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Final Report: Informing Environmental Flow Protection Efforts for the Sustainability of Wetlands in East Matagorda Bay: Phase I Big Boggy

Texas Water Development Board Contract #2000012414

By

Matthew J. Madewell, Texas A&M University
Rusty A. Feagin, PhD, Texas A&M University
Thomas P. Huff, PhD, Texas A&M University
Bill Balboa, Matagorda Bay Foundation

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Final Report:

Informing Environmental Flow Protection Efforts for the Sustainability of Wetlands in East Matagorda Bay: Phase I Big Boggy

Matthew J. Madewell[1], Rusty A. Feagin[1], Thomas P. Huff[1], Bill Balboa[2]

[1]Texas A&M University, [2]Matagorda Bay Foundation

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Executive Summary

The Colorado River of Texas no longer provides direct freshwater flows to the wetlands of East Matagorda Bay. A few small basins, such as that of Big Boggy Creek, provide the only inflowing freshwater. The upstream portions of the Big Boggy watershed were extensively modified in the past and its freshwater inflows have been reduced, negatively affecting the wetlands in this basin. The central objective of this project was to help identify environmental flow standards for the Big Boggy coastal watershed and recommend potential restoration actions to sustain its wetlands. We identified wetland and land cover trends over 1953 – 2020, finding that this watershed has lost more than one-third of its low marsh area since 1953. We then quantified the flow rates into/out of the watershed and created a water budget, finding that relative sea level rise and seasonal droughts are likely responsible for the historical loss of wetlands in this watershed. To combat further loss of low marsh, we recommend a handful of restoration actions that include removal of duck pond levees, modification of moist soil units, and improved drainage at the Gulf Intracoastal Waterway interface. Next, we modeled both historical and future inflows, from the years 1953 to 2100, under various scenarios. We found that rainfall and inflows have been trending positively since the 1950s, however, climate change scenarios suggest that precipitation and inflows will likely decrease in the future. As inflows decrease and become more variable in the future, resource managers will need something to help identify when freshwater inflows are critically low. We developed a MS Excel-based inflow decision tool that can be used by natural resource managers to identify the quantity of supplemental water that is needed to avoid the damaging effects of drought. This decision tool, along with all the datasets collected for this project, can be downloaded from the publicly-available dataset page for the Coastal Ecology and Management Laboratory at Texas A&M University (cml.tamu.edu). Environmental flows are critical to the long-term resilience of wetlands in the Big Boggy Creek watershed and to the estuarine waters of East Matagorda Bay. The restoration actions we have identified, along with the supplemental flow estimates we provide, will aid resource managers in protecting the East Matagorda Bay watershed.

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1. Introduction

Wetlands provide immense value through their numerous ecosystem services (Barbier et al., 2011) and yet they are often vulnerable to a reduction in their inflowing freshwater (Alexander and Dunton, 2002). Adequate freshwater inflows are crucial to sustaining healthy wetland vegetation (Stachelek and Dunton, 2013), and this vegetation provides support for commercial and recreational fisheries (Taylor et al., 2018; Bell, 1997), migratory bird habitat (Darnell and Smith, 2004), flood damage reduction (King and Lester, 1995), and inland erosion mitigation (Shepard et al., 2011). As freshwater inflows are reduced, naturally or anthropogenically, saltwater intrudes further into the watershed and can kill or alter the wetlands (White and Kaplan, 2017).

The Colorado River of Texas no longer provides direct freshwater flows to the wetlands of East Matagorda Bay (EMB), due to the creation of the Colorado River Delta and subsequent construction of the Colorado River Navigation Channel (CRNC). First described by Alonso de Leon in 1690, a series of log jams (also referred to as “log rafts”) impounded sediment and river flows on the Colorado until the summer of 1929 when bank excavation efforts, coupled with a large flood event, swept the collection of drift into Matagorda Bay (Clay, 1949). Sediment filled a portion of the bay basin and connected the former barrier island complex to the mainland, forming the Matagorda Peninsula. The flow of the Colorado River was limited at its mouth until 1934 when the Matagorda County reclamation district cut a channel from the mouth to the Gulf of Mexico, breaching the Matagorda Peninsula. In present day, the Colorado River flows are split between a flood discharge channel and the CRNC to the Gulf of Mexico. Because of these hydrologic modifications, the only significant freshwater inputs to EMB are attributed to a few small basins, such as that of Big Boggy Creek. Long term resilience of the oyster reefs and recreational fisheries in EMB has been an ongoing concern due to hypersalinity resulting from the hydrologic isolation. 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; Morton, 1979). The loss of sediment in the tidal water column since 1934 may be negatively impacting salt marshes in the surrounding watersheds by limiting the inorganic vertical accretion (Peteet et al., 2018; Bricker-Urso et al., 1989).

The Lower Colorado River Authority (LCRA) has managed the lower 600 miles of the Colorado River as a nonprofit public utility since 1934. As part of its duties, LCRA sells water to users in the Colorado River basin for municipal, agricultural, and wildlife management uses. In 2009, LCRA sold water in the Gulf Coast division for wildlife management use at a base charge of $10.41 per acre, plus $13.73 per acre-foot of water delivered (E. Ray, personal communication, October 13, 2021). In 2021, LCRA sells water for wildlife management at the interruptible agricultural rate of $66.14 per acre-foot delivered. In 2008 and 2009, the US Fish and Wildlife Service (FWS) purchased water from LCRA for wildlife management purposes at $5,000 in total. In a report to the Texas Water Development Board (TWDB), AquaStrategies identified a handful of water delivery options to supplement EMB with freshwater from the Colorado River (Austin et al., 2015). One such option is to purchase and deliver water through the Big Boggy/Lake Austin Marsh complex.

The upstream portions of the Big Boggy basin have been hydrologically-modified by agriculture, hydrocarbon extraction, the petrochemical industry, an extensive irrigation and drainage network, and the construction of roads and other barriers to flow. In addition, the influence of saltwater continues to increase with erosion, relative sea level rise, and diversion of freshwater inflows. The combination of reduced freshwater inflow and sediment transport, enhanced saltwater influence, and altered drainage networks have resulted in periods of hypersalinity, wetland loss, and fish kills in the wetlands of the Big Boggy basin.

There are currently no Texas Commission on Environmental Quality (TCEQ) rule-based environmental flow standards for East Matagorda Bay, nor the Big Boggy watershed. The Colorado and Lavaca Basin and Bay Area Stakeholder Committee (BBASC) has identified this as a gap in their ability to sustain the health of this estuary and its dependent resources. As stated in TCEQ rules Chapter 298 – Environmental Flow Standards for Surface Water Subchapter D: Colorado and Lavaca Rivers, and Matagorda and Lavaca Bays §298.310(d), "For East Matagorda Bay, the commission does not adopt environmental flow standards but finds that the sound ecological environment of East Matagorda Bay can be maintained by avoiding further reduction of freshwater inflows, to the extent those reductions can be avoided, and that strategies to provide additional freshwater inflows to East Matagorda Bay should be pursued."

The BBASC's Work Plan for Adaptive Management states that East Matagorda Bay needs a flow regime recommendation and to identify baseline conditions.

- Task 1, sub 2: Review best available science for determining environmental flow regimes for streams
- Task 2, sub 3: Describe relationships between physical habitat and flow
- Task 5: Increase understanding of how different factors affect calculation of flow regime components and hydrologic conditions over time
- Task 12, sub 1: Identify improvements made in methods for determining environmental flow regimes for estuaries
- Task 12, sub 8: Evaluate achievement of the Basin and Bay Expert Science Team (BBEST) freshwater inflow recommendations in Matagorda Bay…and ecological response to those freshwater inflow quantities and distribution
- Task 14: Refine estimates of freshwater inflows to bays

There are no current adopted or specific quantitative standards because of the current disconnection of the Colorado River, and the difficulty of acquiring data for the smaller inflow sources like Big Boggy Creek. Some early work was conducted by Schoenbaechler, Guthrie, and Lu (2011) to predict ungauged flow using a model. Additional work was outlined by Buzan et al. (2011) through the BBEST that discusses the broader relations of these flows with some ecological needs. More generally, the flow dynamics and salinity regimes for the Middle Texas Coast are not well-known, as most previous work has been conducted for the Upper Texas Coast (wet) or Lower Texas Coast (dry) regimes.

The central objective of this project is to assess the Big Boggy coastal watershed and recommend potential restoration actions to sustain its wetlands. The specific objectives of this study are to:

1. Identify wetland and land cover trends from 1953 to 2020.
2. Quantify average water flow rates into/out of the watershed and create a water budget
3. Develop flow rate standards and recommend potential restoration actions for wetlands in the Big Boggy watershed.

2. Methods

2.1. Study area

Big Boggy is a coastal watershed that drains into East Matagorda Bay eight miles northeast of Matagorda, Texas, USA (Figure 1). The southern reaches of the watershed are dominated by salt marsh. In the northern reaches of the watershed, Big Boggy Creek flows through cattle pastures with stream banks maintained and mowed periodically by the Matagorda County Drainage District. Several weir structures are present along Big Boggy creek that impede aquatic movement upstream and may limit freshwater flow downstream.

The study area encompasses 5,700 hectares of the Big Boggy Creek watershed (Figure 1). The study area is limited in its upstream extent by Texas Highway 60. Of this area, 1,500 hectares is operated under the jurisdiction of the U.S. Fish & Wildlife Service (FWS) as the Big Boggy National Wildlife Refuge (NWR). There is an additional 316 hectares of Big Boggy NWR south of Lake Austin; this portion is not considered in the study because it flows to Lake Austin and is in a different watershed, due to hydrologic interruption by Chinquapin Road. The remaining portion of the study area is privately owned and functions primarily as cattle grazing pasture. Ninety acres of rice paddies are present at Big Boggy NWR, all of which is seasonally planted with rye grass to provide winter browse for waterfowl (FWS, 2013). Off the refuge, there are few operating rice paddies present in the watershed.

The southern Big Boggy watershed consists of alluvium deposits created during the Holocene, deposited by Big Boggy Creek and Peyton Creek watersheds (Texas Water Science Center, 2014). The alluvium deposits greatly overlap with the wetlands in the study area. The northern extent of the study area is composed of Beaumont formations, predominately clay and sand, deposited during the Pleistocene. The Beaumont series formation is characterized by deep, poorly drained, and very slowly permeable soils on coastal plains. Much of the wetlands occupying these poor draining areas were reclaimed for agricultural purposes.

Salt marsh occurs primarily in the southern portions of the Big Boggy watershed. The zonation of its plant species is typical and similar to other sites along the central portion of the Texas Coast (Figure 2). *Spartina alterniflora* is the dominant low salt marsh vegetation. Slight elevation gradients within the marsh allows for colonization of halophytic species such as saltwort (*Batis maritima*), dwarf saltwort (*Salicornia bigelovii*), and saltgrass (*Distichlis spicata*). *S. spartinae* is abundant at elevations immediately above the intertidal zone and in areas that are too saline for typical upland grasses. Freshwater marsh vegetation includes cattail (*Typha latifolia*), alligator weed (*Alternanthera philoxeroides*), and common reed (*Phragmites australis*). Upland vegetation includes bushy bluestem (*Andropogon glomeratus*), honey mesquite (*Prosopis glandulosa*), eastern baccharis (*Baccharis halimifolia*), sugar hackberry (*Celtis laevigata*), Chinese tallow (*Triadica sebifera*), and Macartney rose (*Rosa bracteate*).

Like many coastal areas in the U.S., marshes in the Big Boggy watershed are vulnerable to relative sea level rise (RSLR). Based on the two nearest gauges at Rockport and Galveston, the sea level has been rising at a rate of 0.63 cm/year (Holgate et al., 2013). Relative sea level rise, defined as the rate of rising ocean levels relative to the land at a given location, has the potential to outpace natural accretion rates of salt marsh resulting in the drowning of a marsh platform (Reed, 1990). Natural processes that combat RSLR in the Big Boggy watershed have been weakened by the hydrologic isolation of East Matagorda Bay. For example, sediment transport by tidal waters or storm surges has been reduced due to the current flow of the Colorado River as mentioned previously.

Big Boggy NWR is an important destination for migratory waterfowl along the Central Flyway. The Texas Mid-Coast NWR Complex supports more than 100,000 shorebirds annually (FWS, 2013). Among these birds are 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*). Dressing Point, one of most prominent bird rookeries on the Texas coast, is adjacent to Big Boggy. Dressing Point holds an average of 19 pairs of reddish egrets, in addition to being an important site for roseate spoonbills (*Platalea ajaja*) and royal terns (*Thalasseus maximus*).

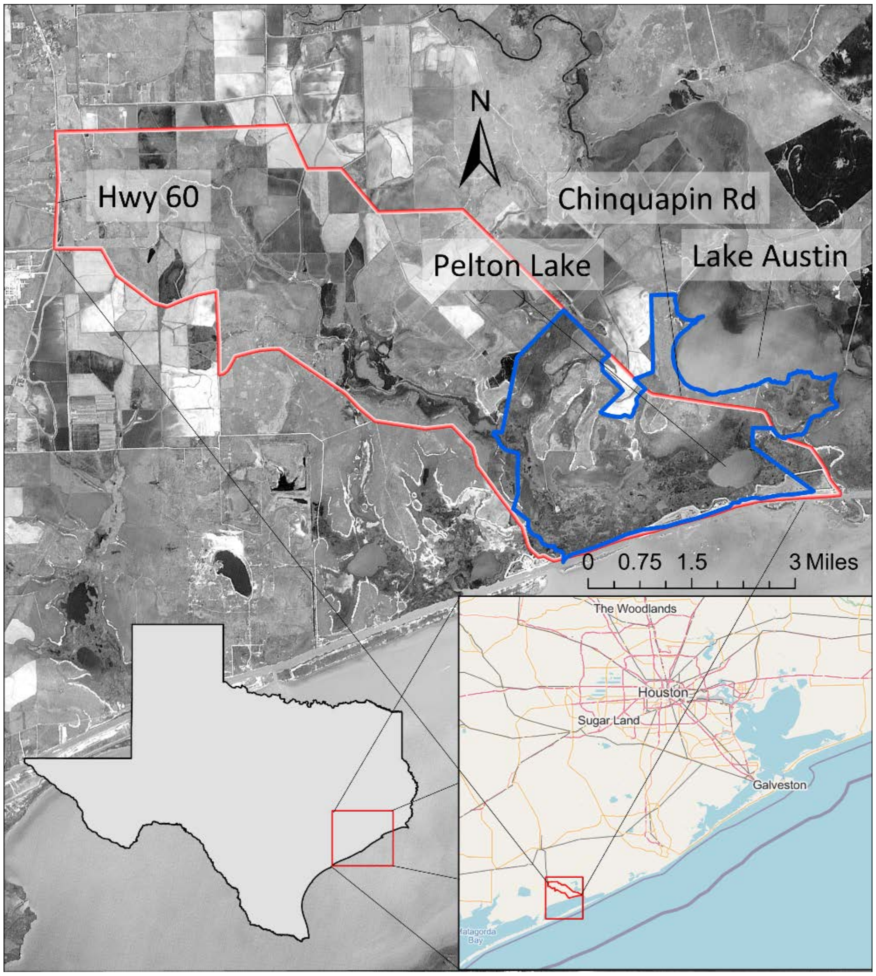

Figure 1. Project study area (outlined in red) located southwest of Houston, Texas and bordering East Matagorda Bay. Big Boggy NWR (outlined in blue) is not entirely contained by the study area.

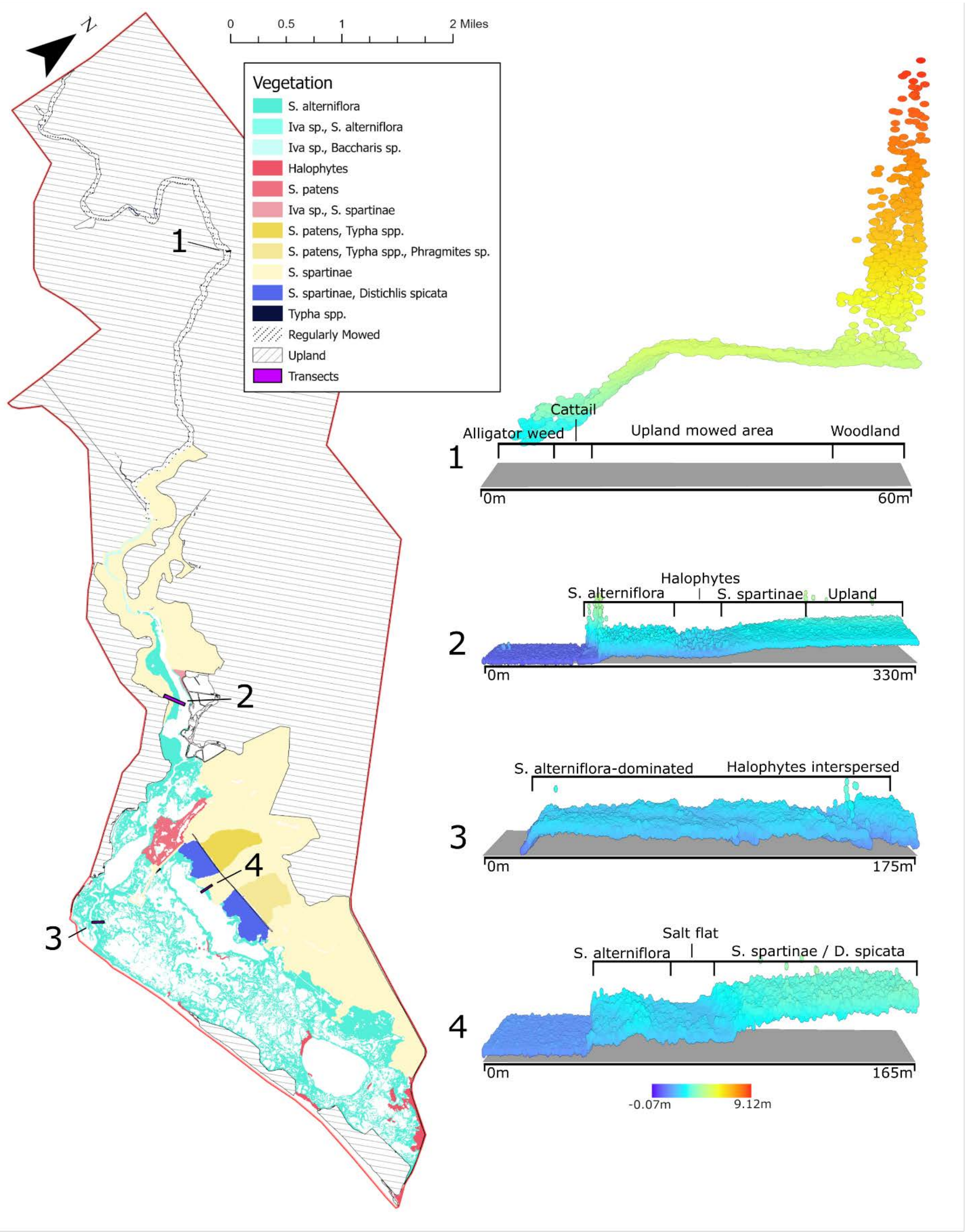

Figure 2. Vegetation cover map for the Big Boggy watershed, illustrating the different vegetation communities at different locations along its length. In the four transect cross-sections on the right, the elevation is depicted as based on LIDAR point data.

2.2. Identify wetland and land cover trends from 1953 to 2020

To identify historical changes in wetland cover and the hydrological network, we analyzed a series of modern (2020) and historic aerial imagery within ArcGIS. Images from 1953, 1982, and 2020 were chosen based on their image quality and distribution in time. Imagery was obtained through the Texas Natural Resources Information System (TNRIS; 1953 and 2020) and the United States Geological Survey's (USGS) EarthExplorer (1982) databases. The 1953 imagery derived from the United States Department of Agriculture (USDA) imagery program was deemed to be the earliest available imagery that included the entire study area and was clear enough to interpret. The 1953 imagery was captured at a 1:20,000 scale. The intermediate imagery, 1982, was obtained by the USDA's National High-Altitude Aerial Photography program (NHAP). The imagery chosen was captured at a 1:58,000 scale and exposed on color infrared positive film. The most recent imagery (2020) was obtained through the USDA National Agriculture Imagery Program (NAIP) and at a 60 cm resolution. The 1953 and 1982 imagery were then geo-referenced to the 2020 imagery.

