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Estimating Freshwater Inflows for an Ungauged Watershed at the Big Boggy National Wildlife Refuge, USA

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Abstract: Bays and estuaries rely on freshwater inflows to maintain the salinity gradient necessary to sustain their fisheries. Reduced freshwater inflows, particularly during summer seasons, can be detrimental to the health of these systems. Despite an extensive network of streamflow gauges in the U.S., many coastal watersheds remain ungauged. The primary objective of this study was to develop methods to build a water budget for an ungauged watershed using limited data to determine the watershed contribution of freshwater to an at-risk bay system. This method was developed and tested for Big Boggy Creek, which flows into East Matagorda Bay (EMB), Texas. The streamflow into and out of Big Boggy Creek was quantified at key upstream and downstream sites. Over the summertime study period, we found average monthly freshwater inflows of 244 megaliters (ML). A simple inflow decision tool was developed to assist resource managers in estimating freshwater inflows during the summer months in the study area. Two recommendations are provided to increase freshwater inflows to EMB, with the most approachable option being purchasing water from a regional river authority. The framework developed herein can be modified and applied to ungauged watersheds to budget, model, and predict freshwater inflow contributions.

Keywords: East Matagorda Bay; national wildlife refuge; freshwater inflows; bays and estuaries; coastal wetlands

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1. Introduction

Bays, estuaries, and coastal wetlands depend on an adequate supply of freshwater from inland rivers [1]. Freshwater inflows are critical to the survival of estuarine organisms through two main avenues: maintaining the salinity gradient and providing sediments and nutrients to the system [2]. Bays along the Texas Coast span the salinity gradient from Galveston Bay on the Upper Texas Coast, containing salinities of 1.8 to 28 practical salinity units (PSUs), to the Laguna Madre on the South Texas Coast with salinities equal to or greater than 35 PSUs. Each respective bay system and its aquatic inhabitants have adapted to its freshwater inflow regime and salinity gradient. For example, while oyster reefs are uncommon in the hypersaline Laguna Madre, what oysters are present have adapted to the hypersaline conditions and may not survive at lower levels of salinity [3]. Conversely, if inflows become limited in bays with typically low salinity, we may expect to see salinities reach levels that are too high for local flora and fauna to tolerate. An adequate freshwater inflow regime helps maintain ecological resilience in bays, estuaries, and coastal wetlands.

Sediment and nutrient influxes are another crucial aspect of freshwater inflows. Sediments delivered by inland rivers help maintain mudflat and salt marsh accretion [4,5]. Without these sediment inputs, salt marsh accretion is stymied and the ability for salt marshes to withstand relative sea level rise (RSLR) is threatened. The widespread loss of salt marshes endanger the health of bays and estuaries due to the large number of benthic and pelagic organisms that use salt marshes at some point in their life cycle [6].

Nutrients are also supplied by freshwater inflows, which support the higher levels of the trophic pyramid. Nutrient inputs can also arrive via freshwater inflows, and these can have positive or negative effects, such as supporting primary production through plankton and benthic organisms, or instigating algal blooms and eutrophication [7–9].

Thus, it is important to quantify the volume of freshwater inflows to bays, estuaries, and coastal wetlands. As of 2018, 8580 river gauges across the US measured both streamflow and water levels, and an additional 1750 only measured water levels [10]. The distribution of these streamflow gauges includes most major rivers yet leaves thousands of smaller watersheds ungauged. While flows for ungauged inland streams may ultimately be captured by streamflow gauges on the mainstem of a river further downstream, coastal watersheds flow directly into bays, estuaries, or the ocean. Therefore, the flows from a large majority of ungauged coastal watersheds are never quantified. Without this knowledge, coastal managers cannot establish environmental flow standards for bays and estuaries.

East Matagorda Bay (EMB) in Texas provides an excellent example of the types of problems that ungauged watersheds can present for coastal managers. For this estuary, the Colorado River of Texas no longer provides direct freshwater inflows to EMB after extensive human modifications re-routed its flow [11]. Today, the only freshwater inflows to EMB are attributed to a few small ungauged watersheds, such as that of Big Boggy Creek. These watersheds may not be providing adequate freshwater inflows to EMB, fostering concern that EMB will become increasingly hypersaline and negatively impact commercial and recreational fisheries. Freshwater inflows into EMB have been modeled since 2003 when the Texas Water Development Board (TWDB) began studying EMB [12]. However, the models were based on rainfall–runoff estimates from the Texas rainfall–runoff (TxRR) model, which does not use empirical inflow data due to a lack of gauged rivers in the watersheds that drain into EMB. Thus, we sought to bridge the gap between the modeled and actual freshwater inflows contributing to EMB.

The primary objective of this study was to build a water budget for an ungauged watershed and determine the contribution of freshwater to an at-risk bay system during the most critical summertime months. We sought to develop this approach for the Big Boggy Creek watershed in EMB and create a tool that could inform resource managers and policymakers in their efforts to set environmental flow standards. Specifically for the hot summer months, we sought to (1) quantify the average streamflow rates into and out of this watershed to build a water budget; (2) construct a data-driven model to estimate its contemporary inflow contributions; and (3) identify restoration actions to increase or supplement freshwater inflows into EMB. Finally, we discuss how this framework can be improved upon and applied to other ungauged coastal watersheds.

2. Materials and Methods

2.1. Study Area

Big Boggy Creek is a coastal watershed that drains into East Matagorda Bay (EMB) eight miles northeast of Matagorda, TX, USA (Figure 1). The southern Big Boggy Creek watershed consists of alluvium deposits created during the Holocene, deposited by the Big Boggy Creek and Peyton Creek watersheds. The southern reaches of the watershed are dominated by salt marshes. The northern Big Boggy Creek watershed lies on the Beaumont Formation from the Late Pleistocene. In the northern reaches of the watershed, Big Boggy Creek flows through cattle pastures, where the stream banks are 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 is located on the Middle Texas Coast and receives an annual average precipitation of 1120 mm. This location lies between the drier Lower Texas Coast, receiving 740 mm of precipitation, and the wetter Upper Texas Coast, receiving 1600 mm of precipitation. In 2020, the annual accumulated precipitation was approximately 100 mm below normal, indicating that our study was conducted in a year with 10% less precipitation.

