Water Quality and Nutrient Dynamics Associated with Freshwater Delivery

Final Report

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Acknowledgments

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Executive Summary

Municipal water demands in Texas have risen substantially, increasing competition among water users and periodically leaving certain demands unmet. Water scarcity is expected to intensify as air temperatures rise, droughts become more frequent or severe, and municipal demand continues to grow. Although legislated efforts to quantify and address environmental water needs in Texas have been underway since the 1970s, sustaining the water necessary to support healthy rivers, streams, and estuaries will be increasingly difficult and will require additional interventions.

The Texas coast and its estuaries support numerous species of ecological and economic importance. Several of Texas's leading commercial fisheries, including brown shrimp, white shrimp, blue crab, and oysters, are estuarine-dependent species that rely on freshwater inflows and low-salinity habitats in bays and estuaries. In 2024, these fisheries generated $90.5 million in commercial landings. To help support these and other key estuarine species during drought, a novel management approach known as "focused flows" was proposed to maintain ecological function in key upper estuarine habitats using substantially smaller volumes of freshwater. Managing limited water resources in support of coastal habitats is becoming increasingly important as water scarcity worsens and land use and agricultural practices continue to shift along the Texas coast.

During the 20th century, agricultural development transformed much of the Texas coast, converting extensive coastal prairie and upland wetlands for agricultural use. Although these agricultural lands provide important ecosystem services, changing land and water use patterns are increasing pressure on both the lands themselves and the services they sustain. On the mid and upper Texas coast, rice farming and wildlife management practices which shallowly flood agricultural fields with irrigation water create surrogate freshwater wetlands for migratory birds on the Central Flyway and contribute freshwater inflows to upper estuarine environments. However, rice production has declined, in part because irrigation water has become less available.

Texas Water Trade and its project partners, Galveston Bay Foundation and Manomet Conservation Sciences, work with regional water suppliers to purchase irrigation water that supports natural and agricultural ecosystems throughout Chambers County. Since 2022, the project team has partnered with landowners and managers to flood agricultural fields for migratory birds and other wildlife. During drought conditions in 2023, salinity in Onion Bayou, an adjacent tidal stream, reached polyhaline levels (>20 PSU), highlighting the need for a more responsive approach to managing salinity and other apparent water quality impairments in tidal streams that serve as important upper estuarine habitat.

This study examined how a highly modified tidal stream environment altered by saltwater barriers, channelization, and surrounding land use responded hydrologically to rainfall and controlled freshwater additions under a focused flows approach. In early summer 2025, 295 acre-feet of irrigation water was introduced into the Onion Bayou tributary, followed by an additional 185 acre-feet in early fall. Water quality response varied spatiotemporally throughout the study area and was responsive to tidal forcing, seasonality, and wet and dry conditions, which in addition to governing water chemistry, influenced the effect of runoff and thus inorganic and organic nutrient concentrations in Onion Bayou. Monitoring results indicate that controlled freshwater introductions may help alleviate issues with water quality degradation or support estuarine productivity in tidal streams, however, additional studies using a targeted experimental design are needed to further evaluate their effectiveness. Future work should also characterize the habitat value of highly modified tidal streams for key estuarine fishery species to determine whether freshwater resources can effectively improve habitat conditions for these species.

Introduction

Municipal water demand in Texas has increased 171% since the 1970s (TWDB), resulting in increased competition among water user groups and periodically leaving certain water demands unmet. Texas's current population of 32 million is projected to grow to 52.3 million people by 2080 with water user demand increasing to 17.4 million acre-feet and water supplies decreasing by 1.5 million acre-feet (TWDB 2026). Alongside growing water demand, climate projections predict that warmer temperatures will result in more frequent and severe droughts in Texas (Nielson-Gammon et al. 2024), with major implications for the state's water supply and environmental water demand, i.e., the freshwater necessary to maintain functioning ecosystems and living resources.

On the Texas coast, freshwater from rivers and streams mix with marine water creating the necessary conditions for estuarine species to flourish. Four of Texas's most valuable commercial fishery species (i.e., white shrimp, brown shrimp, eastern oysters, and blue crabs) are estuarine-dependent species that rely on freshwater inflows and low-saline nursery habitats with commercial landings valued at $90.5 million in 2024 (NOAA). These species in turn support higher trophic levels of critical saltwater recreational fishery species (e.g., redfish, speckled trout, and southern flounder) that support $3.7 billion in economic output (Southwick Associates, 2020).

Unfortunately, as anthropogenic demands increase less water is available to meet environmental demand, particularly at the coast. Johns et al. (2004) modeled a scenario under which all permitted water rights in Texas were exercised and wastewater returns were decreased by 50% through reuse practices to meet future anthropogenic water demand. The study found that that 5 out of 7 of the state's major bays would experience insufficient freshwater inflows necessary for supporting healthy estuarine productivity and species recruitment during key periods (i.e., freshwater inflows below drought tolerance levels for a six-month period from March-October and reduced freshwater pulses from March-June increased) compared to naturalized conditions without anthropogenic demand.

The passage of Senate Bill 3 in 2007 by the 80th Texas Legislature (SB3) directed the development of environmental flow standards (i.e., guidelines for meeting necessary instream flows and freshwater inflows for maintaining healthy rivers and estuaries) and established a process for dedicating unappropriated water and incorporating standards into new surface water permits following its passage. However, these actions failed to consider that much of Texas's surface water was already allocated prior to the passing of the legislation. Additionally, environmental flow conditions outlined in surface water permits that include environmental flow standards can be nullified or suspended during drought and water shortages to minimize adverse impacts to municipalities and industries.

While Texas water law does not allow for the issuance of new appropriative surface water rights for environmental use, it does allow for the amendment of existing water rights to change or add environmental protections through the addition of instream flow as beneficial use. These protections are increasingly incentivized through the use of water markets which involve the voluntary transfer of water rights from willing sellers to willing buyers and have the potential to aid in meeting environmental water demand (Garmany & Wight 2023). Water market transactions can take many forms and include agreements such as long-term or single-year lease or contract sales options, crop fallowing agreements, or permanent water right acquisitions. Under each of these transaction scenarios, water assets can be managed in ways that increase the quality and quantity of environmental flows.

Unfortunately, procuring the volumes of freshwater necessary to meet environmental flows standards developed following the passage of SB3 are increasingly impracticable as water availability declines due to rising air temperatures and drought. A novel management paradigm, “focused flows”, was proposed to address these challenges at the coast by maintaining ecological function of key estuarine habitats during drought using significantly less volumes of water in upper estuarine environments (Montagna et al. 2021).

Upper estuarine environments including tidal streams (e.g., bayous, creeks, and sloughs), estuarine lakes, and deltaic wetlands are most amenable to a focused flows approach given their proximity to existing water supply infrastructure. which can aid in diverting stored, run-of-river, and and/or water returns into these environments. Additionally, their limited size, shallow depths (1-2 m), and increased water residence times, generally due to these environments being partially enclosed, could demand less volumes of water to invoke a hydrological and ecological response. In fact, these same characteristics and their limited watershed size make these environments particularly vulnerable to regional drought, development, and changes in water use patterns, all of which can impact freshwater inflows into these environments.

By the mid-20th century, 5.5 million acres of the Texas coast had been converted to agricultural use (UFWS 1997). In addition to directly replacing coastal prairie and upland wetlands, agricultural development (e.g., construction of drainage ditches, irrigation canals, roadways, and stream channelization to manage runoff and reduce flooding) inadvertently altered coastal hydrology impacting downstream wetlands and facilitating saltwater intrusion (Feagin et al. 2020).

Despite these implications, agricultural lands provide numerous ecosystem services including food and fiber production, improved air and water quality, and essential wildlife habitat valued at $629/acre and face similar pressures due to Texas's growing population and water demand (Putman et al., 2022). For example, conventional rice production involves the shallow flooding (> 6 inches) of leveed agricultural fields to deter the growth of undesired vegetation which inadvertently provides habitat and food resources for numerous migratory birds on the Central Flyway and contributes freshwater inflow benefits to coastal wetlands and upper estuaries. To an extent, rice farming replicates the role of natural coastal prairies and upland wetlands. However, Texas has lost over 500,000 acres of rice acreage since the 1970s due to various factors such as unfavorable market values, high production costs, and water availability (Levihn-Coon, 2024).

In some coastal regions of Texas, upstream and local municipal or industrial demands increasingly outcompete agricultural demand periodically limiting the availability of irrigation water for rice irrigation and the shallow flooding of managed agricultural fields for waterfowl habitat. Similar to rice cultivation, waterfowl management practices typically involve flooding of rice fields after harvest or fields dedicated to moist-soil management that promote the establishment of wetland vegetation beneficial to migratory birds. When irrigation water is unavailable, the extent of freshwater habitat available to migratory birds declines, as do the freshwater inflow benefits that these practices can provide to upper estuarine environments.

An unintended consequence of agricultural development is that upper estuarine function in rural regions can become reliant on agricultural return flows, particularly during regional droughts when these returns may represent the only source of freshwater input. However, the ecological value of agricultural return flows is complex. While they can help sustain freshwater inflows and low-salinity habitat, they may also transport excess nutrients and organic matter that can contribute to water quality degradation, potentially diminishing habitat quality and ecological function within estuarine ecosystems.

Tidal streams are often the first receiving natural environment for return flows in coastal watersheds. These unique estuarine systems, shaped by the interaction of freshwater inflows and tidal processes, are hydrologically dynamic and highly productive habitats that support numerous ecologically and economically important fishery species in Texas. Because of their susceptibility to water quality impairments, tidal streams have been the focus of multiple studies supported by the Texas Commission on Environmental Quality (TCEQ). In addition to elevated bacteria concentrations, many Texas tidal streams experience periods of low dissolved oxygen that can adversely affect aquatic life. These recurring impairments prompted the development of specialized assessment criteria to better evaluate and manage tidal stream health across the state.

With projected increases in water demand and more frequent droughts likely to intensify water scarcity in Texas, agricultural lands and infrastructure will continue to play an important role in managing land and water resources that support coastal wetlands, wildlife, and fisheries. Multiple initiatives are currently working to expand the availability of managed freshwater wetlands on agricultural lands through the use of surface water and groundwater resources. These efforts provide critical habitat for migratory birds, including shorebirds, of which more than half of whose North American species have experienced population declines of 50% or greater (Rosenberg et al. 2019).

Additionally, existing irrigation infrastructure and water right assets can facilitate the management of freshwater resources in support of estuarine habitats and fisheries through a focused flows approach. However, this elevates the importance of understanding how limited freshwater resources can be best managed to support the many facets of coastal ecosystem health and function i.e., migratory bird habitat, agriculture, water quality, fishery species support, etc. The current study contributes to this understanding by evaluating the outcome of introducing irrigation water into a tidal stream in the East Galveston Bay Watershed using existing infrastructure. Specifically, the study collected baseline water quality data, identified potential water quality impairments, and assessed whether controlled introductions of relatively small volumes of freshwater could influence water quality conditions in a highly modified upper estuarine environment.

Methods

Study Area

East Galveston Bay, San Jacinto-Trinity Estuary

The East Galveston Bay Watershed encompasses agricultural lands (58,300 acres), coastal wetlands (53,100 acres), and prairies and upland wetlands (49,800 acres) that support various wildlife species including migratory and resident birds, and ecologically and economically important fishery species (TPWD). The region is largely rural (4,700 acres of urban development), distinguishing it from the western, more urbanized watersheds that include the Houston Metropolitan Area, one of the fastest growing areas in the US. Nonetheless, extensive agricultural development and roadway and canal construction have contributed to freshwater and estuarine wetland loss in the region by restricting watershed connectivity and freshwater inputs and exacerbating saltwater intrusion (Feagin et al 2020).

In addition to agricultural development, changing land use patterns and agricultural practices have impacted wetland ecosystems throughout the region. Planted rice acreage in Chambers County has declined by 56% across the county from its peak in the 1970s (USDA, 2023), contributing to the loss of managed freshwater wetland habitats and associated hydrologic benefits. To address these impacts, conservation efforts have focused on reducing saltwater intrusion, restoring hydrologic connectivity, and sustaining managed freshwater wetlands on agricultural lands.

Texas Water Trade and its project partners, Galveston Bay Foundation, and Manomet Conservation Sciences, work with regional water suppliers to purchase irrigation water in support of natural and agricultural ecosystems throughout Chambers County. Since 2022, the project team has partnered with landowners and managers to flood agricultural wetlands seasonally in support of migratory birds and other wildlife. However, drought conditions in 2023 resulting in polyhaline salinity (>20 PSU) in an adjacent tidal stream, Onion Bayou, prompted the need to be more responsive to these conditions and other apparent water quality impairments in tidal streams.

Onion Bayou & Adjacent Tidal Stream Environments

Onion Bayou is a heavily modified 18-mile stream in Chambers County, TX (Figure 2). Approximately 12.5 miles from its starting point, Onion Bayou diverges westward converging with Oyster Bayou, a larger 23-mile tidal stream, and eastward converging with Jackson Ditch, a 2.8-mile dredged canal that terminates to the east at the Intracoastal Waterway. A saltwater barrier (Figure 1) located approximately 1.2 miles upstream of the fork divides Onion Bayou main stem into tidal and non-tidal segments using a pressure-regulated mechanism that allows freshwater to flow downstream into the tidal segment but prevents saltwater from intruding into the non-tidal segment. A vegetation barrier is located 90 yards upstream from the saltwater barrier to prevent clogging by nuisance floating vegetation of the saltwater barrier. Portions of both the tidal and non-tidal segment of Onion Bayou are channelized with numerous ditches draining stormwater and irrigation runoff from agricultural fields.

Figure 1. Saltwater barrier in Onion Bayou, Texas, a tidal stream in the upper estuarine region of East Galveston Bay.

The lower 6 miles of the Onion Bayou mainstem including the entirety of the tidal segments (i.e., the west and east fork and Jackson Ditch) are adjacent to tidal wetlands on private and public land including the Pace Tract, an over 1,500-acre tract in the Jocelyn Nungaray National Wildlife Refuge (JNNWR) that is managed by U.S. Fish and Wildlife Service (USFWS). Further upstream, adjacent land uses include mainly agriculture including the JNNWR East Unit which manages agricultural fields in support of migratory birds and incorporates waterfowl management, rice farming, and cattle grazing among other management practices.

Study Sites

Study sites were selected to evaluate the spatial extent of water quality response to introduced freshwater and to characterize water quality conditions across a range of hydrologically modified tidal stream environments. Because sites differed in their proximity to the main stem of Onion Bayou, which drains a larger portion of the watershed, they were expected to exhibit varying responses to freshwater inflow events. Onion Bayou Barrier (OBB), located immediately downstream of the saltwater barrier, was anticipated to experience the strongest response to freshwater inputs associated with agricultural return flows associated with rice farming and wildlife management practices, precipitation, and controlled freshwater introductions, followed by Onion Bayou Fork (OBF). In contrast, Onion Bayou West (OBW) and Jackson Ditch East (JDE), while still influenced by freshwater inflows originating from the Onion Bayou watershed, were expected to exhibit lesser responses because of their distance from the main stem. Descriptions and locations of all study sites are provided in Table 1.

Table 1. Location and description of study sites.