Five distinct land cover classes were identified. In the order of increasing relative elevation, the land cover classes were: 1) water, 2) unconsolidated shore, 3) low marsh, 4) high marsh, and 5) upland. The water class was characterized as areas of standing water with no vegetation present. Unconsolidated shore included unvegetated areas directly adjacent to water composed of sand or shell hash. Low marsh intertidal areas were dominated primarily by *Spartina alterniflora* but included halophytes such as *Batis maritima* and *Distichlis spicata*. High marshes were typically dominated by *S. spartinae*, although *D. spicata* was also present. The upland class included all non-wetland classes and human structures or impervious surfaces. Each land cover class was digitized using ArcGIS Pro (ESRI, Version 2.8) at a consistent map scale of 1:2,000. This scale allowed us to maintain fine detail while also allowing for an efficient use of digitizing effort. The classified land cover maps were then analyzed in ArcGIS to determine the land cover changes from 1953 to 2020. Temporal changes were determined using the Intersect tool in ArcGIS Pro, which functions by overlaying the classified layers over each other and then recording the amount each class changes in relation to the other classes.

In addition to land cover changes over time, modern vegetative cover was mapped to help identify notable features of the watershed's hydrologic network. In-situ sight identification of vegetation was used in tandem with aerial imagery to create a more complete view of vegetation distribution across the study area. When possible, vegetation was classified to species, however, in some cases only the dominant vegetative cover was noted. In-situ identification of vegetation took place concurrently with the deployment of water sensors in June and July, 2020 as well as during barrier surveys in January, 2020. More than 100 geo-tagged photos were taken of vegetation in the study area to aid in identification and to use as a reference in the lab.

2.3. Quantify average water flow rates into/out of the watershed and create a water budget

The characteristics of the hydrological network were quantified by determining the amount of water flowing through the watershed using flow data from a series of sensors and gauges. A model of the water budget for the watershed was then developed that incorporated the watershed area and precipitation. The resulting model helped us to determine the minimum environmental flow standard for the watershed and forecast the water budget in the future as precipitation regimes change.

2.3.1. *Sensor Stations*

To collect the hydrological data, a series of sensors and gauges were deployed from June 23, 2020 through March 5, 2021 (Table 1). The sensors included Conductivity, Temperature, and Depth (CTD) dataloggers (CTD-Diver, Van Essen Instruments), Solinst Leveloggers (Levelogger 5 LTC, Solinst Canada Ltd.), Acoustic Doppler Current Profilers (ADCP; Aquadopp Profiler 1 MHz, Nortek Group), and a precipitation gauge (Onset tipping bucket rain gauge). The CTD dataloggers contained a pressure sensor that measures the hydrostatic pressure of the water to calculate total water depth, as well as a 4-electrode conductivity sensor that measures the specific conductivity of the water—a proxy for salinity. The CTD's were set to record measurements hourly. CTD dataloggers were deployed in a PVC pipe securely inserted into the stream bottom. The ADCP units use acoustic Doppler sensors to measure the flow speed of the water column. The ADCP units were affixed to a steel fence post using coated steel cables and placed at the center of the stream channel. The precipitation gauge was deployed in close proximity to the other sensors and recorded the amount of rainfall occurring for each rainfall event. Additional hourly precipitation data was obtained from the LCRA rain gauge at Matagorda, Texas (Gauge Matagorda 1 S), 10 miles southwest of the study area.

Figure 3. Map of sensor stations in the Big Boggy study area at Upper Boggy (1), Lower Boggy (2), and Chinquapin/Pelton lake (3).

We set up the sensors at three stations. The "Upper Boggy" station (or UB) contained an ADCP and CTD sensor and was placed upstream of the salt marsh complex and north of Big Boggy NWR, where the creek banks were more riverine in form and the vegetation indicative of brackish conditions (Figure 3). This station primarily measured the freshwater inflow entering the refuge by way of Big Boggy Creek. The "Lower Boggy" station (or LB) was placed further south within the salt marshes of Big Boggy NWR, where Big Boggy Creek intercepts the Gulf Intracoastal Waterway (GIWW). This second station also had an ADCP and CTD, but primarily measured tidal flow in and out of the watershed. A third group of sensors consisting of one Solinst Levelogger and one precipitation gauge were placed along the eastern edge of Pelton Lake, and an additional CTD gauge was placed in Chinquapin Bayou on the east side of Chinquapin Road, on the other side of a culvert. This group of sensors was put in place to identify the degree of hydrologic isolation of Pelton Lake (the lake immediately below the label numbered 3 in Figure 3), and its connectivity with Chinquapin Bayou. We thus sought to identify the flows between the Big Boggy and Chinquapin watersheds using this third group of paired gauges.

Table 1. Sensor deployment locations and dates

Equipment Deployment Dates			
Sensor Group	**Sensor Type**	**Start**	**End**
1 - North Boggy	ADCP	6/23/2020	9/19/2020
1 - North Boggy	CTD	6/23/2020	3/5/2021
1 - North Boggy	ADCP	4/9/2021	6/15/2021
1 - North Boggy	CTD	4/9/2021	6/15/2021
1 - North Boggy	HOBO rain gauge	4/9/2021	6/15/2021
2 - South Boggy	ADCP	7/3/2020	9/19/2020
2 - South Boggy	CTD	7/3/2020	3/5/2021
2 - Upland	Barometer	6/23/2020	3/5/2021
3 - Pelton Lake	Solinst	6/23/2020	3/5/2021
3 - Pelton Lake	HOBO rain gauge	6/23/2020	9/19/2020
3 - Chinquapin	CTD	7/3/2020	3/5/2021

The water level data from the CTD sensors and the flow rate data from the ADCP sensors were then vertically referenced into North American Vertical Datum (NAVD88) units, using a survey-grade Global Navigation Satellite System (GNSS) that included Global Positioning System (GPS) and GLONASS satellites. Because we used the Virtual Reference Station (VRS) survey method, we also surveyed a nearby USGS benchmark of known elevation during each visit, which allowed us to cross-reference the various surveys that we conducted on different dates and offset the mean bias introduced during each VRS session. We then cross-referenced our datasets with the National Oceanic and Atmospheric Administration's (NOAA) Matagorda City tidal gauge (Station ID: 8773146) nine kilometers southwest of the study area.

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.

2.3.2. ***Hydrological Budget***

We then developed a hydrological budget using the sensor datasets, and used it to ask two questions: (1) what is the quantity of freshwater inflow coming down Big Boggy and how do we expect it to change over the next 100 years? And (2) are the salt marshes showing signs of hydrologic restriction and hypersalinity? To answer the first question, the water budget was divided into two bins based on the Upper Boggy and Lower Boggy stations. At each location, we accounted for the differences between the upstream-versus-downstream flow volumes, and then related them to the precipitation, evaporation, and the expected watershed size. The second question is answered by interpreting data from all sensor stations as well as synthesizing results from the land cover change methods. Groundwater is not explicitly accounted for in this water budget, as it is unlikely to play a large role in this region of coastal Texas due to the low permeability of the clay soils present (Soil Survey Staff, 2021). We assume that while there may be losses or gains to groundwater, they balance out over the study period.

The water budget variables at each station included downstream flows, upstream flows, and precipitation. Although we had hourly data available for each of these variables over longer time frames at various stations, we chose to only use the data from 7/4/2020 to 9/19/2020 to build the budget for dates in which ADCP stations were active. During these dates in 2020, the precipitation balance was just below the mean for the period over the past several decades (see Results for more). This period was uniquely important because it was during these summer months when inflows are at their lowest and most critical. We aggregated over this time frame based on an initial investigation into the hourly timing of the relationship between measured precipitation and perceived flow at the stations, wherein we concluded that these three months of data 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. It is possible that flows during our period of record (July, August, September) do not match flow patterns for other periods throughout the year.

For each station, we first found the imbalance between upstream and downstream flow volume. Upstream flows could include both incoming tides and storm surges. Downstream flows could include outgoing tides and freshwater flows from upstream reaches of the watershed. We then calculated the precipitation volume for the watersheds that fed into each station. To do this, we obtained the precipitation from the Water Data for Texas website operated by the Texas Water Development Board (TWDB) (Texas Water Development Board, 2021). This precipitation dataset combines data from different precipitation stations within a quadrant to estimate precipitation throughout the entire quadrant. We next multiplied these datasets by the “total watershed area” and the “effective watershed area” for each station. The total watershed area was identified using the Watershed tool in ArcGIS Pro and a 1-meter Digital Elevation Model (DEM); two total watershed products were produced to delineate the separate sections of the landscape that uniquely contributed to the Upper Boggy and Lower Boggy stations. The effective watershed area was defined as the area across which the precipitation could be assumed to have fallen (minus any evaporation), that would then be equivalent to the observed quantity of inflow reaching each station. In other words, the effective watershed area is the area of capture that is multiplied by a precipitation measurement to obtain the amount of precipitation-driven inflows (precipitation minus evaporation) that are observed flowing past our sensor station.

2.3.3. ***Hindcasted and forecasted inflow volumes***

Finally, we hindcasted and forecasted the freshwater inflow volume at the Upper Boggy and Lower Boggy stations over the time period from 1954 to 2100. Because of the relatively short period of data collection (6/23/2020-3/5/2021 for CTDs; 7/4/2020-9/19/2020 for ADCPs), there may be additional uncertainty in hindcasting and forecasting, due to the potential variability in how the watershed reacts to periods of high or low precipitation. Because of this, the forecasting scenarios are estimated based on the mean trend. For the hindcasting, the estimated historic freshwater inflows for each year from 1954 to 2019 was aggregated during the same summer months as the budget (July, August, and September). The values were derived from the TWDB precipitation dataset, in the same manner as for the budgeting described previously. To identify past years where net flows were above and below what was considered a typical year for rainfall in the region, we calculated the mean trend across the years and then found the root mean square error (RMSE) deviation from that trend line. We then graphed both the mean trend line and the RMSE ranges, to help depict the most aberrant years. For the aberrant years that fell outside of and below the lower RMSE bound (the drought years), we calculated the amount of supplementary inflow that would be needed to bring the total inflow back up to the lower RMSE bound, as well as back up to the mean. We considered these two values as indicative of the estimated range of supplemental volume that would be needed to bring the inflow out of drought conditions.

For the forecasting, we evaluated the effect of three potential climate change scenarios on the mean inflow volumes, again using the budgeted months. Additionally, the mean trend line used in hindcasting was continued through 2100 as a fourth scenario in which the rates of change between 1954 and 2019 were maintained moving forward. The three climate change scenarios were defined by the Intergovernmental Panel on Climate Change (IPCC) and statistically downscaled by Jiang and Yang (2012), and include the A1B, A2, and B1 scenarios. Jiang and Yang (2012) used a bias-corrected statistical downscaling method to create finer resolution predictions using IPCC projections. The downscaled model was evaluated using the North American Regional Reanalysis (NARR) dataset. Each scenario predicts future trajectories of climate change depending on global changes in demographics, and economical or technological developments (Nakicenovic et al., 2000). The A1B scenario predicts rapid economic growth, peak global population mid-century, introduction of new and more efficient technologies, and a balance between fossil-intensive and non-fossil-intensive energy sources. The A2 scenario predicts a heterogeneous world with a focus on preserving local identities and self-reliance, continuously increasing global population, and more fragmented economic and technological development. The B1 scenario predicts peak global population mid-century (as in A1B), a rapid change to a service and information economy with the introduction of cleaner, resource-efficient technologies.

3. Results

3.1. Identify wetland and land cover trends from 1953 to 2020

Between 1953 and 2020, the Big Boggy watershed experienced notable changes in land cover composition. Of the five cover classes, three classes lost more than a quarter of their total area (Figures 4, 5, 6; Table 1). The unconsolidated shoreline retained only 10% of its total area between 1953 and 2020. Most of this shoreline change occurred along the interface with East Matagorda Bay, perhaps due to the loss of the GIWW dredge spoil island directly across from the study area which then allowed wave erosion to reduce the area of the land cover class. Low marsh lost 35% of its original area, with 43% of this loss converting to open water. Of the nearly 800 hectares of low marsh present in 1953, 512 hectares remain in 2020. Much of this loss is likely due to relative sea level rise. A small portion of salt marsh was lost in the creation of the dredge spoil areas along the GIWW. These dredge spoil areas are isolated and considered upland in this analysis. The total coverage of water in the study area more than doubled from 321 hectares to 681 hectares. High marsh experienced a net loss of 27% or approximately 213 hectares. Low marsh has transgressed onto the former uplands and high marshes north of Pelton Lake and Lake Kilbride (the east-west lying lake to the west of Pelton Lake, but east of Big Boggy Creek), as well as into the moist soil units in the NWR. Interestingly, the low marsh is not transgressing further up the main channel of Big Boggy Creek.

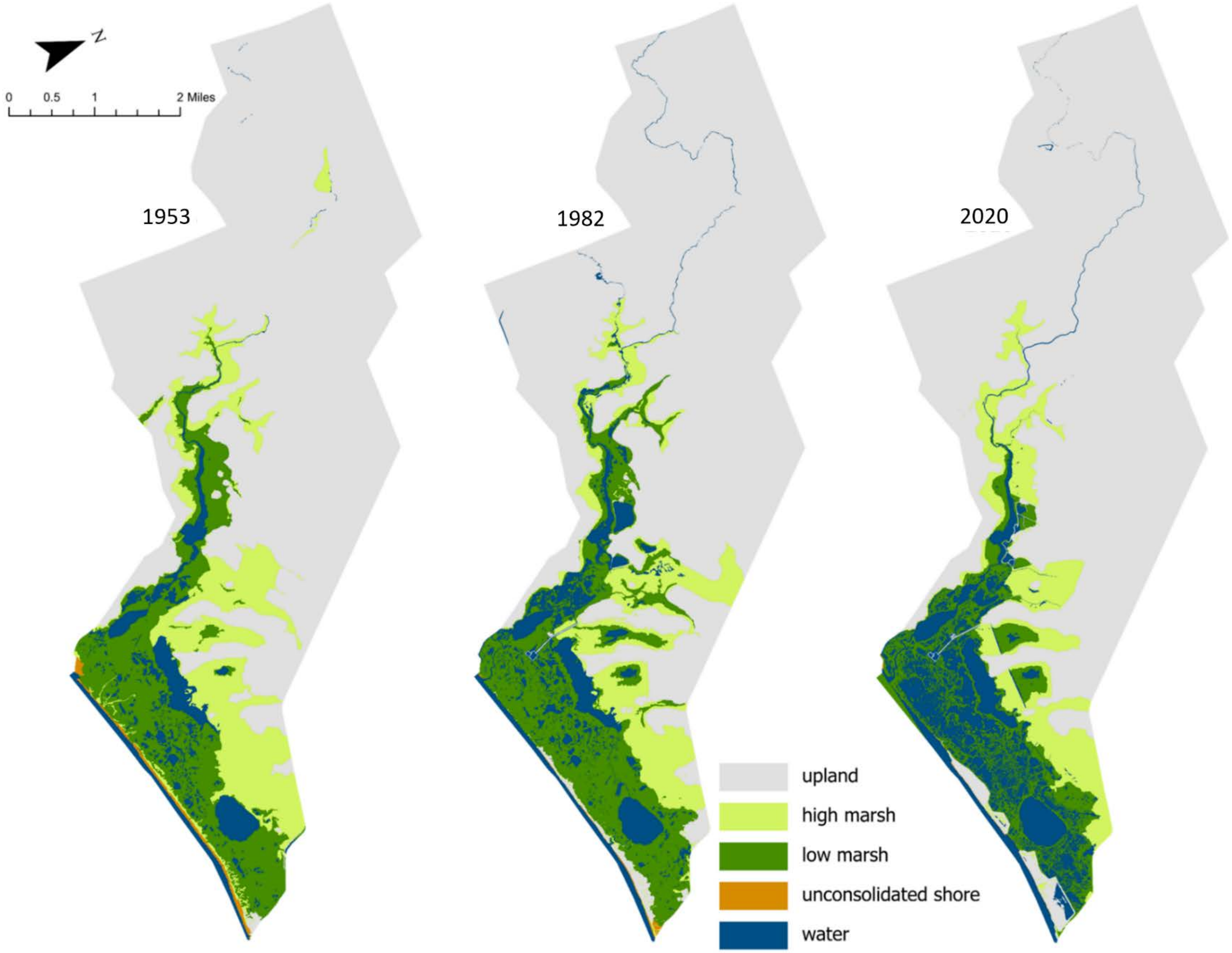

Figure 4. Land cover in the Big Boggy watershed from 1953 to 2020.

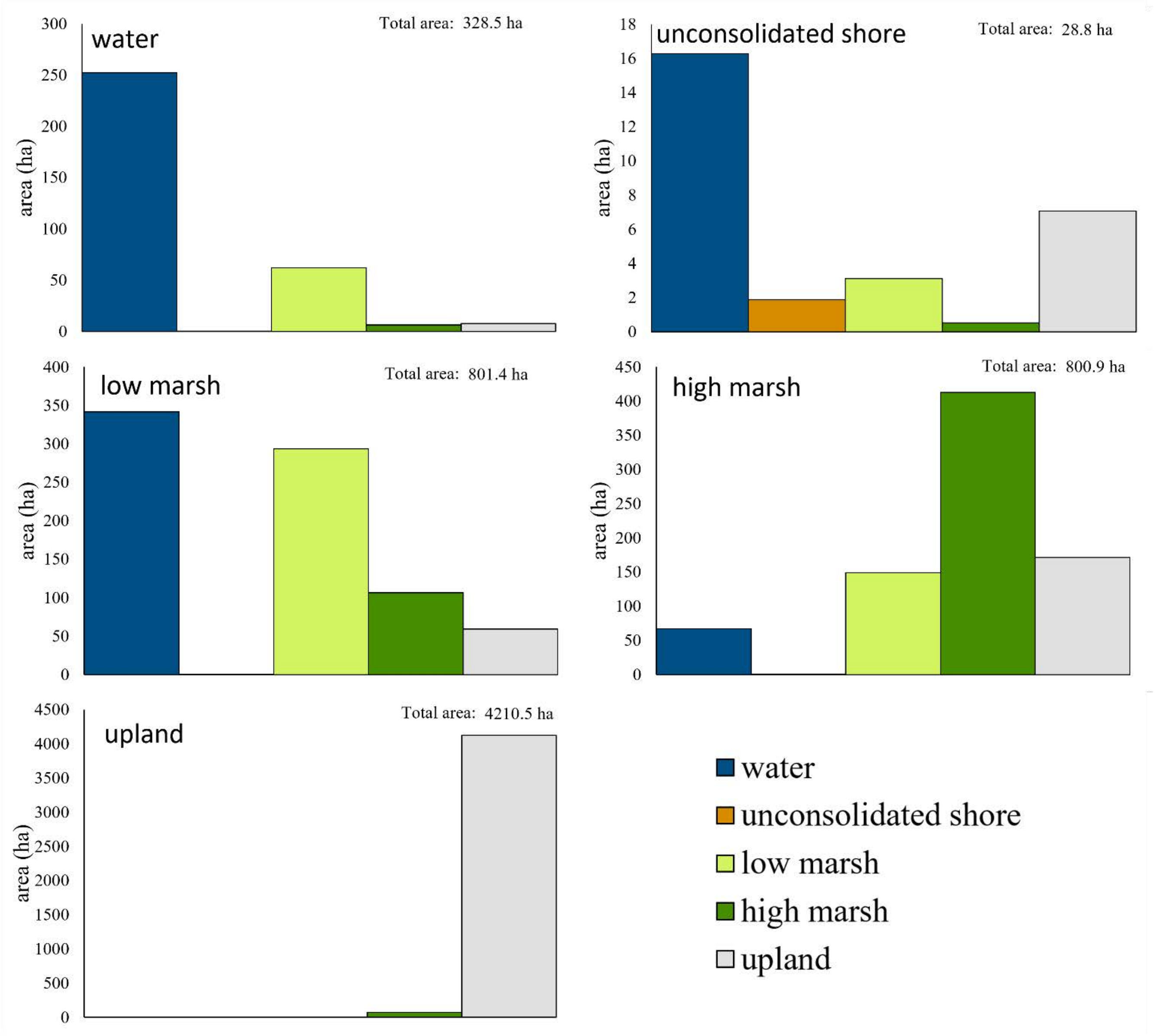

Figure 5. Transition of land cover types in the Big Boggy watershed from 1953 to 2020. Each chart panel signifies the change in land cover for one of six classes: water, unconsolidated shore, low marsh, high marsh, and upland. The changes shown indicate the amount one land cover class converted to each of the other classes between 1953 and 2020. For example, in the low marsh panel 342 hectares of low marsh in 1953 were converted to water in 2020. Additionally, 293 hectares of the original low marsh in 1953 were retained as low marsh in 2020. The 293 hectares retained by the low marsh class do not include the area added by the conversion of other land cover classes to low marsh.

