Distribution of Suspended-Sediment Loads across North Carolina's Saltmarshes: Wetlands Stability Explored through Modern Measurement Systems

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Abstract: (Brief synopsis of the project and its findings)

Saltmarshes in North Carolina are rising in elevation slower than sea-levels, while adjacent subtidal environments are infilling. To explore the effect of levees on suspended sediment gradients from subtidal regions into the marsh, I deployed suites of sensors at sites with varied levee morphologies, tidal ranges, and marsh configurations. Temporally high-resolution optical backscatter turbidity sensors (OBS) were aligned in an edge-normal transect and contemporaneously recorded data. Local sediment was collected and used for lab calibrations of turbidity sensors.

A low-cost, open-source OBS was tested for its applicability to North Carolina's estuaries. Many sensors were built, deployed, and refined, but ultimately none offered effective replacements to the costly commercial sensors for the long-duration intertidal deployments needed to answer the research questions posed here.

Rescaling the project to focus on the commercially available RBR brand Turbidity sensors, we found largely low concentrations of total suspended solids and turbidity (NTU) at the sites. Sensors often recorded high concentrations in the channel and shallow exponential decay in concentrations heading into the marsh interior. These findings offer local evidence of sediment-deprived interior marshes on tidal timescales while forming the initial datasets for an expanding collection of channel-to-marsh suspended sediment gradients needed to explore the depositional disconnect.

Introduction: (What problem were you addressing? Why is it important?)

I was addressing the complex problem of how sediment distribution varies between adjacent environments—salt marshes and tidal channels—in the context of rising sea levels. Specifically, I was investigating why saltmarshes are failing to accumulate sediment at a rate that keeps up with sea-level rise (Ouyang and Lee, 2014; NCDEQ, 2020), while adjacent tidal channels are experiencing increased sediment accumulation. I posed questions about the role of naturally formed elevated "levees" in this process and how they might act as hydraulic barriers, affecting sediment and water flow in these ecosystems. My study aimed to explore whether these levees contribute to the contrasting sedimentation rates and hydrological conditions between the tidal channels and the salt marshes, which has implications for the long-term survival of these ecosystems.

This problem was important because understanding the divergent sedimentation rates between saltmarshes and tidal channels has direct implications for long-term ecosystem sustainability, particularly in the face of rising sea levels. Failing to understand these mechanisms could lead to poor conservation and management decisions. Additionally, understanding the role of levees in these processes could offer key insights into water drainage and sediment distribution. Such information is crucial for mitigating the adverse effects of waterlogging and vegetation die-off in salt marsh interiors. My investigation thus aimed to provide the scientific basis for more effective conservation strategies, especially relevant for microtidal marshes similar to those in the Albemarle and Pamlico estuaries, which are at significant risk of marsh loss in the coming decades due to higher rates of sea-level rise and low sediment supplies.

Specifically, I aimed to determine the influence of levees on the transport of total suspended solids on sub-tidal timescales using arrays of turbidity sensors. The magnitude of levee influence will be determined by the rate of decay of total suspended solids in cross-shore transects.

Hypothesis: Levees with greater elevational and lateral prominence are associated with more rapid attenuation of suspended sediments during tidal flooding (Figure 1).

While mature, high-slope marshes are often drained by dense channel networks, gently sloping low marshes are less channelized causing distance from the marsh edge and elevation to largely determine allochthonous supply to interior areas (Temmerman et al., 2005). In some microtidal marshes, organic accretion is vital for interior marsh survival, while inorganic sedimentation is closely tied to perpendicular distance from sources like tidal creeks (Duran-Vinent et al., 2021). Here, flooding water levels above the bed are often very small, and increases in bed elevation relative to a stationary water level could enhance the overall influence of bed friction for a given flow. The resulting reduced currents would increase particle deposition (Mudd et al., 2010), resulting in lower total suspended solids (TSS) concentrations further into the marsh platform.

The trend between distance, concentration, and deposition is widely observed and recreated in numerical models (Friedrichs and Perry 2001; Fagherazzi et al., 2013; Duran-Vinent et al., 2021), but its manifestation varies and requires direct and multiple marsh platform measurements to determine local patterns and related vulnerability (Ganju et al., 2015; Coleman et al., 2020). In microtidal and mesotidal systems, shore-normal decay to a constant non-zero TSS often occurs in the first 20 meters of the marsh (Duvall et al., 2018, Coleman et al., 2020), hence the proposed sensor spacing (Figure 1). In-situ measurements of suspended sediments will produce one of these potential findings, or support an alternative hypothesis.