Spring and summer are the seasons with the highest average precipitation. Tropical cyclones that form during the hurricane season from June to November greatly contribute to the annual precipitation volume. During the summertime months—defined here as July to September—the amount of precipitation in 2020 was five percent below the historical average, representing a closer to normal summertime compared to the year in total.

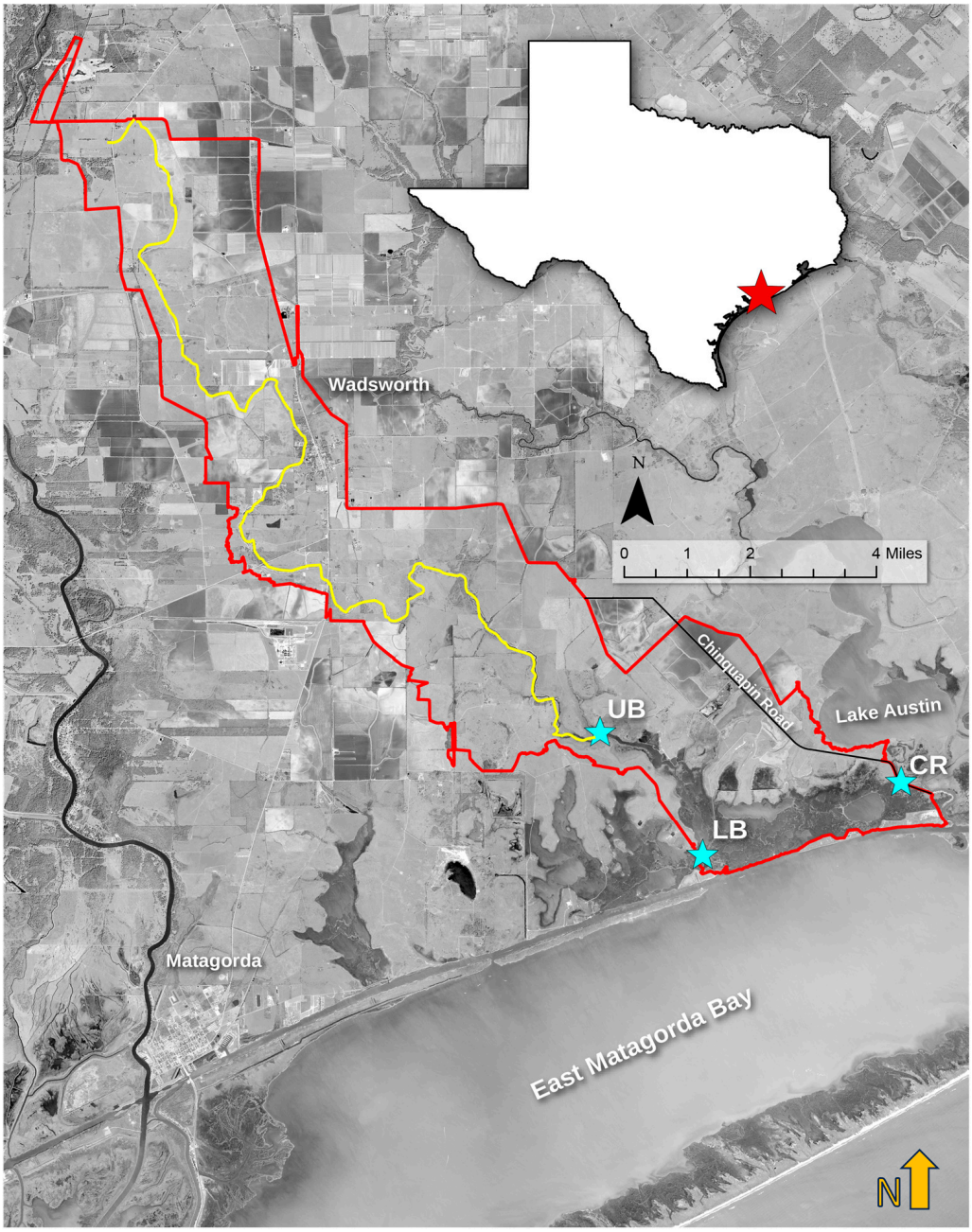


Figure 1. Project study area located 70 miles southwest of Houston, Texas, United States. Red star in inset map denotes study location in the state of Texas. The study area consisted of the entirety of the Big Boggy Creek watershed, outlined in red. Big Boggy Creek itself is shown as the yellow line. The blue stars mark the location of sensor stations at Upper Boggy (UB), Lower Boggy (LB), and Chinquapin Road (CR).

Hydrologically, Big Boggy Creek flows along the western portion of the drainage study area. A handful of small unnamed tributaries flow into Big Boggy Creek along its longitudinal gradient. There are also several irrigation canals or ditches that appear to connect to Big Boggy Creek near its headwaters northwest of Wadsworth, Texas. Historically, there

was one U.S. Geological Survey (USGS) streamflow gauge deployed on Big Boggy Creek near Wadsworth, Texas from 1970 to 1977. This gauge was located at the northern extent of the study area and as such, did not include most of the inflow sources that connect much further downstream or most of the volume that eventually reaches EMB. At approximately six stream kilometers from its mouth, Big Boggy Creek transitions from its narrow channel to a wider form dominated by *Spartina alterniflora* in an expansive salt marsh complex that occupies an area of almost 900 hectares. This salt marsh complex extends six kilometers eastward from Big Boggy Creek to Chinquapin Road (this road lies at the location of the easternmost star in Figure 1). Chinquapin Road serves as a line of demarcation between the Big Boggy Creek and Lake Austin watersheds. However, an unobstructed culvert beneath Chinquapin Road hydrologically connects the two watersheds. The Gulf Intracoastal Waterway (GIWW) forms the southern edge of the study area and separates Big Boggy Creek from EMB.

The study area encompassed the entire Big Boggy Creek watershed (Figure 1), which includes 1500 acres of the Big Boggy National Wildlife Refuge (NWR) under operation by the U.S. Fish and Wildlife Service (FWS). The remaining portion of the study area is privately owned and functions primarily as cattle grazing pastures. Ninety acres of rice paddies are present at Big Boggy NWR, all of which are seasonally planted with ryegrass to provide winter browse for waterfowl [13].