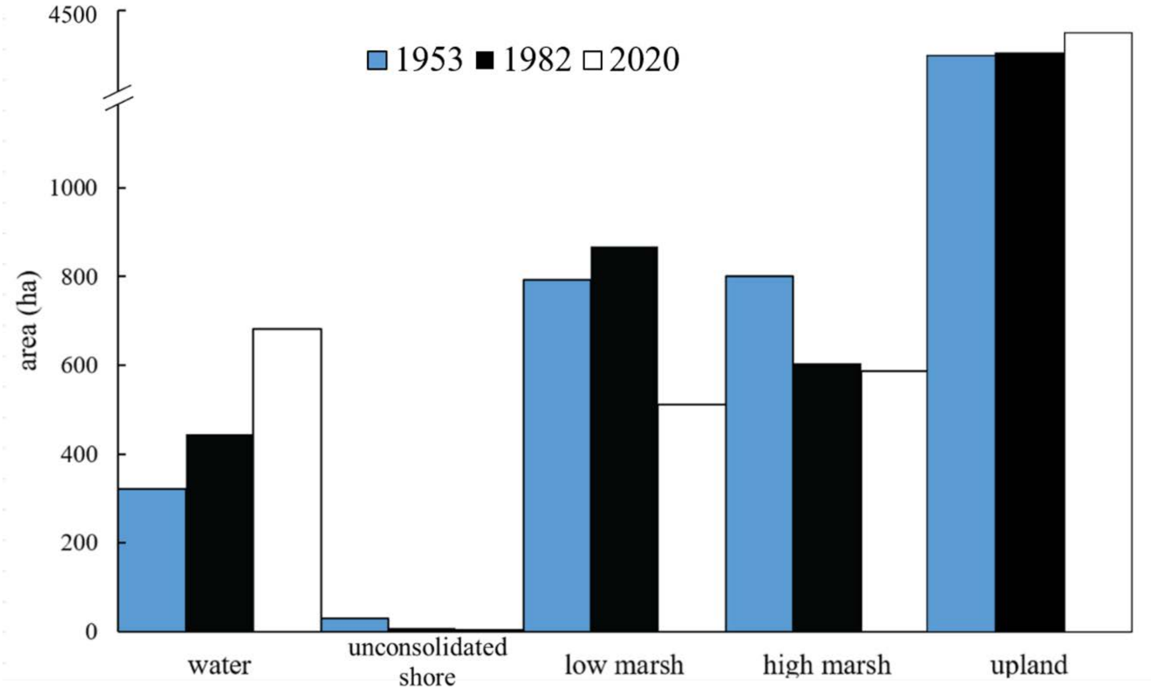

Figure 6. **Land cover areal extent in the Big Boggy watershed from 1953 to 2020. Note the discontinuous y-axis to accommodate the large quantity of upland area.**

3.2. Quantify average water flow rates into/out of the watershed and create a water budget

The total precipitation observed during the study period (June 24th, 2020 – March 4th, 2021) was 60 cm (23 in.; Figure 7a). During this period, two tropical cyclones passed by the area, Hurricane Hanna and Tropical Storm Beta. Precipitation in 2020 (32.36 cm) was 5% lower than the average rainfall from 1954 to 2020 (34.12 cm).

We found that the water level and salinity at all three stations were affected by both tides and precipitation events (Figure 7b). The Upper Boggy (UB) station was most responsive to precipitation as shown with its brief peaks following precipitation events, followed by a generally rapid return to its baseline. The average daily tidal range at UB was approximately 10 cm. Over the course of the study period, the average salinity at UB was 13 PSU, the lowest among the three stations (Figure 7c). Salinity at UB was influenced by the amount of precipitation during an event as well as the storm surge from the GIWW. For example, the precipitation and storm surge from Hurricane Hanna began on July 21, 2020. While large amounts of precipitation were reported (4 cm in an hour at peak), salinity at UB remained relatively steady at 3.3 PSU then sharply rose to 10 PSU on July 26, 2020, as the saltwater wedge from LB made its way upstream into the more riverine channel at UB. Over the coming days and weeks, salinity gradually declined to 4 PSU as saline floodwaters were flushed out of the station area by inflowing freshwater. During periods of sparse precipitation, salinity at UB gradually increased to a peak salinity of 27 PSU.

At the Lower Boggy (LB) station, water level is largely driven by the tide as well as storm surges. Precipitation can also cause water levels at LB to rise, just slightly below those at UB (1.4 m at UB compared to 1.3 m at LB on September 22, 2020). The average daily tidal range at LB was approximately 10 cm. Average salinity at LB was the highest between the three stations at 21 PSU. An interesting pattern in salinity is seen from July 26, 2020, to July 30, 2020. Following the Hurricane Hanna storm surge, as accumulated freshwater forced the saltwater wedge downstream, a steep decline in salinity is observed at LB from 23 PSU to 4 PSU. This event occurs roughly 12 hours after the increase in salinity occurred at UB on July 26, 2020. Through the rest of the study period, salinity remains relatively stable dropping down to as low as 10 PSU following a moderate precipitation event in late December.

The Chinquapin station was the most unique of the three. At times, the Chinquapin station appears to respond differently to precipitation events, and the water levels generally take longer to decrease after these events, suggesting that it was responding to different inflow sources (i.e., Lake Austin). Water level at Chinquapin following Hurricane Hanna further illustrates its connection to a different inflow source. Following the initial peak in water level on July 26, 2020, two smaller peaks are reached on July 30 and August 2, 2020. Each of these secondary peaks are greater than those at UB during the same period. Further, the daily tidal range at Chinquapin was 4 cm, the lowest of the three stations. This is likely attributed to its more hydrologically isolated location. Salinity at the Chinquapin station is the most variable between three while its average salinity falls between UB and LB at 19 PSU. Similar to UB, salinity at Chinquapin decreases following precipitation events, however, it more rapidly rebounds in the absence of precipitation. For example, during Hurricane Hanna, salinity peaked at 30 PSU during the storm surges. Following the storm surge, salinity dropped to 6 PSU. Salinity at Chinquapin rose sharply on August 20, 2020, from 13 PSU to 24 PSU on August 21, 2020. The salinity at Chinquapin maintained levels between 20 PSU and 35 PSU before dropping to 4 PSU due to events not captured in our data. This further suggests response to different inflow sources.

The ADCPs provide stream flow volume and direction (Figure 8b). When coupled with water elevation data from the accompanying CTD (Figure 8a), we obtained a more complete understanding of flows at the UB and LB stations. The volume of flow between UB and LB can differ drastically. At the peak of Hurricane Hanna (July 25, 2020), almost 65,000 m^3/hour was flowing at LB. In contrast, the peak upstream flow at UB was only 19,000 m^3/hour. The flow volumes also vary drastically during regular tidal periods, with a difference of almost 5,000 m^3/hour between the incoming and outgoing tides and at LB, and a difference of only 200 m^3/hour at UB. As shown in Figure 8b, the downstream flows at LB are not in balance with upstream flows. This further supports the notion that there are alternate outlets for LB flow exiting into the GIWW (other than out Big Boggy Creek).

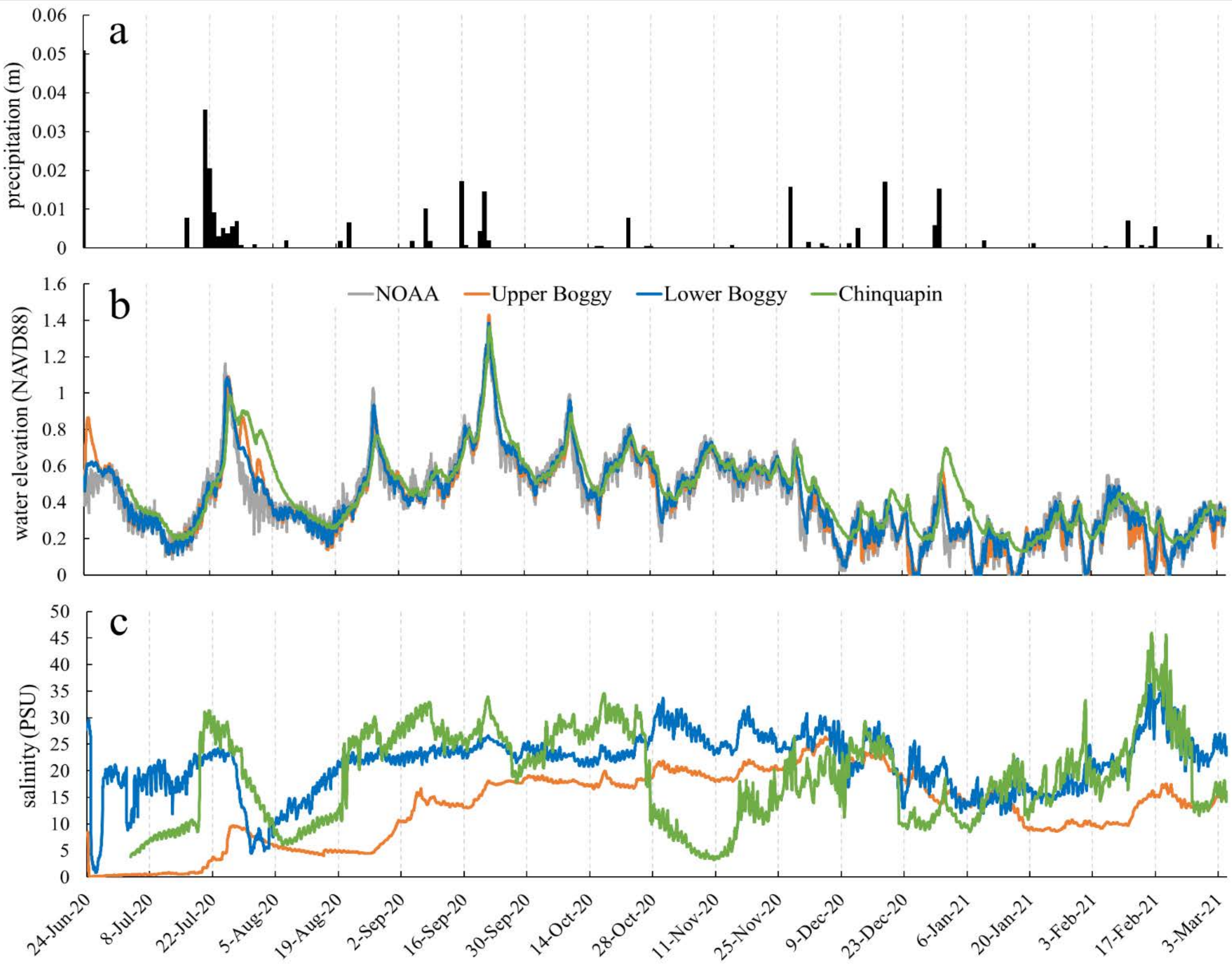

Figure 7. Precipitation (a), water elevation (b), and salinity (c) as obtained from the LCRA rain gauge (a) and the deployed CTDs (b, c). Water elevation is in NAVD88 meters. Salinity is in Practical Salinity Units (PSU), which is similar to a parts per thousand (ppt) measurement.

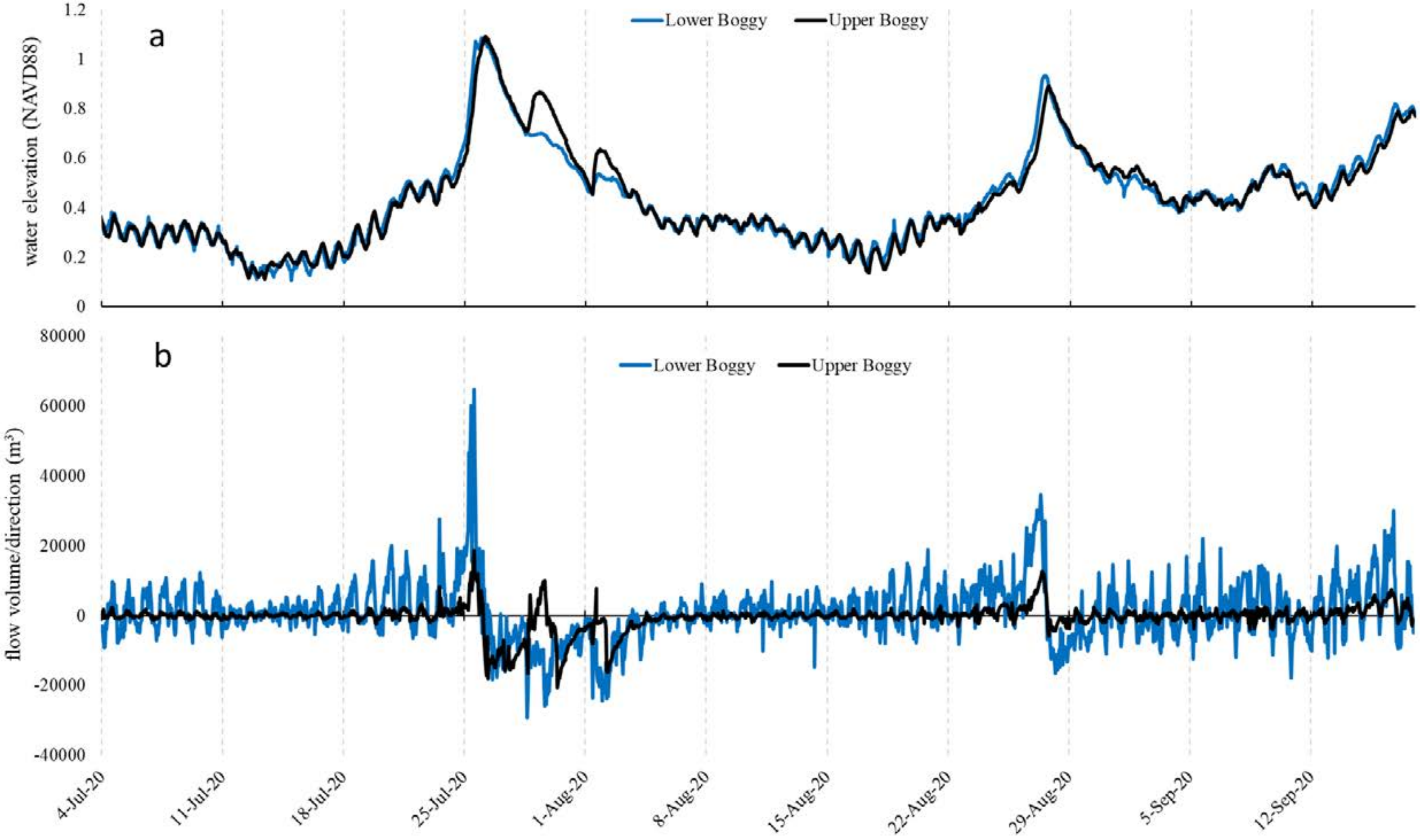

Figure 8. Water elevation (a) and flow volume/direction (b) for ADCP sites at Upper and Lower Boggy. Positive values indicate upstream flows, negative values indicate downstream flows.

3.2.1. *Hydrological Budget*

At the Upper Boggy (UB) station, the total upstream flow during the budgeted period of 7/4/2020 to 9/19/2020 was 1,127 ac-ft (Figure 9) consisting of incoming tides. Total downstream flow measured 1,719 ac-ft, consisting of outgoing tides and freshwater flows. The imbalance between upstream and downstream flows was 592 ac-ft and represented the freshwater inflow quantity. It thus represented the difference between the total precipitation and evaporation in the watershed further upstream, excepting any unbudgeted losses or gains (see Methods).

At the same time, we found that the total watershed area upstream of the UB station was 7,927 hectares (Figure 9). The quantity of precipitation multiplied by this area resulted in a far higher value than the 592 ac-ft observed inflow volume. Thus, the effective watershed area was calculated as 225 hectares, which is only 2.84 percent of the total potential area. This 2.84 percent for the effective watershed area matches what one could expect given direct capture of precipitation minus evaporation in the system only, meaning our sensor station may only be observing water delivered directly into open water bodies, low marsh, and high marsh areas, while overland flows may not play as large a role as previously assumed. There is not a simple explanation regarding the small effective watershed area. One possible explanation is due to the low relief that is present at upland areas. These flat upland areas may not readily flow into the stream and instead might be subject to high rates of evaporation without ever making it to Big Boggy Creek.

At the LB station, the total upstream flow during the study period was 5,393 ac-ft, consisting of incoming tides and storm surges. Total downstream flow measured 3,422 ac-ft, consisting of outgoing tides and freshwater flows. The difference between upstream and downstream flows was 5,985 ac-ft. Precipitation was estimated as 4,022 ac-ft.

It is important to note that there was a large imbalance in the water budget at LB. There was approximately 5,985 ac-ft unaccounted for, and when taking into consideration the downstream flows from UB into LB as well (1,719 ac-ft), there was a total of 7,704 ac-ft. This large surplus of water suggests that there were losses to other outlets in the marsh complex (Figure 10). These outlets likely only connect and move water into the GIWW when water levels exceed 0.45 m (NAVD88). The only alternate outlet that may not be water-level dependent is the culvert beneath Chinquapin Road.