Study Site	**Description**	**Latitude (DD)**	**Longitude (DD)**
Onion Bayou Barrier (OBB)	Tidal segment of Onion Bayou immediately south of saltwater barrier in a channelized stretch of Onion Bayou.	29.6047	-94.4576
Onion Bayou Fork (OBF)	Tidal segment of Onion Bayou at fork where stream diverges westward converging with Oyster Bayou and eastward converging with Jackson Ditch. No obstructions to north, east, or west.	29.5890	-94.4567
Onion Bayou West (OBW)	Tidal segment of Onion Bayou in western fork immediately south of a saltwater barrier that manages salinity of upstream estuarine wetland complex but unobstructed to east- and westward flow.	29.5868	-94.4829
Jackson Ditch East (JDE)	Tidal segment in Jackson Ditch downstream of wetland complex that drains into Jackson Ditch. No obstructions to north, east, or west.	29.5895	-94.4338

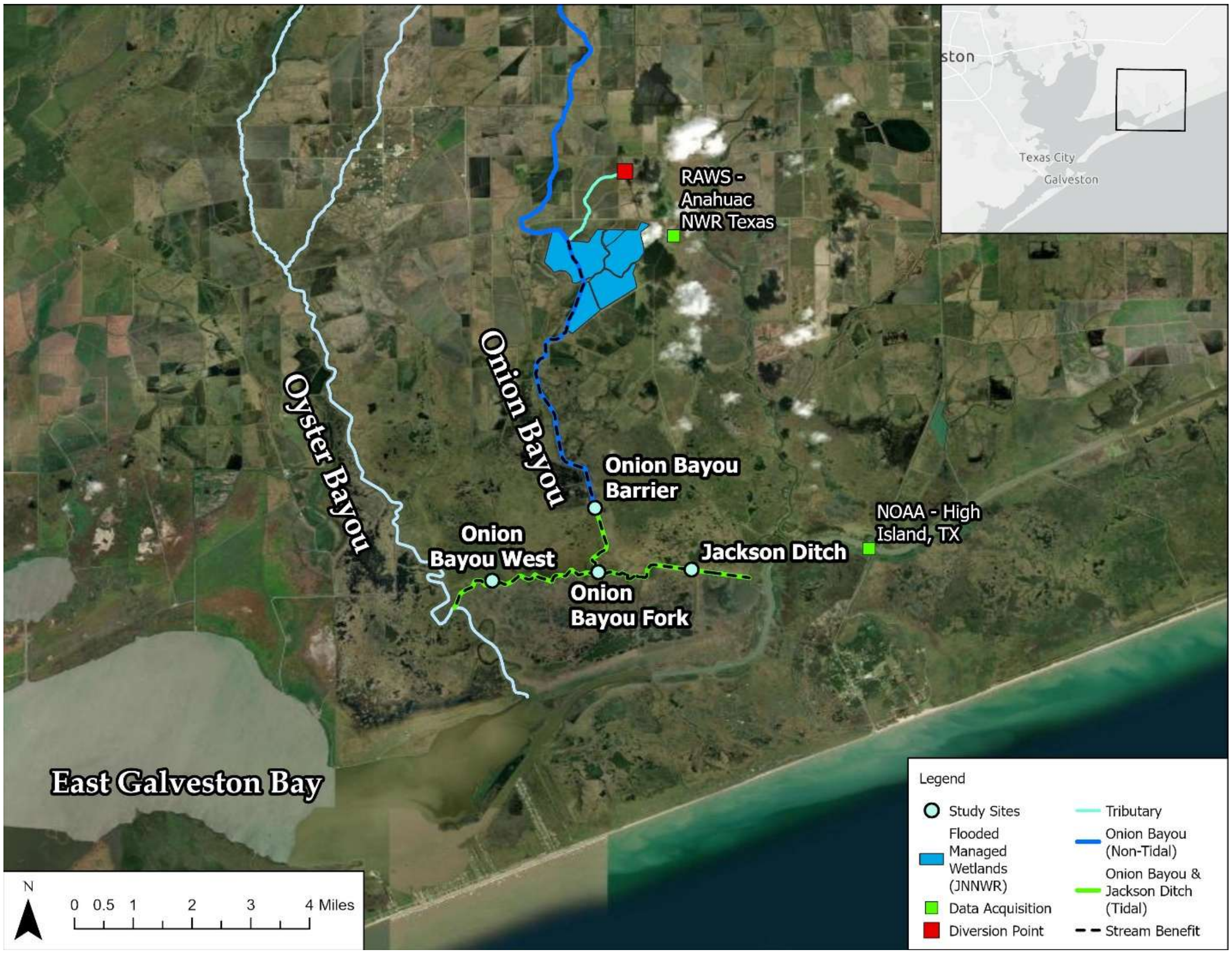

Figure 2. Study sites across tidal stream environments, diversion point and tributary, and stream benefit reach. Also included are managed wetlands flooded in fall 2024 at JNNWR and meteorological and water level data acquisition site locations.

Controlled Freshwater Introduction

In fall 2024, roughly 850 acres of managed agricultural wetlands at JNNWR East Unit were flooded in support of migratory birds (average depth of 1 foot) in partnership with USFWS. The original study goal was to assess water quality response to the release of impounded water (tailwater) into Onion Bayou in spring 2025. However, to manage the growth of nuisance vegetation in fields which had proliferated as a result of wet summer conditions in 2024, USFWS released water in late February 2025 to dry fields out and allow the tillage of fields using tractors. Additionally, fields managed for recreational waterfowl hunting are drawn down in February, after waterfowl season concludes, to permit drying of fields. These releases coincide with the current study's monitoring but are not the main focus. To assess the water quality response to controlled additions of freshwater in early summer and fall, TWT coordinated with the regional water supplier to divert irrigation water into a tributary of Onion Bayou.

Water was diverted from an irrigation canal into a maintained, unnamed tributary of Onion Bayou (Figure 2). A Mace AgriFlo XCi water meter outfitted with an ultrasonic velocity sensor measured water velocity to calculate flow and total water volumes diverted (gravity-fed) through a 23.25-inch pipe (Figure 3). From the diversion point, the tributary flows 1.7 miles to its convergence with the non-tidal portion of Onion Bayou which then flows 5.1 miles to the saltwater barrier and down to tidal study sites, totaling 6.8 miles of non-tidal stream habitat.

Figure 3. Diversion point with water meter measuring water velocity, flow rate, and water volumes diverted from irrigation canal.

Figure 4. Unnamed tributary of Onion Bayou into which irrigation water was diverted.

Data Collection

Study sites were accessed by boat which periodically required specialized watercraft outfitted with a surface drive outboard when water levels did not permit access by conventional watercraft (typically in fall and winter). Water quality instruments were initially deployed in December 2024 and retrieved December 2025. Instruments were fixed to PVC poles 20 cm from the sediment surface to minimize the risk of exposure during low tides. Deployed instruments were swapped monthly with recently maintained and calibrated instruments to mitigate data degradation resulting from sensor drift and biofouling. Additional biofoul controls included outfitting instruments with mechanical wiper brushes programmed to clean sensor faces every hour and covering instruments with fine strainer cloth to exclude aquatic life and vegetation from sensor areas. Deployed water quality instruments collected measurements every 15 minutes (water temperature, dissolved oxygen, pH, salinity, chlorophyll-a, and depth). Chlorophyll-a data collected by instruments was measured in relative fluorescence units (RFU).

During each monthly site visit, water grab samples were collected for analysis of the following parameters: ammonia nitrogen, total Kjeldahl nitrogen, total phosphorus, chlorophyll-a, nitrate-nitrite, total organic carbon, and total suspended solids according to TCEQ Surface Water Quality Monitoring Procedures Manual, Volume 1: Physical and Chemical Monitoring Methods (SWQM Procedures Vol. 1). Samples were immediately stored on ice and transported to a laboratory for testing within 24 hours of sample collection (Eurofins Environmental Testing -145 Greenbriar Dr. Suite A Stafford, Texas 77477, located approximately 80 miles from the Oyster Bayou Boat Ramp).

Data Acquisition

Meteorological data (i.e., air temperature, precipitation, wind speed and direction) collected at the nearby Remote Automated Weather Station (RAWS) Anahuac NWR Texas Station was acquired for the duration of the study. Water level data collected at the nearby NOAA High Island, TX (8770808) station was also acquired for the duration of the study. Additionally, drought data for Chambers County was accessed on drought.gov.

Data Quality Assurance and Control

Prior to field visits, water quality instruments were calibrated using NIST-traceable standard solutions according to their respective manufacturers' manuals. Calibration values were recorded and stored. During each site visit, a handheld multiprobe water quality instrument collected discrete measurements (DO, temperature, conductivity, depth, and pH) to compare to data collected from recently retrieved instruments. After retrieval from the field, instrument sensor readings were tested against known reference solution standards to ensure they operated and performed accordingly throughout their deployment. Deployment and retrieval values and notes were recorded and stored.

Continuous water quality data, deployment, and calibration records were uploaded to Water Data for Texas's Administration Portal (WDFT) which offers a suite of automated tools and manual functions to truncate, review, and verify continuous water quality data according to methods outlined in the Texas Water Development Board Environmental Monitoring Protocols QAPP. Generally, erroneous data was flagged according to known parameter and sensor constraints, flat-line tests, and spike-tests for manual review. After review, flagged data was removed prior to visualization and analysis.

Data Analysis

Analysis aimed to 1) understand spatiotemporal trends in water quality in Onion Bayou and Jackson Ditch, 2) identify potential impairments related to water quality, and 3) assess whether controlled freshwater introductions could influence water quality.

To simplify visualization of long-term trends, water quality, meteorological, and water level data was averaged daily (daily-binned) before plotting. Additionally, to aid in visualizing the potential role of rainfall and the project's controlled freshwater addition on water quality, precipitation and the duration of freshwater additions accompanied water quality plots. Screening levels developed by the Texas Commission on Environmental Quality for tidal streams were included on plots for dissolved oxygen, chlorophyll-a concentration, total phosphorus, ammonia, and nitrate (TSWQS 2024). The TCEQ screening level for nitrate-nitrogen in tidal streams was used to compare to the current study's nitrate-nitrite concentrations.

Nutrient and chlorophyll-a concentration data that did not meet minimum detectable levels due to being too low for reliable quantification were set to zero prior to visualization and analysis. Corrected chlorophyll-a which corrects for the presence of pheophytin was used for visualization and multivariate analysis. Data visualization was performed using Python (Version 3.13.13) Matplotlib (Hunter 2007) in JupyterLab (Version 4.3.4).

Principal component analysis (PCA) was performed using PRIMER-e (Version 7.0.24) multivariate statistical software. To focus on the effect of controlled freshwater additions, continuous water quality data was binned and averaged into pre, during, and post water diversion intervals, deemed study bins hereinafter and are outlined in Table 2. Pre and post study bins were determined by the number of days water diverted into Onion Bayou. The corresponding nutrient sample data for each bin was included in the PCA. All sites had nitrate-nitrite concentrations below the minimum detection level and were excluded from the PCA. Additionally, laboratory-analyzed chlorophyll-a data was used in the PCA since it is generally more reliable than continuous chlorophyll-a data collected from water quality instruments. Draftsman plots were created to identify issues with skewedness and collinearity. Total Kjeldahl nitrogen and ammonia data were transformed (logx+1) prior to analysis to improve right-skewed data due to high occurrences of zero values. Additionally, all parameters were normalized (mean of 0 and standard deviation of 1) prior to PCA to accommodate differences in units and scale across parameters.

Table 2. Outline of project binning dates, duration, and precipitation for principal component analysis.

Study Bins	Dates	Duration (days)	Introduced Freshwater Volumes (acre-feet)	Rainfall
Summer before (S-B)	5/16/2025-6/5/2025	22		101.85 mm (4.01 in)
Summer during watering (S-D)	6/6/2025-6/27/2025	22	295.05	199.64 mm (7.86 in)
Summer after (S-A)	6/28/2025-7/19/2025	22		68.58 mm (2.7 in)
Fall before (F-B)	9/2/2025-9/17/2025	16		0.25 mm (0.01 in)
Fall watering (F-D)	9/18/2025-10/3/2025	16	184.66	47.52 mm (1.87 in)
Fall after (F-A)	10/4/2025-10/19/2025	16		5.84 (0.23 in)

Results

Drought and Seasonal Conditions

The data analysis demonstrated water quality throughout the study area was responsive to tidal forcing, seasonality, and wet and dry conditions, which in addition to governing water chemistry, influenced the effect of natural and agricultural runoff and thus inorganic and organic nutrient concentrations.

Drought conditions and rainfall were a key driver of water quality benchmark conditions and response across study sites. Prior to start of the study period in December 2024, the region was experiencing widespread, moderate to severe drought conditions that persisted through December and abnormally dry conditions persisting into January (Figure 5). Rainfall in late December and early January totaling 2.32 inches (59 mm; Figure 6) mitigated drought conditions until abnormally dry to moderate drought conditions returned, persisting from February through May with rainfall totaling 3.5 inches (89 mm) for that period. Rainfall totaled 25.26 inches (614.68 mm) from June through August, impeding the development of dry or drought conditions. However, abnormally dry to severe drought conditions returned in September and persisted through December with rainfall totalling 4.25 inches (108 mm) for that period.

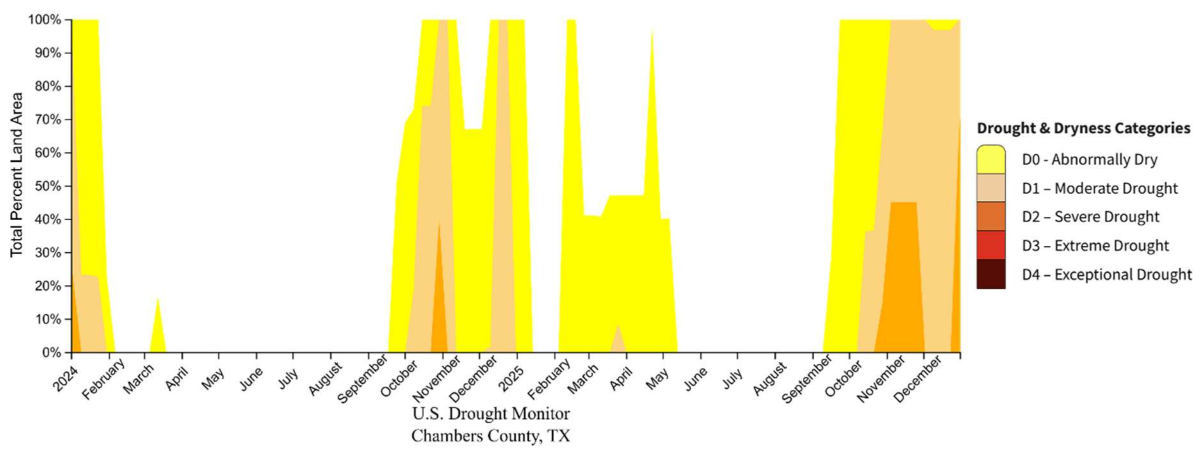

Figure 5. Drought extent and conditions in Chambers County from 2024 to 2025. (https://www.drought.gov/states/texas/county/Chambers).

