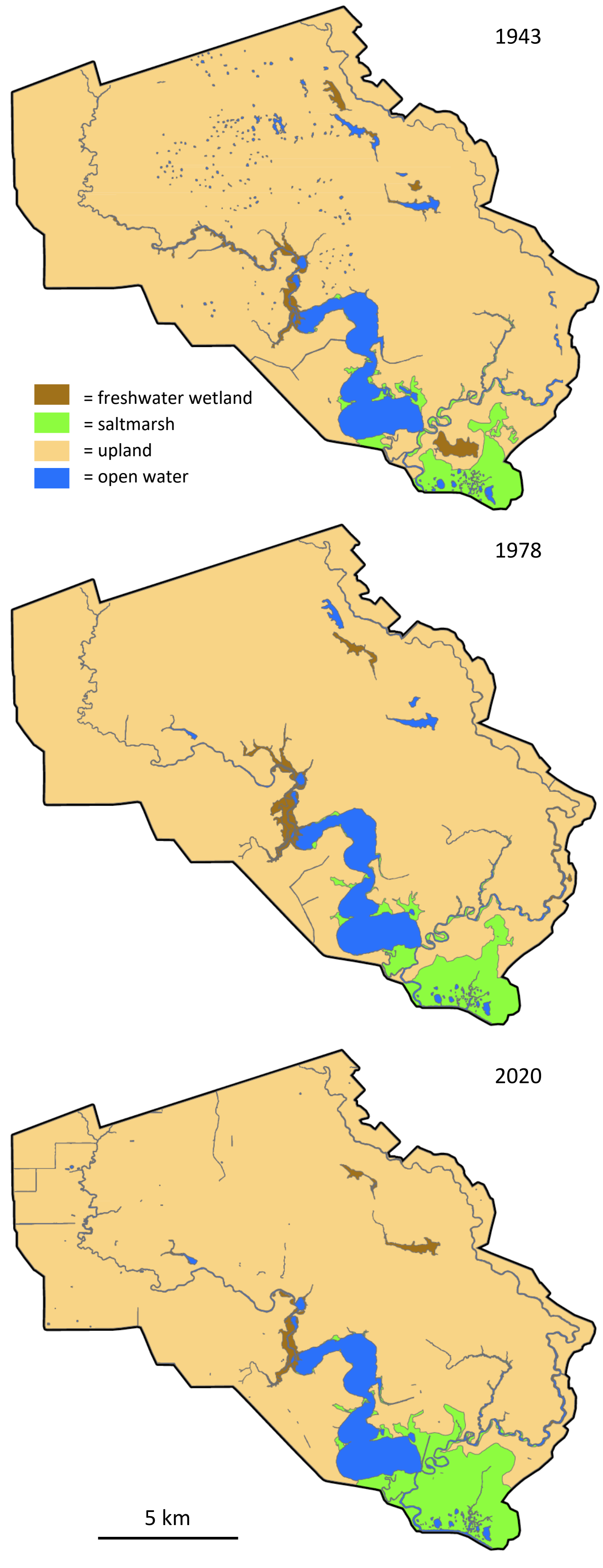

Fig. 16. Land cover change from 1943 to 1978 to 2020, for the entire imagery analysis area.