2.2. Quantify the Average Streamflow Rates into and Out of the Watershed to Build a Water Budget

The characteristics of the hydrological network were quantified using a series of sensors and gauges that were placed in the field during the hot summer months, in addition to remotely sensed data obtained from third parties. A model of the water budget for the watershed was then developed that incorporated the watershed area, field data, precipitation, evapotranspiration, and surface water evaporation. The resulting model helped determine the supplemental inflows required monthly to maintain inflows within a suitable historical range during the summer months of record.

Sensors and Data Collection

A series of sensors were deployed at three sites from 4 July 2020 through 17 September 2020 (see Table 1 for detailed deployment information). The various instruments included conductivity, temperature, and depth (CTD) dataloggers (CTD-Diver, Van Essen Instruments, Delft, The Netherlands), Solinst Leveloggers (Levelogger 5 LTC, Solinst Canada Ltd., Georgetown, ON, Canada), acoustic Doppler current profilers (ADCPs; Aquadopp Profiler 1 MHz, Nortek Group, Vangkroken, Norway), and a precipitation gauge (Onset tipping bucket rain gauge, Bourne, MA, USA). The CTD dataloggers contained a pressure sensor that measured the hydrostatic pressure of the water to calculate the total water depth, as well as a four-electrode conductivity sensor that measured the specific conductivity of the water—a proxy for salinity. The CTD dataloggers were set to record hourly measurements and deployed in a PVC pipe securely inserted into the stream bottom. All the CTDs were placed within a few cm from the bottom at each location, and measured salinity at only that depth. The ADCP units used acoustic Doppler sensors to measure the flow speed of the water column. The ADCP units were affixed to a steel frame, anchored to a fence post using coated steel cables, and placed at the center of the stream channel. The precipitation gauge was deployed near the other sensors and recorded the amount of rainfall occurring for each rainfall event. Additional hourly precipitation data was obtained from the Lower Colorado River Authority (LCRA) rain gauge at Matagorda, Texas (Gauge Matagorda 1 S), 10 miles southwest of the study area.

Table 1. Sensor deployment locations and dates.

Equipment Deployment Dates			
Sensor Group	**Sensor Type**	**Start**	**End**
1—Upper Boggy	ADCP	23 June 2020	19 September 2020
1—Upper Boggy	CTD	23 June 2020	19 September 2020
2—Lower Boggy	ADCP	3 July 2020	19 September 2020
2—Lower Boggy	CTD	3 July 2020	19 September 2020
2—Lower Boggy	Barometer	23 June 2020	19 September 2020
3—Chinquapin Road	Solinst	23 June 2020	19 September 2020
3—Chinquapin Road	HOBO rain gauge	23 June 2020	19 September 2020
3—Chinquapin Road	CTD	3 July 2020	19 September 2020

The sensors were deployed at three stations (Figure 1). The "Upper Boggy" station (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. The purpose of this station was primarily to measure the freshwater inflow entering the refuge by way of Big Boggy Creek. Vertical stratification in salinity likely occurred at the UB station, but we only recorded its temporal fluctuation near the bottom. The "Lower Boggy" station (LB) was placed further south within the salt marshes of Big Boggy NWR near the mouth of Big Boggy Creek where it intercepts the Gulf Intracoastal Waterway (GIWW). This second station also had an ADCP and CTD but primarily measured the saline tidal flow in and out of the watershed. The saline, tidal "Chinquapin Road" station contained a Solinst Levelogger and precipitation gauge placed along the eastern edge of the marsh complex, as well as an additional CTD gauge placed in Chinquapin Bayou east of Chinquapin Road. This group of sensors was put in place to identify the degree of hydrologic isolation of the marsh complex and its connectivity with Chinquapin Bayou. Unfortunately, the Solinst sensor that was deployed suffered a critical failure that rendered the data unrecoverable. The relationship between the Big Boggy Creek and Lake Austin watersheds were thus identified using only the CTD at Chinquapin Road.

The water level data from the CTD sensors and the flow rate data from the ADCP sensors were vertically referenced into North American vertical datum (NAVD88) units using a survey-grade Global Navigation Satellite System (GNSS; R10 model, Trimble, Westminster, CO, USA). 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. The hourly stream flow volumes were calculated by multiplying the ADCP-measured, depth-averaged water velocities in each 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. Bank erosion was negligible during the study period of three months, and so the cross-section itself did not vary over time. The upstream and downstream flows were determined using the ADCP directional measurements.

The evapotranspiration (ET) data was derived from NASA's MODIS satellite-based 8-day terrestrial ecosystem ET product (hereby referred to as MOD16; [14]). The MOD16 data product has a 500-m spatial resolution and is based on the Penman–Monteith equation for ET, using daily meteorological reanalysis data and 8-day remotely sensed vegetation properties. The MOD16 data does not include certain land cover classes, such as open water or wetlands, thus necessitating the inclusion of a data source for surface water evaporation. Surface water evaporation (E) was obtained from the TWDB Water Data for Texas database and multiplied by the area of open water and low marsh in the study area [15].

2.3. Water Budget

A water budget was developed using data from the CTD and ADCP sensors, LCRA precipitation measurements, MOD16 evapotranspiration measurements, and TWDB sur-

face water evaporation estimates to determine the amount of monthly freshwater inflows to EMB. To better parse out the inflow contributions, the water budget was divided into two sub-watersheds based on the UB and LB stations. For each sub-watershed, we calculated the direction and net volume of the surface water flows, total precipitation volume, total evapotranspiration volume, and total surface water evaporation volume. Assuming that groundwater boundaries will follow watershed boundaries, recharging groundwater will either discharge at similar longitudinal distances along the stream channel or discharge further downstream in the watershed, perhaps as submarine groundwater discharge into EMB.

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 4 July 2020 to 19 September 2020 to build the budget for the dates in which both the UB and LB ADCP stations were active. During this period, the precipitation balance was just below the mean for the period over the past several decades (see Results for more).

This July–August–September period (hereby referred to as summer) was uniquely important because it was during these summer months when temperatures were highest and hypersalinity or hypoxia can occur. The water budget variables were aggregated over the entire three-month period based on an initial investigation of the relationship between precipitation and flow, 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 have been limitations in the dataset due to the relatively short period of record. It is possible that the flows during our summer period of record did not reflect the flow patterns for other periods throughout the year, yet this was the challenge that we set—to identify inflows for previously ungauged watersheds with limited data availability.

