INFORMING ENVIRONMENTAL FLOW STANDARDS IN SUPPORT OF WETLANDS IN BIG BOGGY

A Thesis

by

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MASTER OF SCIENCE

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ABSTRACT

The Colorado River of Texas no longer provides direct freshwater flows to the wetlands of East Matagorda Bay, and 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. I first identified wetland and land cover trends over the historical period to today, finding that this watershed has lost more than half of its low marsh area since 1953. I 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. I modeled both historical and future inflows, from the years 1953 to 2100, under various scenarios. I developed a 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. Finally, I recommend several potential restoration options within the Big Boggy NWR and adjacent lands that will improve both flows and habitat.

DEDICATION

To my wife, Lorraine, for her unwavering support.

To my dogs, Sunny, Daisy, and Dash, for always being happy to see me.

To the wild places and all that inhabit them.

ACKNOWLEDGEMENTS

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Contributors

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Dr. Thomas Huff of the Department of Ecology and Conservation Biology provided valuable insight into the development of the hydrological model.

All other work conducted for the thesis was completed by the student independently.

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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 no longer provides direct freshwater flows to the wetlands of East Matagorda Bay, Texas, and a few small basins, such as that of Big Boggy Creek, provide the only inflowing freshwater.

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, 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 Water Development Board (TWDB) 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 Texas Commission on Environmental Quality (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.

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 Mid 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 help develop environmental flow standards for 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 over the historical period to today
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.

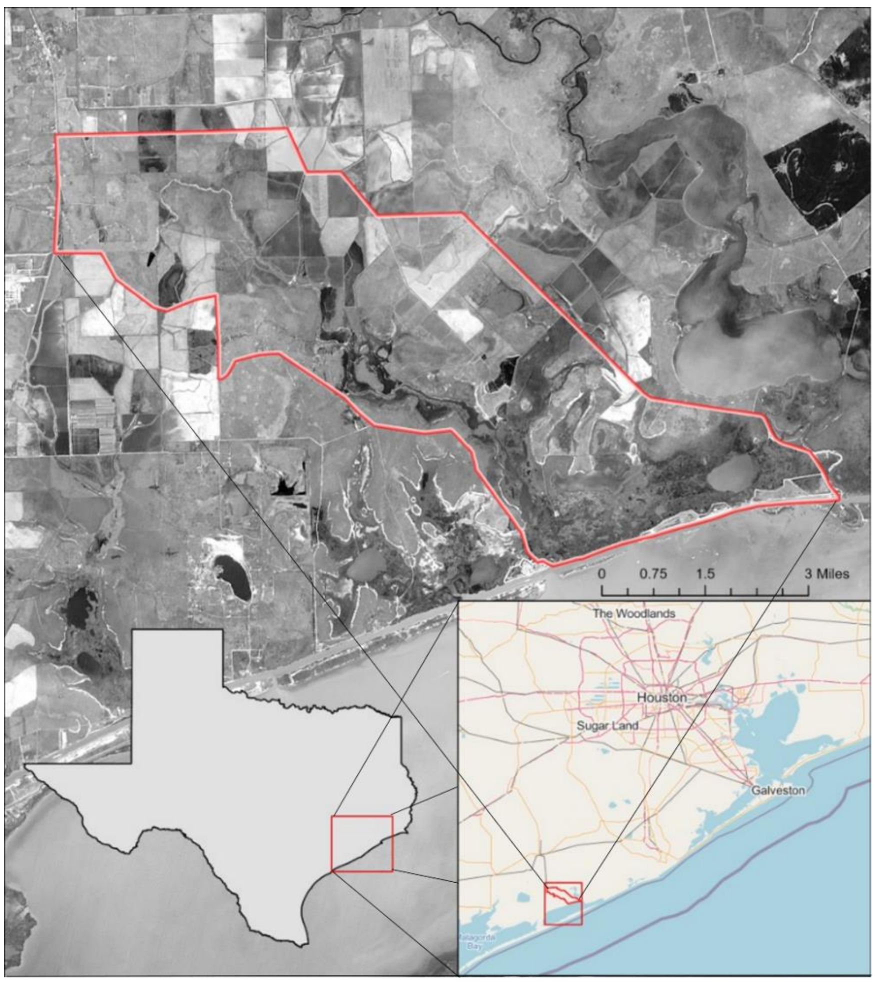

Figure 1. Project study area (outlined in red) located southwest of Houston, Texas and bordering East Matagorda Bay.

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 (USFWS) 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 is 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 (USFWS, 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).

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 (USFWS, 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).

2.2. Identify wetland and land cover trends over the historical period to today

To identify historical changes in wetland cover and the hydrological network, we analyzed a series of modern and historic aerial imagery within a Geographic Information System (GIS). Images from 1953, 1983, 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 (1983) 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, 1983, was obtained by the USDA's National High-Altitude Aerial

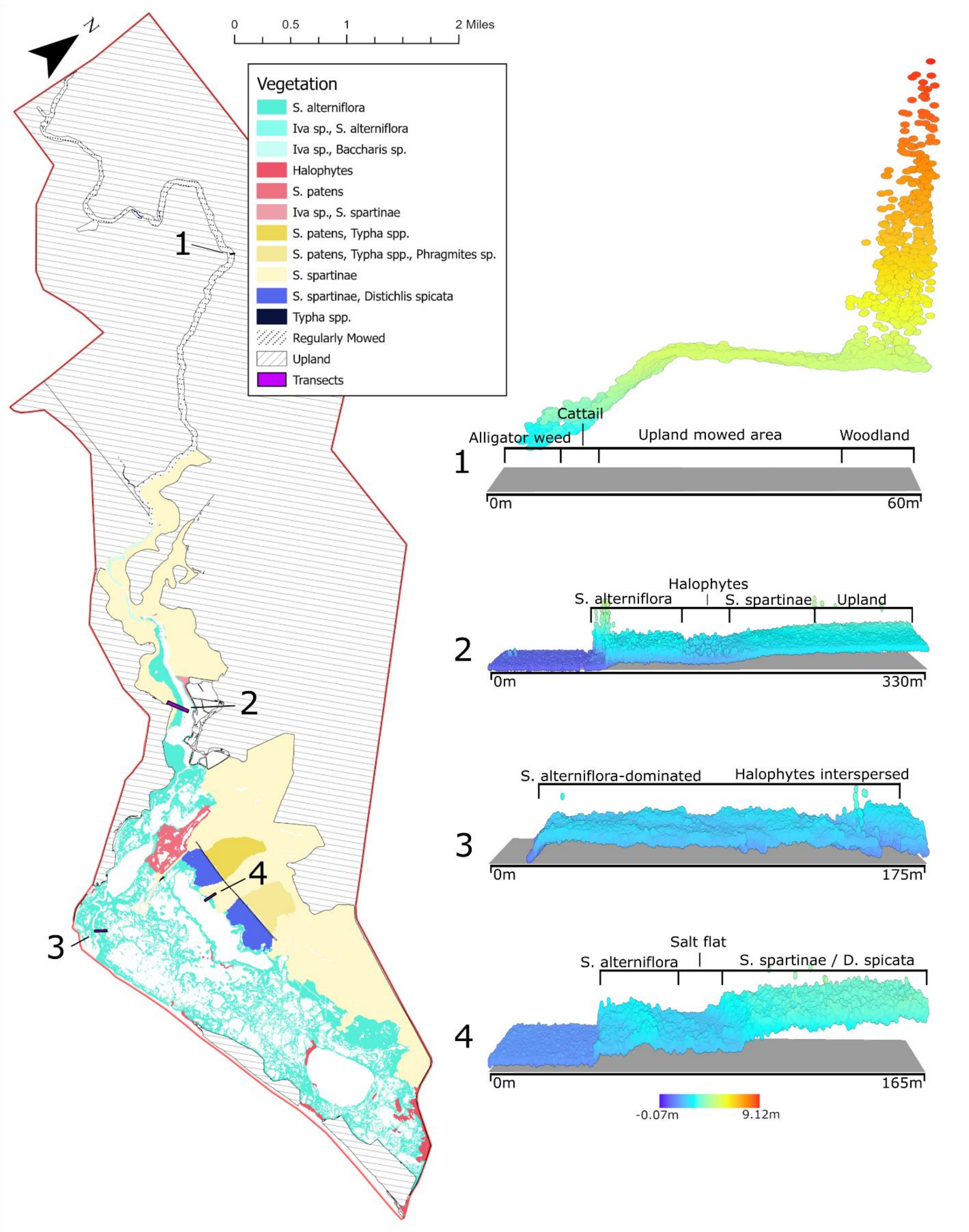

Figure 2. Vegetation cover map for the Big Boggy watershed, illustrating the different vegetation communities at different locations along its length. In the four transect cross-sections on the right, the elevation is depicted as based on LIDAR point data.

on color infrared positive film. The most recent imagery (2020) was obtained through the USDA National Agriculture Imagery Program (NAIP) and at a 60cm resolution. The 1953 and 1983 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 *Spartina 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 feature-class layers over each other recording the amount each class changes to each other class.