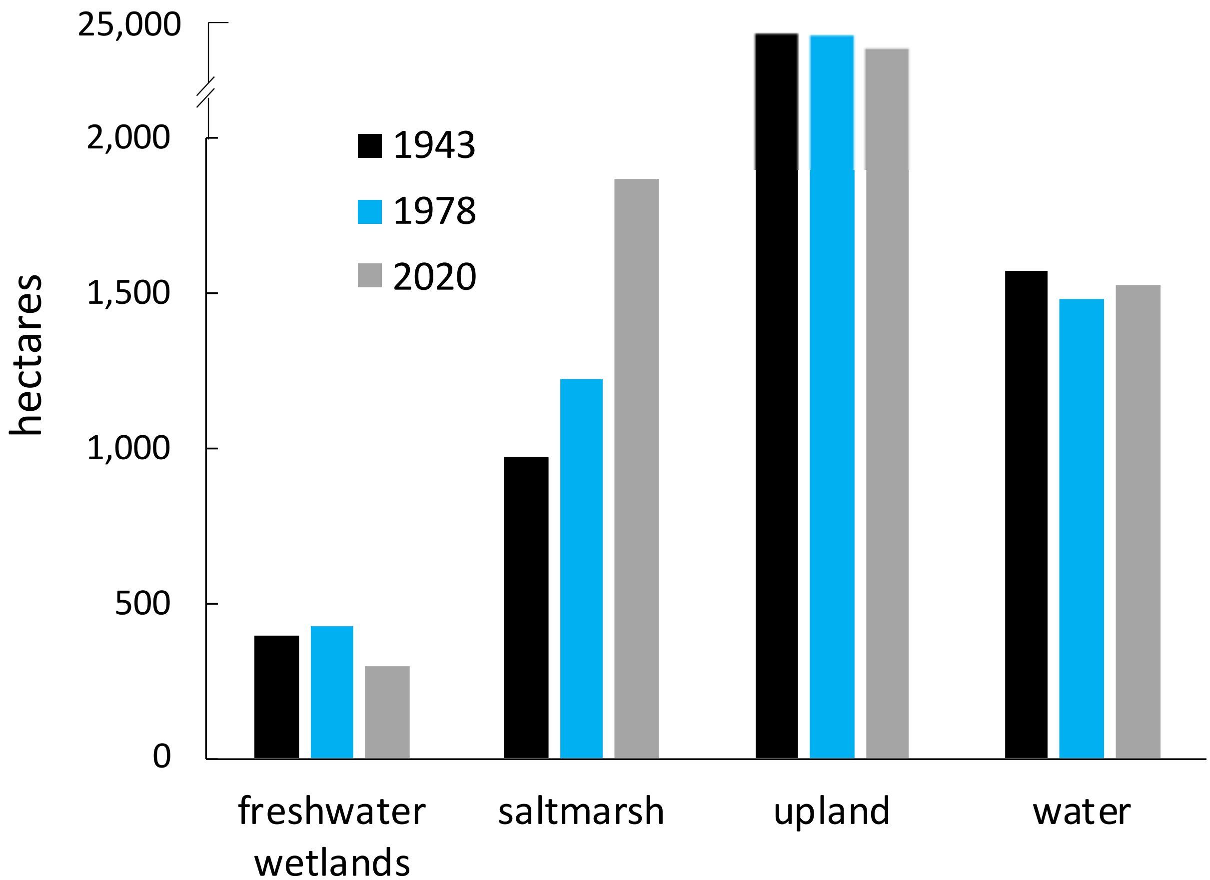

Fig. 17. The analysis was further sub-divided among three sub-watersheds. Land cover change for wetland cover only, over time in the (a) Peyton Creek sub-watershed, (b) Live Oak sub-watershed, and (c) Turkey Island and Chinquapin Bayou sub-watersheds.