Seasonal variation was also a key driver of water quality patterns. Cold fronts which are strong, cold, wind events (>7 m/s) occurred in January and February with additional minor cold fronts occurring through April (Figure 6). After cold fronts ceased, air temperatures generally remained above 20 ˚C from May through late October when cold fronts resumed. Mean daily wind speeds generally stayed below 5 m/s from June through late October.

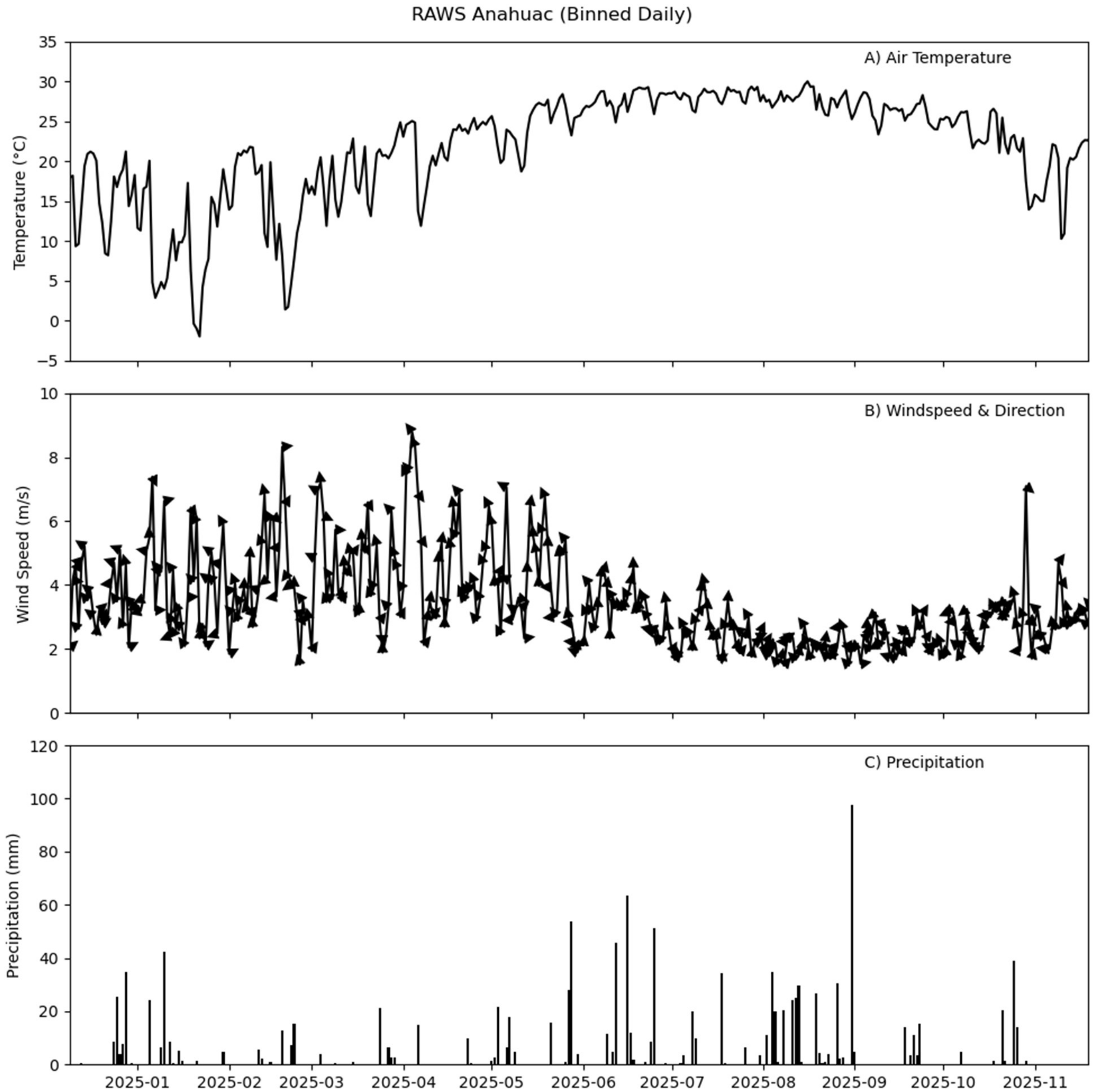

Figure 6. Daily-binned air temperature (˚C), wind speed (m/s) and direction, and precipitation (mm) measured at nearby RAWS Anahuac NWR throughout the study period.

Water level data from the nearby NOAA High Island, TX Station (8770808) was included as a plausible explanatory variable to observed trends. Approved data was not available for January 2025. Observed tides were strongest (interdaily variation in mean water levels > 0.5 m) throughout the spring and water level was also responsive to cold front events occurring in December 2024 and late October and November 2025 (Figure 7). Mean daily water levels were generally greater from mid-April through October with less interdaily variation.

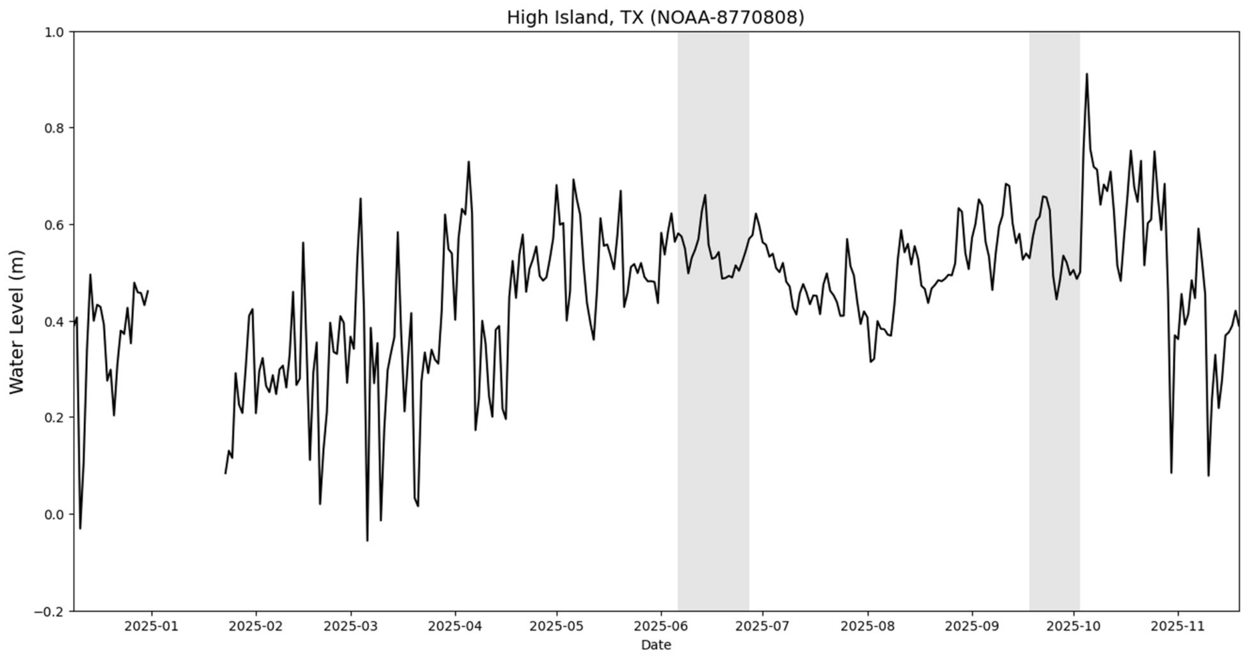

Figure 7. Daily-binned water level (m) measured at High Island, TX (NOAA-8770808).

Controlled Freshwater Introductions

In early summer, a total of 295.05 acre-feet of irrigation water was introduced into the Onion Bayou tributary from 6/6/2025 through 6/27/2025 at a rate of 9 to 20 acre-feet per day. Rainfall was greatest while the water was being introduced totaling 7.86 in. (199.64 mm) for the 22 days during the freshwater introduction (during-bin) followed by the rainfall total of 4.01 in. (101.85 mm) in the 22 days leading up to the freshwater introduction (before-bin) and then the rainfall total of 2.7 in. (68.58 mm) in the 22 days following the freshwater introduction (after-bin).

In early fall, a total of 184.66 acre-feet of irrigation water was introduced into the Onion Bayou tributary from 9/18/2025 through 10/3/2025 at a rate of 14 to 20 acre-feet per day. Fall conditions were drier than in summer with abnormally dry conditions setting into the region (Figure 5). Rainfall totaled 0.25 mm (0.01 in) in before, 47.52 mm (1.87 in) in the during, and 5.84 mm (0.23 in) in after study bins.

Introduced water had non-detectable levels of nitrate-nitrite and ammonia in both summer and fall (Table 3). Fall water had non-detectable levels of total phosphorus and total suspended solids and summer water measured 0.0350 and 6.50 mg/L, respectively. Total organic carbon concentration ranged from 9.4 to 11.4 and chlorophyll-a ranged from 4.02-4.53 µg/L.

Table 3. Laboratory analysis of irrigation water diverted into Onion Bayou Tributary on 6/19/2025 and 9/30/2025.

Collection Date	Nitrate-Nitrite (mg/L)	Ammonia (mg/L)	Total Kjedahl Nitrogen (mg/L)	Total Phosphorus (mg/L)	Total Organic Carbon (mg/L)	Chlorophyll-a (µg/L)	Total Suspended Solids
6/19/2025	0	0	1.30	0.0350	9.40	4.53	6.50
9/30/2025	0	0	1.23	0	11.4	4.02	0

Continuous Water Quality

OBB had the lowest overall mean salinity (2.51 ± 3.49 PSU), pH (6.82 ± 0.23), dissolved oxygen (1.63 ± 2.26 mg/L), and chlorophyll-a levels (1.50 ± 1.73 RFU) across sites throughout the study period (Table 4). Sites located downstream (OBF, OBW, JDE) had similar mean pH levels ranging from 7.31-7.53, mean salinities ranging from 6.99-7.34 PSU, and mean dissolved oxygen concentrations ranging from 4.90-5.82 mg/L. However, mean chlorophyll-a levels at OBW (1.58 ± 1.59 RFU) were more similar to OBB (1.50 ± 1.73 RFU) than OBF and JDE (2.72 ± 2.56 RFU and 3.16 ± 3.43, respectively). Mean water depths at OBB and OBW were greater (0.99 m and 0.94 m, respectively) than at OBF and JDE (0.69 m and 0.57 m, respectively).

Table 4. Water quality parameter means and standard deviations across sites for the study period.

	Salinity (PSU)		**pH**		**Dissolved Oxygen (mg/L)**		**Chlorophyll-a (RFU)**		**Depth (m)**		**Temperature (˚C)**	
Site	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
OBB	2.51	3.49	6.82	0.23	1.63	2.26	1.50	1.73	0.99	0.16	23.26	6.59
OBF	6.99	4.58	7.31	0.31	4.90	2.81	2.72	2.56	0.69	0.19	23.41	6.92
OBW	7.55	4.75	7.36	0.33	5.82	2.58	1.58	1.59	0.94	0.24	23.28	6.93
JDE	7.34	3.86	7.53	0.42	5.12	3.07	3.16	3.43	0.57	0.13	23.46	7.16

Rainfall in late December and early January decreased mesohaline conditions (5-17 PSU, Figure 8) across sites by 9-12 PSU until abnormally dry to moderate drought conditions persisting from February through May increased salinity. Rainfall totaled 25.26 inches (614.68 mm) from June through August mitigating drought conditions and maintaining salinity in tidal fresh (<0.5 PSU) to oligohaline (0.5-5 PSU) conditions across sites. However, abnormally dry to severe drought conditions returned in September and persisted through December resulting in the highest salinities measured throughout the study period (15-23 PSU).

Across summer study bins, mean salinity decreased from before bins to during bins across all sites: OBB (1.47 to 0.18 PSU), OBF (5.21 to 2.84 PSU), OBW (4.97 to 2.73 PSU), and JDE (5.86 to 3.40 PSU). However, mean salinity increased from during bins to after bins at OBB (0.18 to 0.30 PSU) and JDE (3.40 to 3.55 PSU) but continued to decrease at OBF (2.84 to 2.65 PSU) and OBW (2.73 to 2.45 PSU).

Salinity was greater in fall (8.18 PSU) than summer (2.96 PSU) bins and increased across before, during, and after bins across sites: OBB (1.46 to 2.15 to 8.44 PSU), OBF (7.13 to 8.58 to 13.41 PSU), OBW (6.43 to 10.10 to 14.02 PSU), JDE (5.96 to 7.72 to 12.82 PSU).

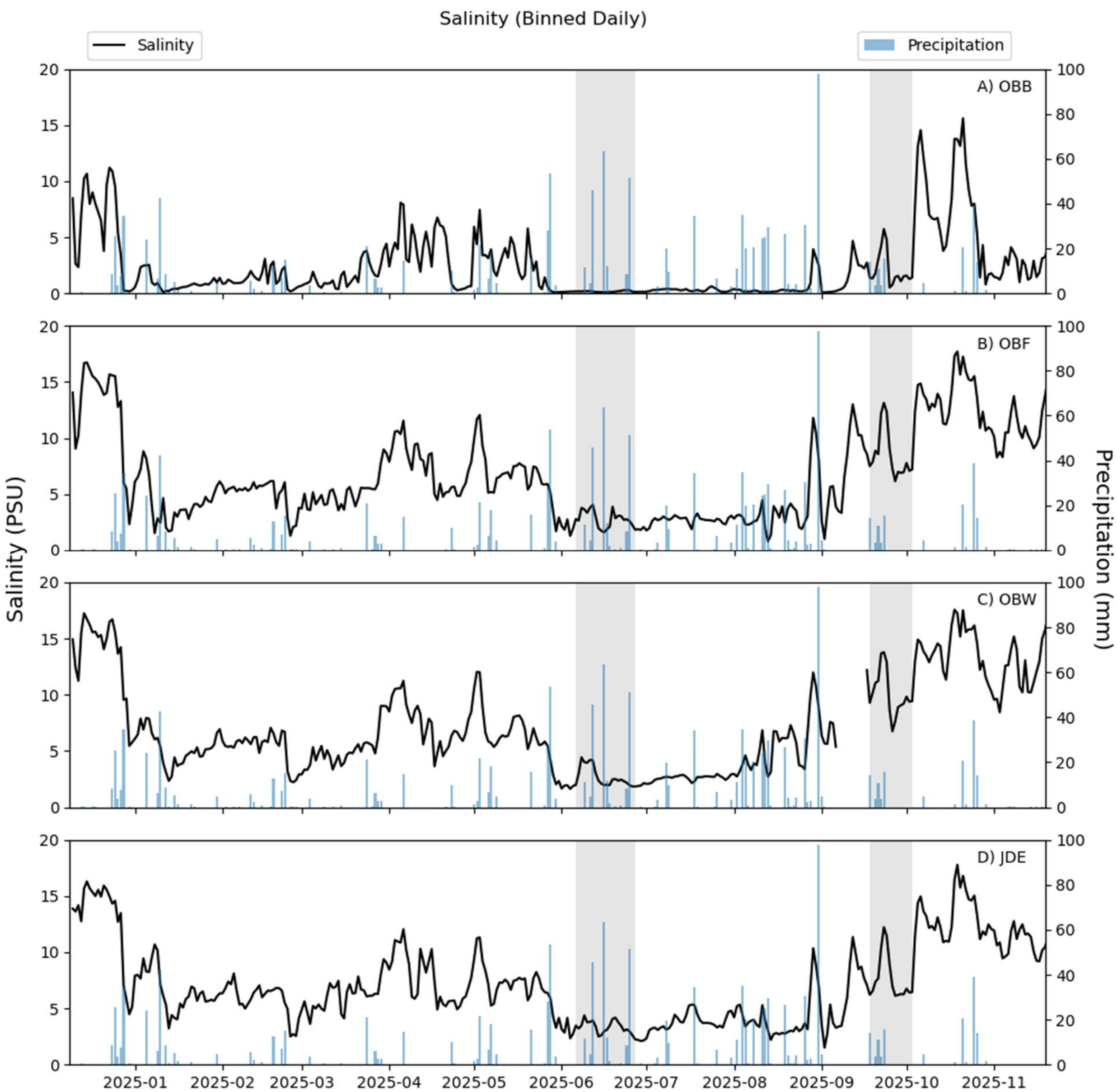

Figure 8. Daily-binned salinity (PSU) across study sites and study period with precipitation (mm) measured at the nearby RAWS Anahuac NWR Texas Station. Gray regions denote duration of controlled freshwater additions into Onion Bayou.