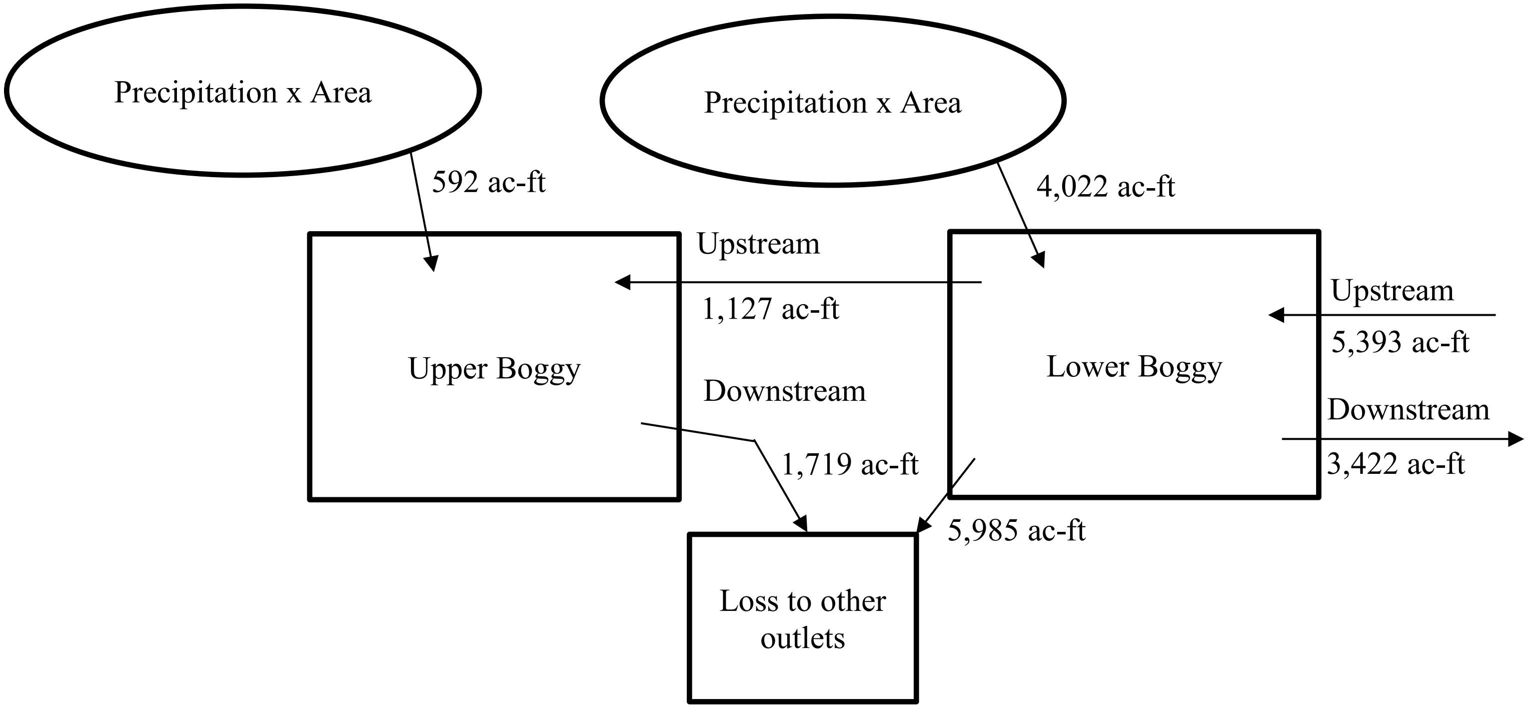

***Figure 9.* A visualization of the water budget for Big Boggy from July 2020 to September 2020.**

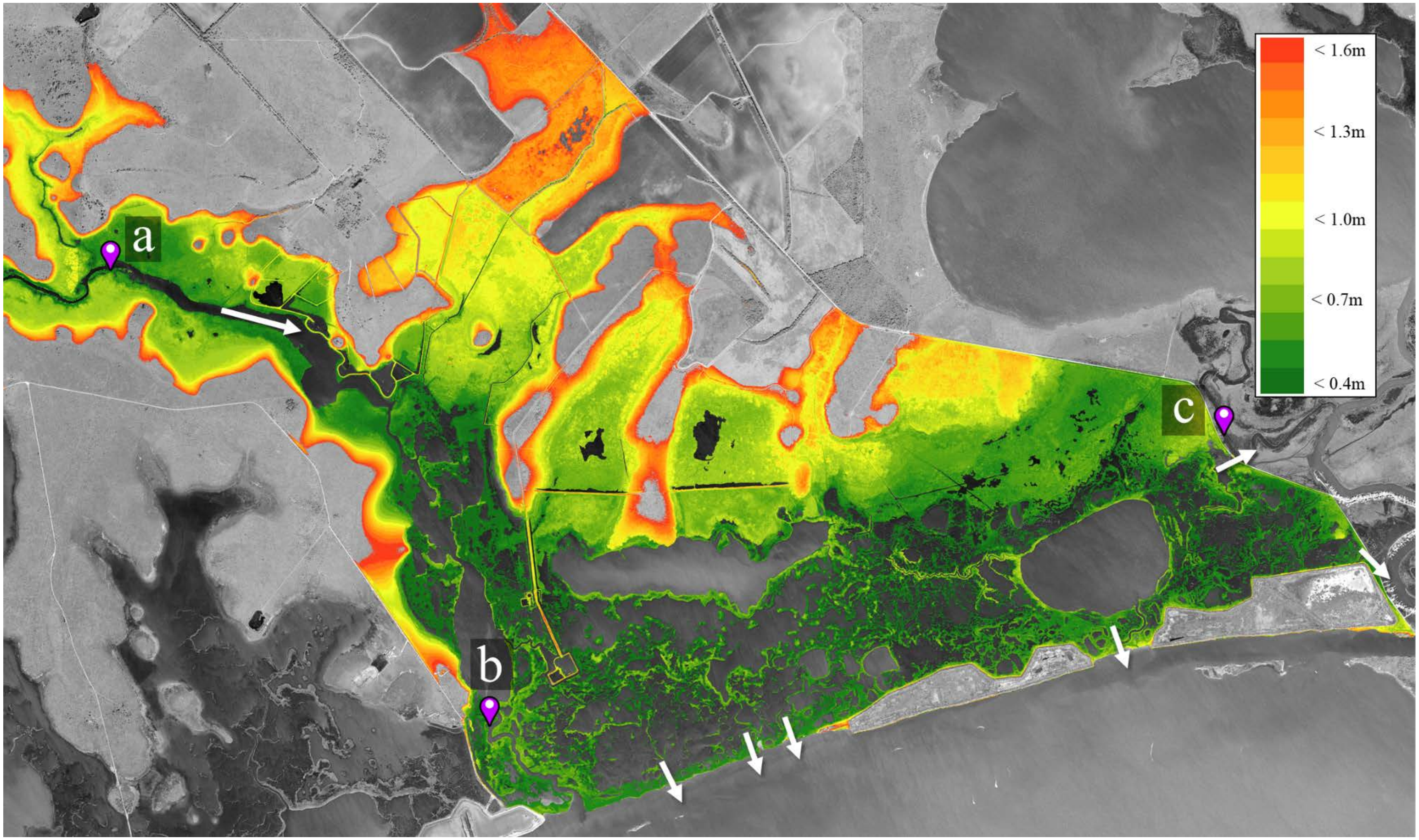

Figure 10. Alternate outlets for flowing water (white arrows) and water elevations needed to flood portions of the watershed (NAVD88 meters). Upper Boggy (a), Lower Boggy (b), and Chinquapin (c) sites are also depicted.

We found that the total watershed area upstream of the LB station (minus that upstream of UB) was 2,780 hectares (Figure 11). The effective watershed area was calculated as 1,532, which is 55% percent of the total potential area. This percent was much higher as compared with UB, because much of the LB watershed is effectively directly capturing the precipitation in open water, low marsh, or high marsh areas.

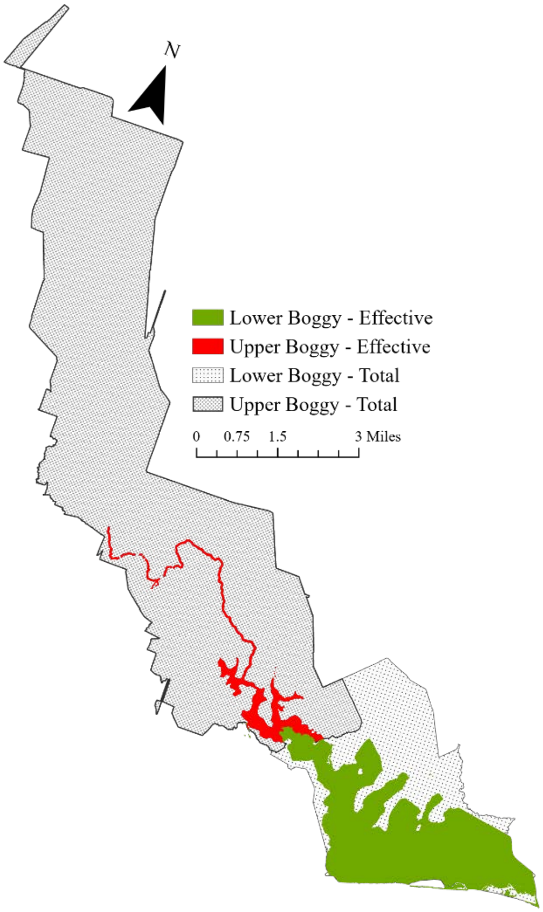

***Figure 11.* The Big Boggy watershed as derived from a 1-meter DEM and processed using ArcGIS Watershed tools.**

3.2.2. *Hindcasted and forecasted inflow volumes*

The hindcasted inflows at Upper and Lower Boggy had a positive mean trend over time, increasing from 1954 to 2019 over the budgeted time period (Figure 12). Due to the sheer size difference in area between the Upper and Lower Boggy effective watersheds, Lower Boggy (LB) experiences much greater volume of inflows accompanied by greater variation between wet and dry years. For example, in the summer months of 2007, the inflows at LB were 9,493 acre-feet per month, or 4,434 acre-feet per month (87%) greater than the expected mean trend (Note: we present this and the following examples and related figures in acre-feet, instead of m^3, as these units are more commonly used by water managers). During this same period, inflows at Upper Boggy (UB) were 1,394 acre-feet per month, or 696 acre-feet per month (100%) greater than the mean trend.

The average inflows at Upper and Lower Boggy were 207 acre-feet per month and 1,414 acre-feet per month, respectively (Figures 13a and 14a). Note that for each year only three months are used to match the study period (July, August, and September).

The forecasted mean inflow scenarios at UB and LB do not strongly deviate from one another through the year 2100, as compared to the annual variability that is possible (Figures 13b-14b). The historical trend will result in inflows that slowly increase at 39% for UB and LB, and this is the best-case scenario. However, this scenario does not account for the complexities and nuance in predictions for a changing climate. The second-best scenario is the B1 scenario. Under this climate scenario, a 4% increase in inflow is predicted at UB and LB. The third scenario, A1B, estimates a 3% increase in inflow at UB and LB. Finally, A2 yields the worst-case prediction, where inflow at UB and LB are predicted to decrease by 4%. It is crucial to note that these are just predicted changes in the mean trend of inflow. Years with inflows higher or lower than the mean and outside of the RMSE bounds will likely occur, and these are more likely to alter ecosystem functioning. In summary, inflow quantities will be less sensitive to mean changes in the climate and more sensitive to its variability over time.

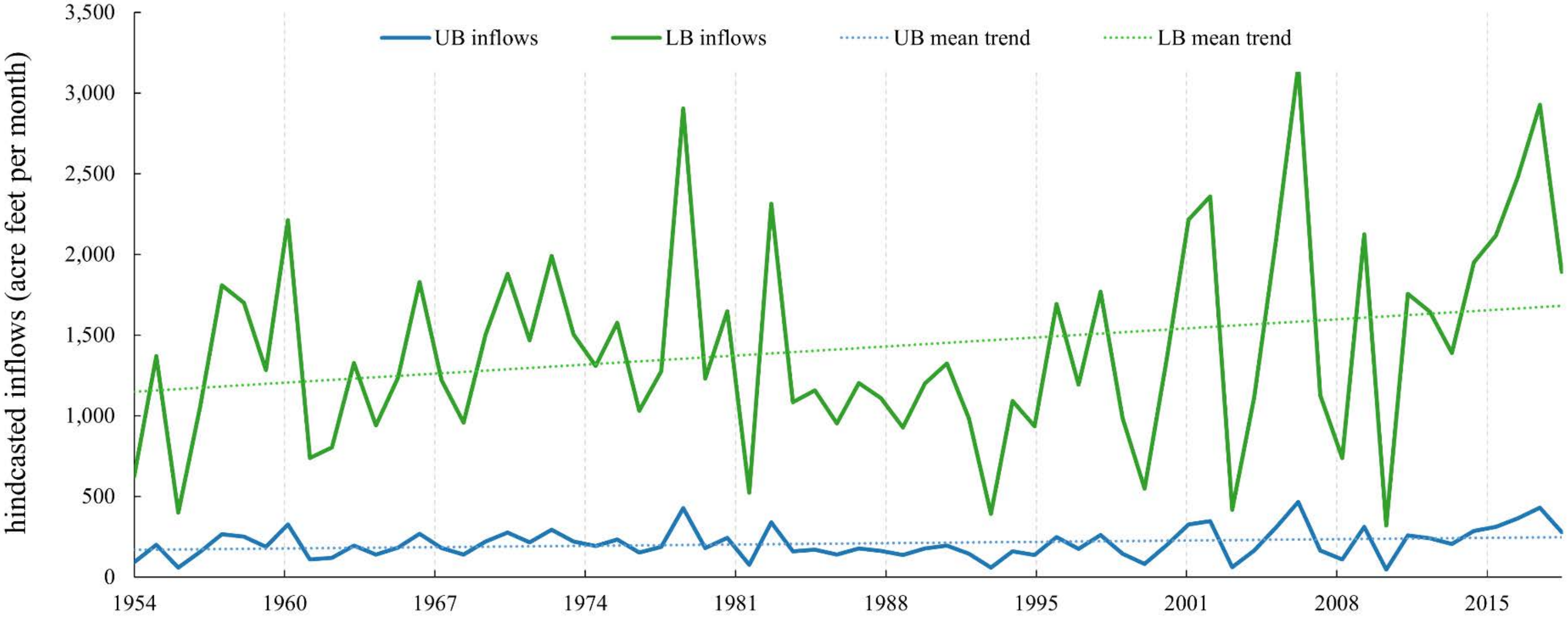

Figure 12. Hindcasted inflow from 1954 to 2019. These values were derived from the hydrologic budget, using precipitation from TWDB as input. The values on the y-axis depict the average inflow for three months of each calendar year (July, August, and September).

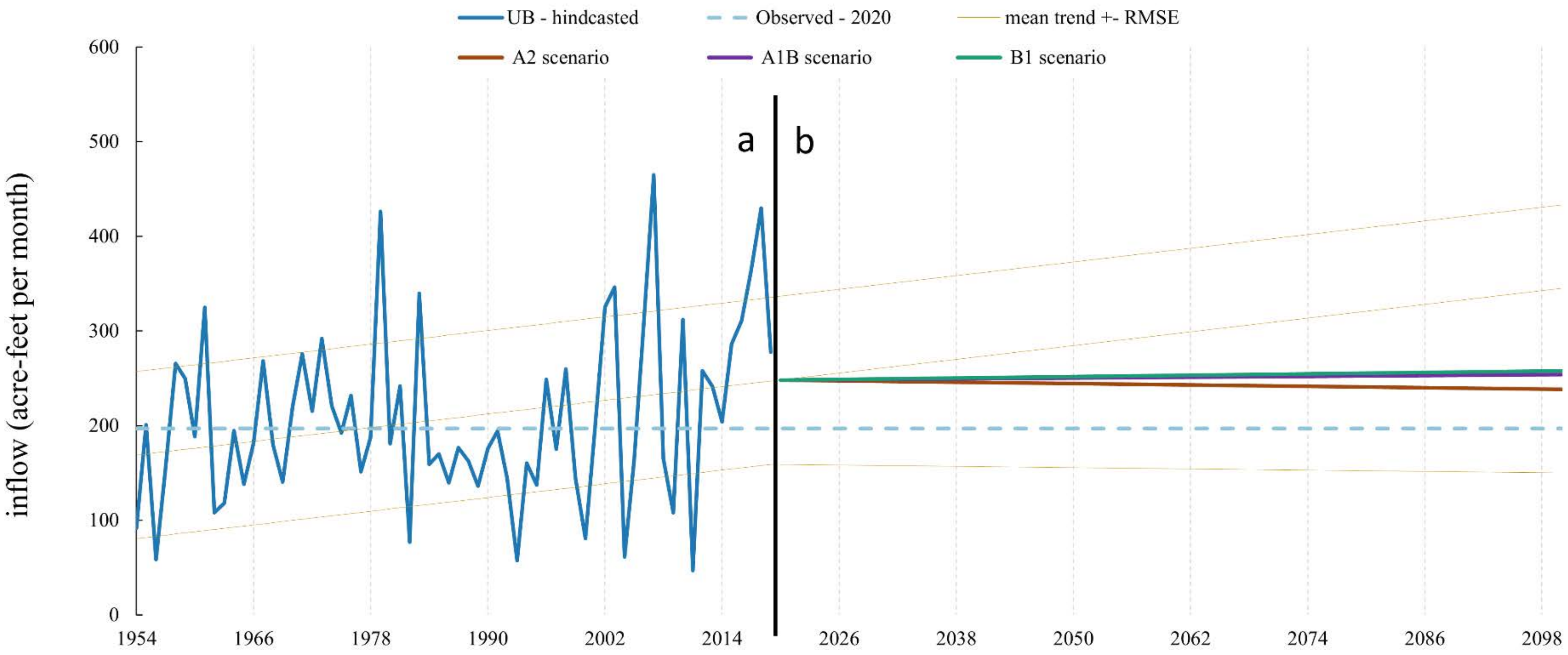

Figure 13. Hindcasted (a; 1954 - 2019) and forecasted (b; 2021 - 2100) inflows per month at Upper Boggy. The per-month rate is the average inflow from the aggregate of three months per calendar year (July, August, and September). The inflow rates observed in the field in 2020 are depicted for comparison.

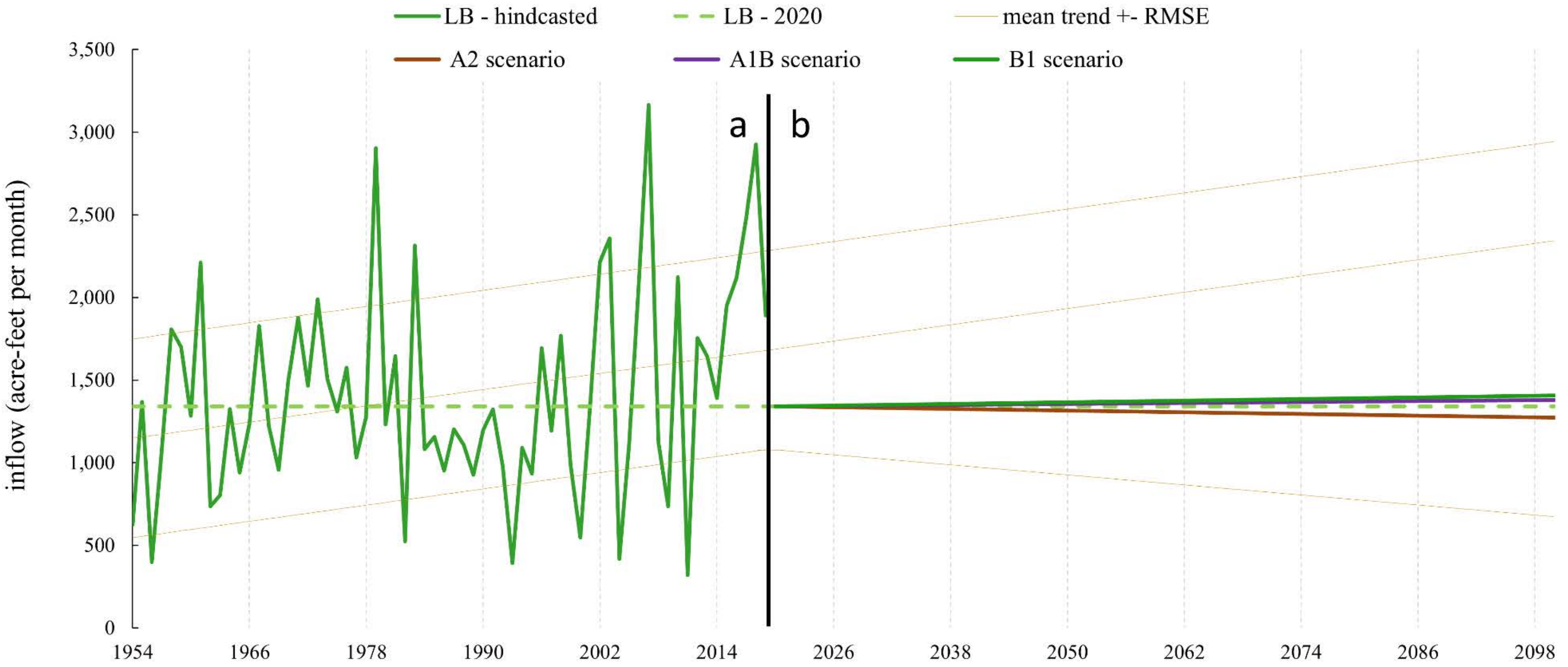

Figure 14. **Hindcasted (*a;* 1954 - 2019) and forecasted (*b;* 2021 - 2100) inflows per month at Lower Boggy. The-per month rate is the average inflow from the aggregate of three months for each calendar year (July, August, and September). The inflow rates that I had observed in the field in 2020 are depicted for comparison.**

4. Discussion

The Big Boggy watershed has lost more than one-third of its low marsh area since 1953. However, during this same period, the freshwater inflow has been increasing on average during the summer months when droughts are most damaging. The combination of these findings suggests that there is likely an alternative cause for the loss, beyond changes in the mean inflow rate during these months. Further, the low marsh in Big Boggy NWR does not show signs of hydrologic restriction and hypersalinity, as posed previously. There appear to be three interconnected causes: relative sea level rise (RSLR), sediment starvation, and inflow variability.