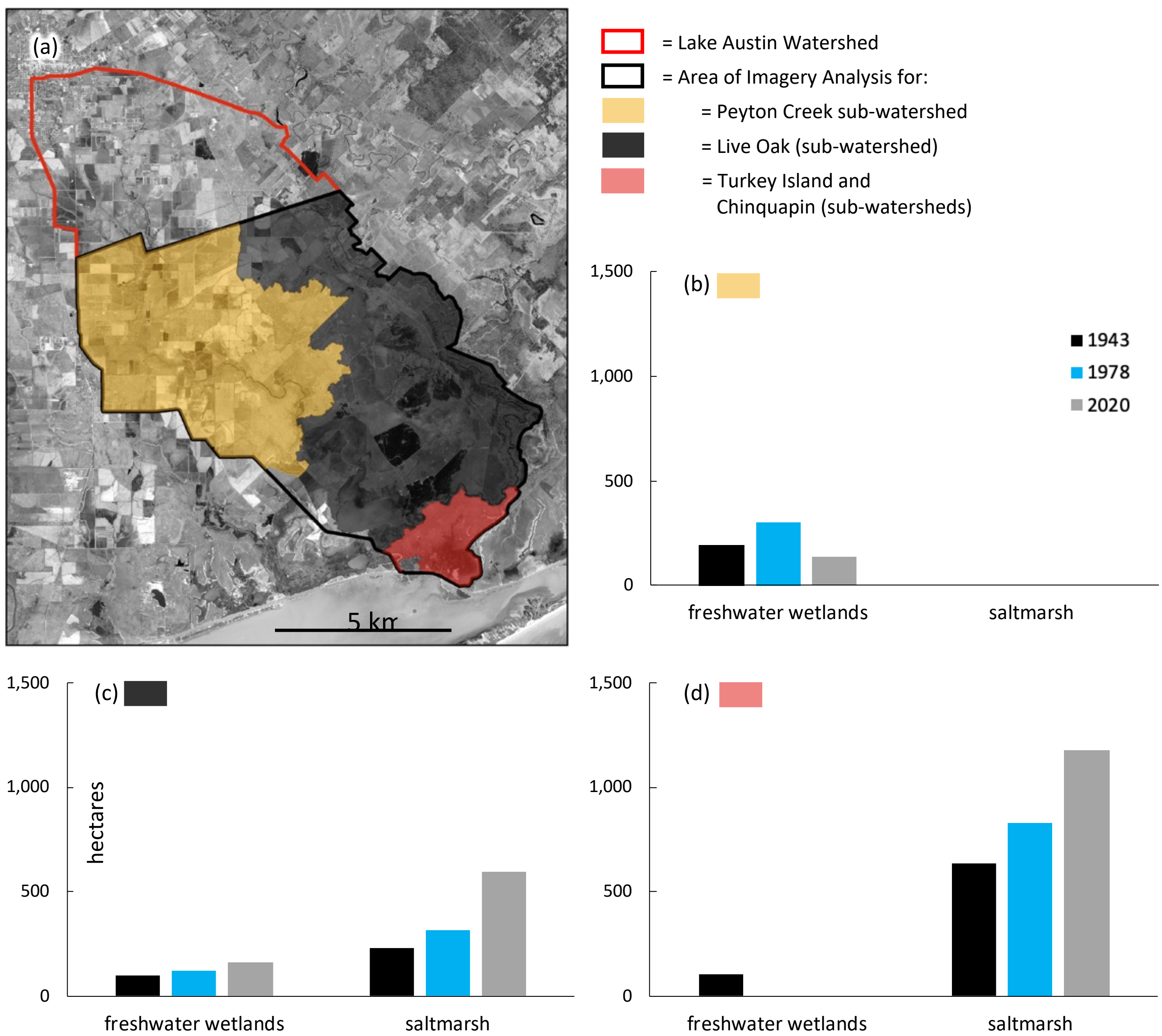

Fig. 18. Shoreline locations in Lake Austin, in 1943 to 2020.

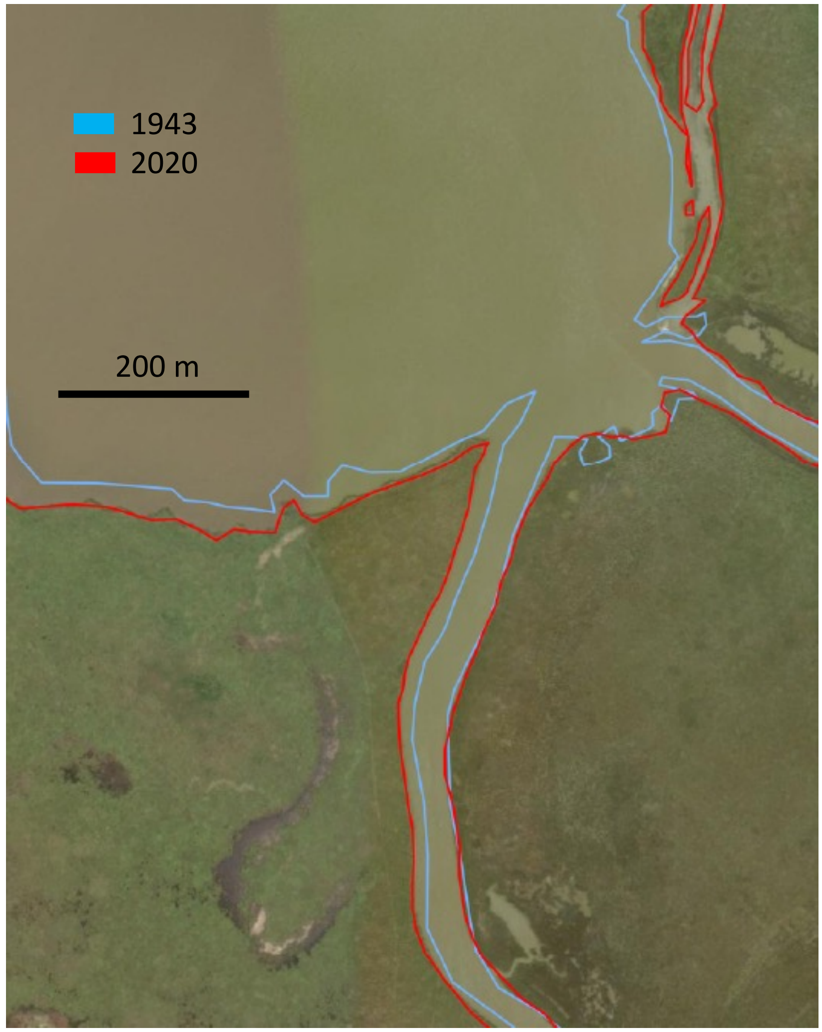

Table 3. Channel width expansion and contraction at station locations near to Lake Austin, 1943 to 2020. Contracting channels are shaded. Five widths were measured for each channel and then averaged.

	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

4. Discussion

3.3 Flow Rate Standards

Today, Lake Austin likely constitutes the largest source of freshwater and environmental flows for EMB. The only other major source is the adjacent Big Boggy Creek watershed. All other watersheds drain much smaller land areas, for example Little Boggy Creek, or are located on the opposite side of the entrance to EMB and lose water directly to the Gulf, for example Caney Creek.