Potential Finding 1 - *Levees as more efficient sinks* - The rate of exponential decay of TSS will increase with increasing levee prominence (height and width).

Potential Finding 2 - *Levees as increased benefittors* - The rate of exponential decay of TSS is the same across levee sizes, and larger levees simply reflect larger incoming TSS

Alternative Hypothesis - Levee prominence has no statistical relation to TSS quantities or gradients

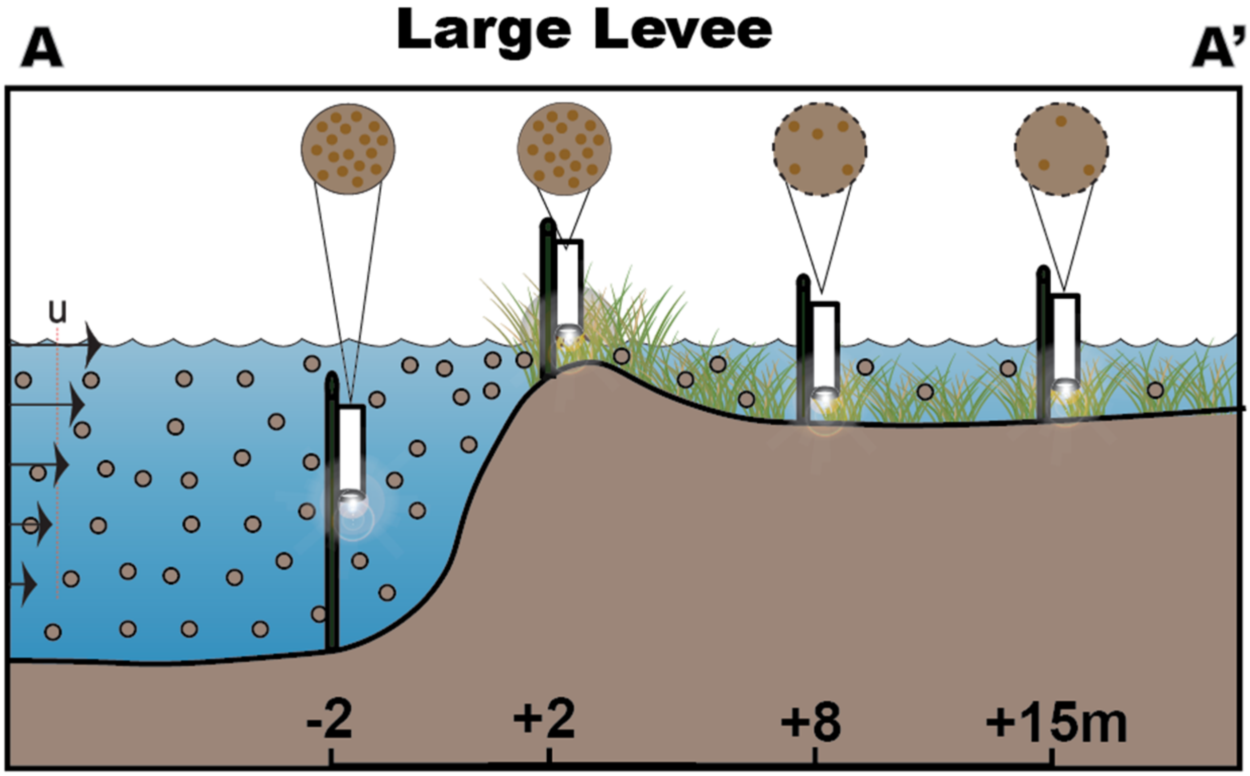


Figure 1: Sensor configuration and hypothesized readings (brown circles): a cross-shore transect taken into the marsh from A to A'. Suspended solids are seen as brown dots in the water column, and hypothesized readings of TSS can be interpreted from the number of brown dots in each sensor's measurement volume (brown circles). Light radiating off sensor-face indicates measurements taken using light in near-infrared wavelengths. Shore-normal velocity component of flow is represented by U and the arrows, showing lower velocities near the channel bed due to shear stress. Levees with greater elevational and lateral prominence are associated with more rapid attenuation of suspended sediments during tidal flooding. Sensors oriented left to right: Channel, Levee, Int1, Int2. Sensor locations in meters from marsh edge are shown at the bottom.