For each station, an imbalance between the upstream and downstream flow volume was found based on the net directionality of the flows within the ADCP dataset. Upstream flows could include both incoming tides and storm surges. Downstream flows could include outgoing tides and freshwater flows from the upstream reaches of the watershed.

The precipitation volume was then calculated for the sub-watersheds that fed into each station. To do this, precipitation data was obtained from the Water Data for Texas website operated by the Texas Water Development Board (TWDB) [15]. This precipitation dataset combines data from different precipitation stations within a quadrant to estimate precipitation throughout the entire quadrant. These precipitation estimates were then multiplied 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-m digital elevation model (DEM). Two total watershed products were produced to delineate the separate sections of the landscape that uniquely contributed inflowing freshwater to the UB and LB stations.

The "effective watershed area" was defined as the area which corresponded to the observed volume of overland flows under a theoretical scenario in which there was no infiltration into the soil, calculated as the product of the total watershed area and the effective watershed coefficient. The effective watershed coefficient was calculated as the quotient of the net downstream flow volume and the total precipitation volume. The difference between the ADCP-measured net flow volume and TWDB-identified total precipitation volume represented the influence of various watershed processes on streamflow. Such processes include ET, E, groundwater recharge/discharge, antecedent soil moisture conditions, and the infiltration rate.

To determine the net contribution of freshwater inflows to EMB, the change in storage (ΔS) was calculated for the UB station only as the following.

$$\Delta S = P - ET - E \pm SW \pm GW \quad (1)$$

where P is the total precipitation volume (m^3), ET is the total evapotranspiration volume (m^3), E is the total surface water evaporation volume (m^3), SW is the net surface water flow (m^3), and GW is the net groundwater exchange (m^3). Since we were able to obtain separate data inputs for both ET (from the aforementioned MOD16 data product) and E (from the TPWD), we chose to model them as unique variables. Based on an initial assessment of the data from both UB and LB (see the below section), nearly all of the freshwater contribution from Big Boggy Creek to EMB arrived from upstream of the UB location. Moreover, the LB sub-watershed tidal saltwater flows were not wholly captured by the instream sensors at LB due to the presence of additional inflow and outflow locations (i.e., the previously mentioned connection to the Lake Austin watershed at Chinquapin Road, see the below section for more). For these reasons, the equation was only applied to the data from the UB station to calculate the net freshwater inflows.

3. Results

The water level and salinity at all three stations were affected by both tides and precipitation events (Figure 2). During the period of record, two tropical cyclones impacted the area—Hurricane Hanna and Hurricane Laura. The precipitation observed during this period was 240 mm (9.5 in.). The total precipitation volume during the study period was approximately 24,450 ML (megaliters), dwarfed by the 42,000 ML of combined ET and E. The precipitation, ET, and E metrics will be further broken down by sub-watershed in a subsequent section below.

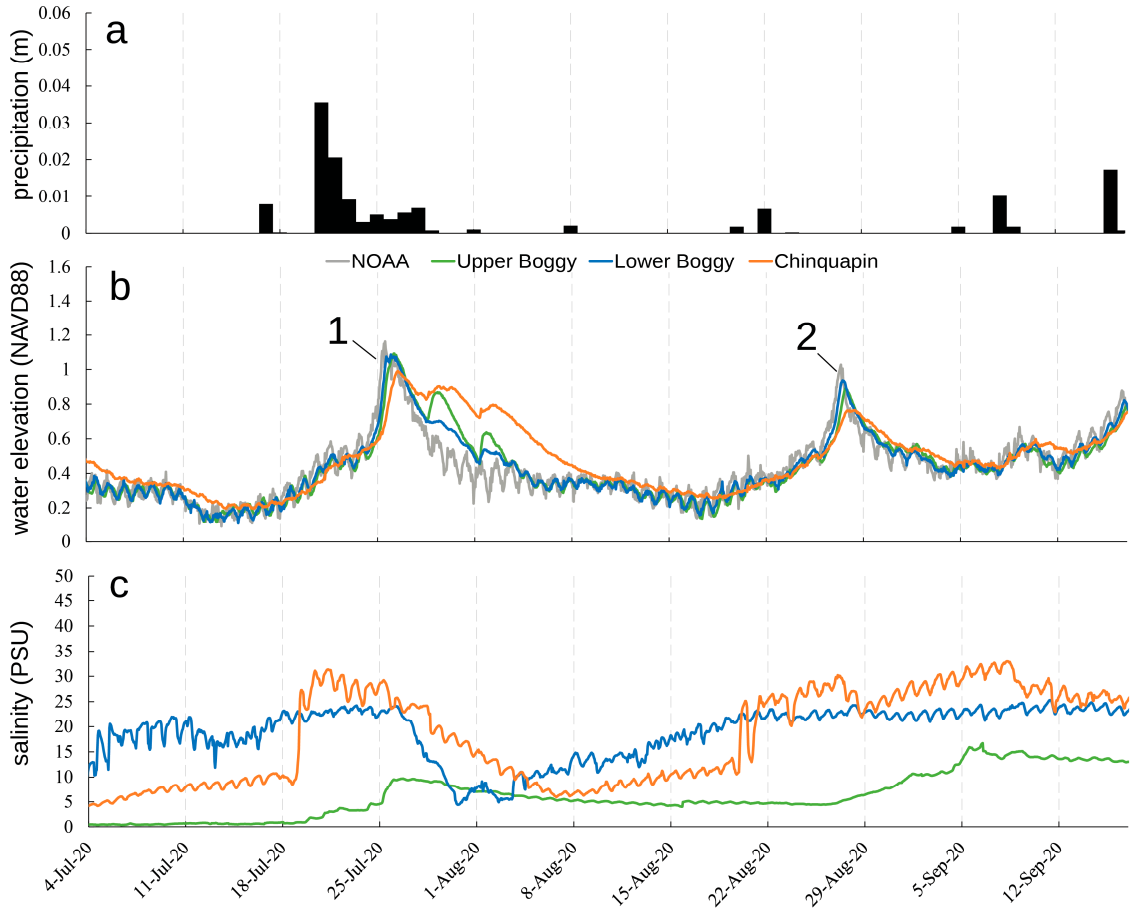


Figure 2. Precipitation (**a**), water elevation (**b**), and salinity (**c**) as obtained from the LCRA rain gauge (**a**) and the deployed CTDs (**b**,**c**). The water elevation is in NAVD88 m. The salinity is in practical salinity units (PSUs), which is similar to a parts per thousand (ppt) measurement. The named tropical cyclones that occurred during the study period and the resulting peak water elevation are indicated as Hurricane Hanna (1) and Hurricane Laura (2).