To compare the volume contributed by Lake Austin with those arriving into EMB from the Big Boggy Creek watershed, we must rely on rough statistical estimates. For Big Boggy Creek itself, Madewell et al. (2021, 2024) found 2,118 upstream – 1,390 downstream = 728 ML of potential freshwater, for the dates of 07/01/20 to 09/30/20. This time period was relatively wet and had 2.9 times more precipitation than expected as compared with the average for those same months in the historical record since 1940 (12.7 / 4.4 in). For the current study of the Lake Austin watershed, we found 10,186 ML of potential freshwater, for 03/23/23 to 04/22/23 – a relatively wet time period with 1.6 times more precipitation (4.7 / 3.0). Adjusting the two estimates of freshwater by their "relative wetness" (note: one must flip the numerator and denominator to standardize for the normal year since 1940; this analysis does not also consider evaporation or evapotranspiration), we arrive at 252 versus 6,502 ML for Big Boggy Creek watershed versus the Lake Austin watershed. Even if we use the maximum possible downstream flow values for both studies (2,118 versus 48,492 ML) or consider that the summer months of the Madewell study likely experienced much more evaporative loss, we arrive at a roughly similar difference in magnitude. In summary, the Lake Austin watershed appears to provide an order of magnitude greater volume of water to EMB, as compared with the adjacent Big Boggy Creek watershed (~26 to 42 times more freshwater to EMB).

Within the broad historical context from 1940 through today, the amount of precipitation in the Lake Austin watershed has been slowly increasing at a rate of 0.2% per year (Fig. 19; this and subsequent figures below created using data from Texas Water Development Board (2024) Quad 912). At the same time, the oscillatory nature of wet versus dry months of precipitation has been becoming more extreme (Fig. 20). Lake Austin is experiencing the potential for both greater flooding (Fig. 21) and worse droughts (Fig. 22) at the same time.

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 (Fig. 23).

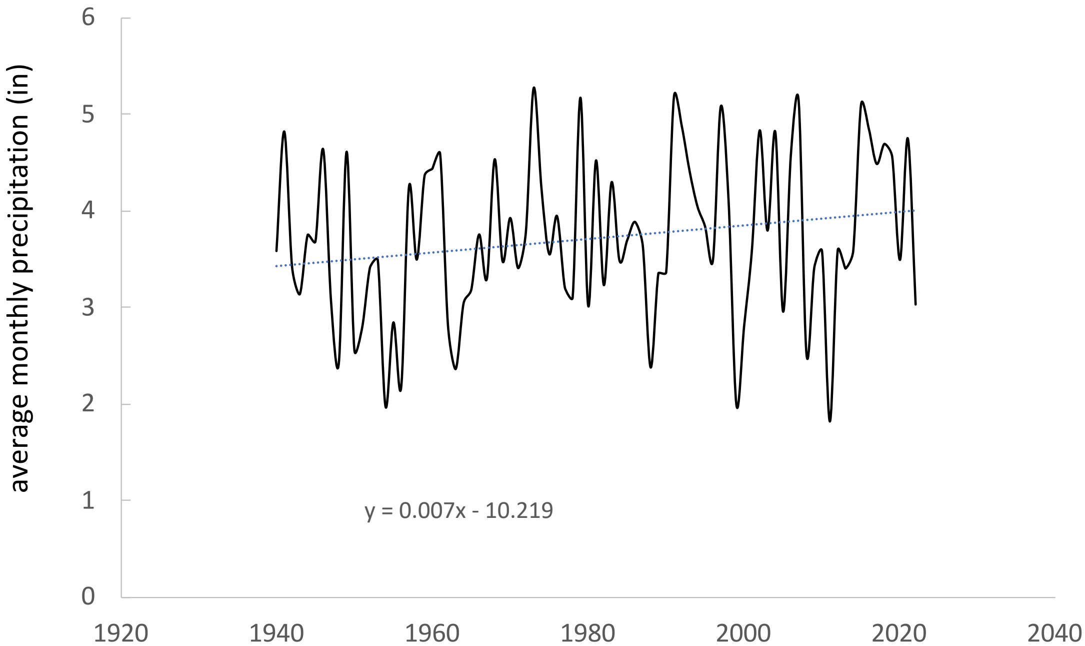

Fig. 19. The Lake Austin watershed has experienced an increase in the average monthly precipitation since 1940. This translates into a 0.2% increase in precipitation per year average, and to a 30% increase for 160 years. Data from Texas Water Development Board (2024).