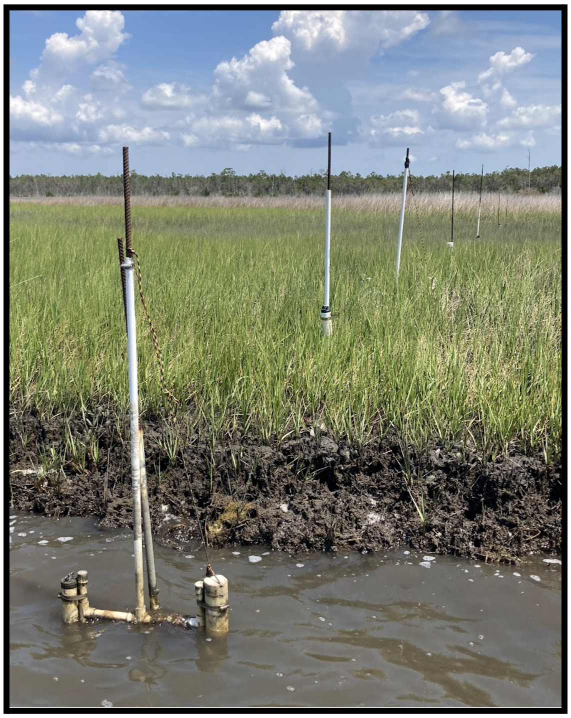
Methods: (What did you do to complete your project? How did this differ from what was proposed?)

Sensor Construction

The objectives here required the construction of additional sensors prior to installation. To address this, I hired and mentored an undergraduate student who aided in the building of fifteen additional sensors to the five existing ones, rounding the total to the desired twenty. The idea was to set out five sensors at each of the four sites contemporaneously. Following the precedent and instructions set forth by colleagues Eidam et al., 2021, the building of the sensors involved basic electrical circuitry training, soldering, vacuum chambering, pressure chambering, resin casting, 3D printing, and software initialization. A UNC-Chapel-Hill undergraduate, David Go, was funded to work on this project and has since carried his expertise into developing sensors in a similar framework for a dissolved gas sensing application.

Figure 2: Fifteen of the constructed OpenOBS units with endcaps sealed and ready for settings to be loaded before field deployment.

Deployments



At each site, RBR Duo and OpenOBS units were secured to rebar at a height of 8 cm above the bed. One pair was placed 2 meters from the marsh edge in the creek (at 50 cm from the bed), one on top of the levee at 2 meters, and two within the interior marsh at 8 meters and 15 meters from the marsh edge. Arrangements deviated from this set up depending on sensor availability throughout the project as well as to address site-specific variation. Sensors, which measure at distinct sampling frequencies (5 Hz for RBR, 200 Hz for OpenOBS), were smoothed to 10-minute averages. Data were parsed, calibrated, and analyzed in Matlab R2021b and Python. Passive sunlight signals, which are systematically measured by the OpenOBS were used to correct the active backscattered-light signal, while the RBRs have effective daylight filters. Biofouling of the optical sensor face limited the duration of deployments or mandated frequent user cleaning, which temporarily disturbs bed sediments.

Figure 3. A Sensor Transect at Long Bay

Using ZebraTech wipers that trigger every 15 minutes, the RBR Duo's produced quality continuous records for as long as the wipers were active, while the OpenOBS units required frequent cleaning which for many was limiting and resulted in short usable data periods as fouling would obscure frequently submerged sensors.

Table 1: Sensor Deployments		
Site	**Configuration**	**Duration**
Gales Creek	4 RBR, 4 OpenOBS Sensors	30 days; August 2023
Pages Creek	5 OpenOBS Sensors	30 days October 2022
Oyster Creek	4 RBR, 5 OpenOBS Sensors	28 days; December 2022
Long Bay	14 Sensors (2 x 7 sensor transects 2 RBR, 5 OpenOBS per)	21 days; August 2022
Hoop Pole	10 Sensors (2 x 5 sensor transects (4 RBR, 6 OpenOBS)	10 days; June 2022

Figure 4: Deployment Sites (with an inset of Pages Creek, located 70km SW of the SW corner of the main map). Sensors were deployed at these sites as described in the table above.