First, RSLR often results in a similar patterning of marsh loss as that seen in the Lower Boggy (LB) marsh areas, wherein the interior of individual marsh islands is lost while the edges remain. In these cases, the vertical accretion of the marsh interior cannot match RSLR (Morris et al. 2002), while the marsh edges receive sufficient sediment inputs and are able to vertically accrete to keep up with RSLR (Duran Vinent et al., 2021). These conditions result in the fragmentation pattern present. The quantity of precipitation and freshwater inflow is known to be a critical feature that can help counteract low marsh loss by promoting vertical marsh accretion (Craft, 2007) through organic growth and deposition (Więski, 2014).

Second, sediment starvation has been shown to be a common factor of marsh loss in other regions (Peteet et al., 2018; Mariotti and Fagherazzi, 2013). The loss of sediment-rich flows from the Colorado River means that marshes in Big Boggy—and the surrounding watersheds—rely on organic sediment accretion to match RSLR. While organic mineral accretion alone can perhaps keep pace with RSLR, it may not be sustainable. Before the Colorado River was diverted, tidal waters from a more sediment-rich Matagorda Bay would have inundated marsh platforms and deposited the necessary inorganic sediments that allowed the marsh to thrive. In the absence of this sediment-rich tidal flow, marsh platforms have been maintaining elevation through organic accretion. However, as is evident in the loss of marsh shown in Figure 4, organic accretion alone is not capable of keeping pace with RSLR at contemporary rates.

Inflow variability, as opposed to a change in the mean trend, also likely plays a large role. Annual or seasonal inflows that fall well above and below the mean trend can impose a greater influence on marsh productivity, than small deviations over time in the trend itself. While increased inflows are generally desired, inundation of the marsh platform over a given threshold of time can lead to marsh drowning (Voss, 2013). Decreased inflows resulting from drought can lead to large-scale marsh die-off, especially when coupled with grazing pressure from marsh periwinkle (*Littoraria irrorata*; Silliman et al., 2005). The latter of the two extremes, drought, can be addressed through input of supplemental water into the system.

The spatial variation in land cover changes throughout the study area does not warrant a blanket statement that relative sea level rise is driving all cover changes. While this may hold true for low marsh in the southern reaches of the Big Boggy watershed, the pattern of low marsh transitioning to high marsh in more northern reaches may be contributed to a combination of factors. The conversion of low marsh in 1982 to high marsh in 2020 may be caused by a decrease in the inundation frequency through deepening of the stream channel. Channelization of Big Boggy Creek, starting at the Upper Boggy station and continuing upstream, may be caused by the regular mowing of stream banks conducted by the Matagorda County Drainage District. Evidence has suggested that channelization of a stream can alter the vegetative community in a riparian area through the rapid stream incision resulting from higher velocity flows (Shankman, 1996). Through these potential morphological changes, inundation rates near the Upper Boggy station may be too infrequent to facilitate *S. alterniflora* growth, yet frequent enough to facilitate *S. spartinae* to dominate the elevations between the low marsh and the pure upland.

The natural coastal processes in the Big Boggy watershed have been interrupted and degraded by the loss of direct flows from the Colorado River into East Matagorda Bay (EMB). There is little that water managers and coastal managers can likely do to return to the pre-Colorado River diversion conditions that existed prior to 1934. Instead, efforts should focus on addressing what can be done to modify the existing landscape and infrastructure to increase freshwater inflows and improve marsh resilience at-large.

4.1. Developing flow rate standards

To determine the supplemental flow quantities that managers could provide to offset a drought or drought-like conditions, we developed a MS Excel-based inflow decision tool for the Big Boggy Creek watershed (Figure 15). Itl can be downloaded from the Coastal Ecology and Management Laboratory data page (cml.tamu.edu). This tool uses inputs of precipitation to calculate the amount of inflow, and then determines the supplemental flow needed to fall within the range "normal", defined here as a value falling between the mean trend and the lower RMSE bound. Monthly inputs of precipitation from either the TWDB's Water Data for Texas website, or the LCRA Matagorda 1 S precipitation gauge can be used to estimate the inflows to the watershed. Additionally, total freshwater contribution to East Matagorda Bay can be estimated using precipitation at any temporal scale (daily, monthly, annually, etc.). This tool will help resource managers and policymakers prepare for years in which precipitation alone may not adequately sustain the health of wetlands in Big Boggy.

Because Upper Boggy (UB) is the most sensitive to rainfall, we use it to show the value of the tool. Using 2011 as an example of a severe drought year, we can estimate the precipitation needed to bring inflows up to the lower RMSE bound of what we consider acceptable (see Figure 13a). Approximately 4.7 inches of additional rainfall would have raised the net inflows to the lower RMSE bound, and 11.8 inches to reach the mean trend (during July to September of that year). The supplemental inflow volumes that one would have needed to acquire between July and September 2011 were 218 ac-ft per month and 547 ac-ft per month, respectively.

An alternative perspective is to think about how much land is needed to capture precipitation and convert it into supplemental inflow - in other words, to increase the effective watershed area and rely on precipitation rather than purchasing supplemental flows. Resource managers can use our tool to estimate the additional effective watershed area needed to offset the decline in inflows.

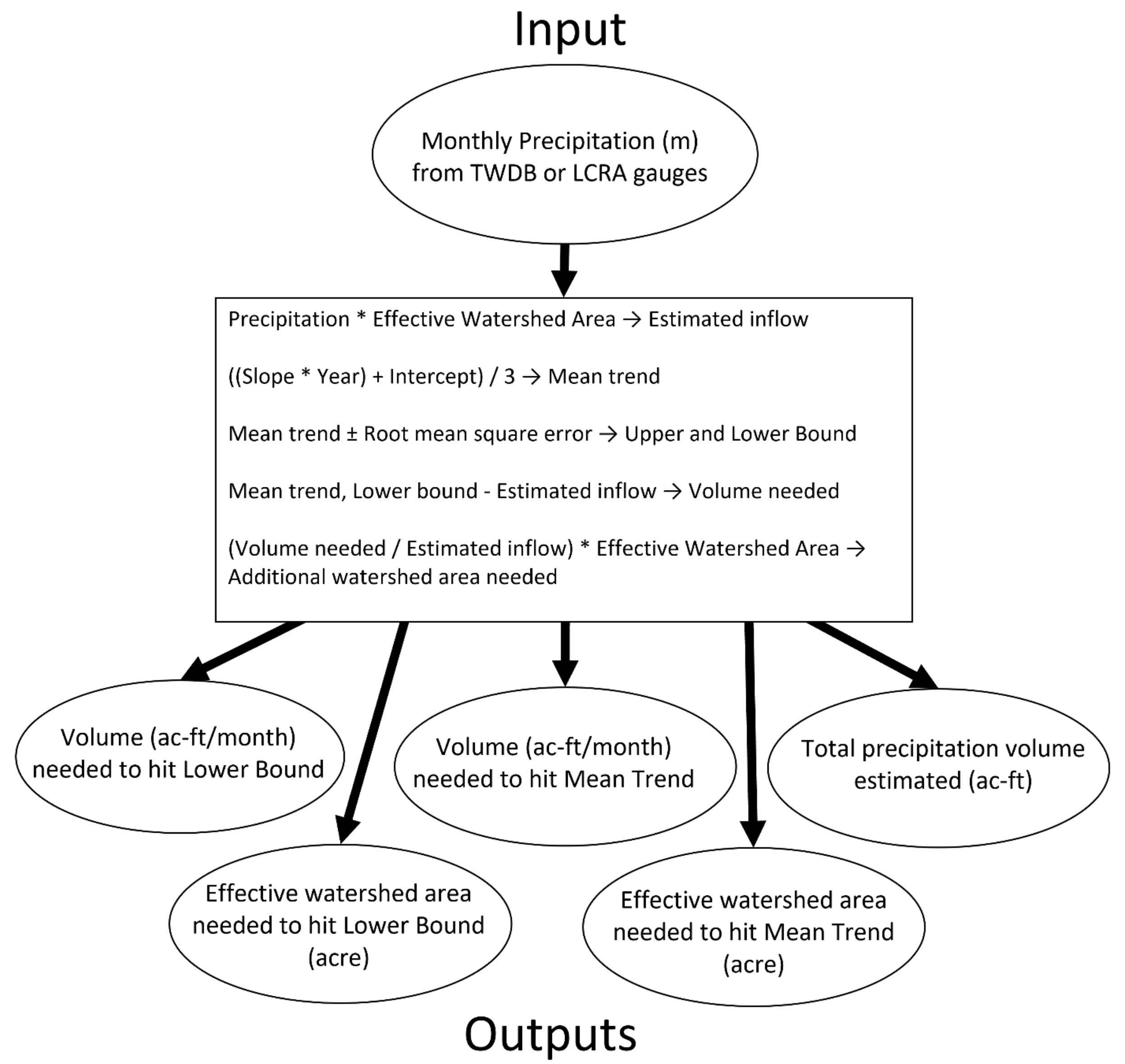

Figure 15. Flowchart of the Big Boggy Inflow Decision Tool displaying the input, equations, and outputs.

Using the 2011 drought example, an additional 362 hectares would be needed to meet the lower bound, and 885 hectares would be needed to reach the mean trend. This would more than double the effective watershed at a minimum. Fortunately, not every drought will be as severe as 2011. Using the data from a less-severe drought in 2009, we estimate that an additional 72 hectares would bring the net inflows to the lower bound, and 299 hectares would bring the net inflow equal to the mean. These are still large areas of land.

For a 2011-magnitude drought in the year 2100 under the worst-case scenario considered, A2, 514 hectares and 1,065 hectares would be needed to reach the lower bound and mean, respectively. To offset the decline in mean net inflows for the A2 scenario in the year 2100, an additional 65 hectares would be needed (above and beyond that already needed in 2011). These forecasts are best used to estimate the change in mean net inflows through 2100. Unfortunately, we cannot capture the future year-to-year variability in this model.

While there is utility in predicting the mean trends for inflows into the future, it is important to recognize that annual totals alone do not tell the whole story. Freshwater inputs are crucial during the summer months when heat and evaporation are greatest. An overall surplus in inflows over a given year does not ensure a healthy wetland if none of the precipitation is captured during the summer. The key feature is whether the wetlands and bay receive the inflowing water during the time periods that they require it for specific ecological processes. Based on data captured by NOAA from 1991-2020 (NOAA, 2006), precipitation in the Big Boggy watershed increases with rising temperatures in the spring and summer. Much of the precipitation is captured during hurricane season, in the latter portions of summer. In times of normal precipitation, the growing season experiences adequate amounts of rainfall. Identifying when drought-like conditions are occurring is important for resource managers seeking to supplement the watersheds of East Matagorda Bay with supplemental freshwater.

4.2. Potential restoration actions for wetlands in the Big Boggy watershed

Because resource managers cannot alter precipitation patterns, they can instead focus on increasing the effective watershed area or purchasing water from the LCRA. Potential candidate lands and restoration actions can be evaluated in support of meeting these needs.

We have identified several potential restoration actions that could be implemented to increase the effective watershed of the area and improve the resilience of the marsh complex. Possible targets for restoration included culverts, weirs, levees, and old irrigation canals. Through field investigations and with aerial imagery, we measured the upstream and downstream extents of relevant man-made structures or hydrologic barriers and estimate their lowest elevations to determine the water levels needed to provide connectivity across the barrier.

Seven low water crossings are present on the main stem of Big Boggy Creek (Figure 16; Table 2). These seven crossings are cement structures with at least one culvert and a pathway large enough for a vehicle to cross (Figure 17). In some cases, the culverts are clogged with sediment or debris and impound stream water, limiting the freshwater inflows to the lower watershed. Additionally, clogged culverts may allow for flowing waters to erode the edges of the structure, degrading the integrity of the crossing (Figure 18).

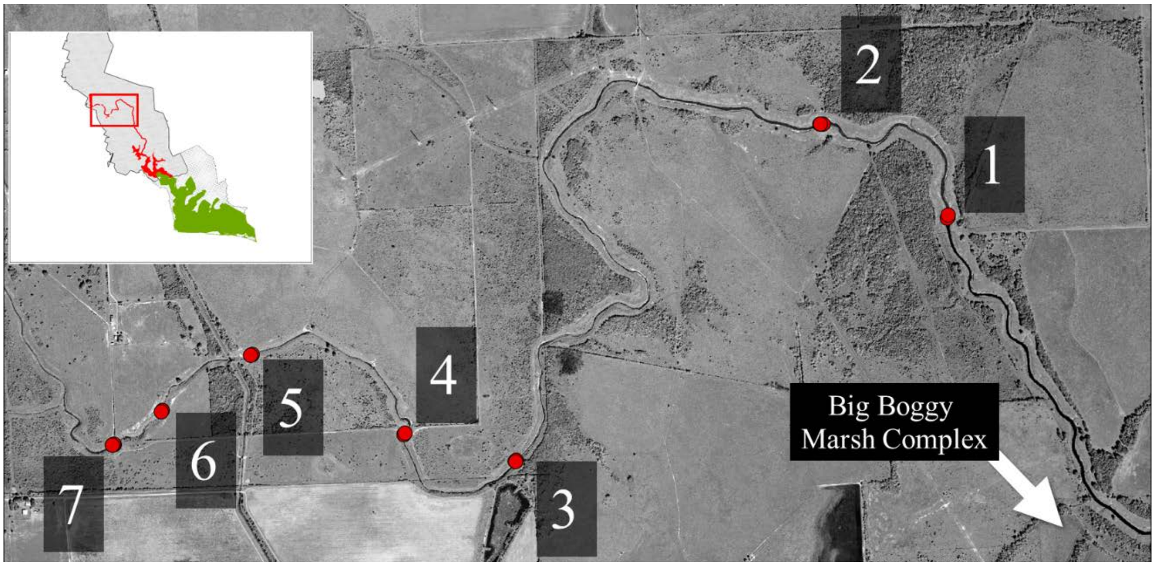

Figure 16. Barriers to flow in the further upstream reaches of the study area.

Table 2. Barriers to flow on Big Boggy Creek and the corresponding water elevation needed to surpass it. Location of these barriers is seen in Figure 15.

Barrier	Elevation
1	0.957
2	1.448
3	2.141
4	2.274
5	2.748
6	3.375
7	3.432

Figure 17. Barrier to flow on Big Boggy Creek. This structure (barrier 1 in Table 2 & Figure 16) does not appear to have culverts and instead allows the water to flow over the top.

Figure 18. Example of a hydrological barrier in the study area, depicted with water flowing around the structure.

The primary benefit to removing these low water crossings would be to allow estuarine fish and nekton access to further upstream areas and enhance aquatic habitat connectivity. These actions would allow salt marsh to migrate upstream in a more natural manner as well, and avoid the problems described in our next example below (the ponds, see below). The removal of these low water crossings would also more quickly move freshwater from the Upper Boggy watershed into the Lower Boggy marsh complex during precipitation events, which could be seen as negative or positive, depending on location. Further surveying and monitoring should be done to determine how much inflow is impounded behind the structures. However, the removal of these barriers alone will likely not provide enough additional inflow to address supplemental needs.

A series of ponds located near Big Boggy NWR also present themselves as potential restoration targets (Figure 19). The ponds in question do not appear to bear adequate freshwater wetland vegetation to be beneficial to waterfowl. As can be seen in Figure 19, the pond levees are only elevated to approximately 1m. This height is not large enough to prevent very high or spring tides from depositing salt water inside them. This has led to hypersaline conditions in the ponds as saltwater overtops the levees and evaporates, leaving behind its salt. This hypersaline water is not suitable for use as a duck pond nor as a water source for cattle. Based on our water elevation measurements, the duck pond levees were overtopped on four separate occasions during our study period: July 26, August 27, September 22, and October 10. Further monitoring of salinity in the duck ponds would be valuable, although we know enough today to recommend their removal. The establishment of *S. alterniflora* would be a likely result, creating more fishery habitat. Given the benefits that we outline above, the effective watershed would increase by approximately 17 hectares.

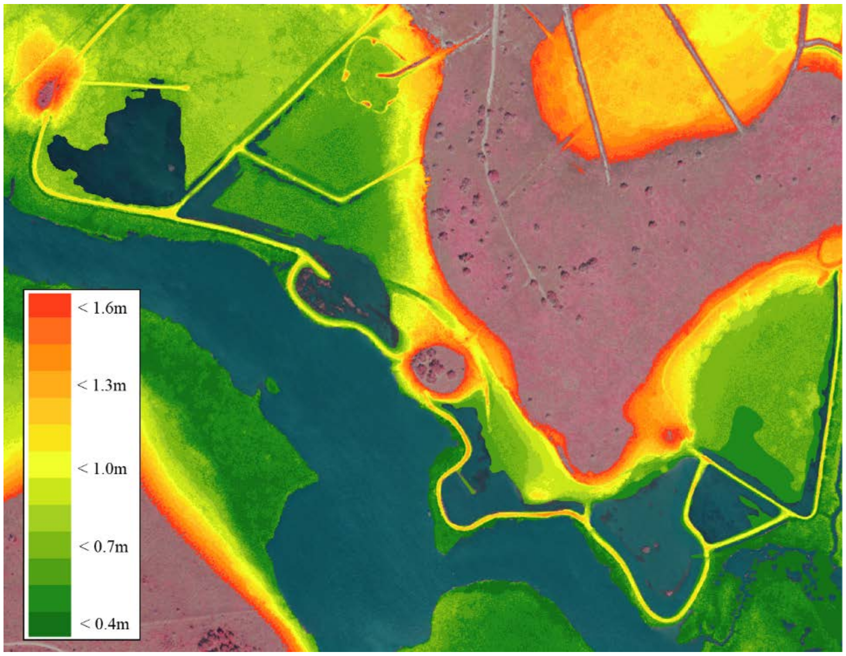

Figure 19. Duck ponds pictured, with land elevation shown.

The FWS manages a handful of moist soil units (MSUs) for the benefit of waterfowl. Each of these MSUs is impounded by a levee road on its southern boundary (Figure 20). The minimum elevation needed to breach the West MSU is 1.19 meters. Based on the water elevations measured at UB during our study period, the West MSU levee was breached once on September 22, 2020. The East MSU has a slightly lower minimum elevation at 1.08 m. During our study period, the East MSU was breached twice: on July 26, and September 22.

Additionally, these moist soil units contain perched gates designed to allow downstream freshwater flows but prevent saltwater intrusion. In practice, the East and West MSU gates are situated at a lower elevation (0.35 m and 0.29 m, respectively) than the surrounding high marsh surface (average of 0.67 m). The East and West gates were exceeded by salt water a total of 11 and 14 times during our study period, as measured using the gauge at UB. The duration of these events varied from a brief 12 hours of inundation on August 1, 2020 to 12 straight days of inundation from September 16 to September 28, 2020. These flooding events suggest that the MSUs are no longer optimized as freshwater habitat for waterfowl (FWS, 2013). Restoration recommendations for the MSUs are 1) to remove the levee road and facilitate transgression of low marsh; or 2) increase the height of the levee road and flow gates to prevent saltwater intrusion and maintain a freshwater habitat.