Dissolved oxygen was generally highest from January through March (8-12 mg/L) and generally decreased from January through July. Dissolved oxygen periodically failed to meet dissolved oxygen TCEQ screening level for tidal streams (24-hour average of 3.0 mg/L, Figure 9). OBB regularly experienced extended periods of hypoxia and anoxia throughout the study period including from late December through early January, in February, from March through early April, and from late May through December. Intermittent hypoxia at other sites lasted from days to a few weeks and was associated with rainfall events throughout the summer and fall when water temperature was generally above 25˚C (Figure 12).

Rainfall events were associated with decreased dissolved oxygen levels. For example, rainfall events in December and January rainfall decreased dissolved oxygen by 2-4 mg/L and pH across sites (Figure 9, Figure 10). This response occurred throughout the study period. Additionally, there was a sharp decrease (>7 mg/L) in dissolved oxygen in February that was not coincident with rainfall and was likely associated with a spring phytoplankton bloom supported further below.

Across summer study bins, dissolved oxygen decreased from before to during bins across all sites: OBB (1.58 to 0.00 mg/L), OBF (3.38 to 2.29 mg/L), OBW (4.54 to 3.52 mg/L), and JDE (3.93 to 2.60 mg/L). However, mean dissolved oxygen increased from during bins to after bins at OBB (0.00 to 0.24 mg/L), OBF (2.29 to 2.69 mg/L), and OBW (3.51 to 4.07 mg/L) but continued to decrease at JDE (2.60 to 1.98 mg/L).

Across fall study bins, dissolved oxygen increased from before to during bins across all sites: OBB (0.02 to 0.39 mg/L), OBF (1.65 to 3.64 mg/L), OBW (2.88 to 4.01 mg/L), and JDE (2.35 to 2.97 mg/L). However, dissolved oxygen continued to increase at OBB (0.39 to 0.50 mg/L) and JDE (2.67 to 2.72 mg/L) but decreased at OBF (3.64 to 2.74 mg/L) and OBW (4.01 to 2.80 mg/L).

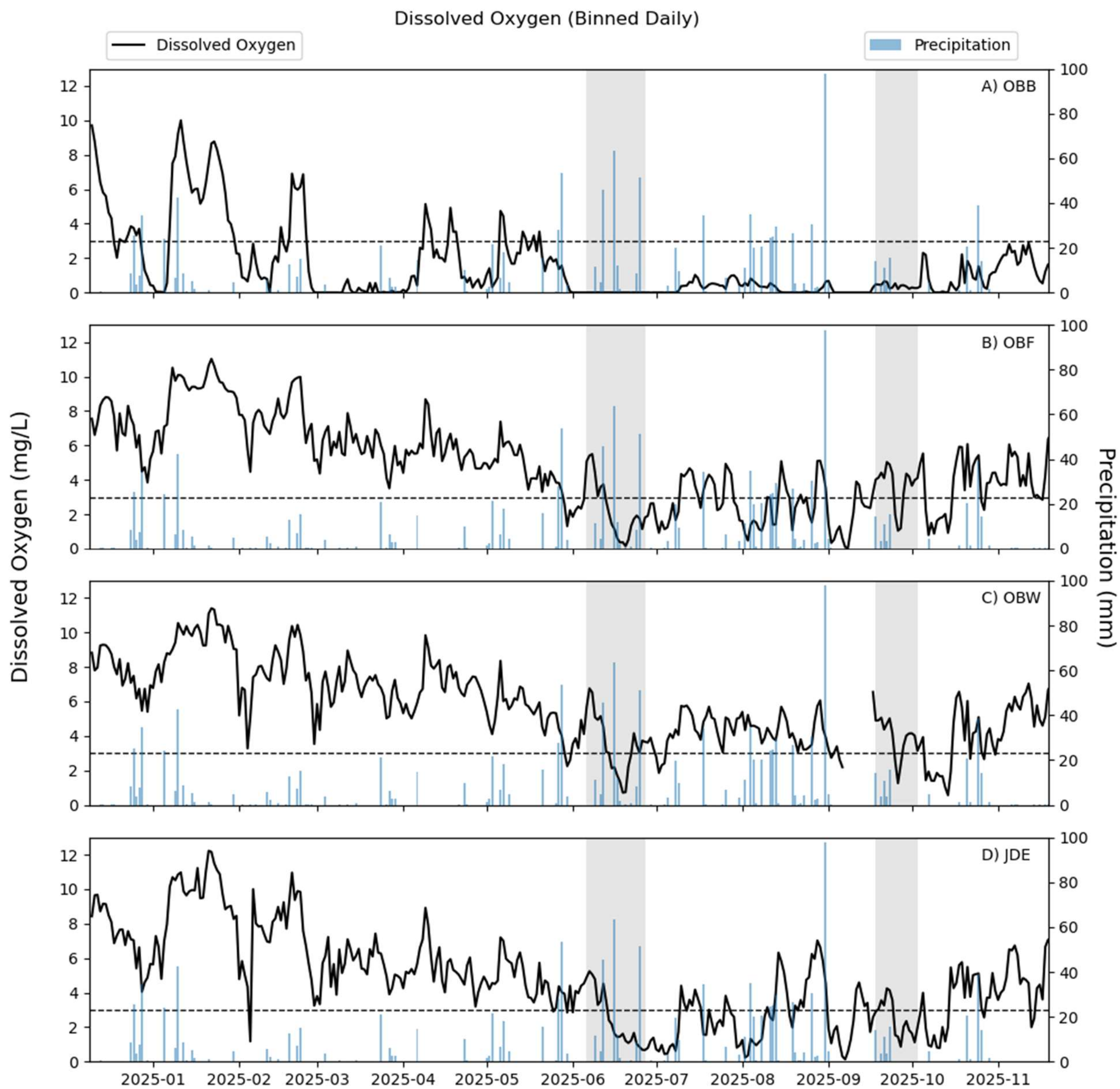

Figure 9. Daily-binned dissolved oxygen (mg/L) across study sites and study period with precipitation (mm) measured at the nearby RAWS Anahuac NWR Texas Station. Dotted horizontal line at y=3 mg/L represents TCEQ dissolved oxygen screening level for tidal streams (24-hour average of 3.0 mg/L). Gray regions denote duration of controlled freshwater additions into Onion Bayou.

pH shared a similar response to drought and rainfall as salinity and pH. Rainfall events were also associated with decreasing pH (0.5 to >2.0) throughout the study period.

Across summer study bins, pH decreased at OBB (6.86 to 6.66), OBF (7.21 to 7.14), and JDE (7.39 to 7.31), but increased at OBW (7.06 to 7.23). pH then increased across all sites in the after bin OBB (6.66 to 6.68), OBF (7.14 to 7.29), OBW (7.23 to 7.43), JDE (7.31 to 7.32).

Across fall study bins, pH increased across all sites OBB (6.5 to 6.66), OBF (6.97 to 7.18), OBW (6.97 to 7.22), and JDE (7.12 to 7.17) from before to during bins. However, pH increased at OBB (6.66 to 6.87) and JDE (7.17 to 7.38) but decreased at OBF (7.18 to 7.11) and OBW (7.22 to 7.09).

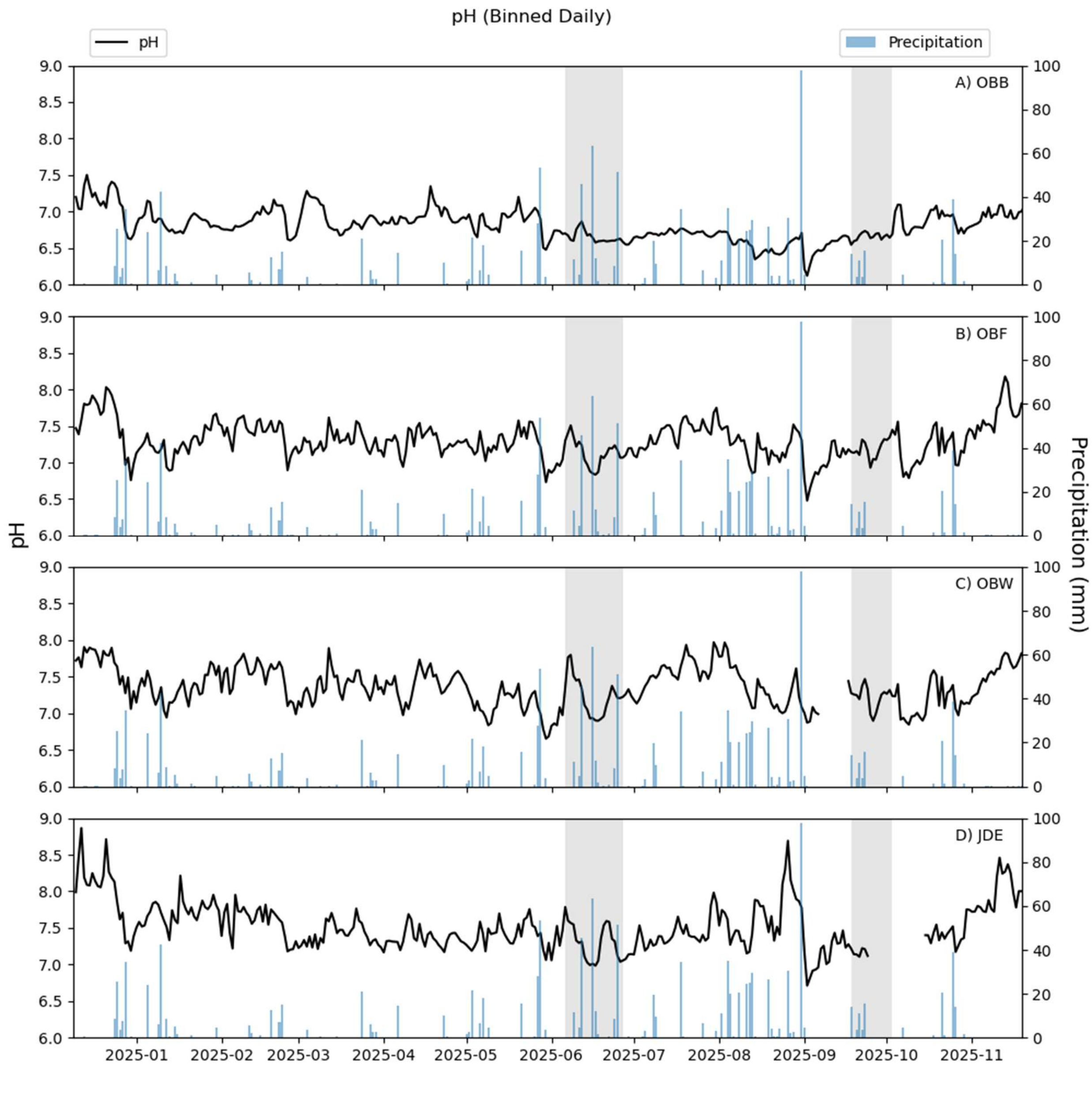

Figure 10. Daily-binned pH across study sites and study period with precipitation (mm) measured at the nearby RAWS Anahuac NWR Texas Station. Gray regions denote duration of controlled freshwater additions into Onion Bayou.

Chlorophyll-a RFU exhibited seasonal trends and a mixed response to rainfall across sites relative to salinity and pH. In February, chlorophyll-a RFU increased sharply across OBF, OBW, JDE, but less so at OBB (Figure 11). This springtime bloom coincided with warmer water and air temperatures (Figure 12, Figure 6) and decreased dissolved oxygen likely due to nighttime respiration of phytoplankton biomass.

Across summer study bins, chlorophyll-a RFU decreased at OBB (2.55 to 1.72 RFU) and JDE (2.01 to 0.52 RFU) but increased at OBW (0.56 to 1.44 RFU) and OBF (1.34 to 2.65 RFU). Chlorophyll-a RFU then increased from during to after bins at OBF (2.65 to 3.46 RFU), OBW (1.44 to 2.23 RFU), and JDE (0.52 to 3.67 RFU) but continued to decrease at OBB (1.72 to 1.00 RFU).

Across fall study bins, chlorophyll-a RFU increased from before to during bins at OBB (0.98 to 1.93 RFU) and OBF (1.16 to 2.10 RFU) but decreased at OBW (0.72 to 0.34 RFU) and JDE (2.20 to 1.22 RFU). Chlorophyll-a RFU then decreased from during to after bins at OBB (1.93 to 1.68 RFU), OBF (2.10 to 1.24 RFU), and JDE (2.08 to 1.22 RFU), but decreased at OBW (0.34 to 0.58 RFU).