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.

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).

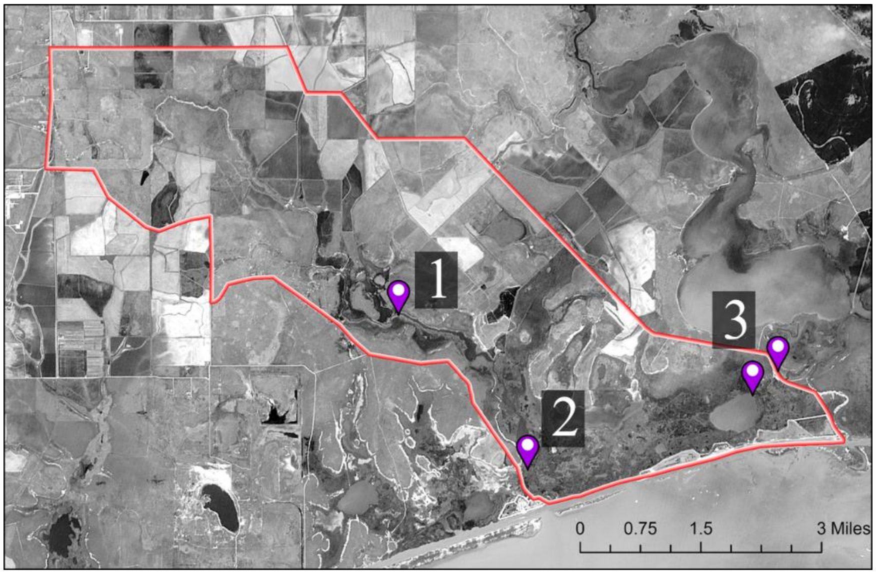

Figure 3. Map of sensor stations in the Big Boggy study area at Upper Boggy (1), Lower Boggy (2), and Chinquapin/Pelton lake (3).

We set up the sensors into 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 NOAA's 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 time?, and (2) Are the salt marshes showing signs of hydrologic restriction and hypersalinity? To answer these questions, 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. 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. 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, precipitation, and evaporation. 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 both ADCP stations were active. During these dates in 2020, the precipitation and evaporation balance was nearly identical to the mean for the period over the past several decades (see Results for more). Importantly, this time 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 this ~3.5 months of data was not sufficiently long enough for us to quantitatively account for timing delays caused by complex watershed effects and antecedent conditions.

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 and evaporation volumes for the watersheds that fed into each station. To do this, we obtained the precipitation and evaporation from the Water Data for Texas website operated by the Texas Water Development Board (TWDB) (Texas Water Development Board, 2021). 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, if we were to assume the watershed consisted wholly of impermeable surface with direct run-off into the basin, the effective watershed area is the amount of land needed to capture the amount of inflow (precipitation minus evaporation) observed flowing past a 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. For the hindcasting, the estimated historic freshwater inflows and total evaporation for each year from 1954 to 2019 during the same summer months as the budget. The values were derived from the TWDB precipitation and gross evaporation datasets, 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 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 further interpreted by Jiang and Yang (2012), and include the A1B, A2, and B1 scenarios. Each 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 over the historical period to today

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. 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.

Sea level rise is suspected as the primary driver of salt marsh loss in the study area. The interior marsh has become dramatically fragmented due to processes related to marsh drowning, while the edges of the marsh have maintained their elevation. 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. The banks of the creek appear to be too steep in this area for low marsh to establish, rather we see increased open water. Stream bank erosion as a result of continued mowing, grazing, or purposeful channelization of the banks is likely another cause of this observed pattern.

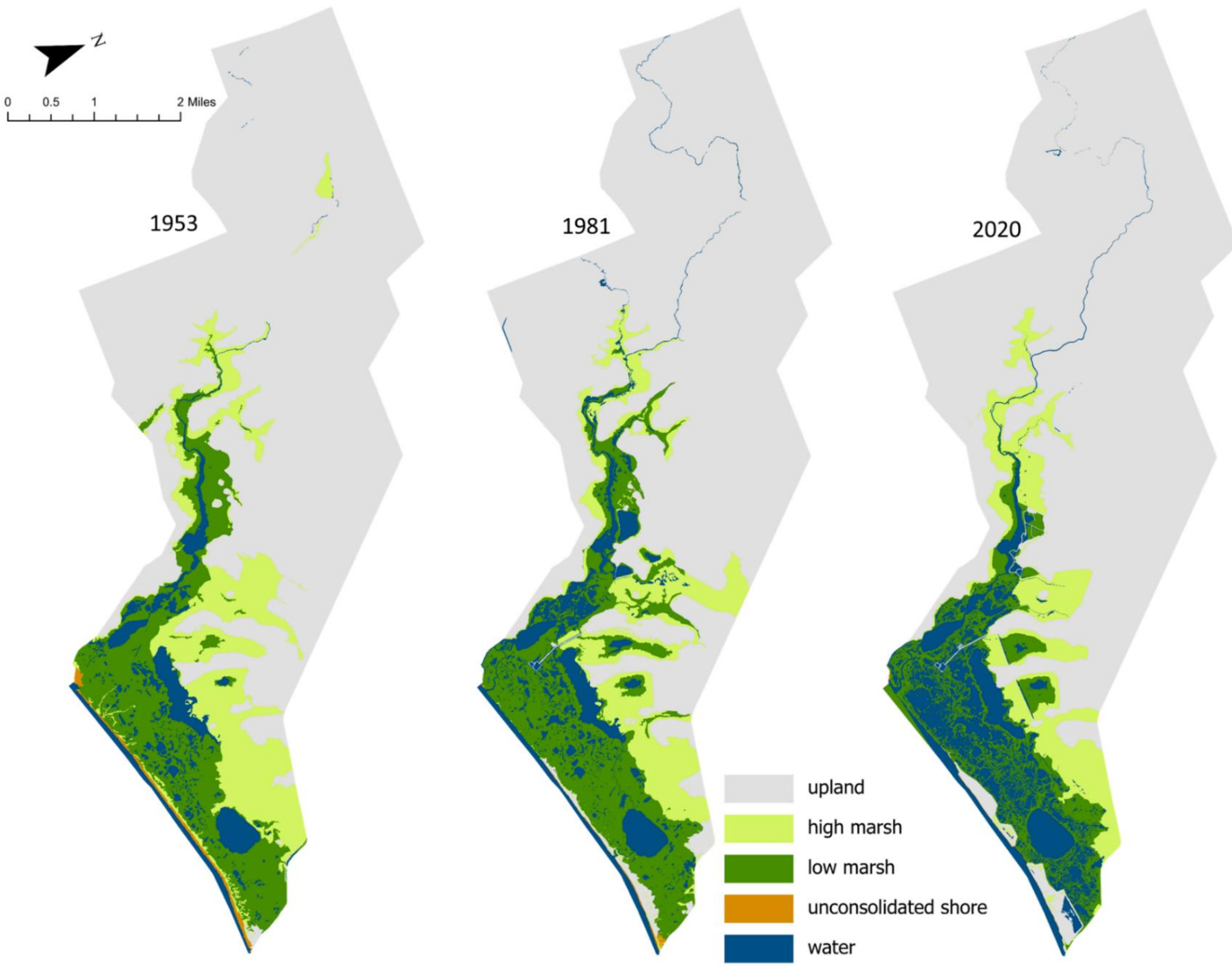

Figure 4. Land cover in the Big Boggy watershed from 1953 to 2020.