The UB station was most responsive to precipitation, as shown with brief peaks after the precipitation events, followed by a rapid return to its baseline. At the LB station, the water level was largely driven by tides and storm surges. Precipitation could have also caused 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 22 September 2020). The Chinquapin Road station was the most unique of the three. At times, the Chinquapin Road station appeared to respond differently to precipitation events with prolonged high water levels following these events. The unique pattern suggests that the Chinquapin Bayou flows were more influenced by the Lake Austin watershed. Additionally, the daily tidal range at Chinquapin Road was 4 cm—the lowest of the three stations—indicating a more hydrologically isolated location.

The ADCPs provided stream flow volume and direction (Figure 3). When coupled with the water elevation data from the accompanying CTD, we obtained a more complete understanding of the flows at the UB and LB stations. The volume of flow between UB and LB differed drastically. At the peak of Hurricane Hanna (25 July 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 varied during regular tidal periods, a difference of almost 5000 m^3/hour between the incoming and outgoing tides at LB, and a difference of only 200 m^3/hour at UB. As shown in Figure 3b, the downstream flows at LB were not in balance with the upstream flows. This supports the theory that there were alternate outlets for flows at LB, in addition to Big Boggy Creek.

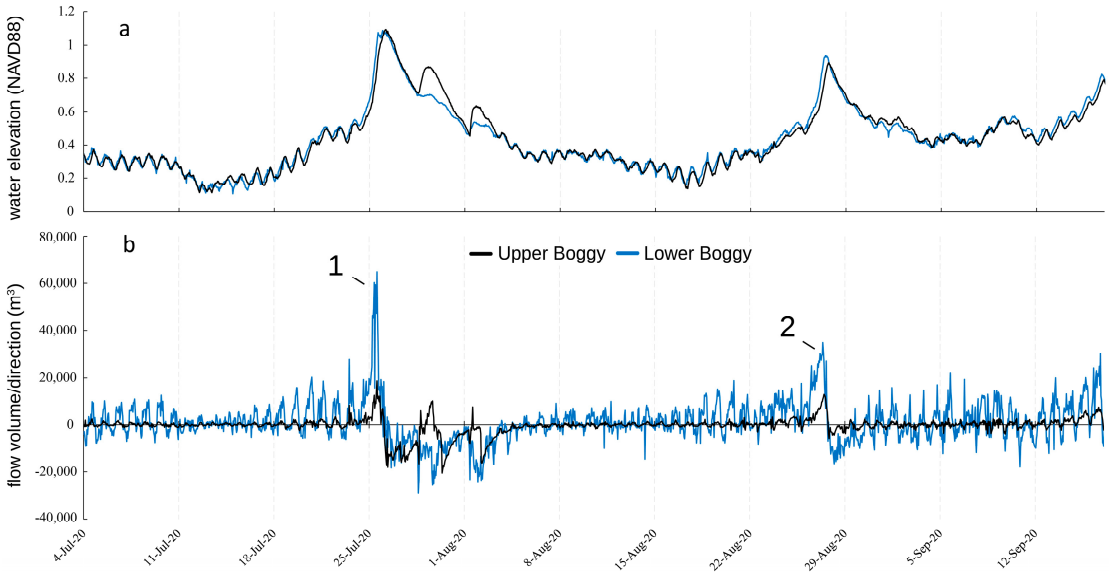


Figure 3. Water elevation (**a**) and flow volume/direction (**b**) measured by the ADCPs at the Upper and Lower Boggy stations. The positive values indicate upstream flows, and the negative values indicate downstream flows. Hurricane Hanna (1) and Hurricane Laura (2) were captured by the ADCPs and are indicated at their respective peak upstream flow volumes.

Since the groundwater contribution was not directly measured, the overall net change in storage as defined in (1) was difficult to quantify. At the UB sub-watershed, the total precipitation volume for the UB sub-watershed was approximately 18,102 ML, which was less than the estimated combined *ET* and *E* volume of 21,353 ML (Figure 4). These values represented a net loss of water from the sub-watershed. However, a measured net downstream flow of 728 ML was present, suggesting that a combination of groundwater and flows from unknown sources contributed up to 4000 ML additional water to the overall water budget. Additional flows from rice paddies in the study area is an example of potential flows from unknown sources.