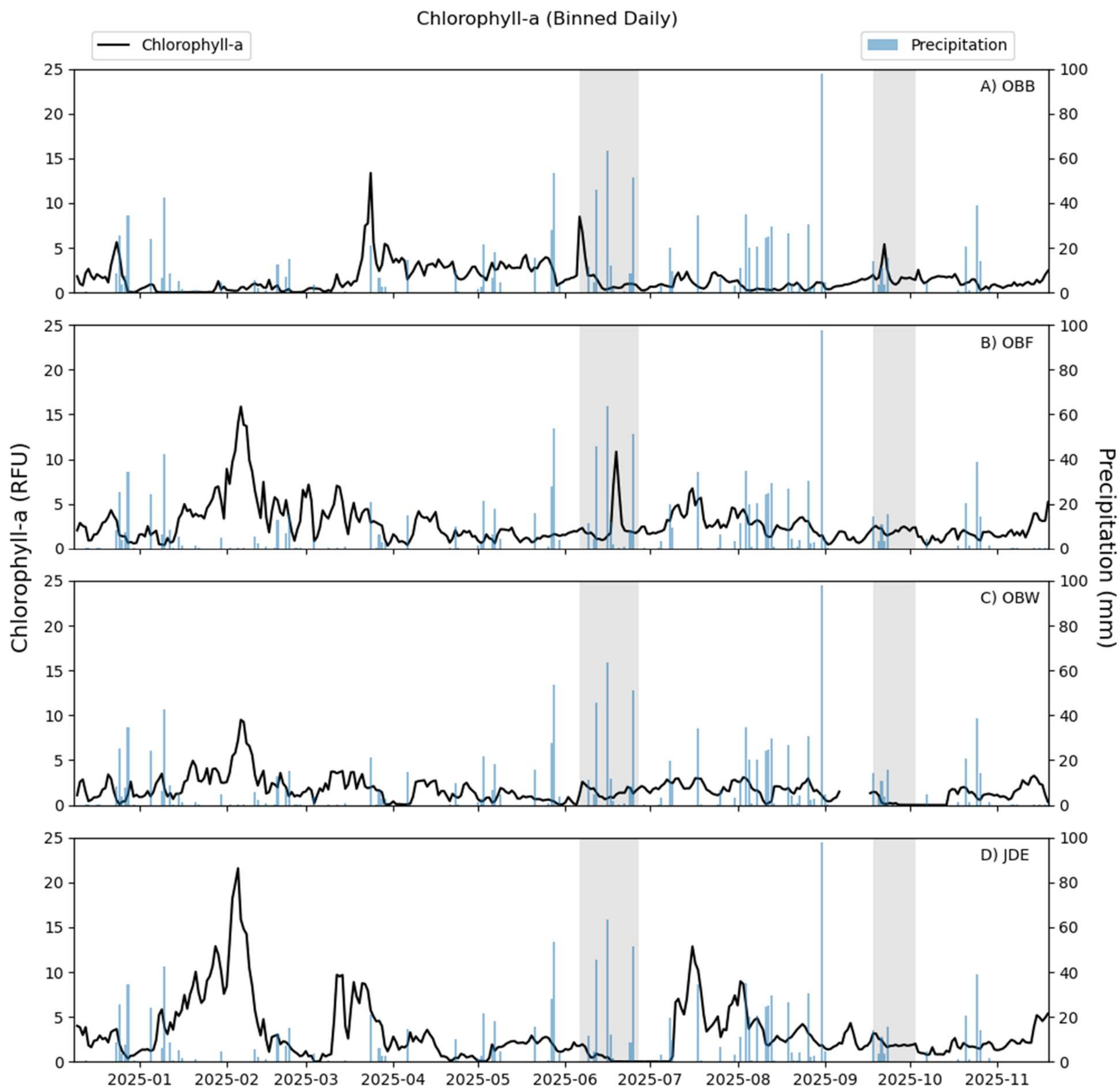

Figure 11. Daily-binned chlorophyll-a (RFU) across study sites and study period with precipitation (mm) measured at the nearby RAWS Anahuac NWR Texas Station. Gray regions denote duration of controlled freshwater additions into Onion Bayou.

Study sites exhibited similar seasonal trends in water temperature throughout the study period (Figure 12). Water temperature episodically dropped >20˚C from strong, cold wind events (>7 m/s) or northerners in January and February with minor fronts occurring through April (Figure 6).

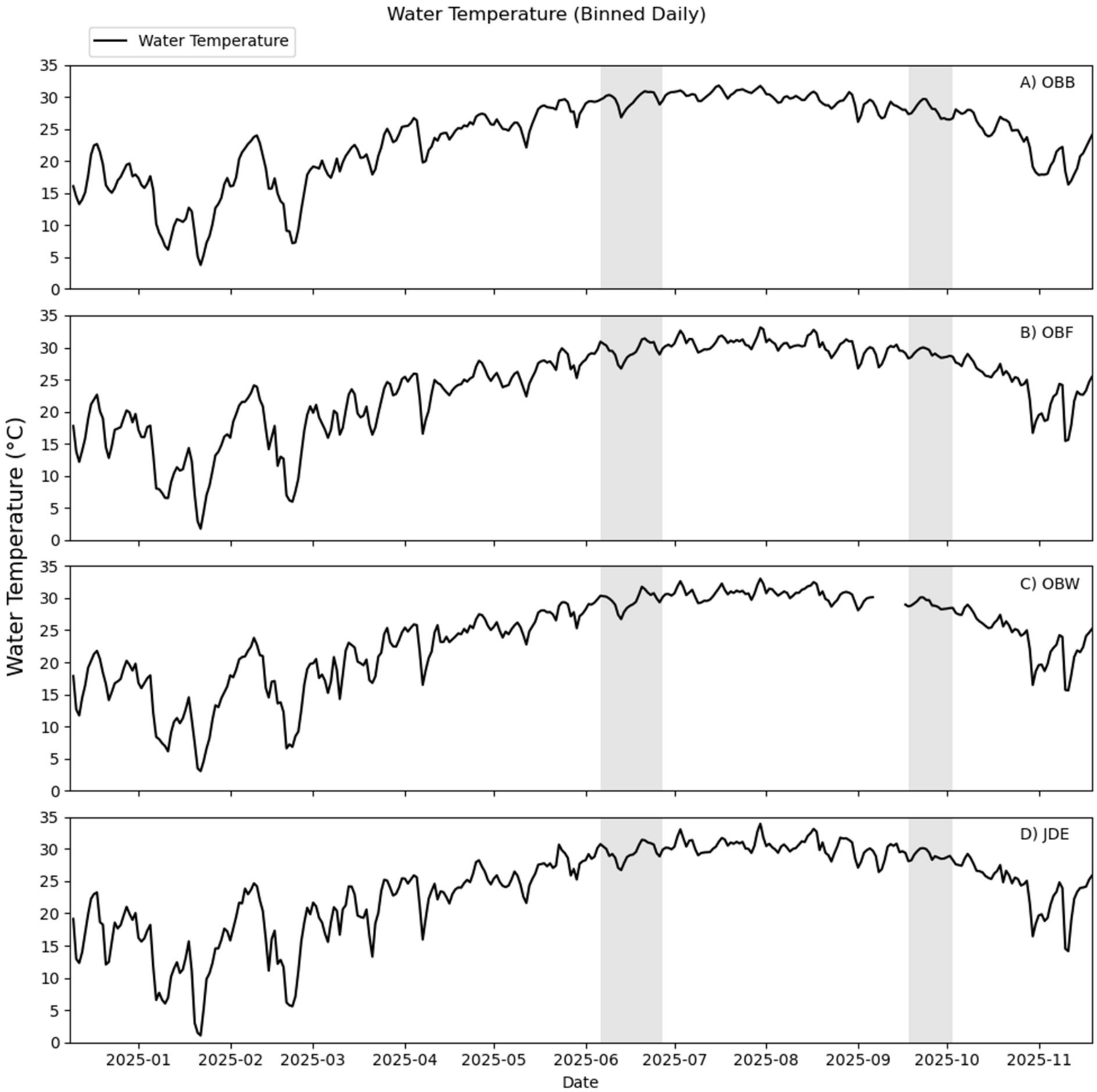

Figure 12. Daily-binned mean water temperature (˚C) across study sites and study period. Gray regions denote duration of controlled freshwater additions into Onion Bayou.

Water depth was also influenced by northerner events and to an extent, mirrored water level patterns measured at the nearby NOAA High Island, TX (8770808) monitoring station (*Figure 7*). However, water depth patterns across sites were less responsive than those observed at the NOAA station.

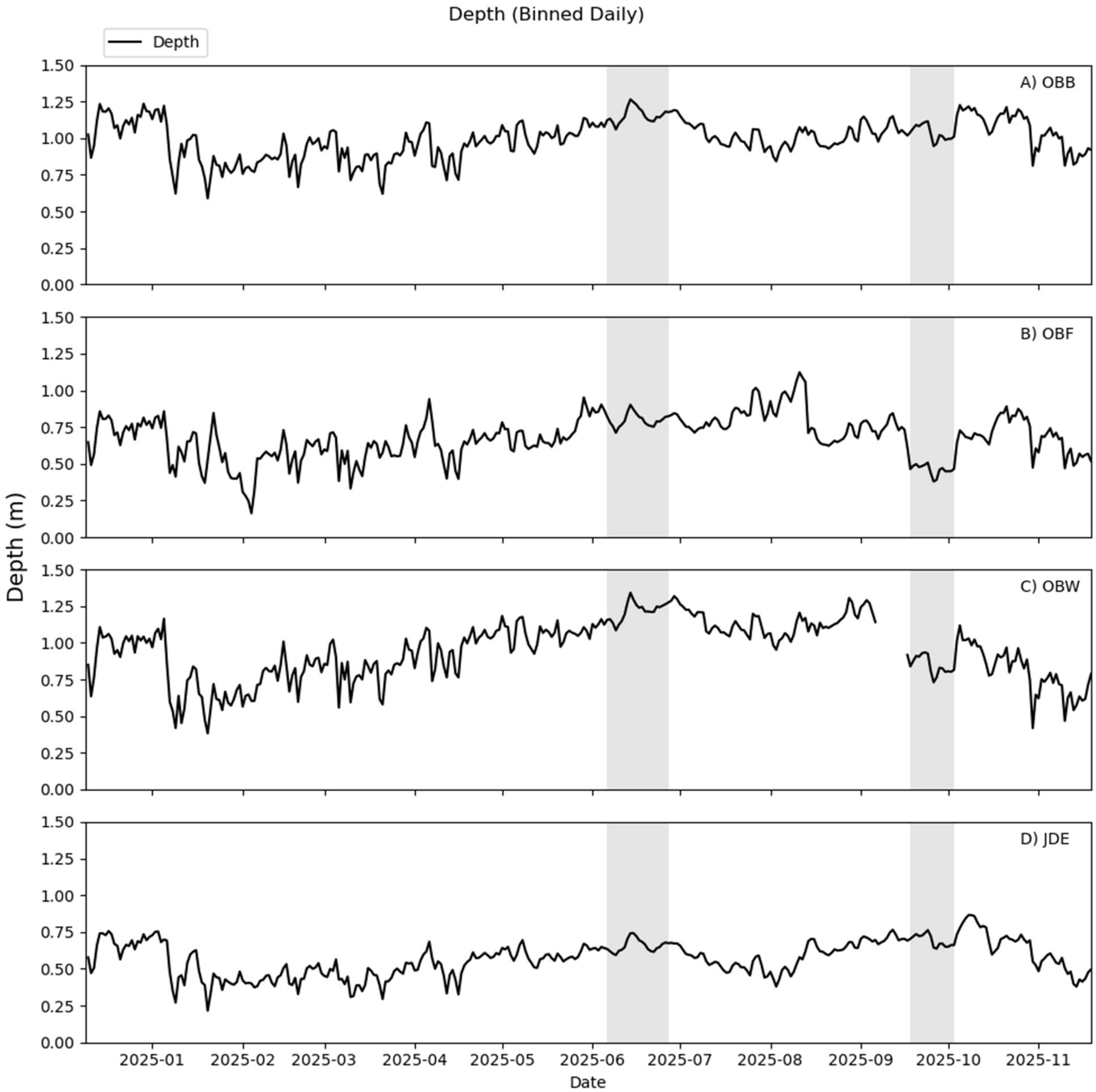

Figure 13. Water depth (m) across study sites and study period with precipitation (mm) measured at the nearby RAWS Anahuac NWR Texas Station. Gray regions denote duration of controlled freshwater additions into Onion Bayou.

Nutrient & Chlorophyll Sampling

Overall mean ammonia concentrations were highest at OBB (0.14 ± 0.17 mg/L, Table 5) with concentrations exceeding the TCEQ tidal stream screening level (0.46 mg/L) in May and July 2025 (Figure 14). Mean ammonia at the remaining sites averaged between 0.02 to 0.03 mg/L, peaking from mid-June through August at OBF (0.0683-0.135 mg/L), in early June at OBW (0.140 mg/L), and in July at JD (0.140 mg/L).

Table 5. Overall mean nutrient and chlorophyll concentrations and standard deviation (SD) across sites for the study period.

	Nitrate-Nitrite (mg/L)		Ammonia (mg/L)		Total Kjedahl Nitrogen (mg/L)		Total Phosphorus (mg/L)		Total Organic Carbon (mg/L)		Chlorophyll-a (µg/L)		Total Suspended Solids	
Site	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
OBB	0.04	0.05	0.14	0.17	2.01	1.01	0.10	0.08	18.93	4.37	12.40	13.26	13.18	13.15
OBF	0.05	0.17	0.03	0.05	6.84	19.56	0.09	0.06	16.39	3.23	17.67	16.01	65.52	41.42
OBW	0.37	1.40	0.02	0.04	2.84	5.32	0.08	0.08	13.31	2.88	18.24	16.26	45.00	25.03
JDE	0.00	0.00	0.03	0.04	2.31	2.10	0.07	0.03	16.94	4.30	22.95	16.87	56.50	32.70

Across summer study bins, ammonia decreased from before to during bins at OBB (0.341 to 0.0782 mg/L) and OBW (0.140 to non-detectable levels) but increased in the after bin at OBB (0.498 mg/L) and remained non-detectable at OBW. In contrast, ammonia increased at OBF (non-detectable levels to 0.0683 mg/L) in the during bin and slightly decreased in the after bin (0.0604 mg/L). At JDE, ammonia was not detectable in either before or during bins but was in the after bin (0.140 mg/L). Ammonia remained below detectable levels across all fall study bins at all sites.

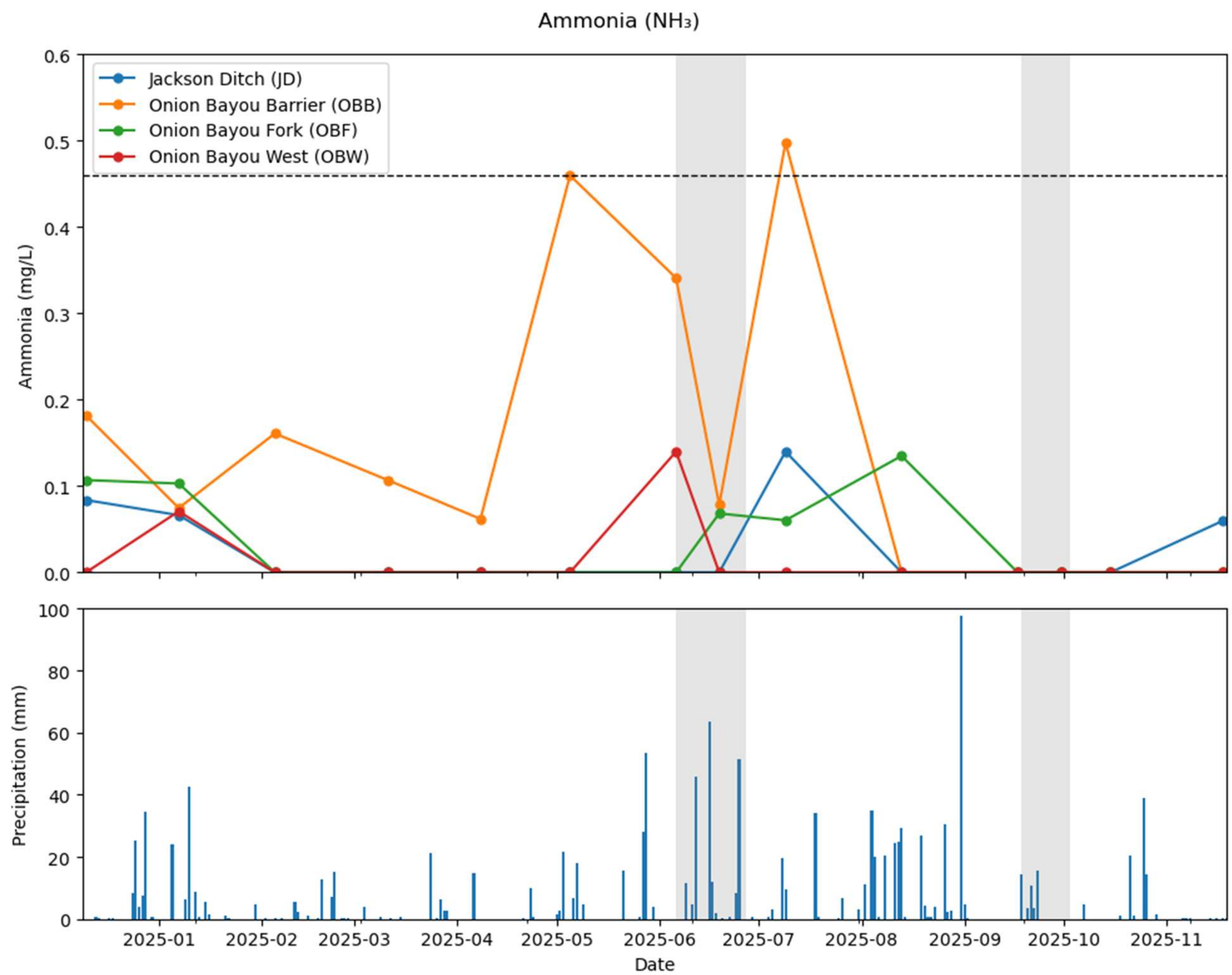

Figure 14. Ammonia concentrations (mg/L) across study sites throughout the study period. TCEQ screening level for tidal streams at 0.46 mg/L.