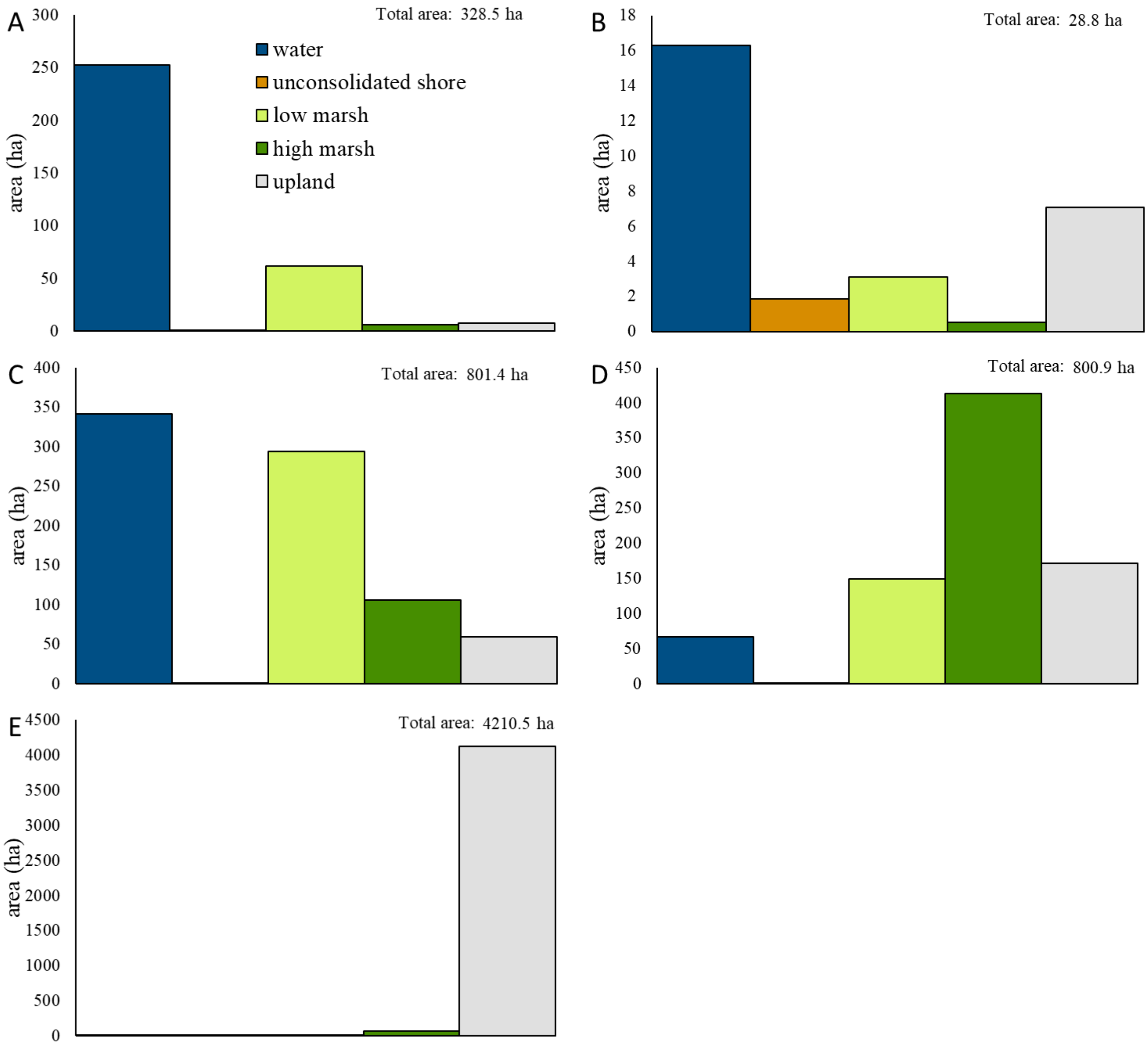

Figure 5. Transition of land cover types in the Big Boggy watershed from 1953 to 2020. Each chart panel signifies the change in land cover for one of six classes: water (A), unconsolidated shore (B), low marsh (C), high marsh (D), and upland (E). The changes shown indicate the amount one land cover class converted to each of the other classes between 1953 and 2020. For example, in panel C 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.

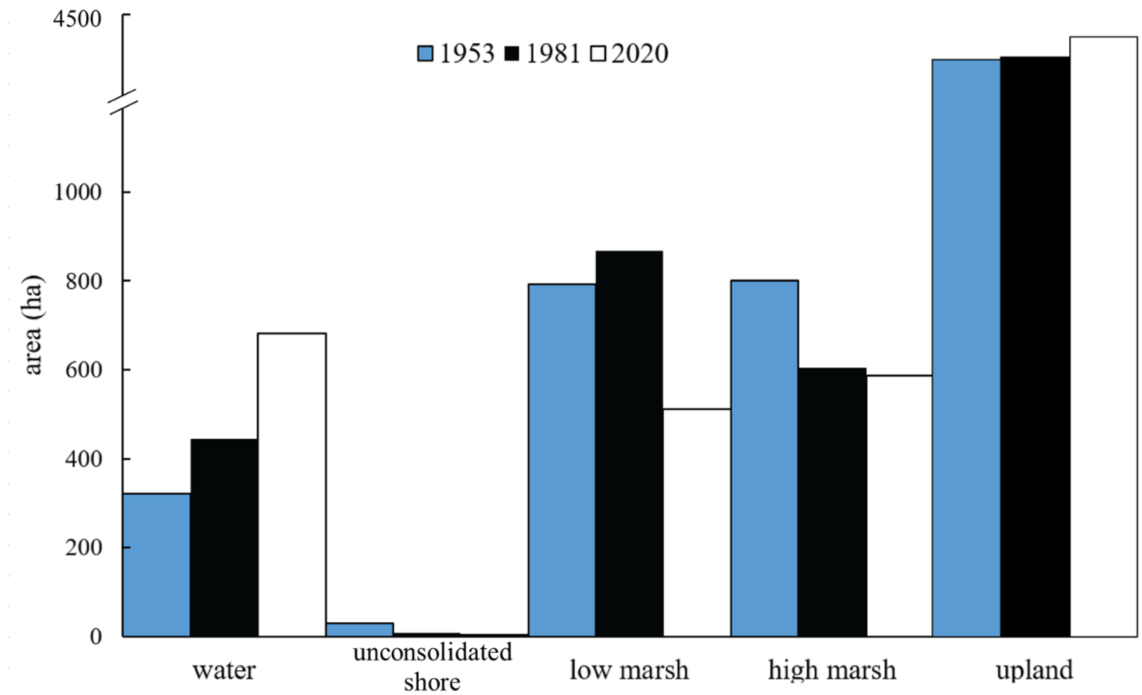

Figure 6. **Land cover changes in the Big Boggy watershed from 1953 to 2020. Note the discontinuous y-axis to accommodate the large quantity of upland area.**

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 time period, two tropical cyclones passed by the area, Hurricane Hanna and Tropical Storm Beta. Compared to previous years, precipitation during the study period can be considered average with its total rainfall less than one percent off of the average from 1954 to 2020.

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 is 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 is 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 ADCP's 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).