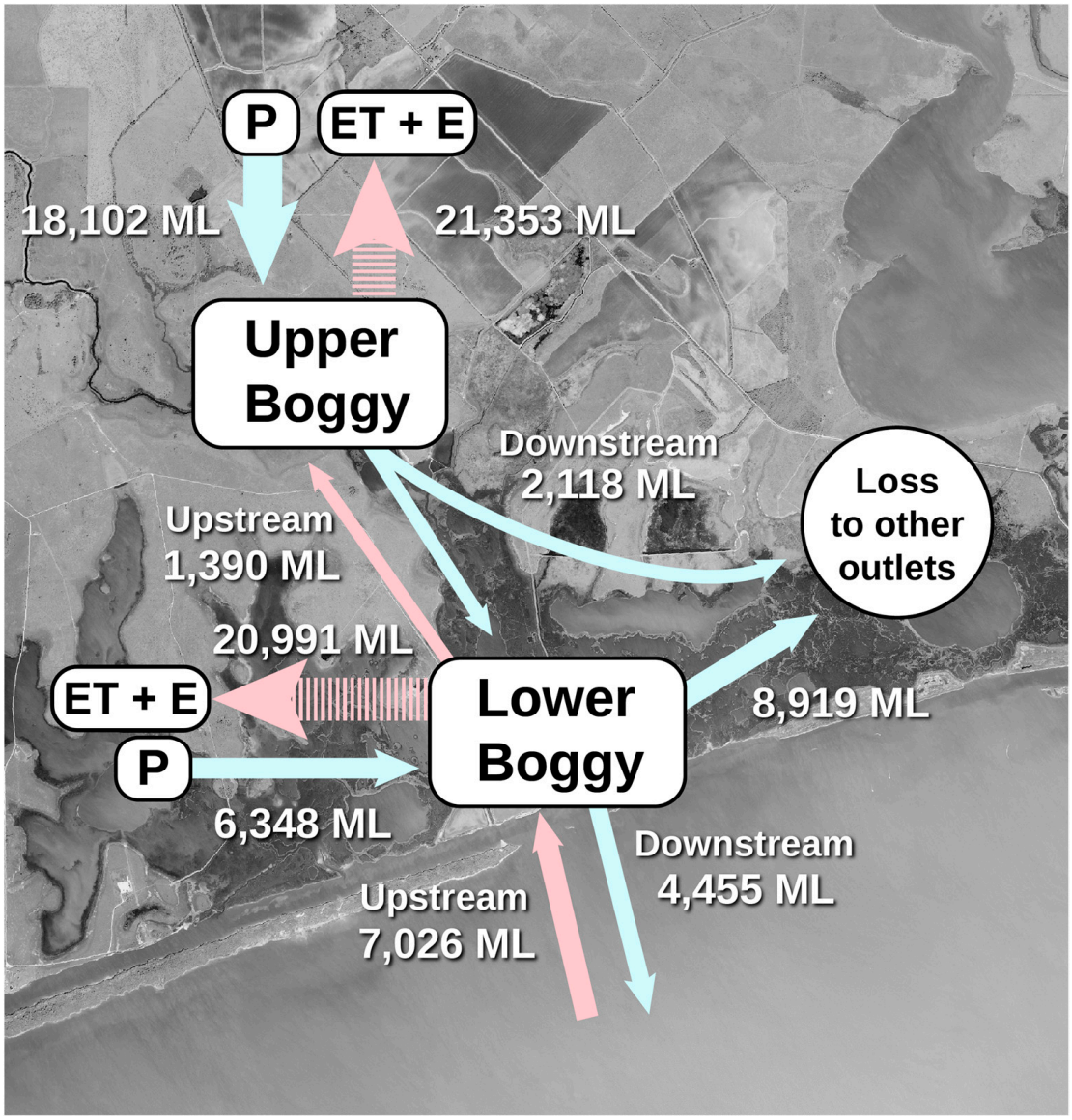


Figure 4. A visualization of the water budget for Big Boggy Creek from July 2020 to September 2020. The arrow thickness is directly scaled with the volume, where UB evapotranspiration plus evaporation (*ET* + *E*) was the greatest volume and the upstream flows from UB was the least volume. The units are in megaliters (ML). The total precipitation (*P*) represents the non-tidal inputs to the watershed, contrasted with *ET* and *E* as the largest outputs of the system.

The total watershed area upstream of the UB station was 7927 hectares. The quantity of precipitation multiplied by this area resulted in a far higher value than the 728 ML observed inflow volume. The resulting effective watershed coefficient was 0.04. Thus, the effective watershed area was calculated as 318 ha (Figure 5). Interestingly, the effective watershed area was only slightly greater than the area of wetland and water cover in the UB sub-watershed. The total wetland and water areal coverage in the UB sub-watershed was 177 ha. These metrics suggest that under the antecedent conditions present in this study, very little overland flow contributed to stream flow in Big Boggy Creek.

At the LB station, the total upstream flow during the study period was 7026 ML, consisting of incoming tides and storm surges. The total downstream flow measured 4455 ML, consisting of outgoing tides and freshwater flows. This flow pattern resulted in a net upstream flow of 2571 ML. Due to the much larger proportional area of wetlands and

surface water, the combined *ET* and *E* greatly outweighed *P* at a volume of 20,991 ML to 6348 ML, respectively.

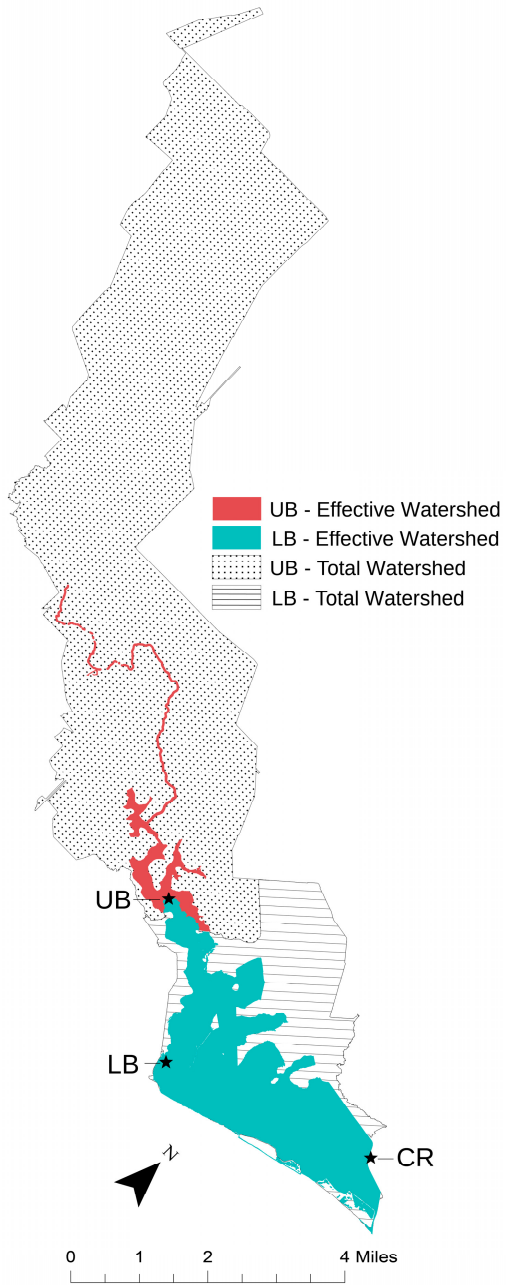


Figure 5. The Big Boggy Creek watershed delineated into four sections: the Upper Boggy (UB) effective watershed, the Lower Boggy (LB) effective watershed, the UB total watershed, and the LB total watershed. The black stars depict the sensor locations for Upper Boggy (UB), Lower Boggy (LB), and Chinquapin Road (CR).

We found that the total watershed area upstream of the LB station—and downstream of UB—was 2780 ha (Figure 5). The net upstream flows at LB made it less straightforward to calculate the effective watershed area based on the percentage of the observed precipitation volume. Instead, the effective watershed area was estimated based on the land cover proportions. The effective watershed area was calculated as 1532 ha; 55% percent of the total potential area. This percentage was much higher than that of the UB sub-watershed due to the much greater area of wetlands and open water in the marsh complex east of the LB station.