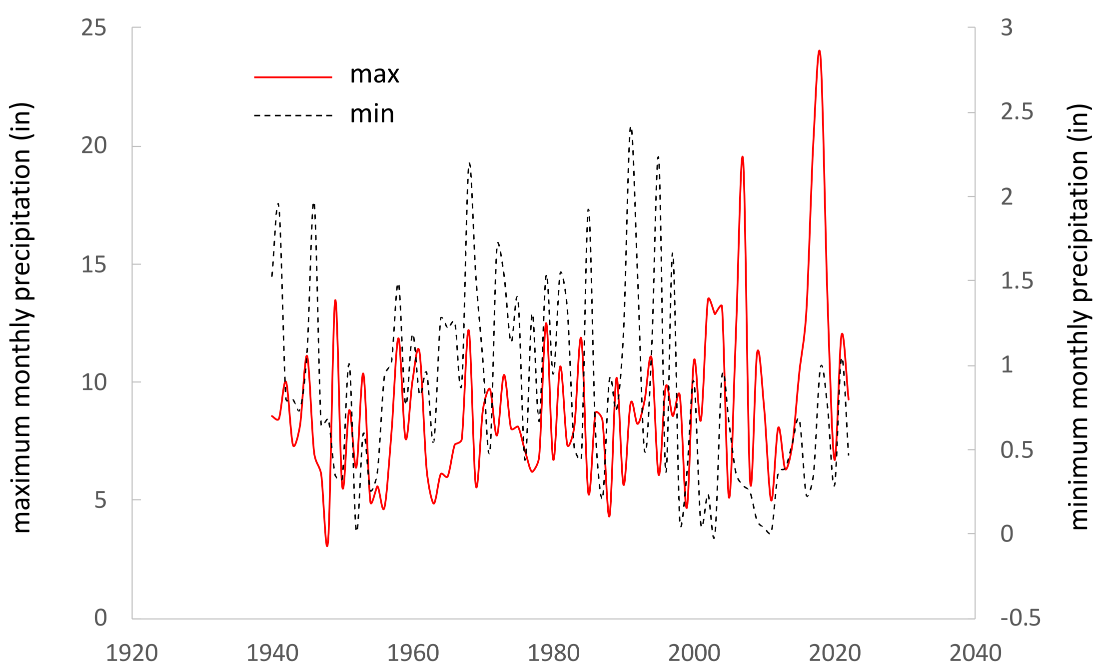

Fig. 20. The Lake Austin watershed has experienced both an increase in the maximum monthly precipitation it receives during any one year, and a decrease as well. In other words, today it is having more extreme wet months and dry months, as compared to the past years. Data from Texas Water Development Board (2024).

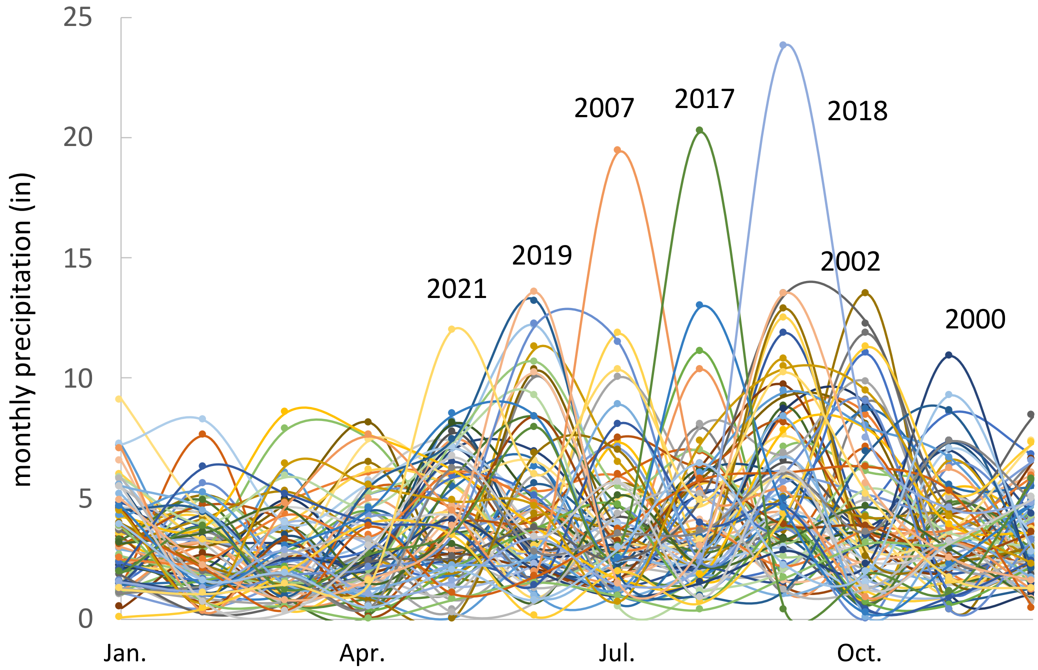

Fig. 21. The likelihood of an extreme precipitation event is increasing for the Lake Austin watershed. Since 1940, the past two decades have seen some of the largest flooding events. Data from Texas Water Development Board (2024).