Overall mean nitrate-nitrite concentrations were highest at OBW (0.37 ± 1.40 mg/L; Table 5), however, this was largely driven by an outlier in November 2025 (5.23 mg/L) which exceeded TCEQ screening levels (1.10 mg/L). Nitrate-nitrite remained well below screening levels and were generally only detectable at OBB and OBF (Figure 15) with detectable levels ranging from 0.055 to 0.134 mg/L at OBB and detectable in January (0.622 mg/L) and in August (0.0473 mg/L) at OBF. Nitrate-nitrite was not detectable at JDE throughout the study period and was not detectable in summer or fall study bins at all sites.

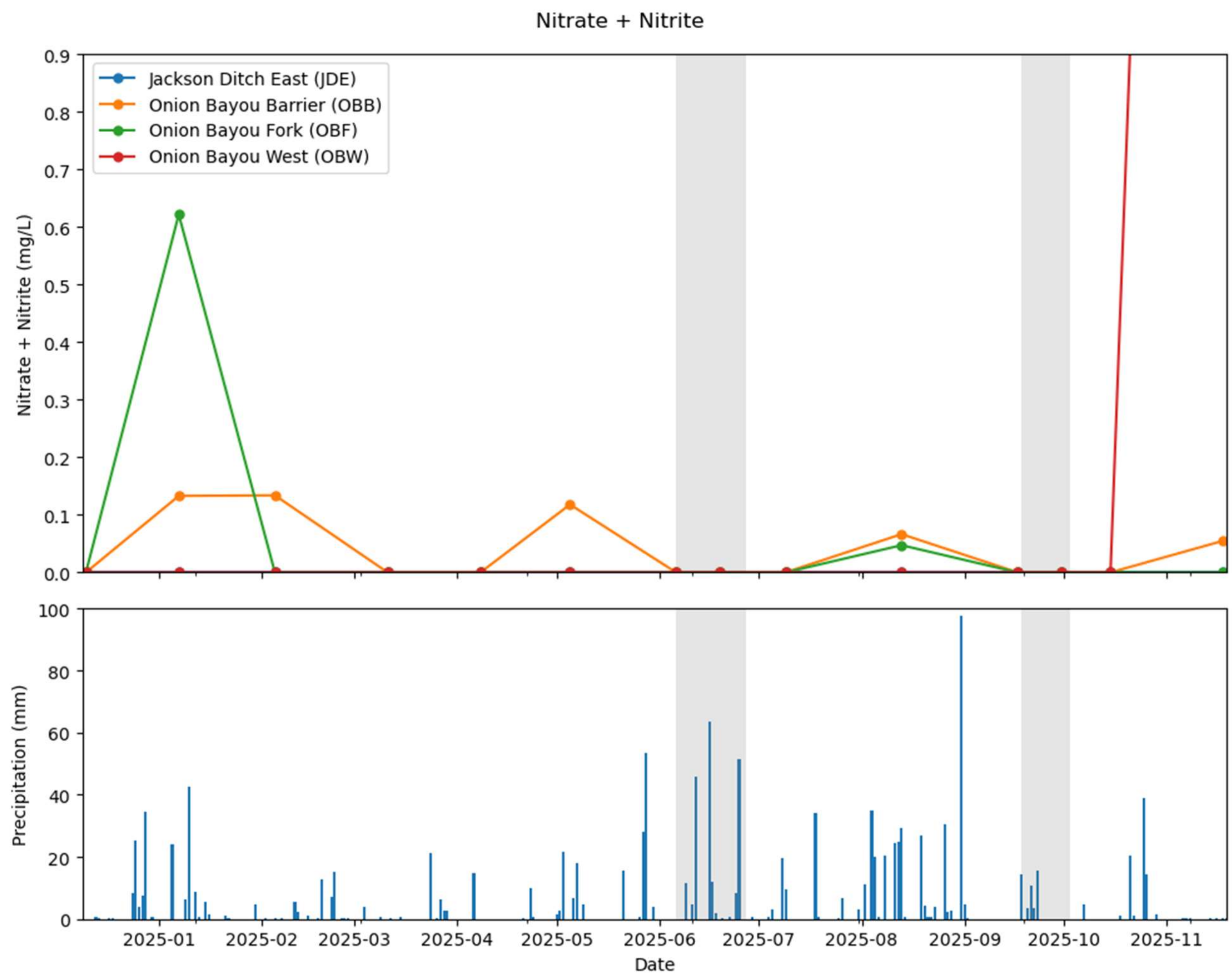

Figure 15. Nitrate-nitrite (mg/L) across study sites throughout the study period. TCEQ screening level for nitrate-nitrogen in tidal streams at 1.10 mg/L. In November, OBW nitrate-nitrite measured 5.23 mg/L which is not shown in plot.

Overall mean total Kjedahl nitrogen (TKN) concentrations were highest at OBF (6.84 ± 19.56 mg/L; Table 5) ranging from 2.01-2.84 mg/L across other sites. TKN was highest at sites in early June (3.83-74.7 mg/L; Figure 16).

Across summer study bins, TKN decreased from its highest observed concentrations in the before bins to the during bins at all sites, OBB (3.83 to 1.54 mg/L), OBF (74.7 to 1.19 mg/L), OBW (21.00 to 1.26 mg/L), JDE (8.99 to 1.91 mg/L). TKN then increased in the after bin at all sites: OBB (1.54 to 2.70 mg/L), OBF (1.19 to 3.40 mg/L), OBW (1.26 to 1.64 mg/L), and JDE (1.91 to 2.40 mg/L).

Across fall study bins, TKN decreased from before to during bins at all sites: OBB (2.79 to 2.03 mg/L), OBF (2.50 to 1.85 mg/L), OBW (3.89 to 2.09 mg/L), and JDE (2.24 to 1.97 mg/L).

TKN then increased from during to after bins at OBB (2.03 to 2.19 mg/L), OBF (1.85 to 2.17 mg/L), and JDE (1.97 to 2.86 mg/L) but continued to decrease at OBW (2.09 to 1.61 mg/L).

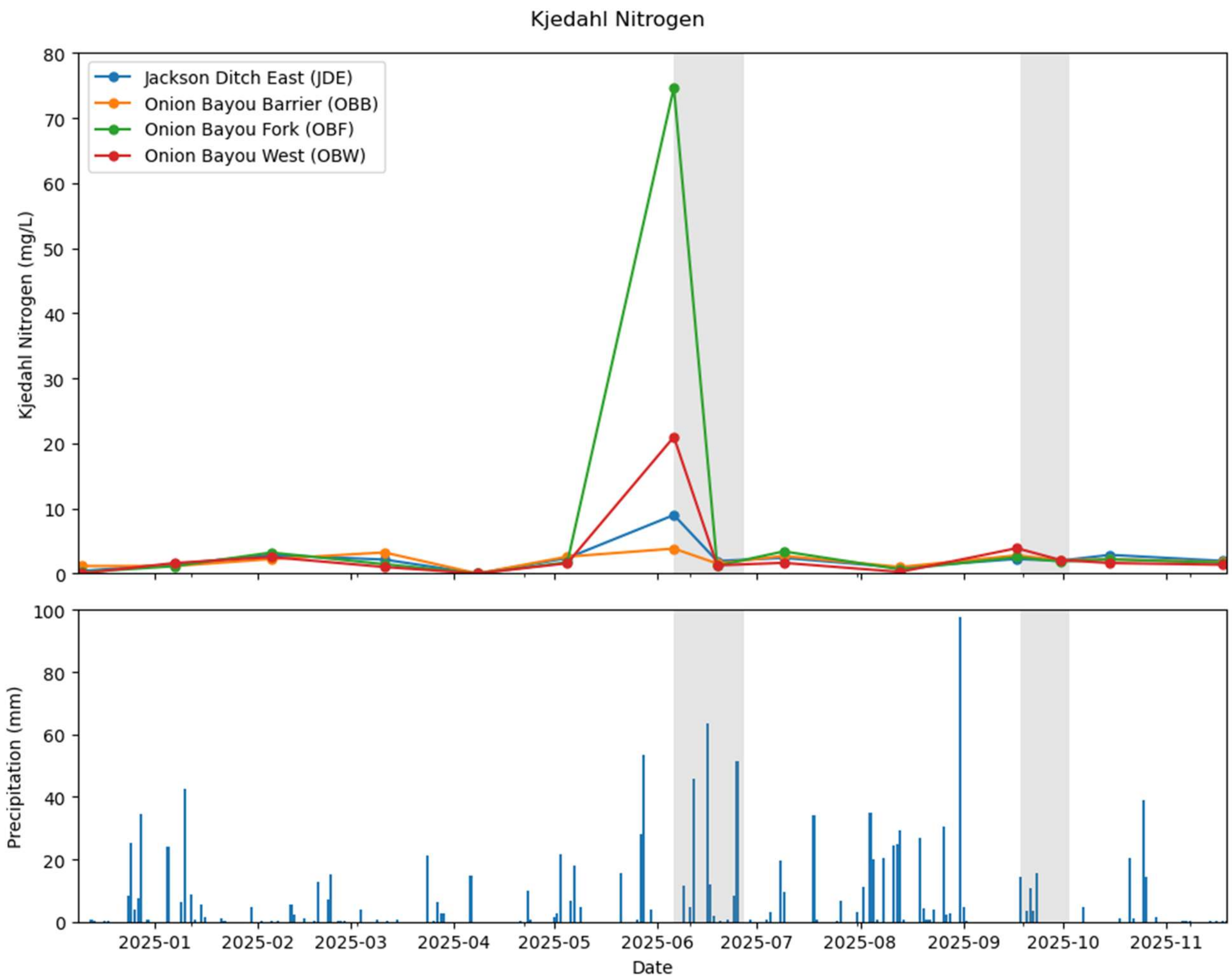

Figure 16. Total Kjedahl nitrogen concentrations (mg/L) across study sites throughout the study period. There are no TCEQ screening levels for total Kjedahl nitrogen concentrations for tidal streams.

Total phosphorus (TP) concentrations remained below the TCEQ screening level for tidal streams (0.66 mg/L) averaging 0.07-0.10 mg/L across sites for the study period. TP was generally highest in June-August at OBB, OBW, and OBF (0.147-0.297 mg/L).

In the summer, TP decreased at OBW (0.297 to 0.147 mg/L) and OBB (0.295 to 0.250 mg/L) but then continued to increase in the after-bin at OBB (0.0810 mg/L) while decreasing at OBW (0.177 mg/L). TP increased at OBF (0.158 to 0.226 mg/L) and JDE (0.0730 to 0.0890 mg/L) but then decreased at OBF (0.111 mg/L) and continued to increase at JDE (0.104 mg/L) in the after bins.

In the fall, TP decreased at OBB (0.069 to 0.046 mg/L), OBF (0.066 to 0.056 mg/L), and JDE (0.077 to 0.079 mg/L) from before to after bins, but increased at OBW (0.069 to 0.079 mg/L). TP then decreased at OBW (0.035 mg/L), continued to decrease in the after bin at JDE 0.057 (mg/L) and OBF 0.054 (mg/L), and increased at OBB (0.062 mg/L).

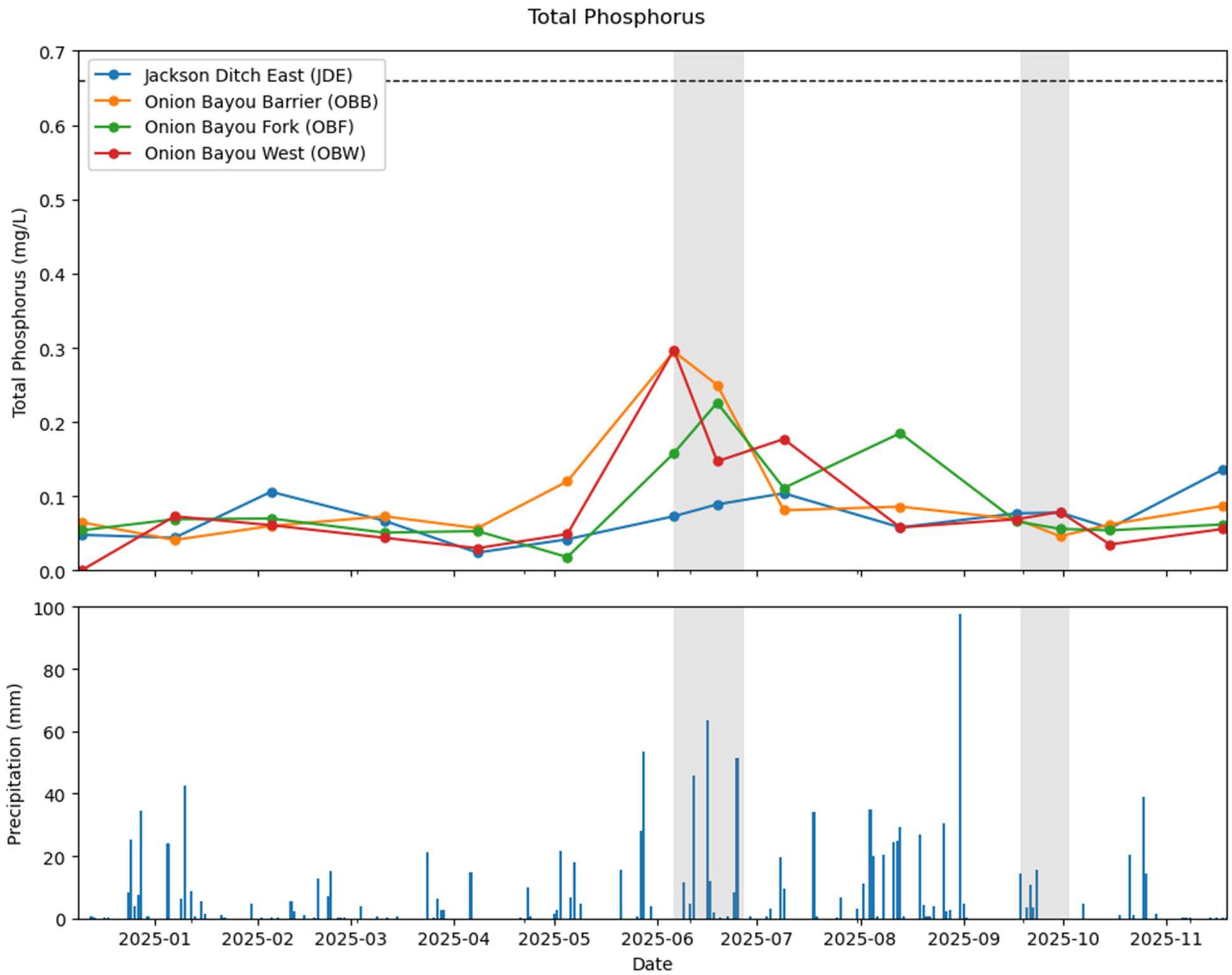

Figure 17. Total phosphorus concentrations (mg/L) across study sites throughout the study period. TCEQ screening level for total phosphorus n in tidal streams is 0.66 mg/L.