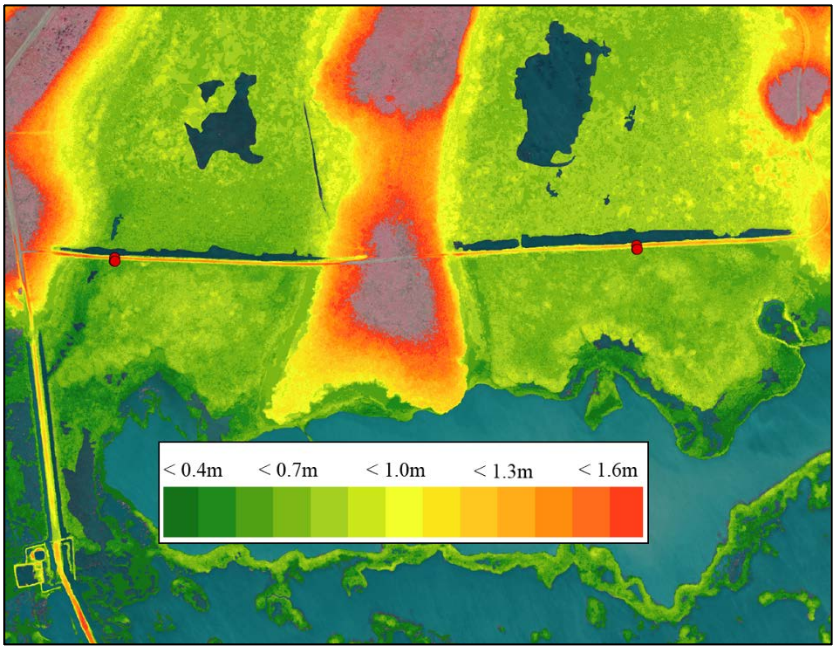

Figure 20. Moist soil units shown with the location of the gates marked with a red circle. Note the more defined channel on the left unit.

Agriculture in the area utilizes irrigation canals to transport water. These canals could be used to provide supplemental freshwater flows at a reasonable cost. Water purchases from the LCRA were made by the Big Boggy NWR in 2008 and 2009 for $5,000 (FWS, 2013). The existing water delivery canals could bring water into the MSUs, and then out the flow gates into the surrounding low marsh. However, due to micro-topography surrounding the gate outflows, some relatively minor elevation modifications would be required. Restoration recommendations for water delivery are 1) to resume freshwater purchase from the LCRA; and 2) excavate subtle channels in the high marsh surrounding the gate outflows to allow for freshwater to readily flow into the marsh complex. In 2021, water purchases from LCRA are available at a rate of $66.14 per acre-foot delivered (E. Ray, personal communication, October 26, 2021). This is the most straightforward option for providing supplemental flows into the Big Boggy watershed and EMB, however, water purchase may not be available in times of drought when ecosystems need it most.

Marsh drowning is a serious concern in the Big Boggy watershed. As suggested by the large imbalance of flows at Lower Boggy (Figure 9), the periods of high-water levels (Figure 7), and marsh elevation (Figure 10), it is possible that low marsh in Big Boggy NWR is subject to inundation periods above the threshold at which marsh drowning can occur. A study by Smith and Lee (2015) provided evidence that constant inundation of a *S. alterniflora* marsh during a single growing season can cause a major decline in plant density which can lead to a loss of vegetative cover. Other studies infer that there is a critical threshold of inundation depth above which marsh platforms convert to ponds or tidal flats (Duran Vinent et al., 2021). One possible action to address the excess water inundating the Big Boggy marsh system is to excavate channels clogged with sediment and that no longer drain into the GIWW (Figure 10, white arrows along the southern edge of the study area). This action would also open up a channel to Pelton Lake from the South, allowing for more exchange between Pelton Lake and EMB, preventing Pelton Lake from becoming isolated and hypersaline.

Increased wave energy resulting from the loss of the GIWW dredge spoil islands may have negative effects on salt marsh in Big Boggy NWR. As demonstrated by Feagin et al. (2009), marsh vegetation does not significantly mitigate lateral erosion occurring at a marsh edge. Currently, there is a longer fetch length (almost four miles) which results in waves with greater energy that can cause further erosion to the remaining unconsolidated shoreline and the existing marsh platforms. A restoration action would be to replace the dredge spoil island material when dredging of the GIWW occurs. This will allow for the potential restoration of unconsolidated shorelines that shield the marsh edge from wave energy.

Finally, upland areas could be modified to increase the effective watershed. These areas could be graded to drain into an existing channel more readily or into an artificial channel. Their slopes could be graded to facilitate upslope marsh migration in response to sea level rise. Proximity to existing wetlands or stream channels would be preferred (Figure 21). The total potential gain in effective watershed resulting from these areas is 386 hectares.

The stretch of upland just west of Big Boggy Creek bordering Baer Ranch Road is an ideal location for this type of restoration and would increase the effective watershed by 142 hectares. However, this would require purchasing the properties from the private landowner. A 65-hectare area is within a conservation easement, and another 59-hectare section is private. The rest falls within the Big Boggy NWR.

In their current state, the lands further upstream along the banks of Big Boggy Creek are too steep to allow for effective low marsh migration (not pictured). If these areas were graded to 50 meters from current water, the effective watershed would increase by 107 hectares. At 100 meters, the increase would be 214 hectares. This restoration action would also decrease erosion by stabilizing the stream banks. Many of these lands, however, are privately owned. Incentives such as fee simple land acquisition or cost-sharing would likely be necessary for landowner cooperation. If all these suggested upland areas were converted, including the ones depicted in Figure 21, then approximately 600 hectares would be added to the effective watershed.

Increasing the effective watershed area should, in theory, increase the freshwater delivery to the Big Boggy wetlands and thus to East Matagorda Bay. Inversely, decreasing the effective watershed area should lead to a decrease in freshwater delivery. Similarly, an observed decrease in freshwater delivery may be attributed to a modification in the watershed that decreases the effective watershed area, such as a constructed road crossing impounding water that is then lost to evaporation. This suggests that the existing structures impeding flow (culverts, weirs, etc.) likely decreased the effective watershed area.

In summary, the most realistic and immediately impactful restoration actions likely will not significantly alter freshwater inflow. These include altering impounding structures in the duck ponds and MSUs, both of which could significantly improve avian and fishery habitat. Increasing the effective watershed area (and therefore freshwater delivery) would require more significant investment in removing barriers or converting upland areas.

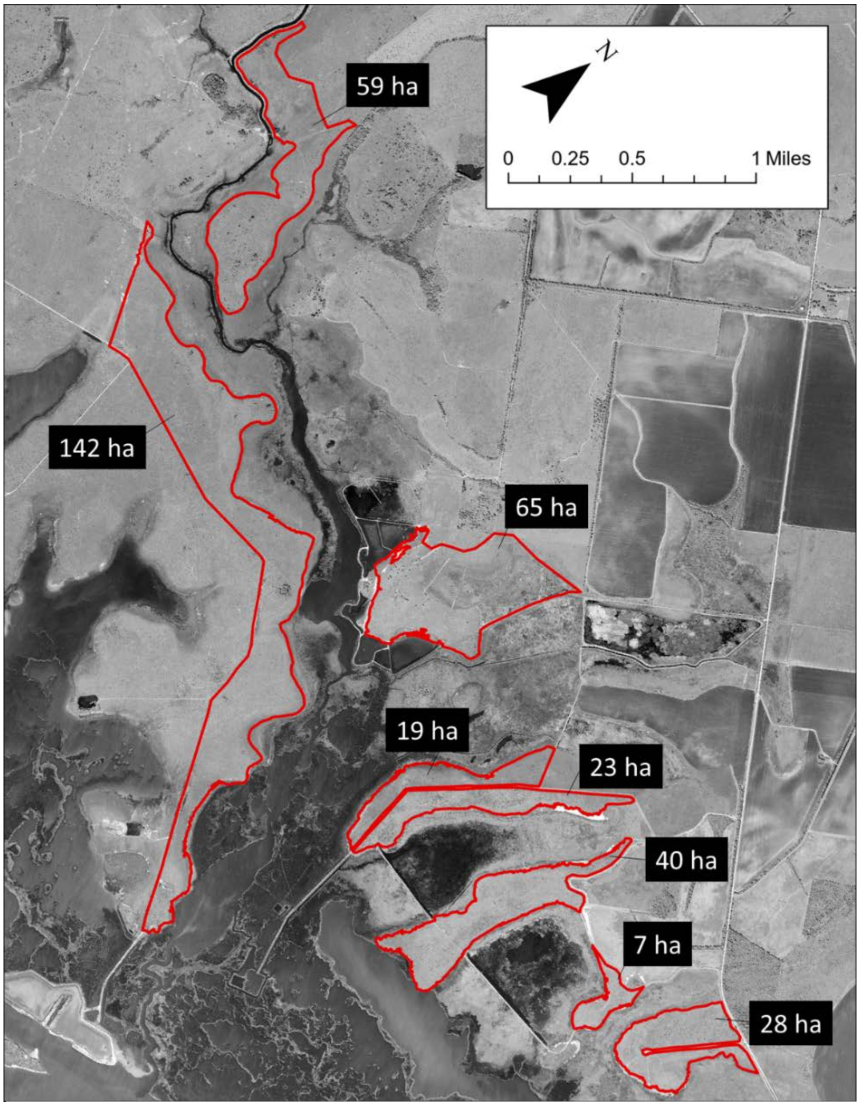

Figure 21. Potential upland areas for conversion to low marsh-accessible drainage areas.

5. Conclusion

Environmental flows are critical to the long-term resilience of wetlands in the Big Boggy Creek watershed and to the estuarine waters of East Matagorda Bay. Both relative sea level rise and seasonal droughts are likely responsible for the loss of wetlands in this watershed. Our flow decision tool for the Big Boggy Creek watershed is a key output that can be used to identify the quantity of supplemental water that would be needed to avoid the damaging effects of drought on these resources. In addition, we have identified several potential restoration options within the Big Boggy NWR and adjacent lands that would immediately improve habitat.

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7. Appendix A - Deliverables

7.1. Summary of existing literature related to freshwater inflow to East Matagorda Bay and methodologies to determine relationships between freshwater inflow and sustainability of wetland plants.

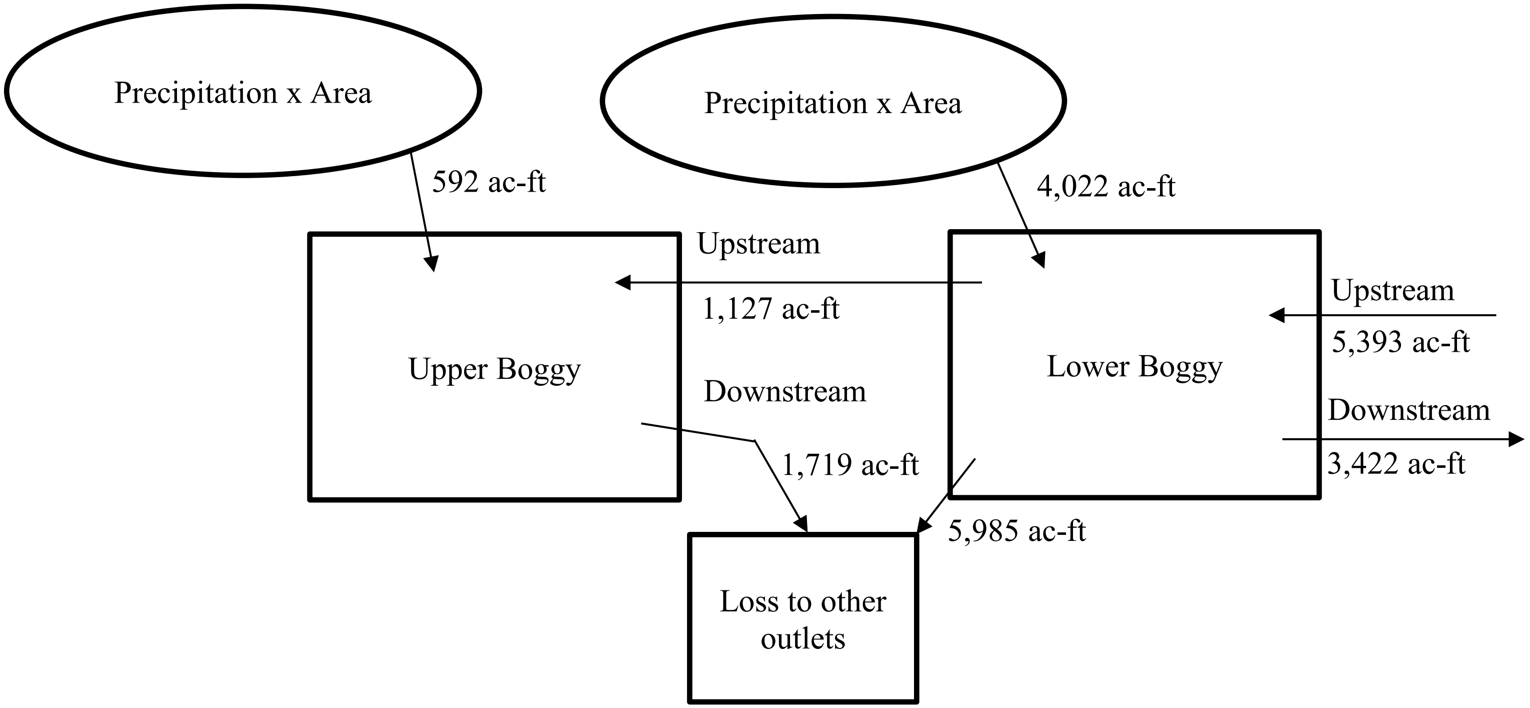
The Colorado River of Texas no longer provides direct freshwater flows to the wetlands of East Matagorda Bay (EMB), due to the creation of the Colorado River Delta and subsequent construction of the Colorado River Navigation Channel (CRNC). First described by Alonso de Leon in 1690, a series of log jams (also referred to as "log rafts") impounded sediment and river flows on the Colorado until the summer of 1929 when bank excavation efforts, coupled with a large flood event, swept the collection of drift into Matagorda Bay (Clay, 1949). Sediment filled a portion of the bay basin and connected the former barrier island complex to the mainland, forming the Matagorda Peninsula. The flow of the Colorado River was limited at its mouth until 1934 when the Matagorda County reclamation district cut a channel from the mouth to the Gulf of Mexico, breaching the Matagorda Peninsula. In present day, the Colorado River flows are split between a flood discharge channel and the CRNC to the Gulf of Mexico. Because of these hydrologic modifications, the only significant freshwater inputs to EMB are attributed to a few small basins, such as that of Big Boggy Creek. Long term resilience of the oyster reefs and recreational fisheries in EMB has been an ongoing concern due to hypersalinity resulting from the hydrologic isolation. 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; Morton, 1979). The loss of sediment in the tidal water column since 1934 may be negatively impacting salt marshes in the surrounding watersheds by limiting the inorganic vertical accretion (Peteet et al., 2018; Bricker-Urso et al., 1989).

The Lower Colorado River Authority (LCRA) has managed the lower 600 miles of the Colorado River as a nonprofit public utility since 1934. As part of its duties, LCRA sells water to users in the Colorado River basin for municipal, agricultural, and wildlife management uses. In 2009, LCRA sold water in the Gulf Coast division for wildlife management use at a base charge of $10.41 per acre, plus $13.73 per acre-foot of water delivered (E. Ray, personal communication, October 13, 2021). In 2021, LCRA sells water for wildlife management at the interruptible agricultural rate of $66.14 per acre-foot delivered. In 2008 and 2009, the US Fish and Wildlife Service (FWS) purchased water from LCRA for wildlife management purposes at $5,000 in total. In a report to the Texas Water Development Board (TWDB), AquaStrategies identified a handful of water delivery options to supplement EMB with freshwater from the Colorado River (Austin et al., 2015). One such option is to purchase and deliver water through the Big Boggy/Lake Austin Marsh complex.

There are currently no Texas Commission on Environmental Quality (TCEQ) rule-based environmental flow standards for East Matagorda Bay, nor the Big Boggy watershed. The Colorado and Lavaca Basin and Bay Area Stakeholder Committee (BBASC) has identified this as a gap in their ability to sustain the health of this estuary and its dependent resources. As stated in TCEQ rules Chapter 298 – Environmental Flow Standards for Surface Water Subchapter D: Colorado and Lavaca Rivers, and Matagorda and Lavaca Bays §298.310(d), "For East Matagorda Bay, the commission does not adopt environmental flow standards but finds that the sound ecological environment of East Matagorda Bay can be maintained by avoiding further reduction of freshwater inflows, to the extent those reductions can be avoided, and that strategies to provide additional freshwater inflows to East Matagorda Bay should be pursued."

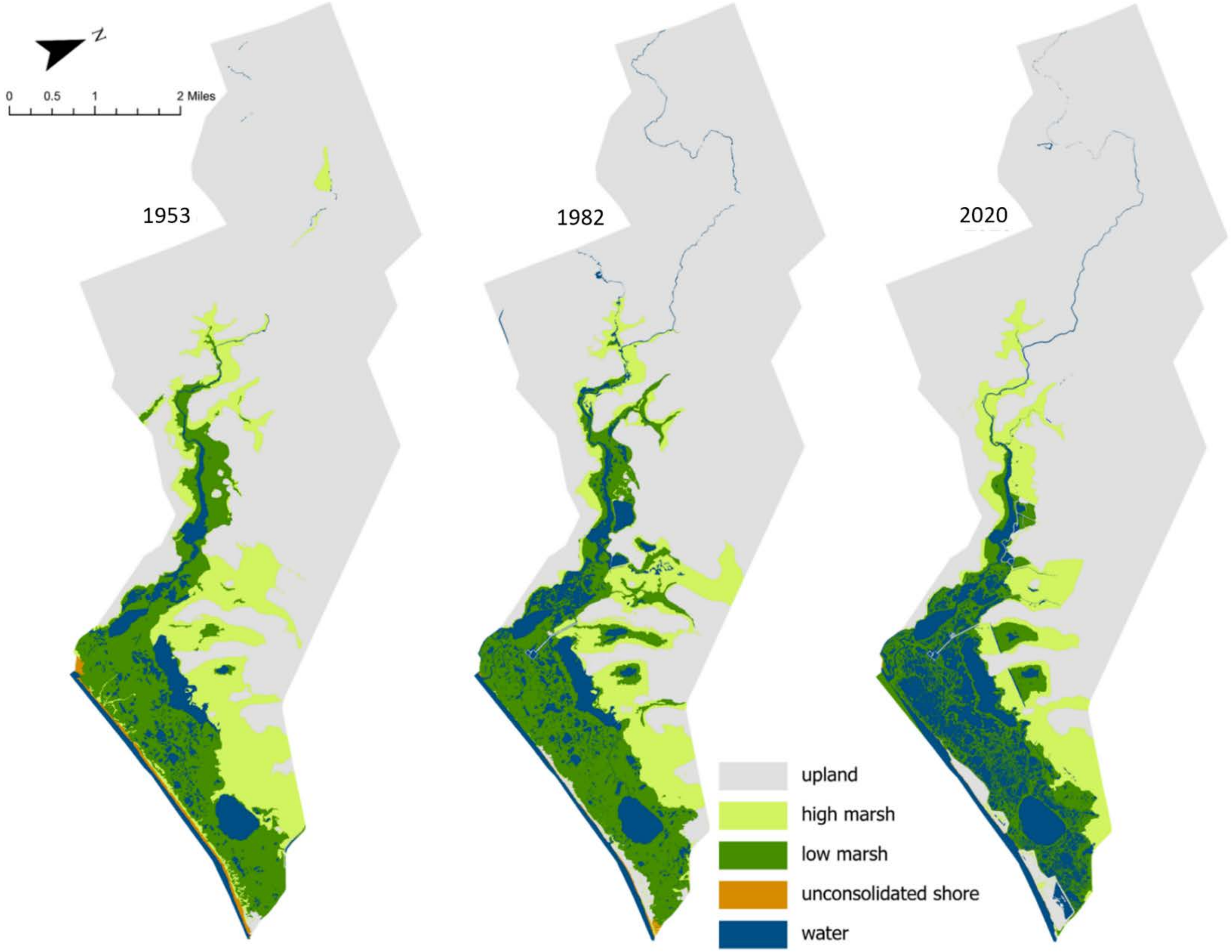
There are no current adopted or specific quantitative standards because of the current disconnection of the Colorado River, and the difficulty of acquiring data for the smaller inflow sources like Big Boggy Creek. Some early work was conducted by Schoenbaechler, Guthrie, and Lu (2011) to predict ungauged flow using a model. Additional work was outlined by Buzan et al. (2011) through the BBEST that discusses the broader relations of these flows with some ecological needs. More generally, the flow dynamics and salinity regimes for the Middle Texas Coast are not well-known, as most previous work has been conducted for the Upper Texas Coast (wet) or Lower Texas Coast (dry) regimes.