It is important to note the large net upstream imbalance in the water budget at LB. In total, there was approximately 9648 ML unaccounted for at the LB station. This total volume was the sum of the net upstream flows (2571 ML), sub-watershed precipitation volumes (6348 ML), and downstream flows from the UB sub-watershed (729 ML). This large surplus of water suggests that there were other significant outlets in the marsh complex (Figure 6). These outlets appeared to only connect with the GIWW when water levels exceed 0.45 m (NAVD88). The only outlet that may not be water level dependent was the culvert beneath Chinquapin Road. However, due to the sensor failure in the marsh complex, we were unable to quantify how much water exited the watershed through this outlet. Groundwater flux may account for some of the missing surface water; however, it likely does not account for much of the volume as tidal waters are generally not expected to recharge groundwater at any appreciable rate due to a lower hydraulic head pressure.

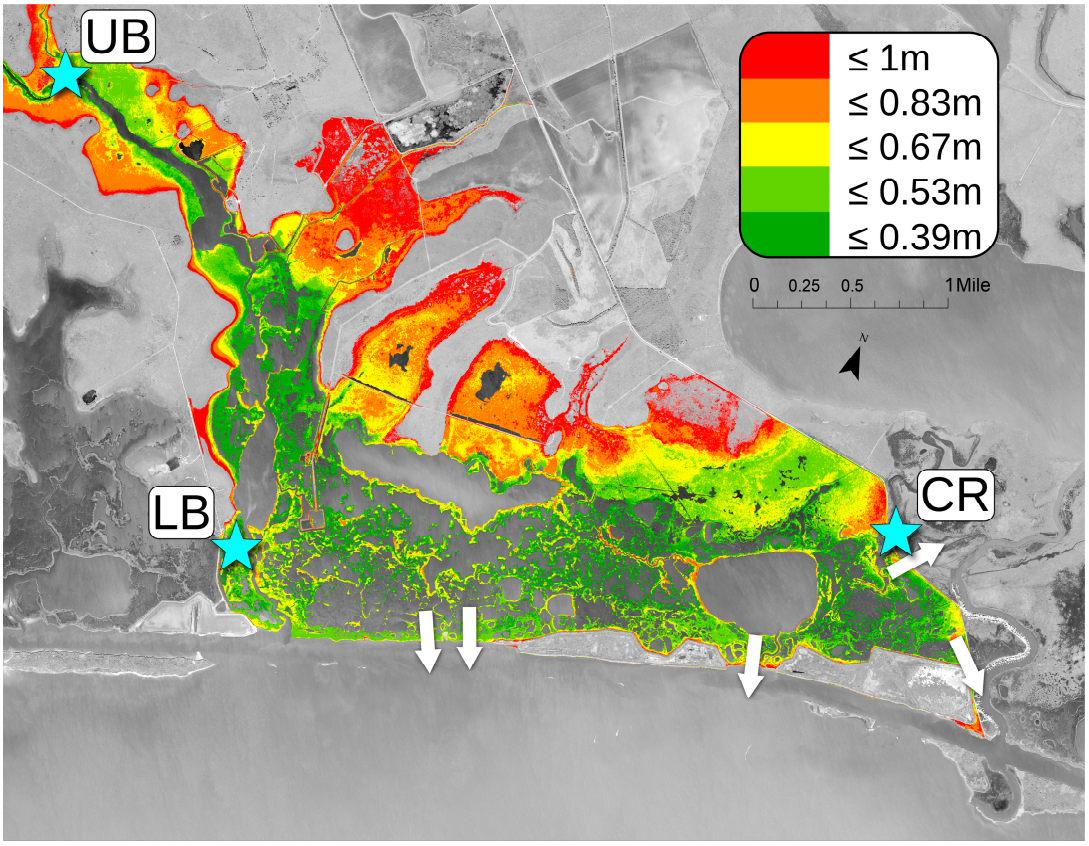


Figure 6. Alternate outlets for flowing water (white arrows) and water elevations needed to flood portions of the watershed (NAVD88 m). The Upper Boggy (UB), Lower Boggy (LB), and Chinquapin Road (CR) sites are depicted as blue stars.

There were two key outcomes to this research. First, this was the only study to have estimated the freshwater inflow contribution to EMB using empirical flow data. This data was obtained and analyzed for the summer months from July to September, a critical period in which reduced freshwater inflows may result in hypoxic and hypersaline conditions in conjunction with higher temperatures. There are currently no environmental flow standards in place for EMB, nor is there infrastructure for direct freshwater delivery. The results of this study will help inform resource managers and policymakers in their efforts to set environmental flow standards. However, additional data should be obtained for complete year-round flows. Two options for increasing freshwater delivery through the Big Boggy Creek watershed are presented in the following section.

Second, we presented a general framework for estimating freshwater inflows that can be replicated in other tidally influenced watersheds. Ungauged watersheds far outnumber

gauged watersheds in coastal zones across the globe. While region-specific variables need to be accounted for, researchers in virtually any coastal setting can use our study as a framework to determine freshwater inflows in historically ungauged watersheds. Improvements to our framework are discussed in greater detail below.

3.1. Potential Management and Restoration Actions to Increase Inflow

As part of its mission, the LCRA sells water to users in the Lower Colorado River basin for municipal, agricultural, and wildlife management uses [13]. Existing agriculture in the area utilizes irrigation canals to transport water, and at least one canal is adjacent to the NWR [13]. In 2021, water purchases from the LCRA were available at a rate of $81.55 per ML delivered ($66.14 per acre-foot; LCRA Staff, personal communication, 26 October 2021). If the historic 2011 drought happened in the summer of 2023, it would cost ~$14,000 per month to return the conditions to within the normal flows. To put this cost into perspective, the ex-vessel value for commercial fisheries landings in EMB was $317,458 in 2019 alone [16]. The cost of purchasing freshwater is, therefore, relatively low compared to the economic value of fisheries in EMB.