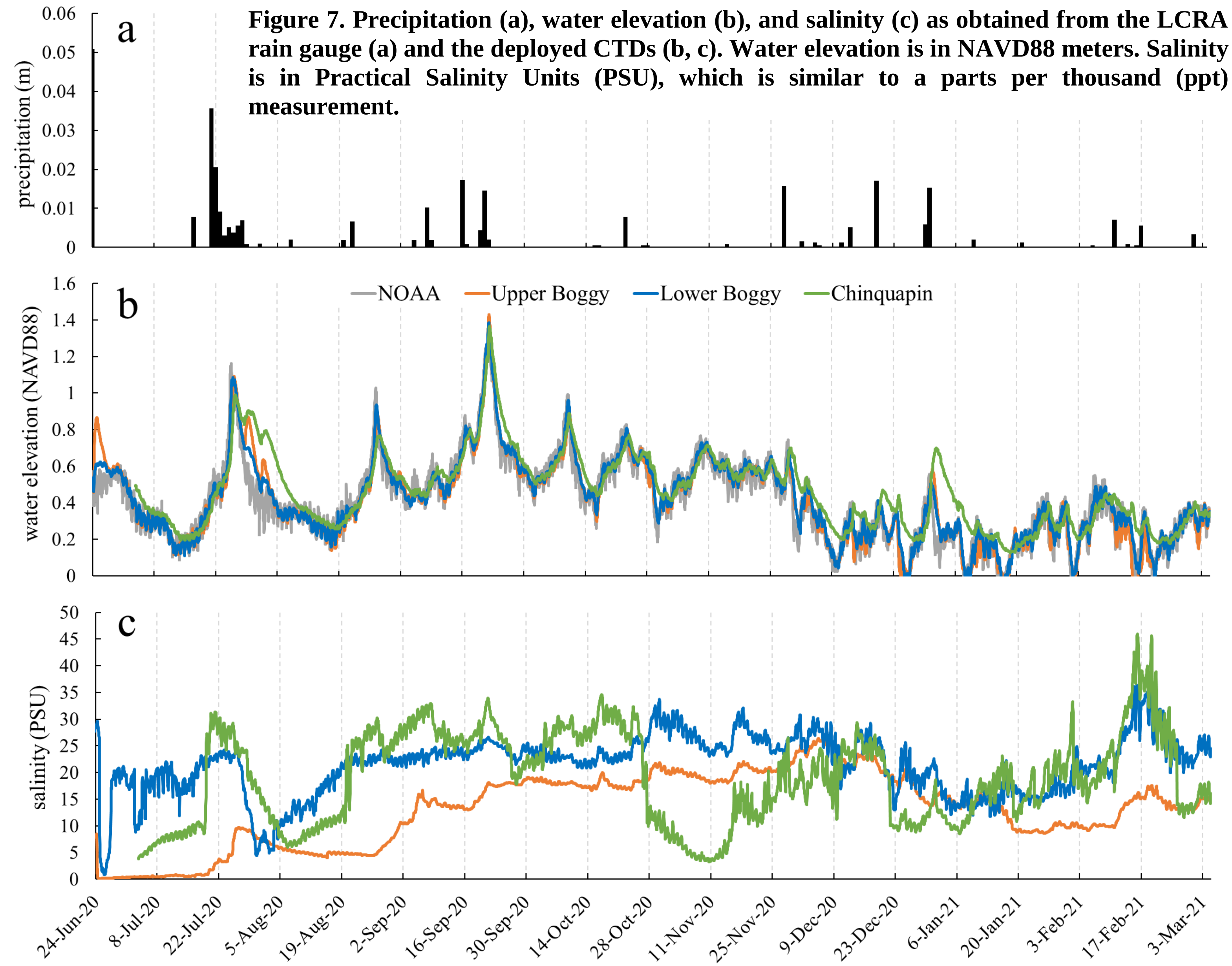

Figure 7. Precipitation (a), water elevation (b), and salinity (c) as obtained from the LCRA rain gauge (a) and the deployed CTDs (b, c). Water elevation is in NAVD88 meters. Salinity is in Practical Salinity Units (PSU), which is similar to a parts per thousand (ppt) measurement.

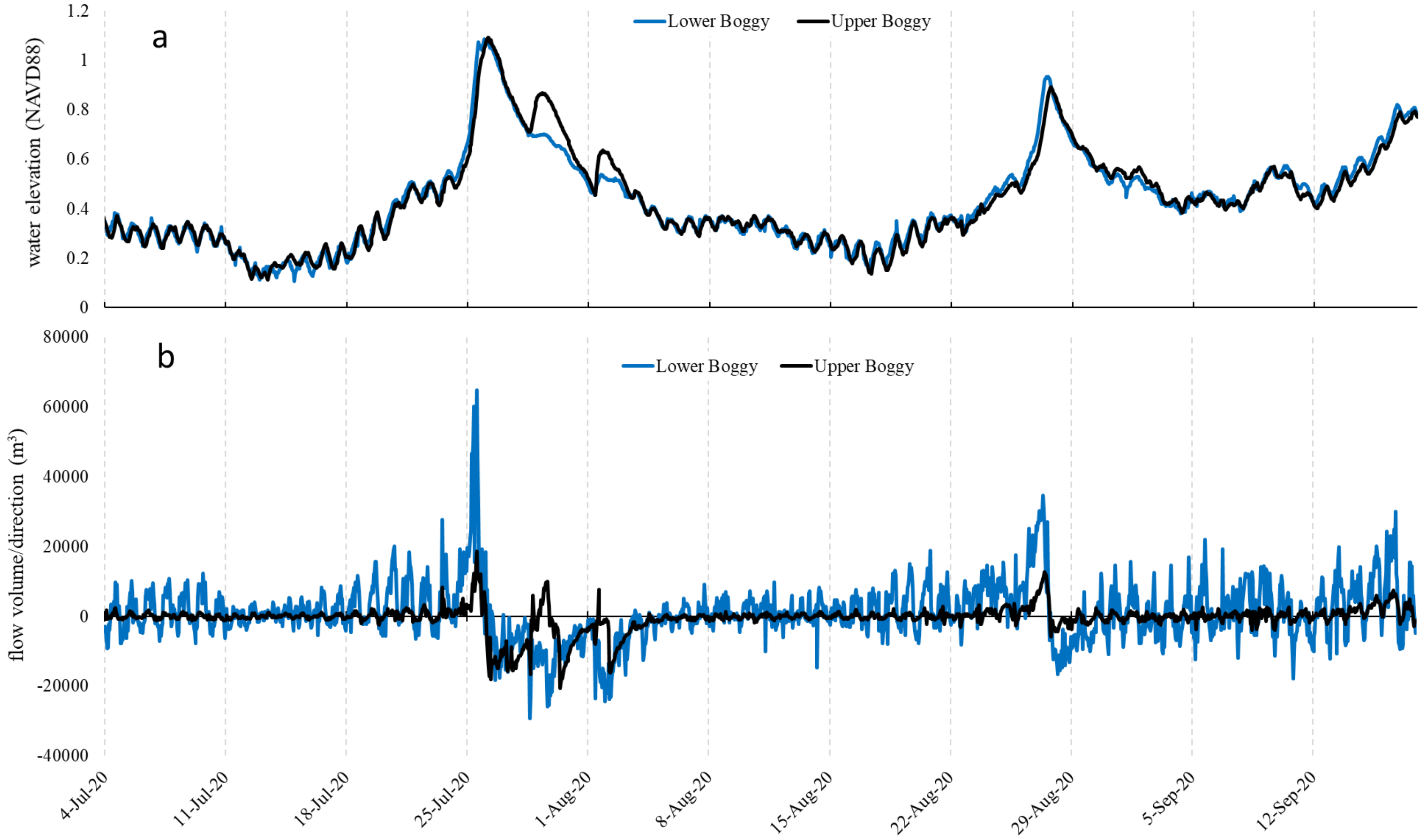

Figure 8. Water elevation (a) and flow volume/direction (b) for ADCP sites at Upper and Lower Boggy. Positive values indicate upstream flows, negative values indicate downstream flows.

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 1.39 million m^3 (Figure 9) consisting of incoming tides. Total downstream flow measured 2.12 million m^3, consisting of outgoing tides and freshwater flows. The imbalance between upstream and downstream flows was 728 thousand m^3 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). An additional 991 thousand m^3 of water evaporated in the UB watershed during the study period.