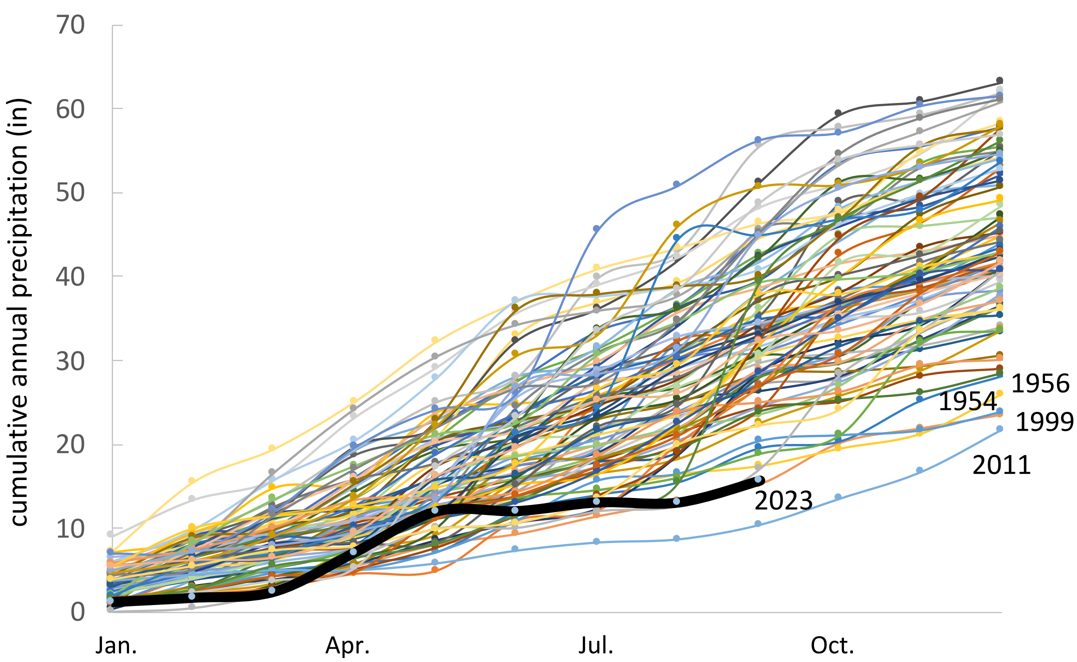

Fig. 22. The likelihood of an extreme drought event is increasing for the Lake Austin watershed. Since 1940, the past 25 years have seen three of the worst five droughts on record. The year of our field datasets (2023) was in an extreme drought. Data from Texas Water Development Board (2024). Note: Dataset continuity was unavailable for end of 2023, as of publication date.

Fig. 23. *Spartina alterniflora* salt marsh on Live Oak Bayou (near LO) during extreme drought in August 2023 (above).

The tidal water level had not reached above the marsh surface for at least two months (as indicated by the data in Fig. 9) by the time these pictures were taken in August 2023.

Low water level near the Pelton Lake (PL) station (right). The water in this picture was hypersaline at the time it was taken, > 70 mS.

The ability to purchase freshwater during such extreme drought conditions, for example from the Lower Colorado River Authority (LCRA), is likely to be difficult and expensive because other users also have need of these resources. In addition, the volumes required to make an impact for the Lake Austin watershed are likely to be unattainable. For the Live Oak Bayou sub-watershed, its relatively low elevation, geomorphic land form, 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. Although our data is limited, this value should be ~13-25 times larger (excerpting the Live Oak Bayou quantity) than the standard recommended in Madewell et al. (2021) for Big Boggy Creek: ~269 to 675 ML per month for a drought equivalent to that in the summer of 2011 or 2023 (or ~218 to 547 acre feet of water per month). The rough math leads to filling a need for ~3,700 to 17,000 ML per month (or ~3,000 to 14,000 acre feet per month), during such a drought (~$200,000 to $1,000,000 per month, at 2021 prices). This volume seems reasonable compared to the estimates made in Schoenbaechler et al. (2011) and Neupane et al. (2023) for the entirety of EMB over the course of a year, considering the upper end values cover the lowest periods of flow during a typical year (similarly, it also coincides with Colorado and Lavaca Basin and Bay Area Stakeholder Committee 2011). 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. (2015) 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 and placing them into Moist Soil Units (MSUs) in Big Boggy NWR, immediately adjacent to the PL station at Pelton Lake. We investigated the quality of the MSUs and canals and communicated their status to TWT (Fig. 24). We additionally worked with TWT as they submitted a proposal to the Matagorda Bay Mitigation Trust (MBMT) to fund this water delivery.

Fig. 24. Canal infrastructure (left, middle) leading to the Moist Soil Units near the PL station (bottom) in Big Boggy NWR.

4.2 Potential Restoration Actions

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

Lake Austin acts a perched tidal basin that can provide relatively large freshwater discharge into EMB, regardless of whether its own water level is going up or down. This behavior of Lake Austin is relatively unique and likely due to its geomorphic position on the landscape and its recent history of land cover change. The evidence that we collected (the relative water level and salinity at the stations, the land cover and shoreline change over time, channel widening and contraction, and the manner that Lake Austin discharges through LO into EMB) suggests that the following sequence of events likely occurred in the past:

Prior to the 1800's, 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 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 1800's, 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 salty. 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 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, then entirety of Lake Austin will become fully saline and its upper portion at PO 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.

4.2.2. Restoration Actions

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* (Fig. 25). Moreover, as compared to the adjacent Big Boggy Creek watershed (Madewell et al. 2021), there were also fewer possibilities to remove hydrologic barriers upstream.