7.2. Water budget diagram by source (volumetric exchanges across time, specific to sources of saltwater tides, freshwater inflow, and rainfall) (Task 1)

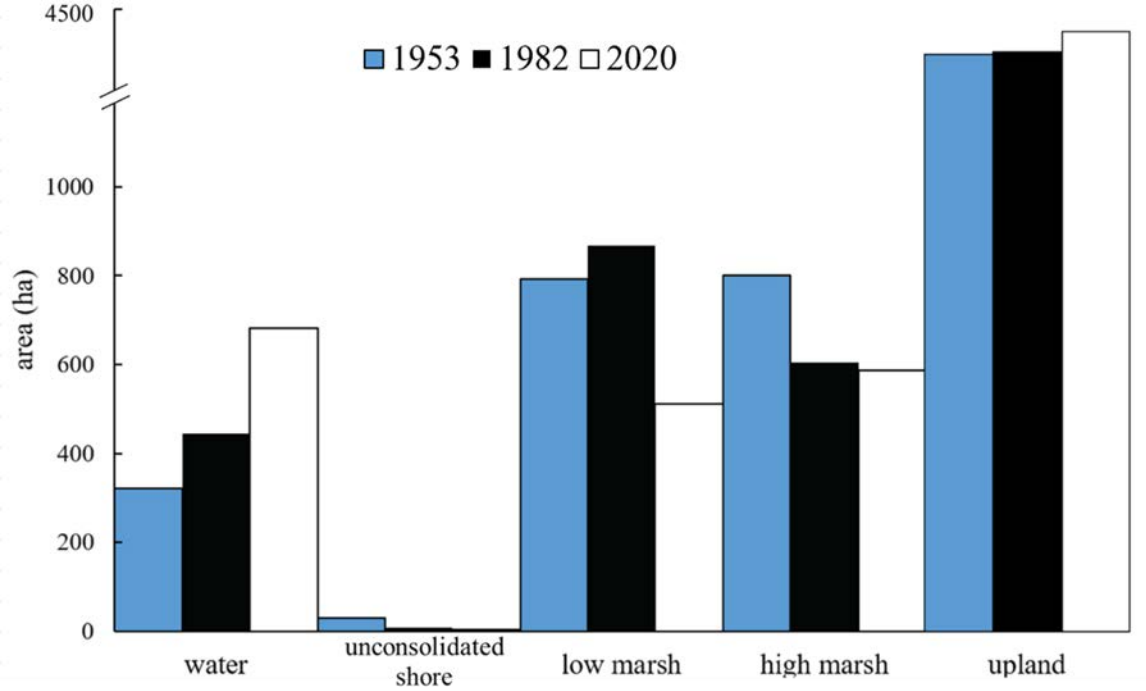


A visualization of the water budget for Big Boggy from July 2020 to September 2020.

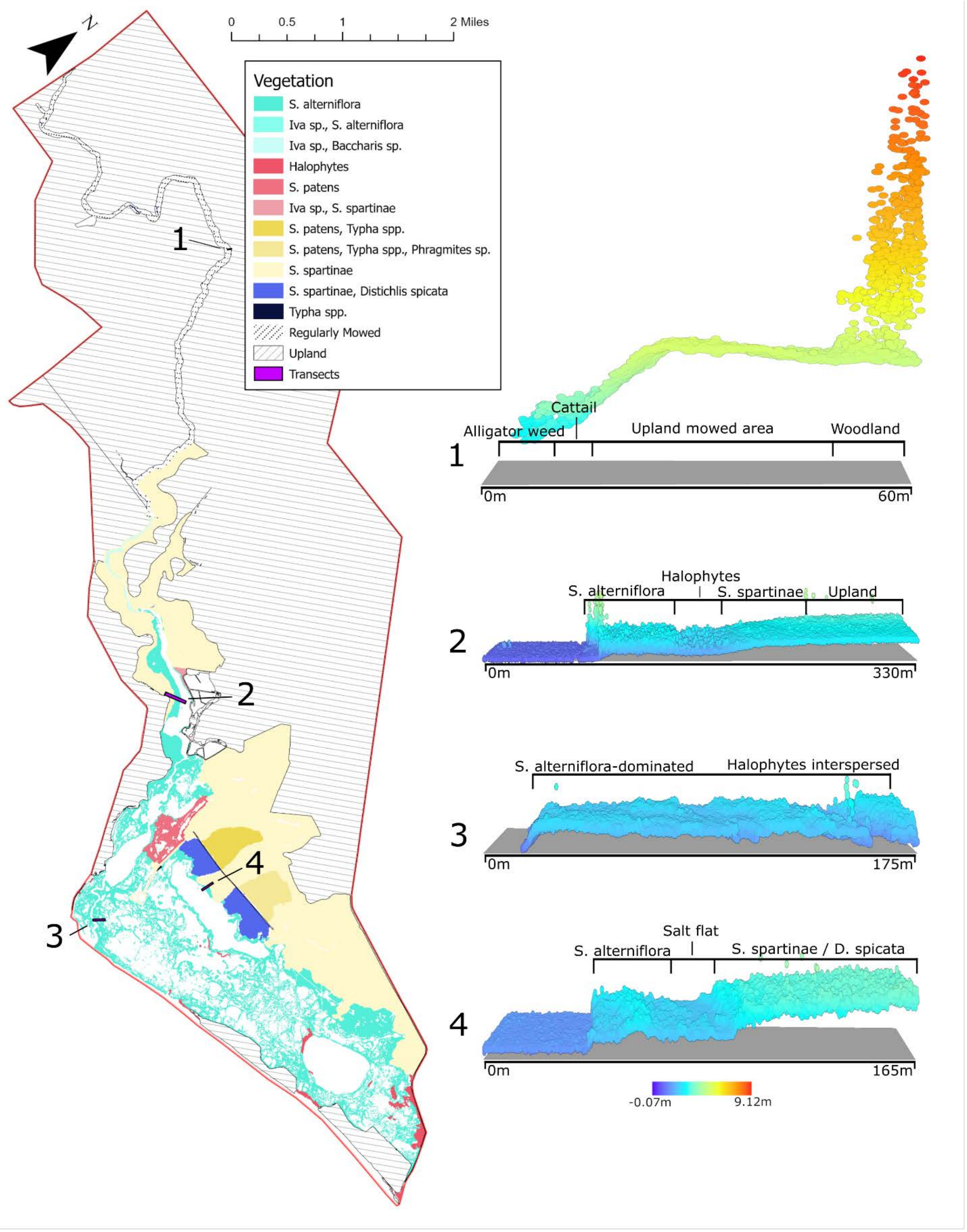
7.3. Map identifying hydrologic network changes over the historical period from 1941 to present (Task 2)



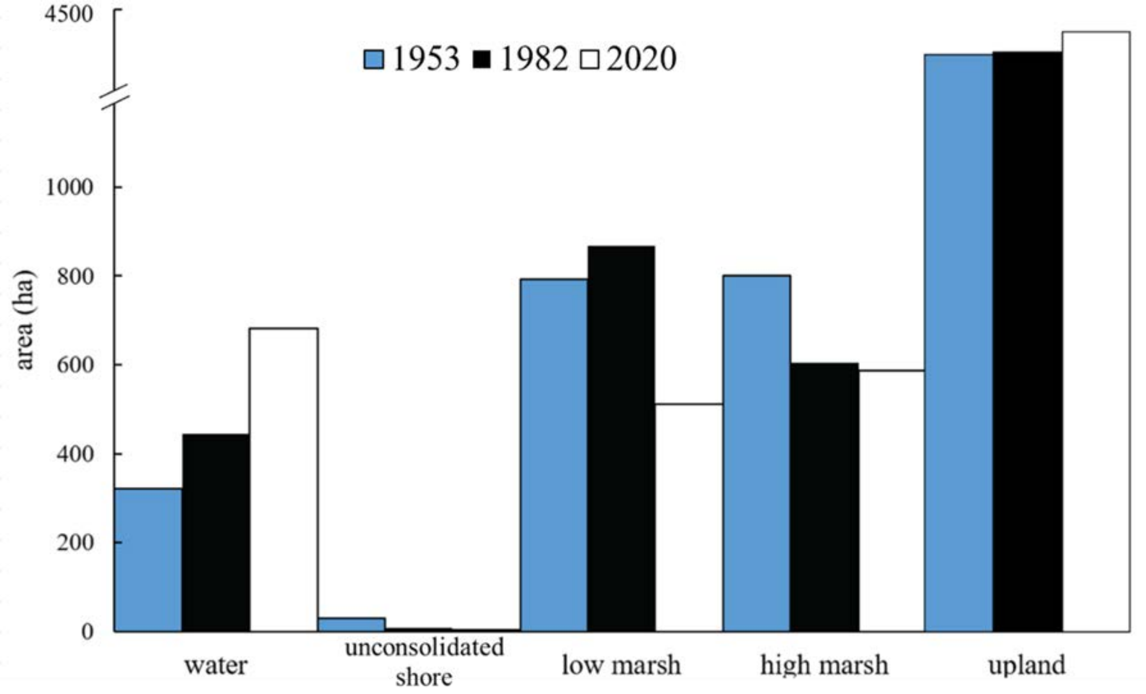
7.4. Graph detailing areal change (hectares) of water surface and canal network coverage on landscape from 1941 to present (Task 2)



7.5. Map of modern-day wetland cover (Task 3)



7.6. Graph detailing areal coverage (hectares) by land cover (Task 3)

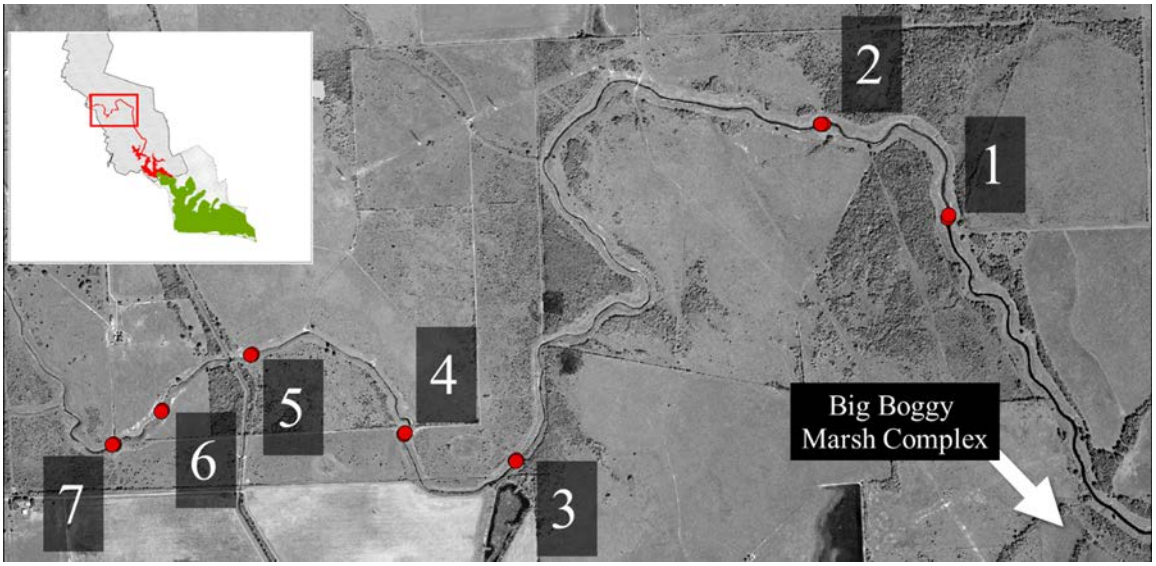


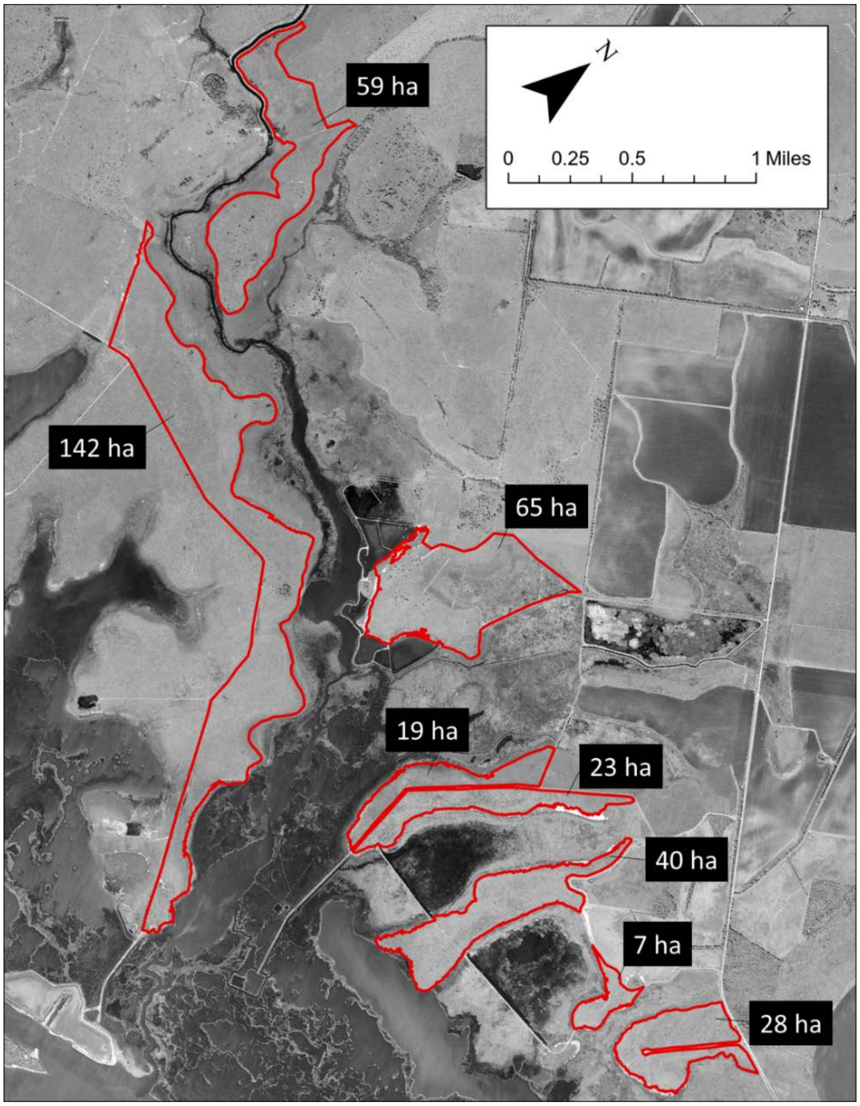
7.7. Basin-specific environmental flow recommendation (Task 4)

To determine the supplemental flow quantities that managers could provide to offset a drought or drought-like conditions, we developed a MS Excel-based inflow decision tool for the Big Boggy Creek watershed. This tool uses inputs of precipitation to calculate the amount of inflow, and then determines the supplemental flow needed to fall within the range “normal”, defined here as a value falling between the mean trend and the lower RMSE bound. Monthly inputs of precipitation from either the TWDB’s Water Data for Texas website, or the LCRA Matagorda 1 S precipitation gauge can be used to estimate the inflows to the watershed. Additionally, total freshwater contribution to East Matagorda Bay can be estimated using precipitation at any temporal scale (daily, monthly, annually, etc.). This tool will help resource managers and policymakers prepare for years in which precipitation alone may not adequately sustain the health of wetlands in Big Boggy.

Because Upper Boggy (UB) is the most sensitive to rainfall, we use it to show the value of the tool. Using 2011 as an example of a severe drought year, we can estimate the precipitation needed to bring inflows up to the lower RMSE bound of what we consider acceptable (see Figure 13a). Approximately 4.7 inches of additional rainfall would have raised the net inflows to the lower RMSE bound, and 11.8 inches to reach the mean trend (during July to September of that year). The supplemental inflow volumes that one would have needed to acquire between July and September 2011 were 218 ac-ft per month and 547 ac-ft per month, respectively.

7.8. Map of potential restoration locations, with possible volumetric changes denoted for each action (Task 4)

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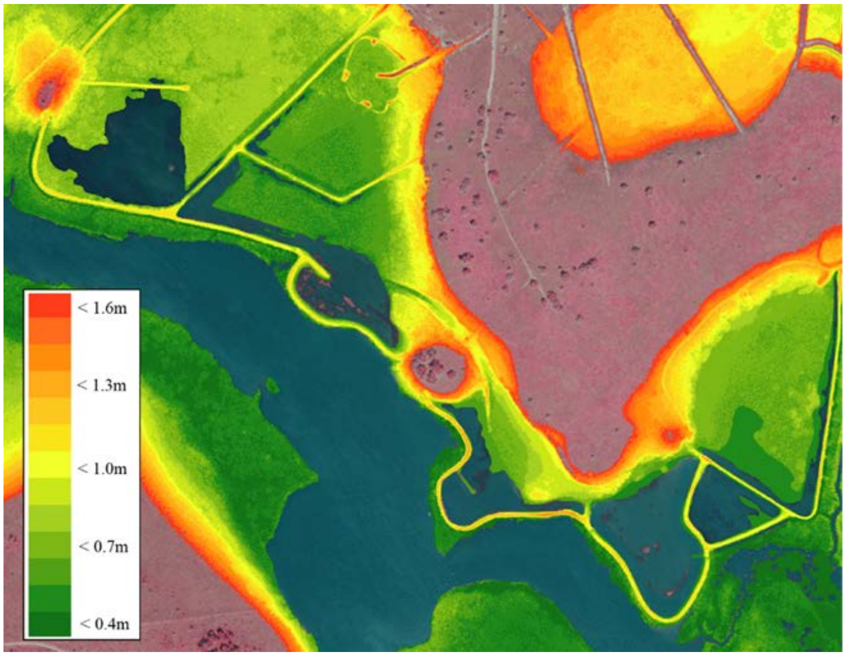
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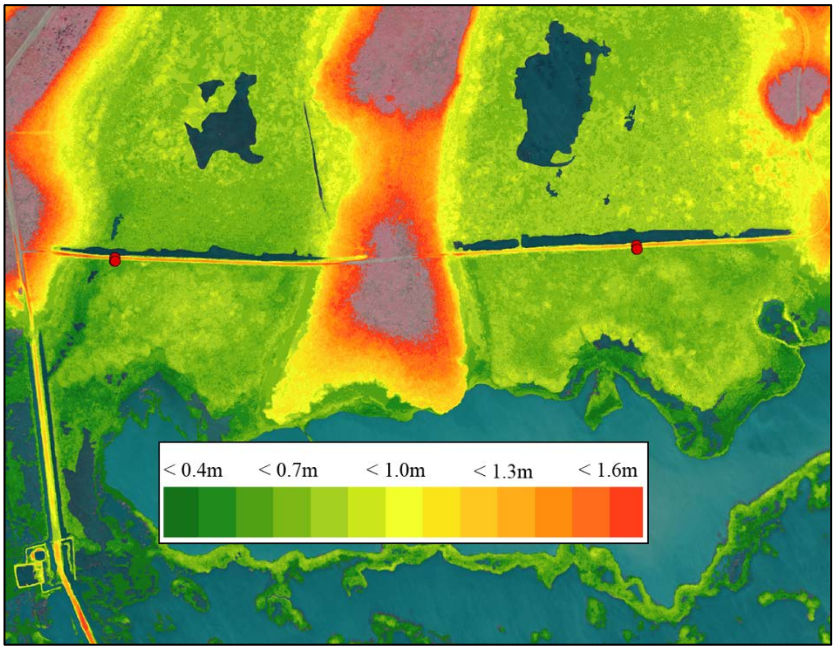
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7.9. A discussion linking the results and summary of findings to previous work by the BBEST and published literature (Task 5)

The Big Boggy watershed has lost more than one-third of its low marsh area since 1953. However, during this same period, the freshwater inflow has been increasing on average during the summer months when droughts are most damaging. The combination of these findings suggests that there is likely an alternative cause for the loss, beyond changes in the mean inflow rate during these months. There appear to be three interconnected causes: relative sea level rise (RSLR), sediment starvation, and inflow variability.