Lab Calibration Experiments

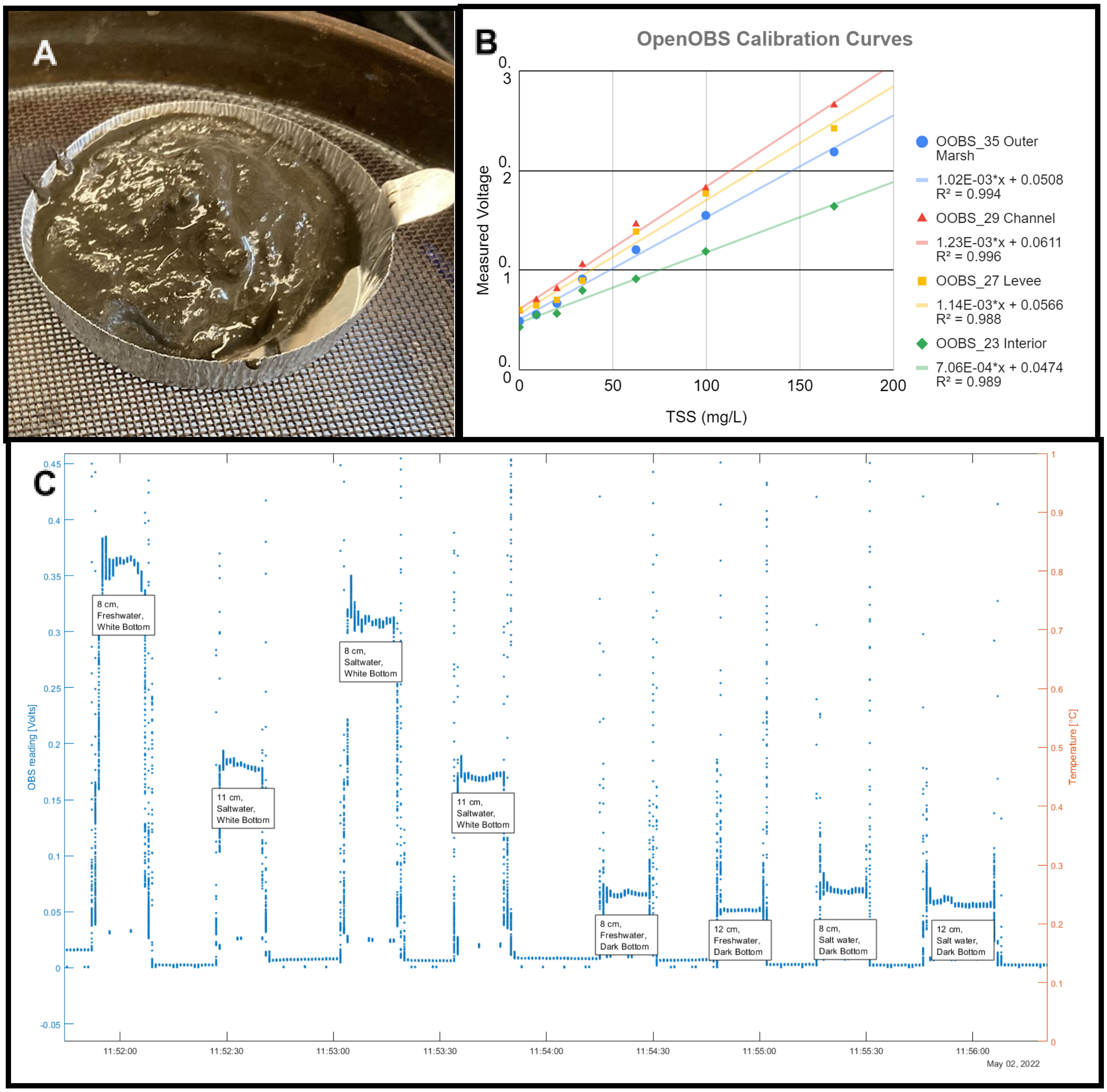


Figure 5: A.) Weighed and hydrated mud sample to be added to a known volume of water to create a slurry of known concentration. B.) Calibration curves using field sediment for 4 OpenOBS Sensors showing linear response to increasing TSS (Total Suspended Solids) in lab-controlled settings. C.) Readings from a single OpenOBS unit exposed to a variety of containers previously used in calibrations to prove the influence of water volume and container color on readings - especially at zero and low TSS concentrations.