Fig. 25. Most of the Lake Austin shoreline does not have any wetlands. Rather, it is composed of an 1-2 m high embankment, backed by coastal prairie.

However, a few areas stuck out where restoration and conservation action appeared to be warranted (Fig. 26):

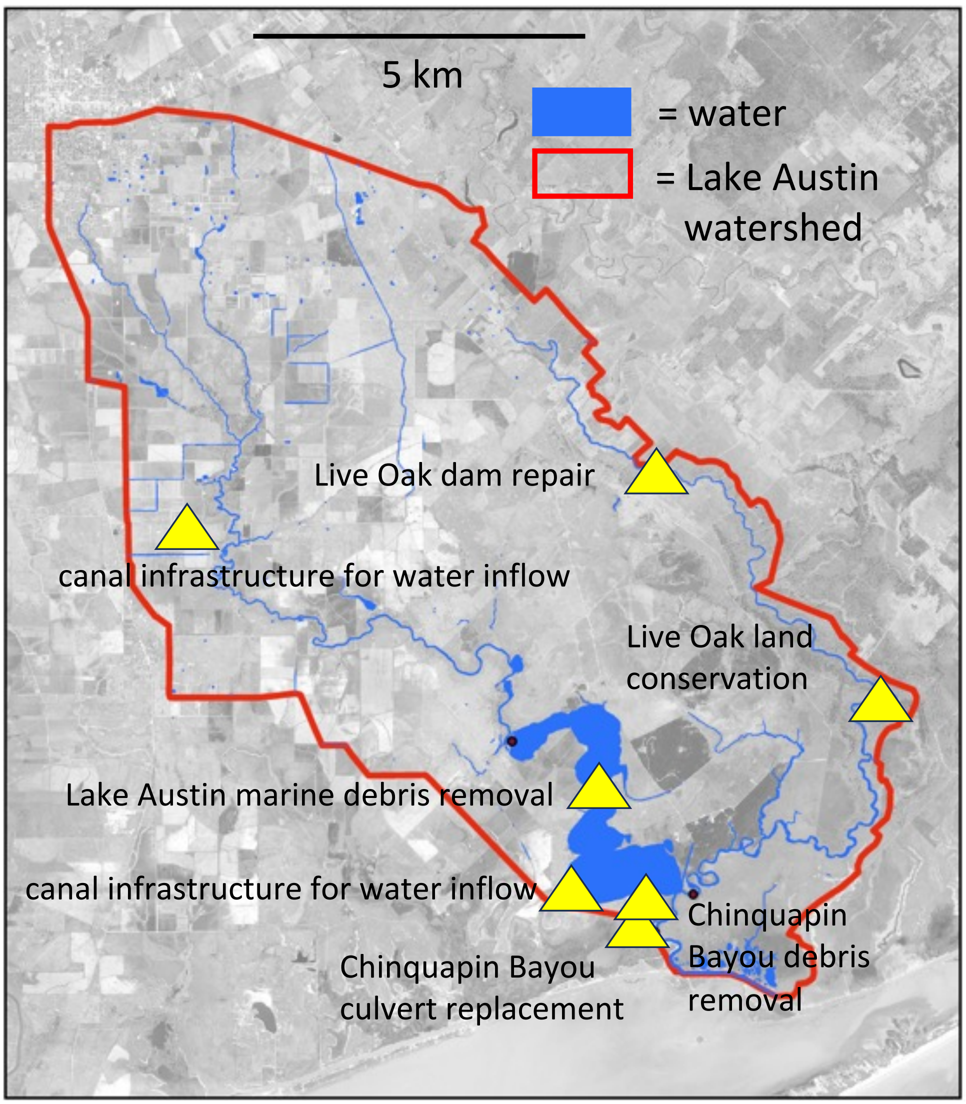

Fig. 26. Map of potential restoration and conservation opportunities in the Lake Austin watershed

4.2.2.1 Lake Austin Marine Debris Removal

Many old pilings traverse the width of Lake Austin and impede recreational boat traffic (Fig. 27). While some of these pilings are visible, many lie below the water's surface. It is not uncommon for boats to hit these pilings and suffer damage. These pilings are remnants from an old bridge that crossed Lake Austin in its prior history.

The removal of these pilings presents the best opportunity for work in Lake Austin and would provide the greatest immediate benefit for the local fishing community.

Fig. 27. Pilings from an old bridge impede boat traffic in the central portion of Lake Austin. Photo graciously provided by Ryan Ashcraft, Ashcraft Aviation.

4.2.2.2 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 (Figs. 5, 28), but it has long been a question about whether they provide sufficient flow. Madewell et al. (2021) was 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 in them during the drought (Figs. 5, 28). 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.

Fig. 28. The low-lying Chinquapin Road separates the Lake Austin watershed from the Big Boggy Creek watershed (left), and has only two small culverts running under it (right).