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 minus evaporation, multiplied by this area resulted in a far higher value than the 728 thousand m^3 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 the water is delivered directly into open water bodies, low marsh, and high marsh areas, while excluding overland flows from uplands.

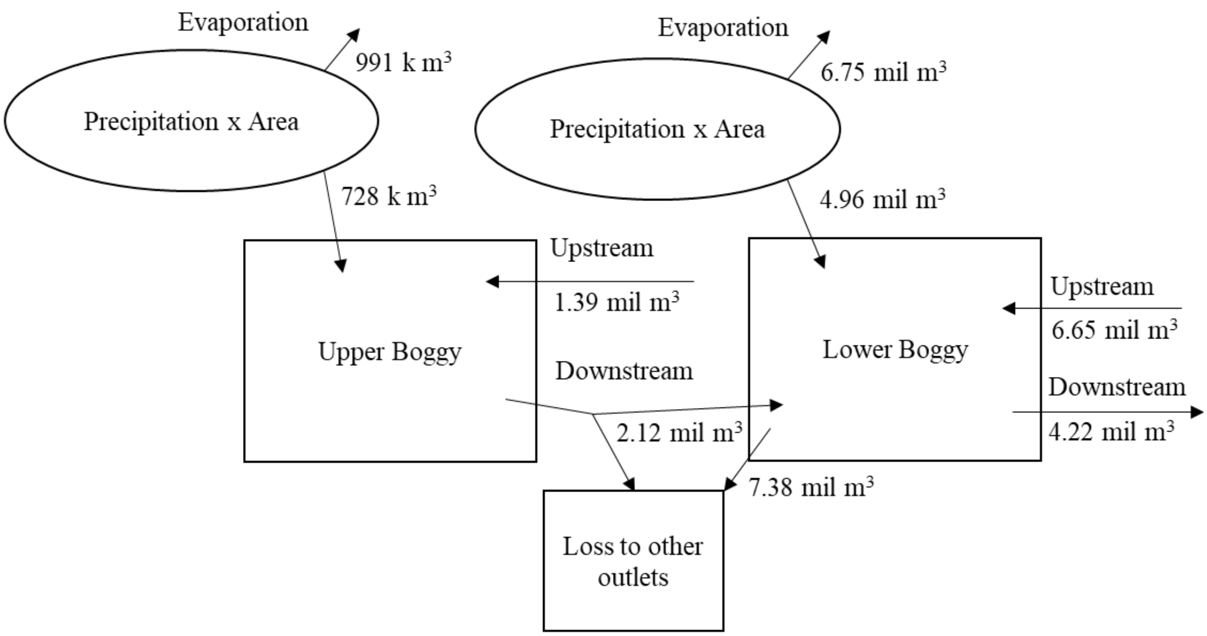

Figure 9. **A visualization of the water budget for Big Boggy.**

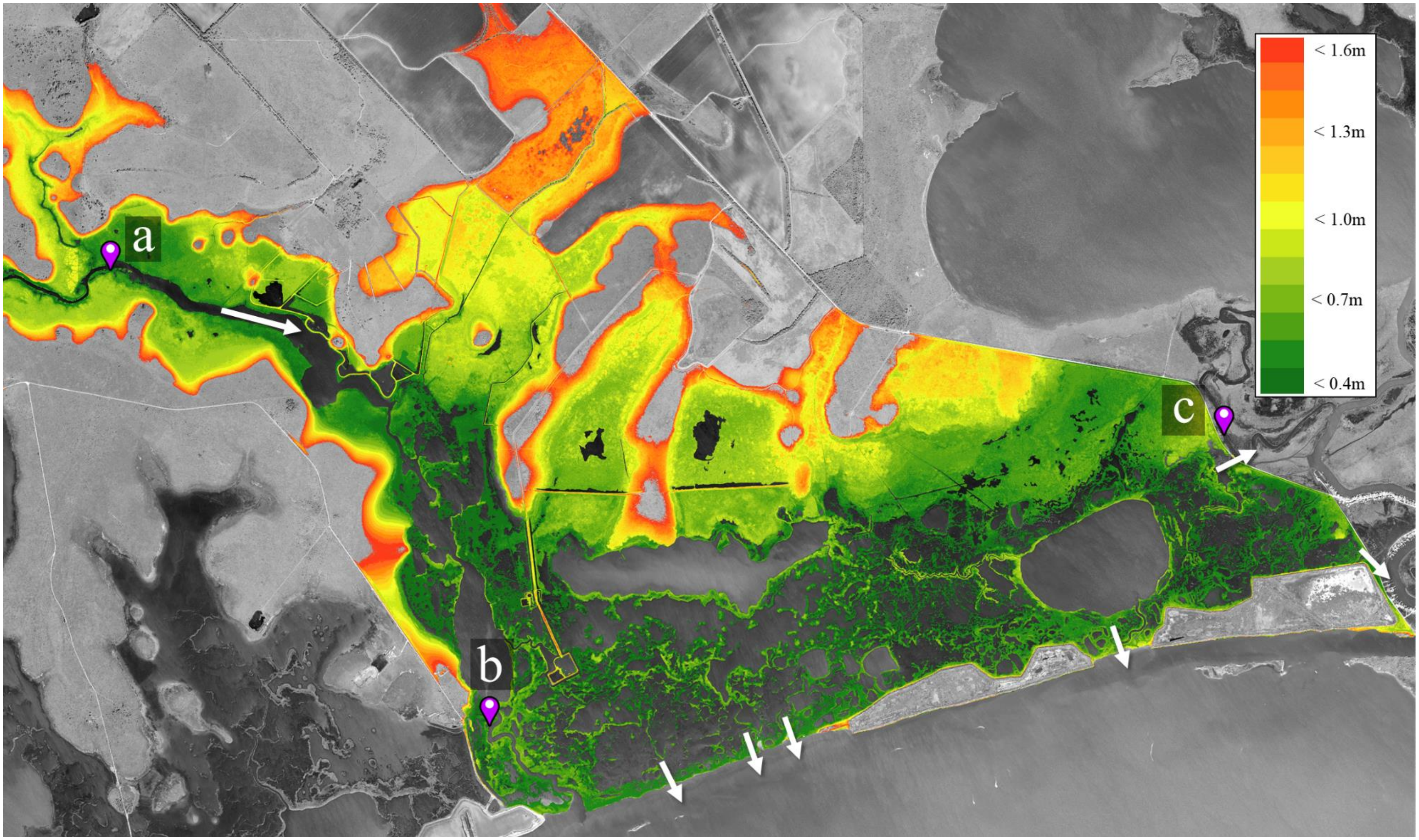

Figure 10. Alternate outlets for flowing water (white arrows) and water elevations needed to flood portions of the watershed (NAVD88 meters). Upper Boggy (a), Lower Boggy (b), and Chinquapin (c) sites are also depicted.

At the LB station, the total upstream flow during the study period was 6.65 million m^3 consisting of incoming tides and storm surges. Total downstream flow measured 4.22 million m^3, consisting of outgoing tides and freshwater flows. The difference between upstream and downstream flows was 2.42 million m^3. Precipitation was estimated as 4.96 million m^3. An additional 6.75 million m^3 of water evaporated in the LB watershed during the study period.