Overall mean total organic carbon (TOC) concentrations ranged from 13.31 mg/L at OBW to 18.93 mg/L at OBB (Table 5). TOC concentrations were highest in Fall (>20 mg/L) at OBB, OBF, and JDE (Figure 18).

Across summer study bins, TOC increased from the before to during bins at OBW (15.0 to 19.3 mg/L) and JDE (18.9 to 19.6 mg/L) but decreased at OBB (20.9 to 19.1 mg/L) and OBF

(19.4 to 19.0 mg/L). In the after bin, TOC decreased at all sites: OBB (19.1 to 18.3 mg/L), OBF (19.0 to 14.7 mg/L), OBW (19.3 to 11.8 mg/L), and JDE (19.6 to 15.5 mg/L).

Across fall study bins, TOC increased from the before to during bins at all sites: OBB (20.0 to 25.3 mg/L), OBF (16.2 to 20.1 mg/L), OBW (10.1 to 18.1 mg/L), and JDE (18.8 to 21.0 mg/L). In the after bin, TOC continued to increase at OBF (20.1 to 23.7 mg/L) and JDE (21.0 to 27.3 mg/L) but decreased slightly at OBB (25.3 to 25.1 mg/L) and at OBW (18.1 to 15.6 mg/L).

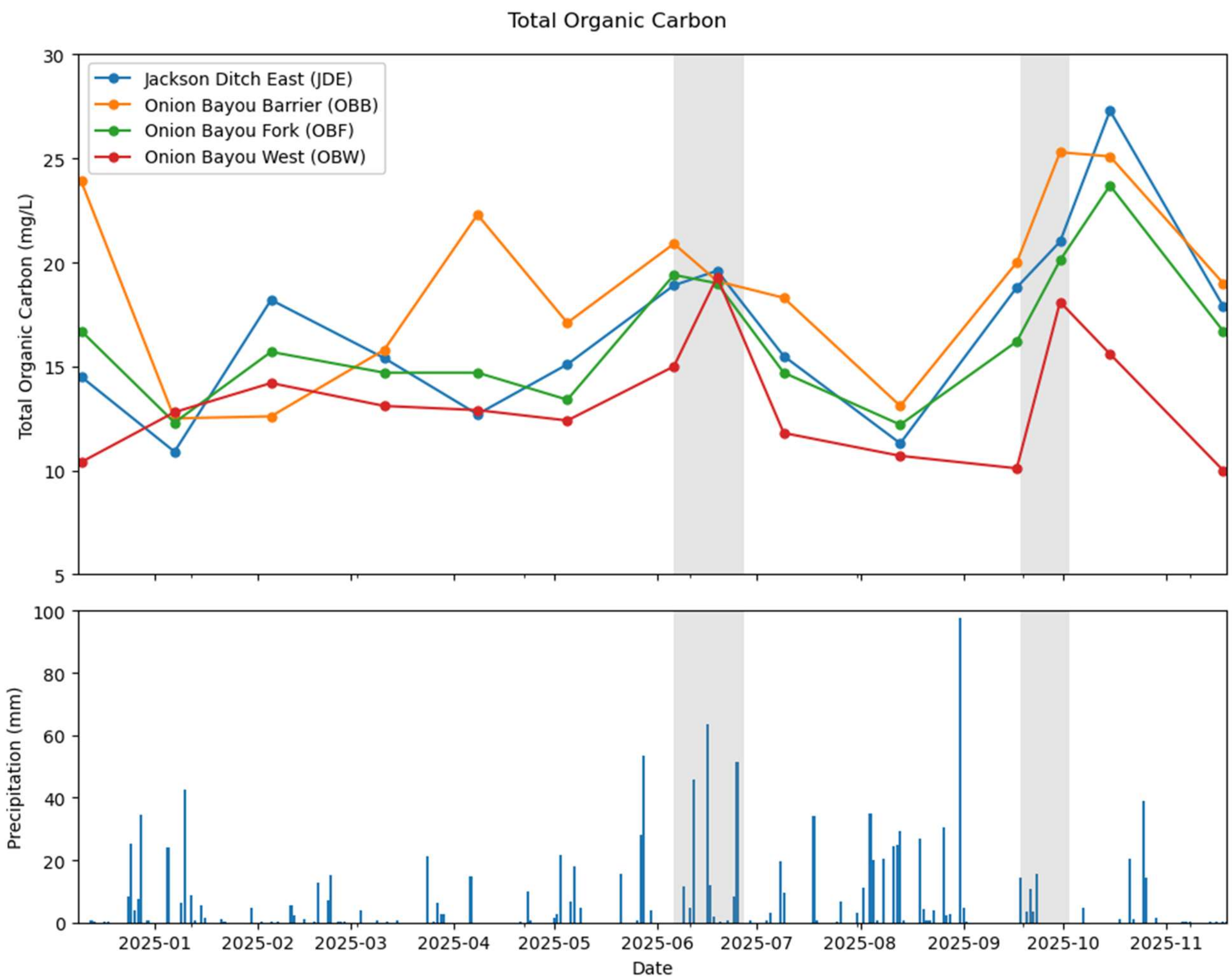

Figure 18. Total organic carbon concentrations (mg/L) across study sites throughout the study period. There are no TCEQ screening levels for total organic carbon concentrations for tidal streams.

Overall mean chlorophyll-a was lowest at OBB (12.40 ± 13.26 μg/L) and highest at JDE (22.95 ± 16.87 μg/L; Table 5). Chlorophyll-a exceeded the TCEQ tidal stream screening level (21.0 μg/L) at JDE, OBF, and OBW in February, March, May, and July 2025 (Figure 19). JDE and OBW exceeded the screening level in August and late September, while OBB exceeded the screening level in March and May. The highest chlorophyll-a concentrations occurred in February at JDE, OBF, and OBW, ranging from 60.5 to 67.6 µg/L.

In summer study bins, chlorophyll-a decreased from before to during bins at OBB (13.4 to 5.34 µg/L) and OBF (21.4 to 7.2 µg/L) but increased at OBW (8.9 to 9.79 µg/L) and JDE (7.12 to 9.79 µg/L). In the after bins, chlorophyll-a concentrations increased at all sites except OBB, ranging from 25.8 to 46.3 µg/L, while OBB decreased further to 3.56 µg/L.

Across fall study bins, chlorophyll-a concentrations increased from the before to during bins at all sites: OBB (1.78 to 15.1 µg/L), OBF (0 to 16.0 µg/L), OBW (0 to 13.0 µg/L), and JDE (0 to 21.4 µg/L). Concentrations then decreased in the after bin at all sites: OBB (15.1 to 4.45 µg/L), OBF (16.0 to 7.12 µg/L), OBW (23.1 to 8.9 µg/L), and JDE (21.4 to 8.9 µg/L).

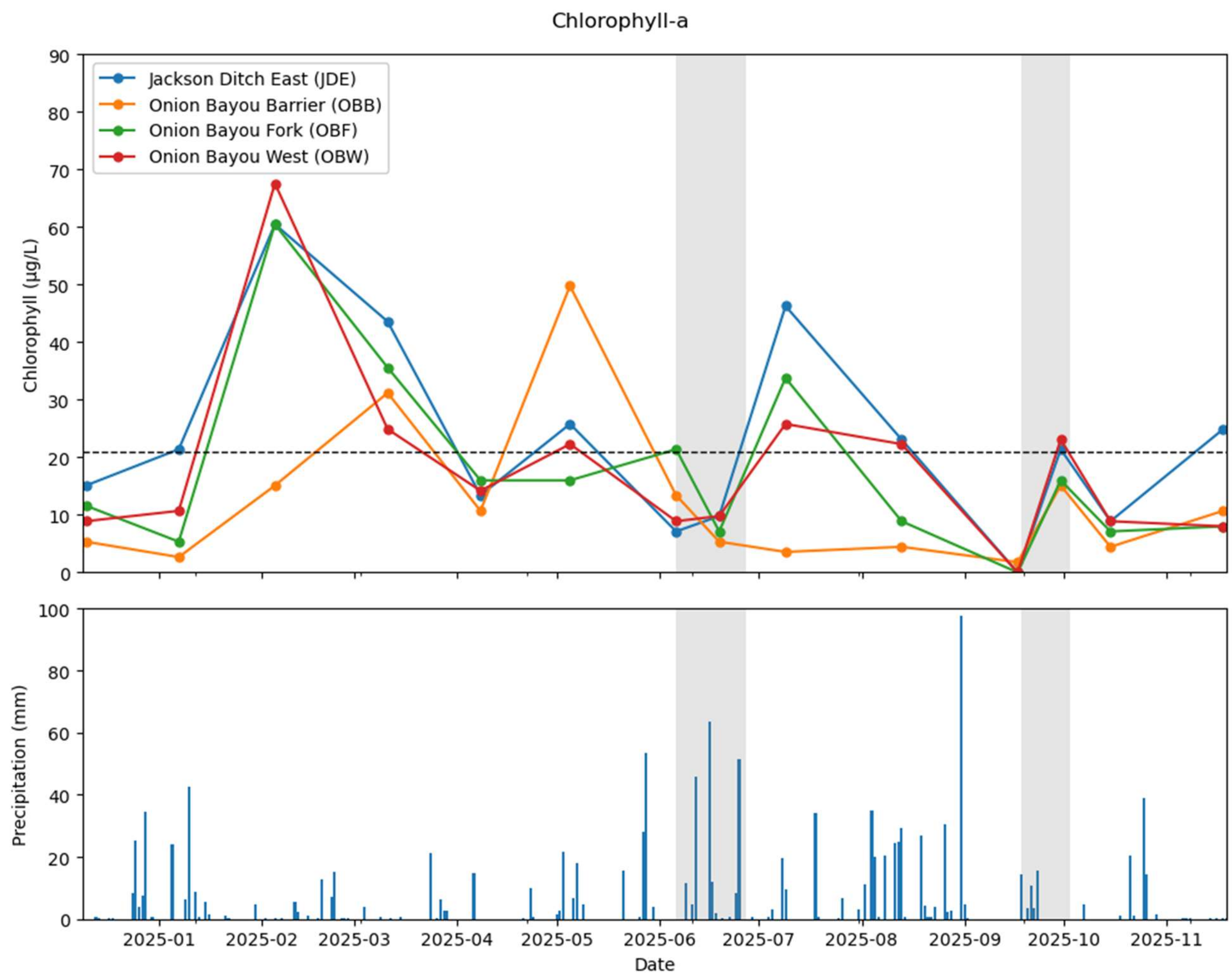

Figure 19. Chlorophyll-a (µg/L) across study sites throughout the study period. TCEQ screening level for chlorophyll-a in tidal streams is 21.0 mg/L.

Overall mean total suspended solids was lowest at OBB (13.18 ± 13.15 mg/L) and ranged from 45.00 to 65.52 mg/L across other sites for the study period.

In summer, TSS decreased at OBF (120.0 to 40.7 mg/L), OBW (53.3 to 24.8 mg/L), and JDE (48.3 to 23.3 mg/L) but increased at OBB (0 to 22.7 mg/L). All sites had higher TSS ranging from 68.3 to 87.5 mg/L in the after study except for OBB which was not detectable.

Across fall study bins, TSS increased at OBF (25.3 to 28.4 mg/L), OBW (30.2 to 38.5 mg/L), and JDE (34.9 to 35.5 mg/L) from before to during bins, but decreased at OBB from 6.46 mg/L to non-detectable levels in both during and after bins. TSS at OBF continued to increase from during to after bin (28.4 to 51.0 mg/L) but decreased at OBW (38.5 to 14.9 mg/L) and JDE (35.6 to 8.3 mg/L).

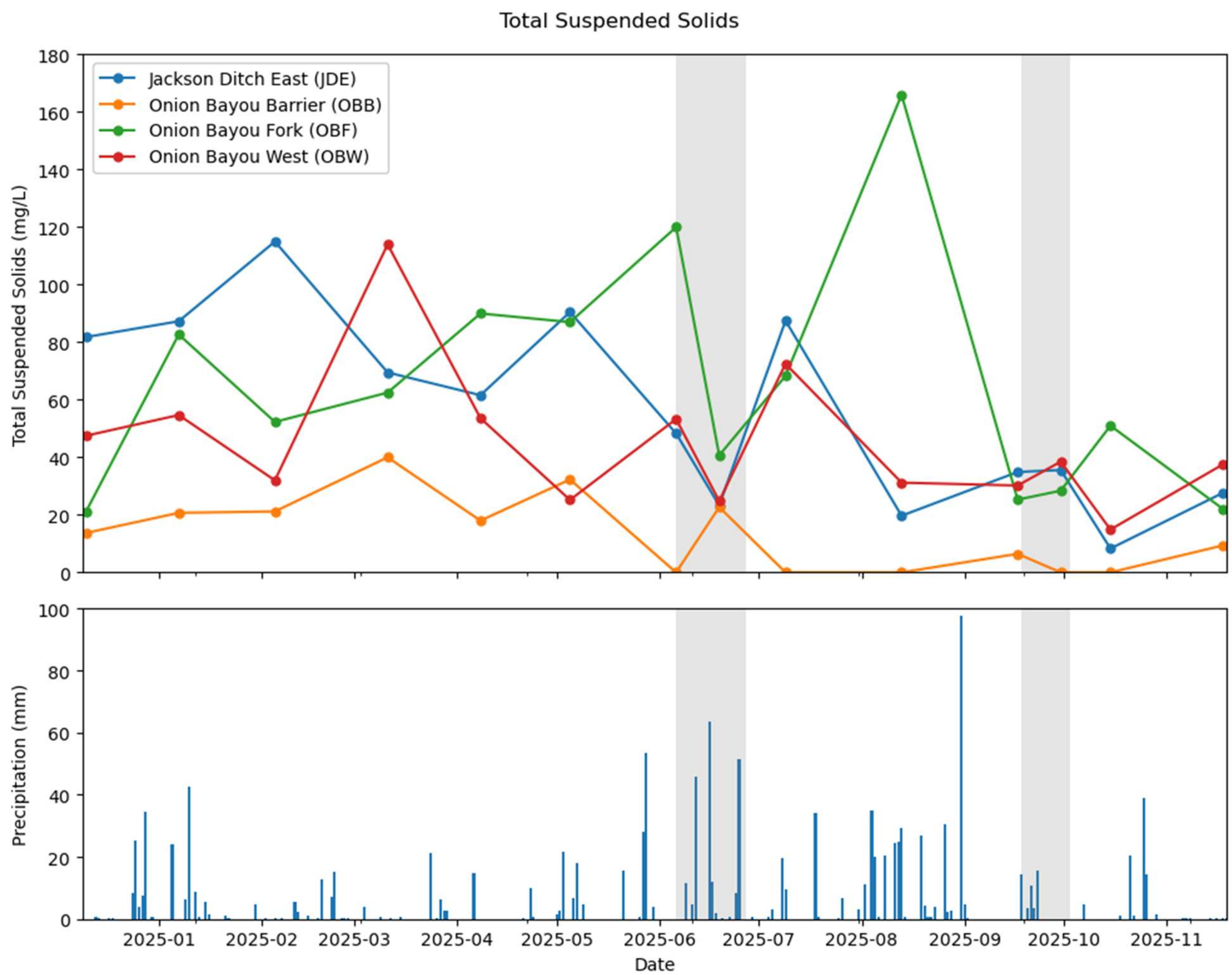

Figure 20. Total suspended solids (TSS) across study sites throughout the study period. There are no TCEQ screening levels for total suspended solids in tidal streams.