4.2.2.3 Chinquapin Bayou weir/bridge removal

There is an old, damaged bridge that could be removed along Chinquapin Bayou (Fig. 29). This structure lies within the Big Boggy NWR. The structure is not blocking hydrologic flow, but it is no longer in use and is in disrepair. It should be removed.

Fig. 29. An old, damaged bridge on Chinquapin Bayou.

4.2.2.4 Dam repair/removal at Live Oak Bayou and Highway 521

There is an old, damaged dam that needs to be repaired and/or removed along Live Oak Bayou (Fig. 30). The intention of this dam is to block saline water from traveling upstream, while also allowing freshwater to travel downstream. The dam currently allows some water to travel under its rocks, so it does not appear to be in optimal shape for its intended purpose. Some salt water is able to go upstream during storm surges, yet the dam blocks most fish passage in both directions. Just upstream from the dam, the habitat is good for alligators and water hyacinth due to pooling. From an ecological perspective, it would be better to remove the dam for hydrologic connectivity and fish passage.

However, the dam currently keeps the upstream water fresher, which helps stakeholders and landowners as those who own crawfish farms, rice farms, and other agricultural interests. Because it is in disrepair and allows some salt water to pass under the rocks, an ideal solution would repair the dam to prevent further intrusion, but in a manner that would also allow for greater fish passage.

Fig. 30. An old, damaged dam that obstructs some hydrologic connection on the upper portion of Live Oak Bayou.

4.2.2.5 Canal Infrastructure for Water Inflow

The existing canal infrastructure in Matagorda County could be used to route freshwater inflow into both the Lake Austin and Big Boggy Creek watersheds (Fig. 31). 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 good 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 down them. Another option would be to route the water down the same pathway but create a new canal of ~1,000 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 1900's 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.

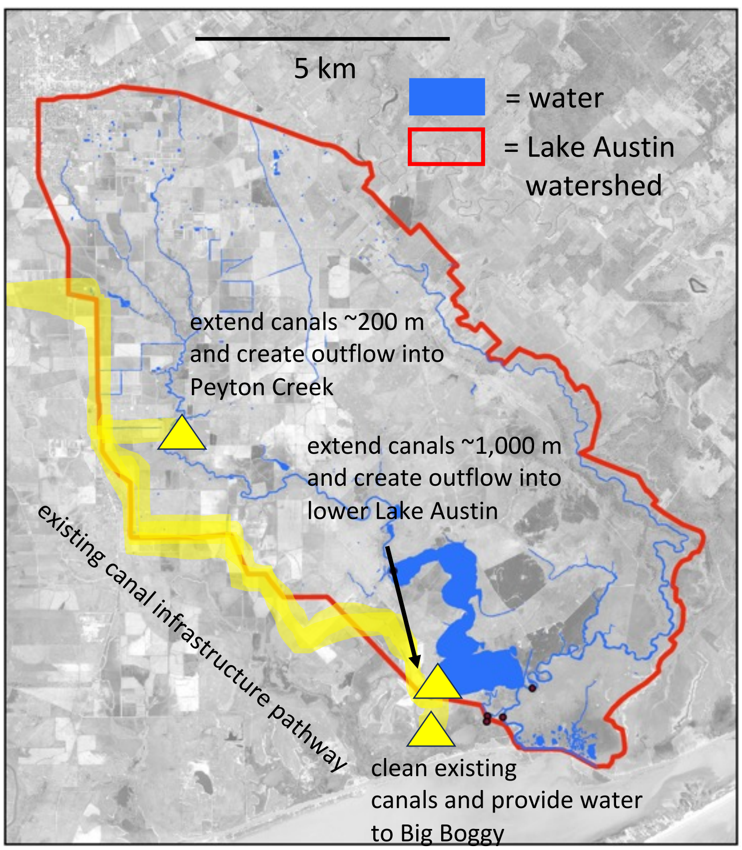

Fig. 31. Map of existing canal infrastructure (yellow highlighted pathway) that could be used as pathways to provide freshwater inflow from the Colorado River to the Lake Austin watershed.

4.2.2.6 Live Oak Bayou conservation

Live Oak Bayou contains a broad expanse of relatively isolated bottomland forest, which constitutes a portion of the Columbia Bottomlands (Fig. 32). The Columbia Bottomlands contain nearly all of the remnant coastal bottomland forest in Texas. The large majority of the land along Live Oak Bayou is owned by Hawkins Ranch Ltd., stretching roughly from Highway 521 down to the Hawkins tract of the San Bernard NWR. South of the NWR, the large majority is owned by the Baer G Estate.

Conservation initiatives are underway for these lands and other lands in the nearby Big Boggy Creek watershed (US Fish & Wildlife Service 2024), and the landowners are interested in managing the natural resources for maximum benefit of all ecosystem services. However, more efforts by conservation groups could help these efforts.

Public access trails could be constructed in the Hawkins tract of 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.

Fig. 32. The view along Live Oak Bayou in the Hawkins tract of San Bernard NWR.

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