First, RSLR often results in a similar patterning of marsh loss as that seen in the Lower Boggy (LB) marsh areas, wherein the interior of individual marsh islands is lost while the edges remain. In these cases, the vertical accretion of the marsh interior cannot match RSLR (Morris et al. 2002), while the marsh edges receive sufficient sediment inputs and are able to vertically accrete to keep up with RSLR (Duran Vinent et al., 2021). These conditions result in the fragmentation pattern present. The quantity of precipitation and freshwater inflow is known to be a critical feature that can help counteract low marsh loss by promoting vertical marsh accretion (Craft, 2007) through organic growth and deposition (Więski, 2014).

Second, sediment starvation has been shown to be a common factor of marsh loss in other regions (Peteet et al., 2018; Mariotti and Fagherazzi, 2013). The loss of sediment-rich flows from the Colorado River means that marshes in Big Boggy—and the surrounding watersheds—rely on organic sediment accretion to match RSLR. While organic mineral accretion alone can perhaps keep pace with RSLR, it may not be sustainable. Before the Colorado River was diverted, tidal waters from a more sediment-rich Matagorda Bay would have inundated marsh platforms and deposited the necessary inorganic sediments that allowed the marsh to thrive. In the absence of this sediment-rich tidal flow, marsh platforms have been maintaining elevation through organic accretion. However, as is evident in the loss of marsh shown in Figure 4, organic accretion alone is not capable of keeping pace with RSLR at contemporary rates.

Inflow variability, as opposed to a change in the mean trend, also likely plays a large role. Annual or seasonal inflows that fall well above and below the mean trend can impose a greater influence on marsh productivity, than small deviations over time in the trend itself. While increased inflows are generally desired, inundation of the marsh platform over a given threshold of time can lead to marsh drowning (Voss, 2013). Decreased inflows resulting from drought can lead to large-scale marsh die-off, especially when coupled with grazing pressure from marsh periwinkle (*Littoraria irrorata*; Silliman et al., 2005). The latter of the two extremes, drought, can be addressed through input of supplemental water into the system.

The spatial variation in land cover changes throughout the study area does not warrant a blanket statement that relative sea level rise is driving all cover changes. While this may hold true for low marsh in the southern reaches of the Big Boggy watershed, the pattern of low marsh transitioning to high marsh in more northern reaches may be contributed to a combination of factors. The conversion of low marsh in 1982 to high marsh in 2020 may be caused by a decrease in the inundation frequency through deepening of the stream channel. Channelization of Big Boggy Creek, starting at the Upper Boggy station and continuing upstream, may be caused by the regular mowing of stream banks conducted by the Matagorda County Drainage District. Evidence has suggested that channelization of a stream can alter the vegetative community in a riparian area through the rapid stream incision resulting from higher velocity flows (Shankman, 1996). Through these potential morphological changes, inundation rates near the Upper Boggy station may be too infrequent to facilitate *S. alterniflora* growth, yet frequent enough to facilitate *S. spartinae* to dominate the elevations between the low marsh and the pure upland.

The natural coastal processes in the Big Boggy watershed have been interrupted and degraded by the loss of direct flows from the Colorado River into East Matagorda Bay (EMB). There is little that water managers or coastal managers can likely do to return to the pre-Colorado River diversion conditions that existed prior to 1934. Instead, efforts should focus on addressing what can be done to modify the existing landscape and infrastructure to increase freshwater inflows and improve marsh resilience at-large.

8. Appendix B

TWDB Comments Received on the Draft Report and Responses

REQUIRED CHANGES

General Draft Final Report Comments:

1. Please add the following statement to the front page of the report: *Pursuant to Senate Bill 1 as approved by the 86th Texas Legislature, this study report was funded for the purpose of studying environmental flow needs for Texas rivers and estuaries as part of the adaptive management phase of the Senate Bill 3 process for environmental flows established by the 80th Texas Legislature. The views and conclusions expressed herein are those of the author(s) and do not necessarily reflect the views of the Texas Water Development Board.*

Response: Added as suggested.

2. Throughout the report, please be more specific when referring to the time period or historical period. For example, instead of using the phrase "historical period to today", state "1953 – 2100".

Response: Revised as suggested.

3. Throughout the report, please be consistent in caption placement for the figures. For example, the caption in Figure 7 is at the top but the caption is at the bottom in Figure 8. Revised as suggested.

Response: Revised as suggested.

4. Throughout the report, please fix the spacing within the paragraphs.

Response: Revised as suggested.

5. Throughout the report, please be consistent in the capitalization of common names.

Response: Revised as suggested.

6. Throughout the report, please italicize scientific names.

Response: Revised as suggested.

7. Please include the literature report as part of the final report. Can be added as an appendix.

Response: Revised as suggested.

8. Please follow the TWDB contract report guidelines for formatting.

Response: Revised as suggested.

Specific Draft Final Report Comments:

1. Executive Summary, P. 2: Please include your significant findings and recommendations.

Response: Revised as suggested.

2. Executive Summary, P. 2, 1st paragraph, 1st sentence: This sentence is hard to follow and may be a run-on sentence. Please rephrase the sentence.

Response: Revised as suggested.

3. Executive Summary, P. 2, 2nd paragraph, 2nd sentence: Please correct the discrepancy when referring to the loss of low marsh habitat. The discussion refers to more than half of low marsh habitat lost but the results on P. 12 refers to 35% of low marsh habitat being lost.

Response: Revised as suggested.

4. Executive Summary, P. 2, Last Paragraph: Delete either required or needed.

Response: Revised as suggested.

5. Executive Summary, P. 2, Last Paragraph: Since the summary refers to a product (decision tool) please list how and where this tool can be downloaded/obtained. If this is an electronic file that needs to be housed by the TWDB, please communicate to the contract manager how this can be accomplished within the contract for the final deliverables.

Response: Revised as suggested.

6. Introduction, P. 3, 3rd Paragraph: Please make the correction that the Texas Commission on Environmental Quality (TCEQ), not the TWDB, sets the environmental flow standards.

Response: Revised as suggested.

7. Introduction, P. 4, 1st paragraph, 3rd line: Please check the reference "Schoenbaechler et al. (2011)" the correct reference may instead be "Schoenbaechler, Guthrie, and Lu (2011)".

Response: Revised as suggested.

8. Introduction, P. 4, 2nd paragraph, 4th sentence: Delete "is" between "it" and "flows."

Response: Revised as suggested.

9. Methods, P. 8, 1st paragraph: Please clarify whether the imagery was within ArcGIS or within GIS.

Response: Revised as suggested.

10. Methods, P. 8, 1st paragraph: Please add a space between 60 and cm.

Response: Revised as suggested.

11. Methods, P. 8, 1st paragraph, 2nd line: Instead of "modern", please specify the year.

Response: Revised as suggested.

12. Methods, P. 8, 1st paragraph, 6th sentence: Please clarify the date of the imagery used. This discussion references 1983 as the date of the intermediate imagery. By contrast, Figure 4, on p. 13, and Figure 6, on p. 15, refer to 1981 imagery.

Response: Date corrected.

13. Methods, P. 8, 4th paragraph, 2nd sentence: Please expand on how many sites constituted the in-situ sight identification and when it occurred.

Response: Revised as suggested.

14. Methods, P. 9, 1st Paragraph: The measured hydrological data used was for a period of approximately eight months, from 6/23/2020–3/5/2021. This data may not be representative of a long period of record (e.g., a full range of hydrologic conditions) as some summers may be very wet and some summers may be very dry. Please discuss the caveats of using a short period of record with respect to the uncertainty of future projections.

Response: Revised as suggested.

15. Methods, P. 10, 4th Paragraph, 2nd Sentence: Please clarify what is meant by "time" in the first question (e.g., seasonally, over the next 100 years, etc.).

Response: Revised as suggested.

16. Methods, P. 10, 4th Paragraph, 2nd Sentence: Please clarify that the second question is answered by the sensor stations and not the hydrological budget.

Response: Revised as suggested.

17. Methods, P. 10, 4th Paragraph, 2nd Sentence: Please clearly address this question in the results or discussion.

Response: Question addressed in discussion, as suggested.

18. Methods, P. 10, Last Paragraph: Please add supporting references for the statement that "(groundwater) is unlikely to play a large role in this region of coastal Texas".

Response: Revised as suggested.

19. Methods, P. 11, 1st paragraph, 6th line: Delete one "several" from "several several".

Response: Revised as suggested.

20. Methods, P. 11, 1st paragraph: Please add discussion of the limitations of using a short period of record and/or why it is appropriate. The use of such a short period-of-record raises questions about the extent to which rainfall and runoff patterns during a single season, even if the seasonal rainfall total matches long-term average levels, can be generalized to be representative for all such seasons.

Response: Discussion added as suggested. However, it should be noted that for the hindcasting and forecasting we do not use the inflows to be representative for all seasons, just the summer months of years in the past/future.

21. Methods, P. 11, 1st paragraph of Hindcasted and forecasted inflow section, 2nd sentence: Please clarify. One or more words appears to be missing from this sentence making it difficult to understand.

Response: Revised as suggested.

22. Methods, P. 11, last paragraph of Hydrologic Budget section, last sentence: Please provide additional explanation for the following. The value and purpose of the calculation of an effective watershed area based on assumption of impervious cover is unclear, and further explanation of how this relates to real-world conditions in the watershed would be beneficial.

Response: Revised as suggested.

23. Methods, P. 12, 2nd Paragraph: Please add more information. For forecasting purposes, IPCC data for three different scenarios (B1, A1B, and A2) have been used. Please add more details of the climate change data used, including whether you used bias-corrected data and how many Global Circulation Models (GCMs) were used.

Response: Additional information added in text. Bias-corrected data was used, however it is not indicated how many Global Circulation Models (GCMs) were used.

24. Results, P. 12 2nd paragraph, 1st sentence: Please clarify. The previous paragraph discusses relative sea level rise as the primary cause of loss of marsh habitat. This sentence seems to attribute it to direct sea level rise. The discussion should be harmonized.

Response: Revised as suggested.

25. Results, P. 20, 2nd paragraph under hydrological budget: Please provide further explanation. This finding appears to be highly significant in terms of understanding hydrology within the watershed. However, there is no explanation of why the effective watershed calculation results in such a small value. As noted, a calculation of precipitation minus evaporation results in a much higher figure than resulting from the water balance. Some discussion of that issue would be helpful.

Response: Additional discussion added as suggested.

26. Results, P. 20, 2nd paragraph under hydrological budget, last sentence: Please clarify. The last sentence references exclusion of overland flows from uplands. The concept here seems to be that the effective area is used as a surrogate for such overland flows. If that is correct, the sentence is confusing. If that is not correct, the concept is confusing.

Response: The concept has been reworded to be clearer.

27. Results, P. 20, last sentence: please clarify. The sentence currently reads: “If declines in evaporation outpace increases in inflows, we will see a negative trend in net inflows.” That is counterintuitive and “declines” likely should be replaced with “increases.”

Response: Section removed per previous edit.

28. Discussion, P. 27, Developing flow rate standards,1st paragraph, 1st sentence: Please consider adding additional information. Without the Excel-based decision tool to review, it is difficult to understand how it is proposed to be used. For example, it is unclear over what time frame calculations would need to be made in determining when supplemental flow would be necessary and would provide the most benefit without incurring undue costs.

Response: Further information about the decision tool has been added.

29. Discussion, P. 27: Please clarify why the exterior of marsh islands or edges remain while the interior vanishes. This refers to this statement "Approximately 150 hectares or 18% of low marsh is converted into high marsh or upland."

Response: Further clarification added in discussion, as well as in first section of results.

30. Discussion, P. 27, 4th paragraph: Please describe the equations developed for the decision tool in detail. Please also include a flowchart that details the inputs and output of the tool.

Response: Revised as suggested.

31. Discussion, P. 31, 1st paragraph, 3rd sentence: Please fix reference. Reference should be to Figure 18.

Response: Revised as suggested.

32. Discussion, P. 31, 1st paragraph, 4th and 6th sentence: Please clarify. Reference to "breaches" of the levees in this context is confusing. From the context, it appears that overtopping of levees, with the levees remaining intact, is what is being discussed. If that is accurate, a change in terminology would make the discussion more easily understandable.

Response: Revised as suggested.

Figures and Tables Comments:

1. Figure 1: Please add a North directional arrow and increase the scale bar and label font size for easier reading.

Response: Revised as suggested.

2. Figure 3: Please illustrate where LCRA's Gauge 1 S is located. If including the gauge would impact the maps extent, please refer to where the gauge is located in the text (e.g., 9 miles southwest of the study area).

Response: Revised as suggested.

3. Figure 3: Please label the fourth additional instrument site and including its information in the figure's caption.

Response: The fourth instrument site (Pelton Lake) has been coupled with Chinquapin site to be named station three. Equipment for station three is stated in Table 1.

4. Figure 5: Please improve clarity.
    1. One potential option for making the figure easier to understand would be to replace the letters identifying the five component charts with a descriptive label. In addition, it might be helpful to show, for each chart, the area of the habitat being shown as lost represented by a dashed line or lighter color to help communicate that the area of habitat lost is being represented as habitat gain in the other bars.
    2. Another option would be to eliminate the bar for the habitat being lost and just describe that component in text.

Response: Labels added for clarity.

5. Figure 6: Please clarify the caption. The current caption is misleading and reads as though change is represented on the y-axis. Caption could read "Land cover areal extent in the Big Boggy watershed in 1953, 1981, and 2020. Note the discontinuous y-axis to accommodate the large quantity of upland area."

Response: Revised as suggested.

6. Figure 9: Please include the period of record reflected in the water budget and the precipitation and area values.

Response: Period of record added to figure caption as suggested.

7. Figure 9: Please explain the evaporation values in this figure in the text. The evaporation values for Lower Boggy (6.75 mil m^3) and Upper Boggy (991 k m^3) are counterintuitive given the differences in area (Lower Boggy: 2,780 hectares; Upper Boggy: 7,927 hectares). Some discussion or explanation would be beneficial.

Response: Content removed per previous edit.

8. Figure 9: Please clarify: To make the water balances work, it seems that the 2.12 mil m3 outflow from Upper Boggy would have to be allocated between the loss to other outlets and flow to Lower Boggy. As currently represented, the numbers do not appear to balance.

Response: Revised to make it clearer.

9. Figure 14: Please clarify. Figure caption should have "Lower Boggy", not "Upper Boggy".

Response: Revised as suggested.

10. Figures 13 and 14: Please clarify. The reference in both figures to data prior to 2020 as observed data is confusing. Presumably, that data has been hindcasted rather than observed.

Response: Revised as suggested.

11. Figures 13 and 14: Please provide additional explanation in the text. It is counterintuitive that the inflows to Upper Boggy in 2020, as shown in Figure 13, would be below the

mean trend while the inflows to Lower Boggy in 2020, as shown in Figure 14, would be far above the mean trend. It would be helpful to have some explanation of what might account for that difference.

Response: This issue has been resolved per previous changes.

SUGGESTED CHANGES

General Draft Final Report Comments:

1. Please consider changing the title. The title for the draft report does not accurately describe the primary focus of the scope of work or the actual report. The focus of the Colorado/Lavaca Basin and Bay Area Stakeholder Committee (BBASC) with respect to East Matagorda Bay has been on identifying affirmative strategies to improve inflows rather than on developing specific environmental flow standards for that bay system. (See Section 7.6 on P. 117 of the BBASC report). The BBASC develops recommendations. The content of the draft report reflects that BBASC focus much more accurately than the title of the report. The scope of work also matches the content better than the title.
    a. One potential option would be to retitle it as “Informing Environmental Flow Protection Efforts for the Sustainability of Wetlands in East Matagorda Bay: Phase I Big Boggy.”
    b. Alternatively, the phrase “environmental flow standards” could be replaced throughout the report with the phrase “environmental flow recommendations.”

Response: Title revised as suggested.

Specific Draft Final Report Comments:

1. Executive Summary, P. 2: Please consider combining the three paragraphs of the executive summary into either one, or two paragraphs as several of the paragraphs only have two sentences in total.

Response: Revised as suggested.

2. Executive Summary, P. 2, Second Paragraph, Last Sentence: Please clarify. For consistency, suggest adding either “finally we…” or “we then…”

Response: Revised as suggested.

3. Introduction, P. 4, Last paragraph, first sentence: Please clarify. If the title is changed to option A above, please consider deleting the phrase, “help develop environmental flow standards for” from that sentence and insert “assess” in its place so that the sentence

would read as follows: "The central objective of this project is to assess the Big Boggy coastal watershed and recommend potential restoration actions to sustain its wetlands."

Response: Revised as suggested.

4. Methods, P. 8, 1st paragraph: Please add more information on how sea level changed from 1953-2020 and why or why it wasn't included in the analysis.

Response: Sea level rise at Big Boggy added to the introduction section.

5. Methods, P. 8, 3rd paragraph: Please clarify the last sentence. For example, other and then recording the amount each class changes in relation to the other classes.

Response: Revised as suggested.

6. Methods, P. 9, 2nd paragraph: Please change "into three" to "at three…."

Response: Revised as suggested.

7. Methods, P. 11, 3rd paragraph: Please add a discussion of the precision and accuracy of the rainfall and evaporation values applied to these tracts. Given the critical role that these rainfall and evaporation values play in the analyses and recommendations developed, it would be helpful to better understand the accuracy of the data.

Response: Revised as suggested.

8. Results, P. 12, 2nd paragraph, 1st sentence: Please consider adding additional discussion. The report acknowledges the significance of the loss of the dredge spoil island on the opposite side of the ICWW. The potential for an impact to marsh habitat as a result of a change in amplitude of tidal fluctuation and in wave energy as a result of the loss of the spoil island would seem to merit discussion.

Response: Text added in Discussion addressing the loss of dredge spoil islands and marsh erosion.

9. Results, P. 16, 1st paragraph, last sentence: Delete the word "off" between "percent" and "of."

Response: Revised as suggested.

10. Results, P. 16, 1st paragraph, 3rd sentence: Please consider including the mean annual rainfall from 1954-2020.

Response: Revised as suggested.

11. Results, P. 20, 1st paragraph under Hydrological Budget, last sentence: Please clarify. It appears that, except for the last sentence, the discussion in this paragraph relates only to the budgeted period of 7/4/2020 to 9/19/2020. The last sentence, which addresses evaporation, refers to the study period. It is unclear how that sentence relates to the remainder of the paragraph.

Response: Content removed per previous edit.

12. Results, P. 22: Please consider adding a table of descriptive statistics related to hindcasted inflows and evaporation data to accompany Figure 12. This would help the

reader understand the annual variability and would also be helpful for the net flow discussion in Figure 14.

Response: The concept/data has been simplified.

13. Discussion, P. 27, 4th paragraph: Please add "a" to "we developed a MS…"

Response: Revised as suggested.

14. Discussion, P. 27, 4th paragraph: Please correct the grammar in the following, "This tool will be value help resource managers…"

Response: Revised as suggested.

15. Discussion, P. 27, Developing flow rate standards: Please consider adding additional information. From a BBASC perspective, a broader understanding of freshwater inflow patterns (e.g., seasonality, annual variation, etc.) would help inform a variety of protection strategies (in addition to the supplemental water approach that is proposed). Moreover, any additional data summaries and statistical analysis aimed at inflow characterization would be beneficial.

Response: Additional information added, as suggested.

16. Discussion, P. 28 4th paragraph: Please correct the grammar in, "an additional 65 hectares would needed (above….."

Response: Revised as suggested.

17. Discussion, P. 28, last paragraph: Please consider adding discussion of the following recommended restoration efforts that are aimed at alterations of culverts, weirs, levees, and old irrigation canals in order to increase effective watershed area, questions arise about whether the effective watershed area may have changed over time as these features were added or altered. If that is likely to have occurred, it would be helpful to include discussion of the potential significance of such changes in the future.

Response: Further discussion regarding alteration to the watershed and the effective watershed area has been added.

18. Discussion, P. 34, 3rd paragraph: Please elaborate on what the more severe actions are.

Response: Revised as suggested.

Figures and Tables Comments:

1. Figure 1: Please consider labeling Highway 60, Lake Austin, Lake Pelton, and Chinquapin Road and delineate Big Boggy National NWR as they are referenced in the text.

Response: Revised as suggested.