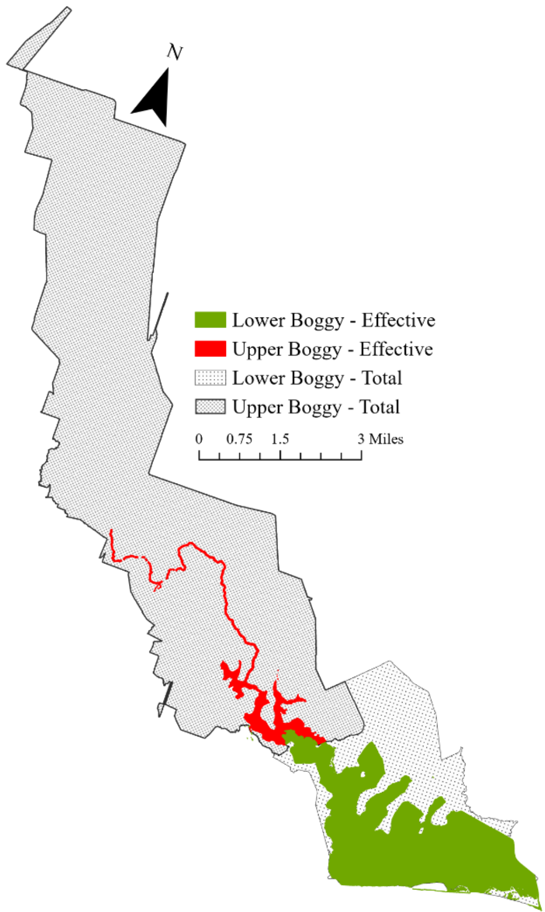

Figure 11. **The Big Boggy watershed as derived from a 1-meter DEM and processed using ArcGIS Watershed tools.**

It is important to note that there was a large imbalance in the water budget at LB. There was approximately 7.38 million m^3 unaccounted for, and when taking into consideration the downstream flows from UB into LB as well (2.12 million m^3), there was a total of 9.5 million m^3. 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.

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.

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 2007 the inflows at LB were 11.71 million m^3, or 5.47 million m^3 (87%) greater than the expected mean trend. During this same period, inflows at Upper Boggy (UB) were 1.72 million m^3, or 859 thousand m^3 (100%) greater than the mean trend. At both Upper and Lower Boggy stations, net inflows were negative more often than not with average net inflows of -190 thousand m^3 and -3.55 million m^3, respectively (Figures 13a and 14a). Net inflows are defined as the difference between the total volume of inflows and evaporation. If declines in evaporation outpace increases in inflows, we will see a negative trend in net inflows. It is interesting to note that the evaporation quantities were much larger at LB, due to the large area of exposed surface water.

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 net inflows that slowly increase at 51% for UB and 0.16% for 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 10% decline in net inflows is predicted at UB and a decline of 2.8% is predicted at LB. The third scenario, A1B, estimates a 37% decrease in net inflow at UB and 10% decrease at LB. Finally, A2 yields the worst-case prediction, where net inflows at UB are predicted to decrease by 81%, accompanied by a 22% decrease at LB. 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.

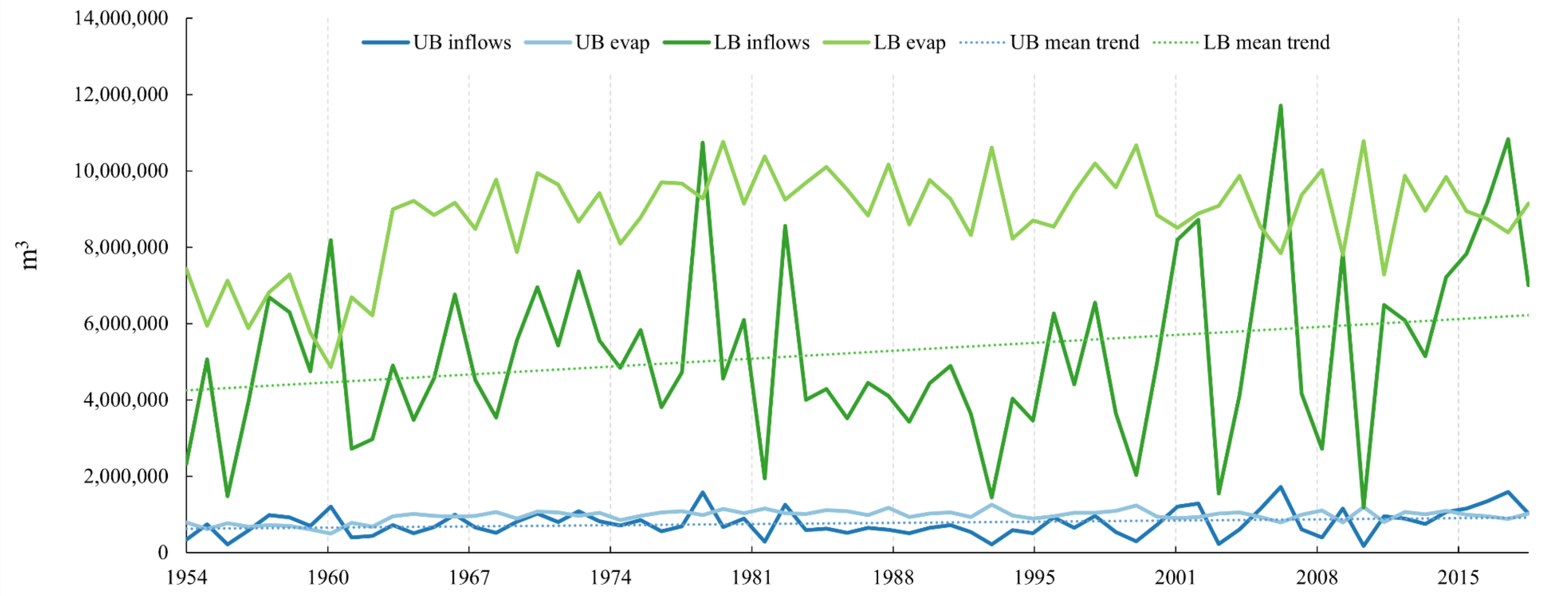

Figure 12. Hindcasted inflow and evaporation from 1954 to 2019. These values were derived from the hydrologic budget, using precipitation and evaporation data from TWDB as input.

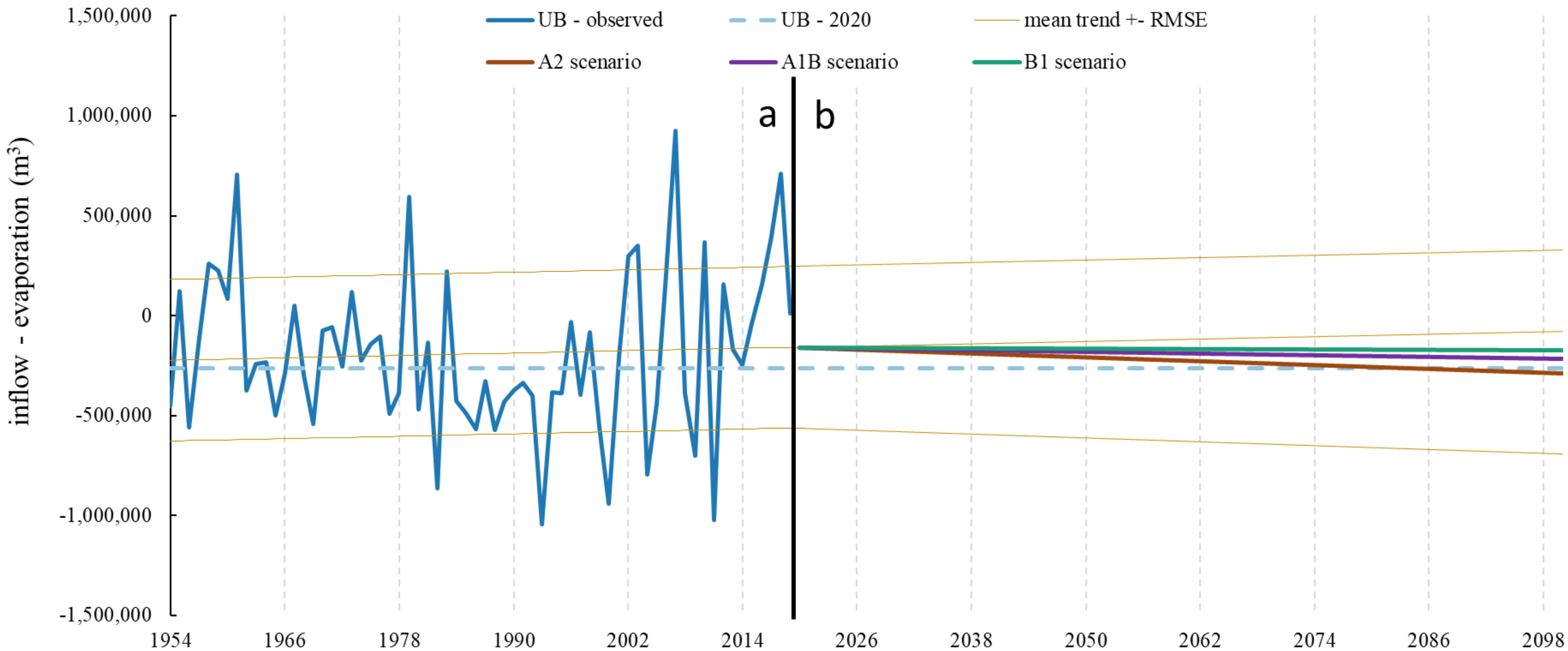

Figure 13. Hindcasted (a; 1954 - 2019) and forecasted (b; 2021 - 2100) net inflows at Upper Boggy. The inflow rates that we had observed in the field in 2020 are depicted for comparison.