An alternative course of action is to think about how much land is needed to capture precipitation and convert it to supplemental inflow—in other words, to increase the effective watershed area and rely on precipitation rather than purchasing supplemental flows. In addition to ensuring additional inflows, these practices would also create salt marsh habitats. To further assist resource managers, we developed a decision tool to better synthesize our data and put it into the hands of resource managers and stakeholders. The excel-based tool requires a user to input monthly precipitation data and estimate the freshwater inflow volume based on the observed effective watershed coefficient. The estimated effective watershed area is also calculated, along with comparisons to estimated historical inflows.

Resource managers can use this inflow decision tool to estimate the additional effective watershed area needed to offset the decline in inflows. Using the historic 2011 drought as an example, an additional 885 hectares would be needed to reach the mean trend. A series of ponds located immediately north of Big Boggy NWR present themselves as potential restoration targets, but the effective watershed area would increase by only 17 hectares. An additional 386 hectares of upland areas could also be graded to drain into an existing channel more readily and facilitate upslope marsh migration in response to sea level rise. However, most of these lands are privately owned and incentives would be necessary for landowner cooperation (e.g., fee simple land acquisition or conservation easements). In summary, the most realistic and immediately impactful action would be to purchase water through the LCRA during times of drought.

3.2. Limitations and Directions for Further Study

The framework presented here can be applied to ungauged coastal watersheds throughout the globe. Without making any significant changes to the methodology, researchers can similarly develop a water budget for a discrete portion of the year. However, we have identified three modifications that could be made to improve our results.

Groundwater flux is notoriously difficult to quantify in aquatic settings, requiring specialized equipment and complicated methods. The lack of information on this flux was a limitation to our study. Previous studies on the Beaumont Formation sediments present in the study area suggested that there was low vertical hydraulic conductivity but a relatively high horizontal hydraulic conductivity [17,18]. This indicated that there was likely to be an exchange between surface water and groundwater; however, a lack of region-specific data hindered our ability to estimate the net porewater exchange. In a review of salt marsh hydrogeology, ref. [19] found a positive relationship between the tidal range and submarine groundwater discharge. Given the micro-tidal setting, we may not have expected groundwater exchange to be a significant contributor, however, it may have provided up to 4000 ML to the UB sub-watershed. Since we did not directly

measure groundwater, there may have been other contributors to the 4000 ML volume. Future studies should consider implementing seepage meters [20], mini-piezometers [21] or radioactive isotopes [22] to quantify the surface water–groundwater exchange.

The precise contribution of evapotranspiration (*ET*) and surface water evaporation (*E*) to the water budget model were not directly captured in this study. Instead, these metrics were obtained through remotely sensed or interpolated means. The MOD16-derived *ET* data was spatially and temporally coarse compared to the resolution of the flow and precipitation data. Despite this shortcoming, it was likely adequate to get an approximate measure of *ET* during the study period. The same can be said for the *E* data obtained through the Water Data for Texas portal. Future studies should plan to capture the data necessary for calculating *ET* in the study area or ensure there is a sufficient third-party source of this data. Quantifying the loss via *ET* could be accomplished using various methods. Lysimeters reveal plants' water use by continuously weighing a block of soil [23,24]. This method is intrusive and difficult, requiring the excavation and installation of a lysimeter. Alternately, one could measure vapor flux with an eddy covariance (EC) tower. EC towers use micrometeorological techniques to measure various exchanges, including water, between the biosphere and the atmosphere [25]. These towers can be expensive [26,27], ranging in cost from $16,000 to $25,000. A more affordable alternative is to deploy weather stations that measure each needed parameter to calculate *ET* using the Penman–Monteith equation. Such weather stations can be obtained from various sources for approximately $2000. Proper care should be taken to include *ET* as an integral part of the study, especially in regions where *ET* rates are high.

As with nearly all studies, more data—in this case a longer time series—would lend itself to a more accurate budget and model. For most ungauged watersheds, however, there are constraints due to geographical isolation, limited financial resources, and unforeseen events. For example, we withdrew our ADCP sensors from the field after only three months due to the threat posed by Tropical Storm Beta. This period had two hurricanes and several thunderstorms and should have provided a good sample of the potential range of freshwater inflows in our study area from July to September. However, it is possible that the Big Boggy Creek watershed could behave differently under different antecedent conditions. For example, a summertime season following a wet spring will likely have a significantly different streamflow than if it followed a dry spring.

For this reason, a second deployment was conducted at UB from April to June 2021 to gather additional data with the intention of validating our original deployment data. Instead, we found that the effective watershed coefficients during this second deployment were eighteen times greater than during the first deployment. There were likely several factors that influenced the effective watershed coefficient during this period. For instance, comparing the second deployment to the first, the average temperature was twelve degrees cooler, the *ET* volume was 2000 ML less, and precipitation events occurred more rapidly. The latter phenomenon was particularly interesting, as it suggested that the soil moisture content was an important predictor in stream flows. Future studies should seek to quantify soil moisture throughout the study period. Studies conducted in forest [28] and blanket peatland [29] settings have demonstrated a similar phenomenon. Additionally, there may be unidentified watershed-specific features that do not provide freshwater inflows until a certain precipitation volume or intensity threshold is surpassed. A larger dataset that encompasses different seasons and various extremes is the simplest way to address these concerns. However, a lack of data was the key driver behind the motivation for this study and tends to be a ubiquitous issue for small watersheds. Even when extreme weather, a lack of funding, faltering equipment, or geographical isolation come into play, one may still need to develop a water budget. The ideas outlined in this study can help guide researchers to develop sound water budgets in coastal watersheds throughout the globe.

4. Conclusions

This study provided the first measure of empirical freshwater inflows into East Matagorda Bay (EMB) from Big Boggy Creek. Over the summertime study period, we found average monthly freshwater inflows of 244 megaliters (ML). These inflows were observed despite measuring the flows during summer with greater evaporation and evapotranspiration than precipitation, suggesting that there must be a source of freshwater outside of precipitation. Groundwater likely plays a greater role in the region than previously assumed. The findings also provide valuable insight for policymakers in support of establishing environmental flow standards for EMB. For example, if the historic 2011 drought happened in the summer of 2023, it would cost ~$14,000 per month to return the conditions to within the normal flows, a cost that is an order of magnitude lower than the estimated economic benefit to the fisheries of the bay. Additionally, this study introduced a methodological approach that can be replicated and improved upon in other ungauged watersheds to quantify freshwater inflows to bays, estuaries, and coastal wetlands.

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