Principle Component Analysis

Water quality and nutrient data were combined, grouped into study bins representing conditions before, during, and after freshwater introductions in summer and fall (Table 2), and analyzed using PCA. PC1 and PC2 explained 32.1% and 24.4% of variation in the dataset, respectively (58.5% total; Figure 21). Along PC1, TOC and ammonia were inversely associated with TSS, pH, DO, and chlorophyll-a. OBB scored highest on PC1 due to greater TOC and ammonia concentrations which generally differentiated it from OBF, OBW, and JDE. Along PC2, salinity, total organic carbon, pH, and DO were inversely associated with ammonia, water temperature, and total phosphorus. Fall during and after study bins for OBF, OBW, and JDE scored highest on PC2 generally differentiating from summer conditions, particularly those observed at OBB. Water quality conditions at sites downstream of OBB exhibited the greatest similarity following freshwater introductions in both summer and fall.

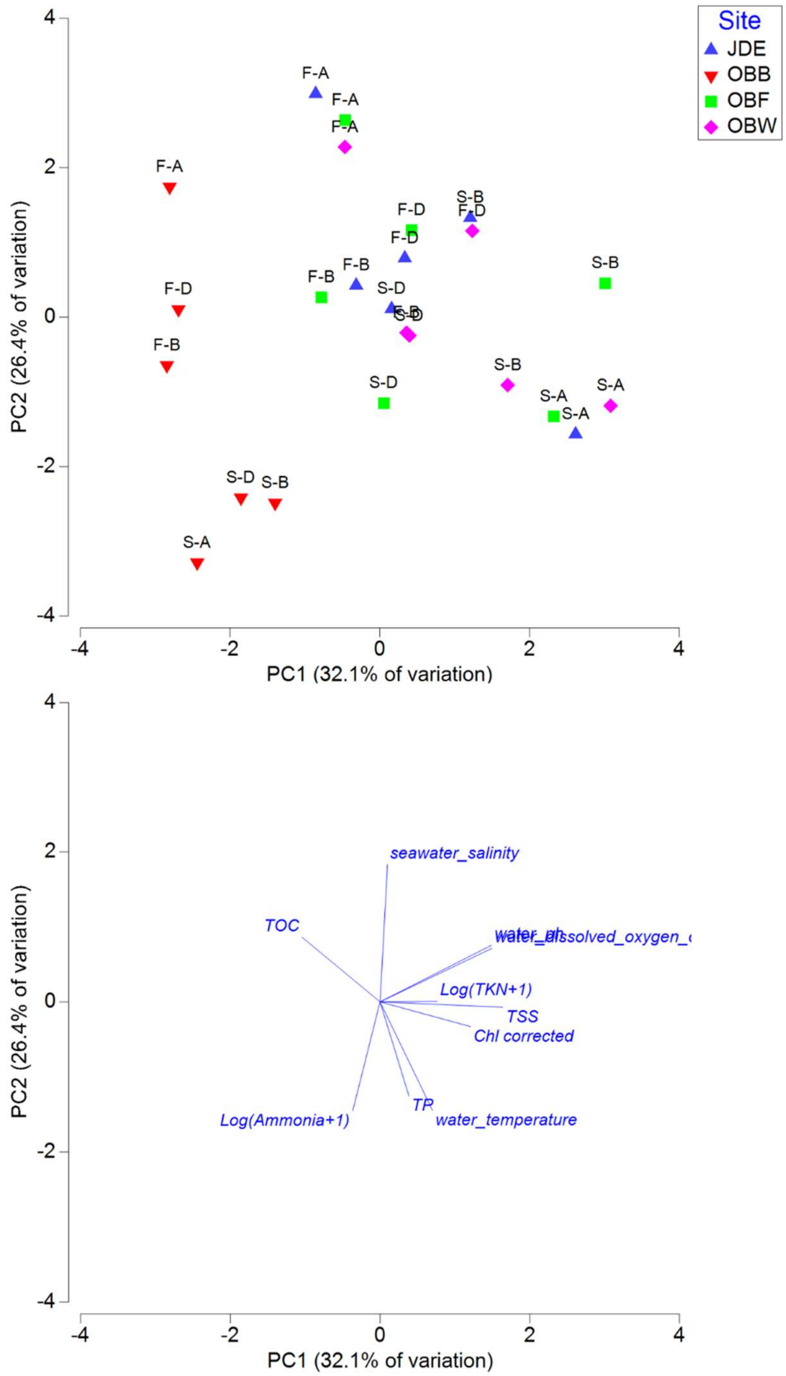

Figure 21. Principle component analysis (PCA) of study bins denoted as follows: Summer-Before (S-B), Summer-During (S-D), Summer-After (S-A), Fall-Before (F-B), Fall-During (F-D), Fall-After (F-A). Top: Study bin scores across study sites. Bottom: Variable loads denoted as follows: total organic carbon (TOC), log-transformed ammonia (Log(Ammonia+1)), water temperature (water_temperature), chlorophyll-a (Chl corrected), total suspended solids (TSS), log-transformed total Kjedahl nitrogen (Log(TKN+1)), pH (water_ph), dissolved oxygen (water_dissolved_oxygen), salinity (seawater_salinity).

Discussion

Study sites had notable water quality impairments related to chlorophyll-a and low dissolved oxygen with the severity and duration varying spatiotemporally due to seasonal water temperatures, runoff, stream geomorphology, and hydrological modifications. While there was indication of nutrient enrichment related to agricultural runoff, inorganic nitrogen and total phosphorus concentrations were generally well below water quality criteria set by TCEQ with moderate spikes occurring intermittently throughout the study periods while impairments occurred ubiquitously. Instead, the observed water quality impairments were likely exacerbated by natural runoff and exacerbated by hydrological modifications such as stream channelization and saltwater barriers.

The study site located immediately downstream of the saltwater barrier (OBB) was characterized by reoccurring anoxia and hypoxia, limited primary productivity, and high concentrations of total organic carbon and ammonia. Water in the Onion Bayou tidal main stem periodically exhibited a dark coloration similar to blackwater environments (i.e., swamps, blackwater rivers) whose characteristics arise from the high rate of decomposition of vegetation resulting in high tannin concentrations in addition to low pH and dissolved oxygen. Collectively, these characteristics indicate that the depletion of dissolved oxygen may be driven by the microbial decomposition of high concentrations of organic matter that is accumulated at both the saltwater barrier and upstream vegetation barrier in the form of floating nuisance vegetation and dead vegetation.

Saltwater barriers (e.g., pressure-regulated or manually operated saltwater barriers and dams) play an important role in protecting upstream freshwater supplies and saline-sensitive wetlands and wildlife species from saltwater intrusion. However, these structures can also contribute to water quality degradation and reduced tidal stream function (Pizano-Torres et al. 2016). During dry periods, saltwater barriers prevent the conveyance of freshwater downstream, increasing salinity to lower reaches and wetlands and reducing the availability of low-salinity habitat for estuarine-dependent fishery species. Texas's projected increases in water demands, more frequent and severe droughts, changing agricultural practices, and relative sea level rise are expected to exacerbate saltwater intrusion into upper estuarine environments. These pressures may necessitate additional salinity-management infrastructure, but such measures could further reduce the extent of low-salinity habitat available to dependent species, contributing to a process known as estuarine squeeze (Little et al. 2022).

In regions where upstream freshwater supply, habitats, and wildlife require protection through use of saltwater barriers, it is imperative that coastal managers address factors that contribute to estuarine squeeze to preserve estuarine function (i.e., agricultural returns, hydrological and stream restoration, focused flows management). The current study provides insights into how the hydrology of highly modified upper estuarine environments affected by saltwater barriers, channelization, and land use respond to rainfall and controlled additions of freshwater.

Rainfall events were associated with temporary decreases in salinity, pH, and dissolved oxygen concentrations across study sites, while flood tides returned conditions towards those prior to rainfall. The mechanisms that may drive these responses to rainfall may include: 1) the streamflow forcing of upstream tidal fresh to oligohaline water with low pH and dissolved oxygen concentrations to downstream study sites and subsequent tidal forcing of downstream saline water upstream, an outcome representative of the dynamic ebb and flow nature of tidal streams, 2) overland runoff of organic matter resulting in an acute enhancement of microbial processes, and 3) the stratification of the water column resulting in limited dissolved oxygen exchange between surface and bottom water.

The observed water quality response to controlled additions of freshwater was complex, influenced by additional factors such rainfall, land management practices, hydrological modifications, and tidal processes. It is clear that tidal processes forced water with differing water quality characteristics up- and downstream of fixed study sites. These tidal-driven signatures complicated the assessment of water quality response to controlled additions of freshwater particularly for the PCA which analyzed site-specific water quality data to characterize conditions before, during, and after controlled additions of freshwater. However, by comparing summer and fall water introductions, the impact of introduced water on water quality and nutrient dynamics in Onion Bayou is better understood.

Prior to the introduction of water in summer, rainfall (4.01 in or 101.85 mm) may have contributed to natural and agricultural runoff resulting in relatively high total Kjeldahl nitrogen and total phosphorus concentrations. While the residence time of these nutrients throughout the study area is not currently well understood, heavy rainfall (7.86 in or 199.64 mm) and the study's introduction of oligotrophic water (295.05 acre-feet), water previously stored in a reservoir, may have contributed to the dilution or flushing of these nutrients in the study area. Additionally, there was evidence that chlorophyll-a and total organic carbon concentrations may have been flushed as water was introduced across sites in the main stem of Onion Bayou (OBB and OBF) while increasing concentrations at sites to the east and west (JDE and OBW). The role of introducing water on the hydraulic flushing and transport of nutrients and phytoplankton in the upper estuary should be further explored through an improved experimental design in future studies applying the learning from this study. Additionally, future studies should incorporate multiyear analyses to capture interannual variation in wet and dry climatic cycles.

The fall study period provided a better representation of what water quality response to introduced water during dry periods. With the exception of organic carbon, conditions in the fall may have resulted in less nutrient loading than in the summer (i.e., non-detectable concentrations of ammonia, less total Kjedahl nitrogen and total phosphorus) likely due to: 1) dryer conditions minimizing the potential for agricultural and organic matter runoff, 2) the application of fertilizers to agricultural fields in the watershed were more likely to occur earlier in the spring and summer, and 3) stormwater canals in the region are maintained early in the year to prepare for tropical rainfall during hurricane season and this may contribute to organic matter in runoff. Under these conditions, there was indication that freshwater inflows increased primary production as indicated by increased chlorophyll-a concentrations while water was introduced and its subsequent decrease after the introduction of water stopped and as the region slipped into drought. Both summer and fall water quality responses have implications for the quality of habitat in Onion Bayou for the numerous species that rely on tidal stream environments in the upper estuary that could be used to inform management of freshwater resources.

Targeted habitat objectives should determine the timing of delivering freshwater into estuarine environments. The current study aimed to understand and improve water quality in a tidal stream when economically and ecologically important species are migrating into estuarine nursery habitats which generally occurs from spring through fall with seasonal peaks. A prudent approach, therefore, could be to introduce water when elevated salinity is present at these times. While previous studies have found that tidal stream faunal assemblages were mainly driven by salinity and not dissolved oxygen (Tolan & Nelson 2009), it is not clear how estuarine species would respond to the impaired dissolved oxygen conditions occurring consistently near the saltwater barrier and episodically in other regions of the study period. It is important to note that freshwater inflow events (i.e., rainfall and controlled freshwater introductions) did not improve impaired oxygen conditions in the summer near the saltwater barrier, however, this response could vary under dry summer conditions.

There are several limitations to consider when implementing focused flows using irrigation water. Foremost among these is the availability of water during periods when drought exerts the greatest pressure on Texas estuaries and freshwater supplies. Partnerships with regional water suppliers can facilitate the diversion of water from more reliable sources, such as major rivers, streams, and reservoirs, to vulnerable coastal habitats. However, conveying water through irrigation canal networks requires existing infrastructure and is most efficient when coordinated with other water demands, including agricultural, municipal, and industrial use, to minimize conveyance losses and total project water requirements. In rural regions such as Chambers County, where municipal and industrial demands are relatively limited, focused flows will likely need to coincide with the seasonal flooding of rice fields and managed waterfowl habitats from March through November, a period that overlaps with the use of upper estuarine habitats by many estuarine-dependent species. Additionally, to maximize the ecological benefits of increasingly scarce freshwater resources acquired through water transactions or other mechanisms, practitioners should prioritize baseline monitoring and real-time data collection to inform adaptive management and identify when habitat or water-quality objectives have been achieved.

Despite its historical impact on coastal hydrology and water quality, agriculture will continue to serve a critical role within rural communities and on coastal ecosystem health. Multiple stakeholders along the Texas coast are partnering with public and private landowners, lessees, and managers to increase the availability of freshwater wetlands by flooding managed agricultural fields particularly as increased droughts and warming temperatures restrict the extent of naturally occurring habitats. Maintaining these practices on the Texas coast will be imperative in maintaining freshwater wetland availability, combatting estuarine squeeze, and implementing focused flows through irrigation canals as reduced irrigation demand decreases canal efficiencies threatening the long-term availability of surface water for certain coastal regions for both agricultural and environmental demands. Further understanding the relationship between land use, hydrological modifications, estuarine hypoxia, and ecologically and economically important fishery species will improve our ability to manage upper estuarine regions during droughts or in highly modified coastal watersheds.

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