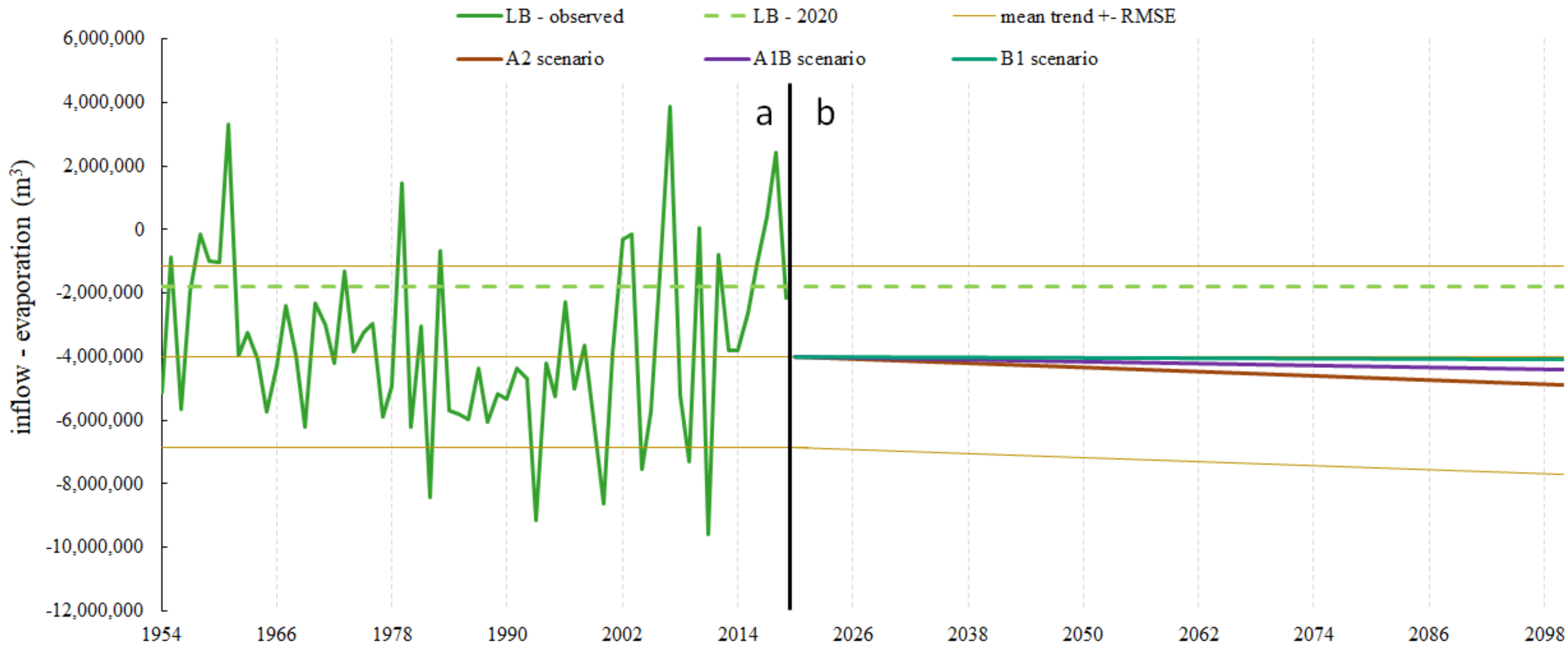

Figure 14. **Hindcasted (*a;* 1954 - 2019) and forecasted (*b;* 2021 - 2100) net inflows at Upper Boggy. The inflow rates that we had observed in the field in 2020 are depicted for comparison.**

4. DISCUSSION

The Big Boggy watershed has lost more than half of its low marsh area since 1953. However during this same time 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 two likely causes, which may act in concert.

First, relative sea level rise 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 cannot match sea level rise (Morris et al. 2002) and this fragmentation pattern results. 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), because freshwater delivers both mineral sediments (Bianchi et al. 2018) and promotes organic growth and deposition (Więski, 2014).

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.

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 MS Excel-based flow decision tool for the Big Boggy Creek watershed (see deliverables). This tool uses inputs of precipitation and evaporation 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. This tool will help resource managers and policymakers to 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 12 cm of additional rainfall would have raised the net inflows to the lower RMSE bound, and 30 cm 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 270,019 m^3 and 675,049 m^3, 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. Similar to the tool above, resource managers can use our tool to estimate the additional effective watershed area needed to offset the decline in inflows.

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 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.

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. 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 15; Table 2). These seven crossings are cement structures with at least one culvert and a pathway large enough for a vehicle to cross (Figure 16). 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 17).

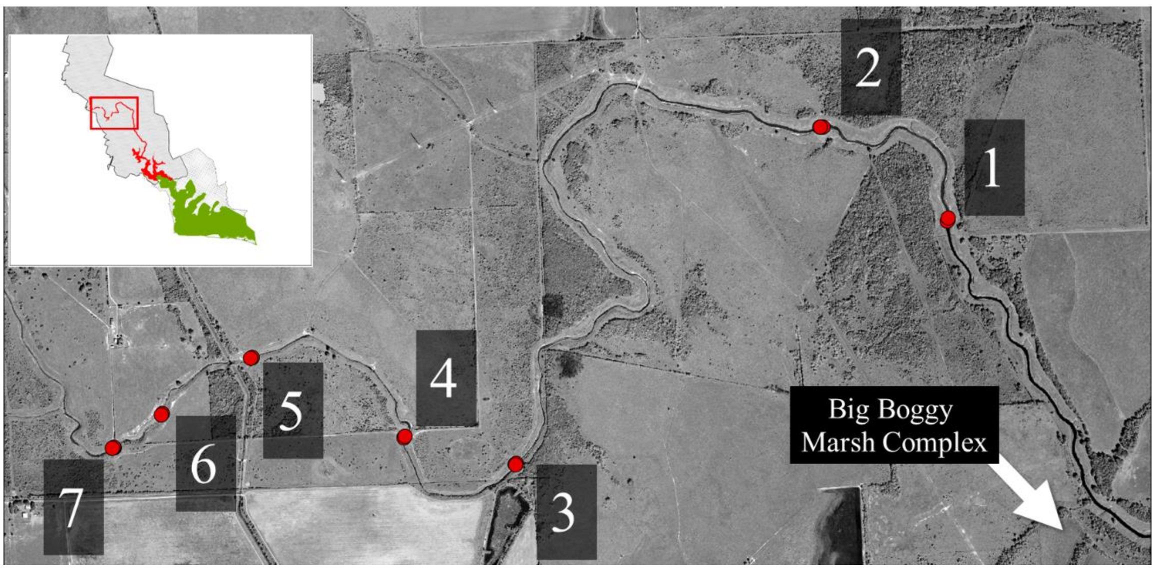

Figure 15. Barriers to flow in the further upstream reaches of the study area.