Lab calibrations were performed many times for OpenOBS sensors using sediment local to each site where they were deployed. Lilian Cooper and McKenzie McLean, two UNC-Chapel Hill undergraduates, helped with lab calibrations and worked with me to refine the methodology for these calibrations. While the response of the sensors was linear in a controlled lab environment, these calibration curves often were offset from field observations. An explanation may be the water sampling volume being larger than expected and interfering with vegetation or bed sediment beyond the cleared zone. To interpret offset post-calibration field observations is not impossible, but requires either field sampled water TSS measurements taken contemporaneously to sensor readings, or requires acceptance of correct trends but incorrect magnitudes. For example, water bottle samples can be retrieved at several time-points throughout the sensor deployments, ideally capturing the full range of turbidity and ambient lighting conditions, then used to offset or tether the calibration curve, granted offset values are consistent across time-points. Alternatively, if sufficient water bottle samples are obtained, the field samples solely can be used for the construction of a lab-independent calibration curve.

Fouling Experiment

To test the effect of inundation duration on fouling intensity with the hope of detrending data from fouled sensors, an experimental array of OpenOBS sensors was installed at a fixed elevation in a highly accessible marsh. Every 24 hours, a sensor was plucked from the array and dried in the lab. The fouling mass was then collected from each sensor face, redried, and weighed. The results were highly non-linear, yielding no clear trend in increasing fouling mass with days of exposure. Potential explanations are that rain events can scatter sediment from the marsh surface onto the sensor face, and flotsam can adsorb to the sensor face.

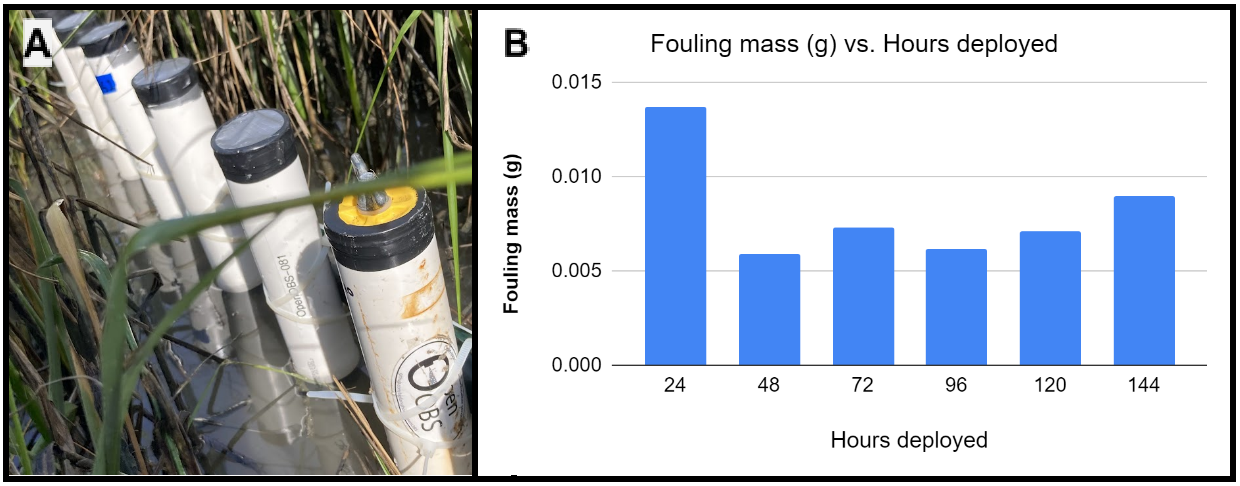


Figure 6: A.) Fouling experimental array affixed in marsh. B.) Data yielded from the experiment as masses.

Mapping Efforts

Mapping sites relied on the use of Structure-from-Motion (SfM) photogrammetry. sRGB Images were acquired in a gridded pattern using a DJI Mavic 2 Pro with a Hasselblad L1D-20c image sensor (5472 x 3648 pixels per image) from ~80 meters above ground level. Five ground control points were surveyed using a Trimble R8 real-time kinematic GNSS (RTK GNSS), vertically in the North American Vertical Datum of 1988 (NAVD88), and horizontally in Universal Transverse Mercator Zone 18N (NAD83; UTM 18N). Targets were used to precisely render the produced map products on earth's surface in a way that is compatible with other existing public data products. The resulting RGB maps have ~2 cm/pixel ground-sampling distances and the digital surface maps (Figure 8) contain vegetation canopy elevation and mudflat elevations.