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

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.

Figure 16. Barrier to flow on Big Boggy Creek. This structure (barrier 1 in Table 2 & Figure 15) does not appear to have culverts and instead allows the water to flow over the top.

Figure 17. 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 18). The ponds in question do not appear to bear adequate freshwater wetland vegetation to be beneficial to waterfowl. As can be seen in Figure 17, 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 breaches 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 breached 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. Into the benefits that we outline above, the effective watershed would increase by approximately 17 hectares.

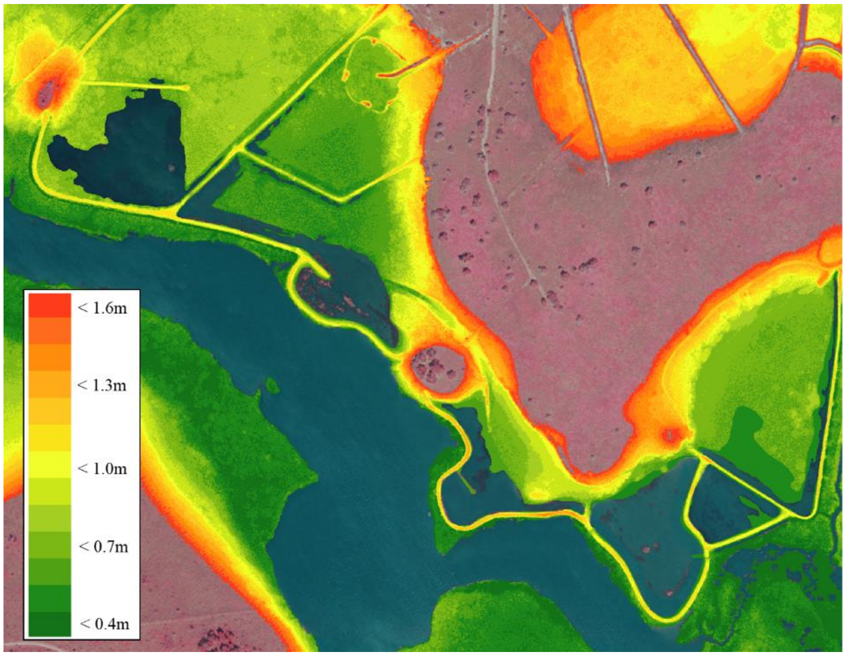

Figure 18. Duck ponds pictured, with land elevation shown.

The USFWS 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 19). The minimum elevation needed to breach the West MSU is 1.19 m. 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 (USFWS, 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.

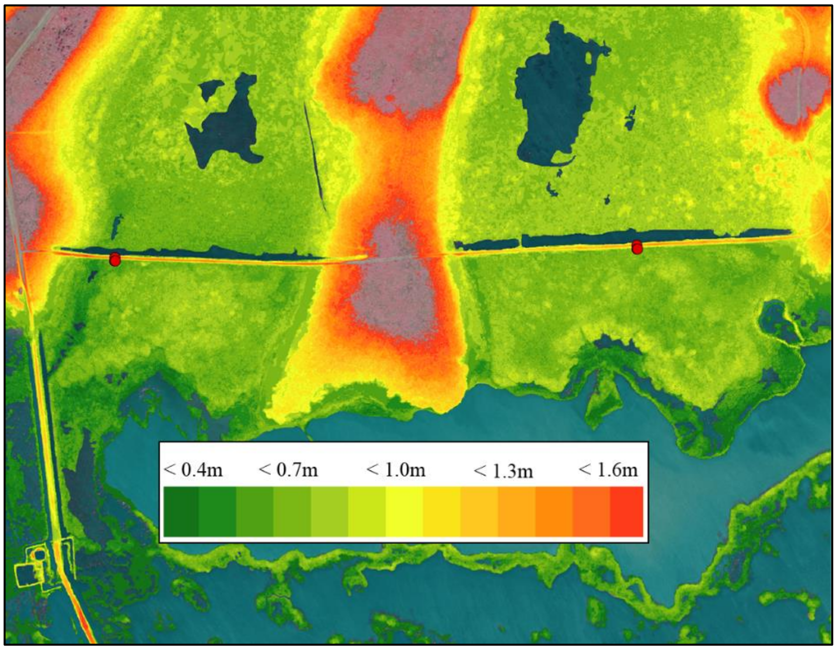

Figure 19. Moist soil units shown with the location of the gates marked with a red circle. Note the more defined channel on the left unit.

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 (USFWS, 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 microtopography 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.

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 20). The total potential gain in effective watershed resulting from these areas is 386 hectares.

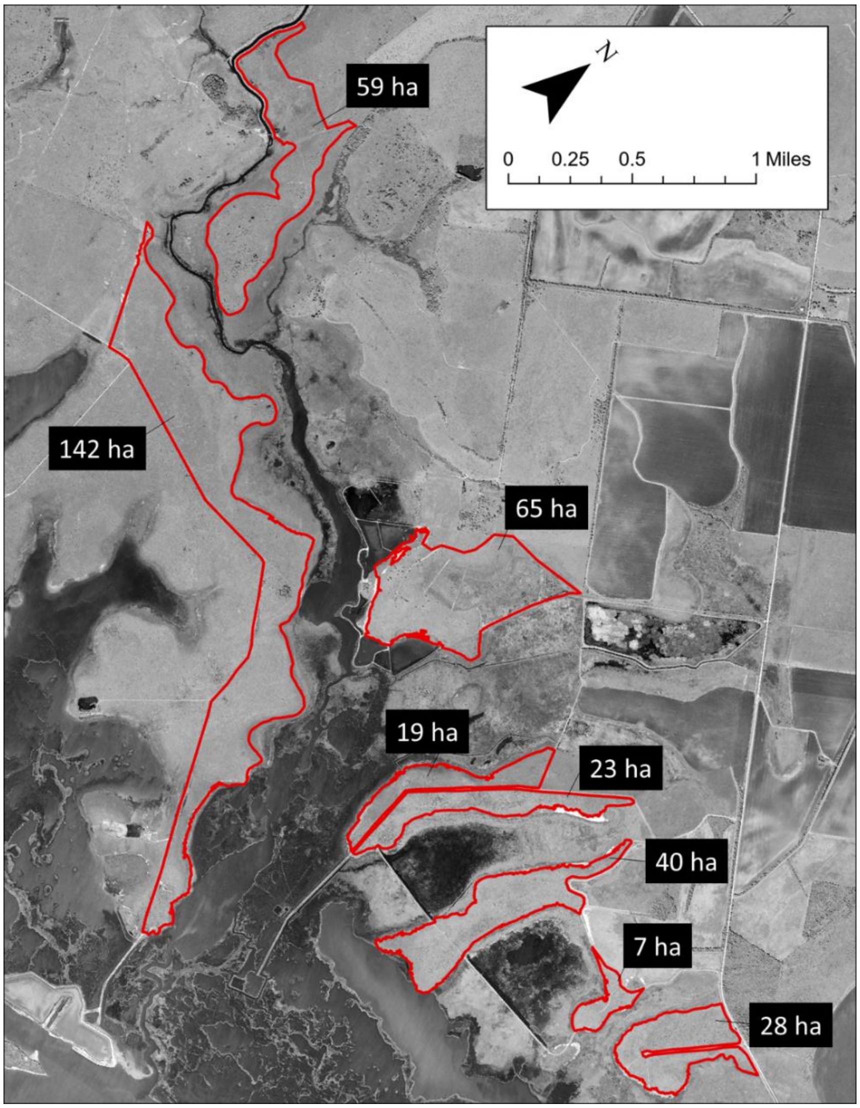

Figure 20. Potential upland areas for conversion to low marsh-accessible drainage areas.

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 a distance of 50 meters from current water, the effective watershed would increase by 107 hectares. At a distance of 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 of these suggested upland areas were converted, including the ones depicted in Figure 20, then approximately 600 hectares would be added to the effective watershed.

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. To increase the quantity of inflow by increasing the effective watershed area, more severe actions would need to take place.

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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