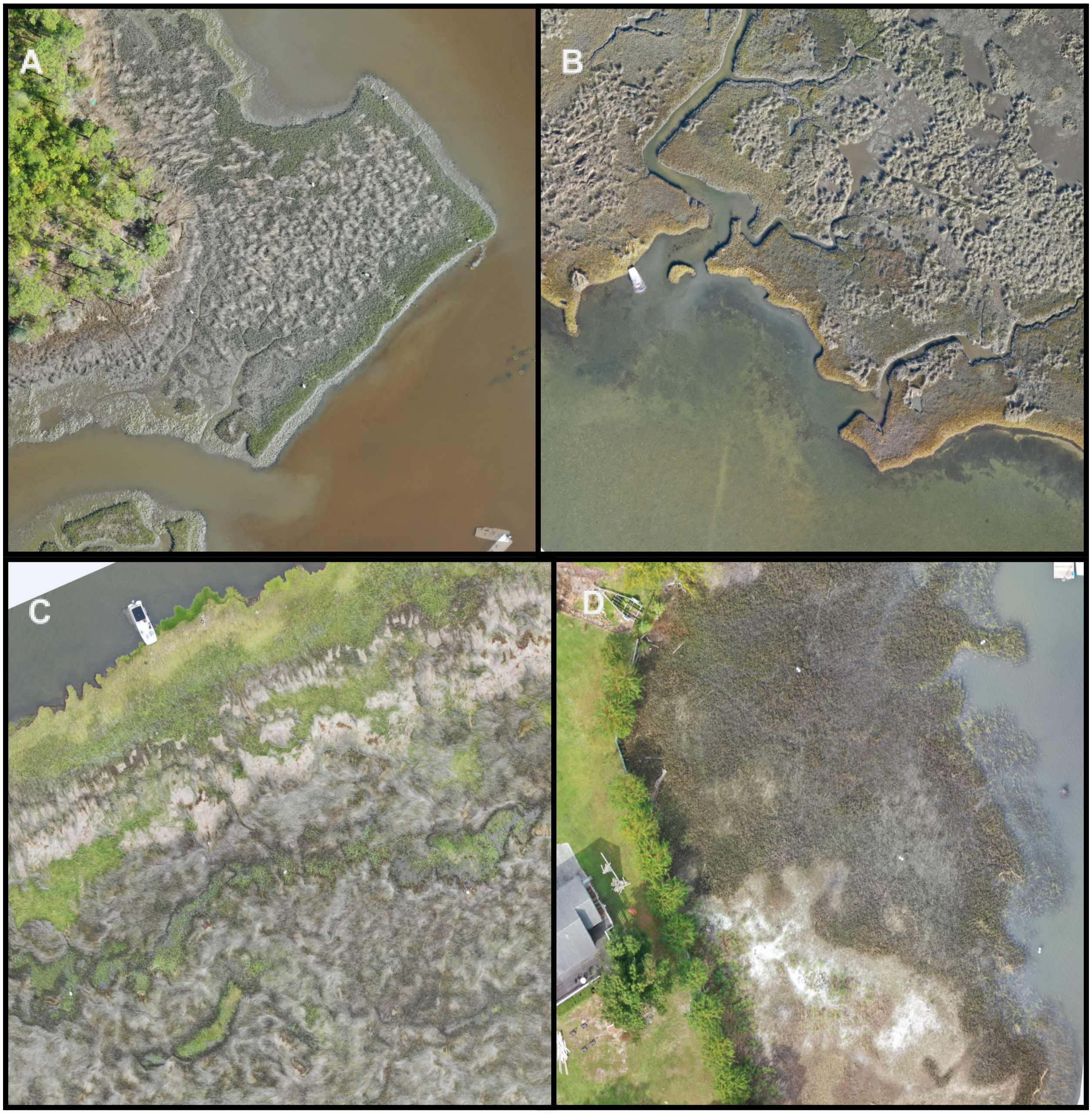


Figure 7: Georectified Orthomosaics of 4 Study Sites, clockwise from top left: A.) Gales Creek, B.) Oyster Creek, C.) Long Bay, D.) Pages Creek

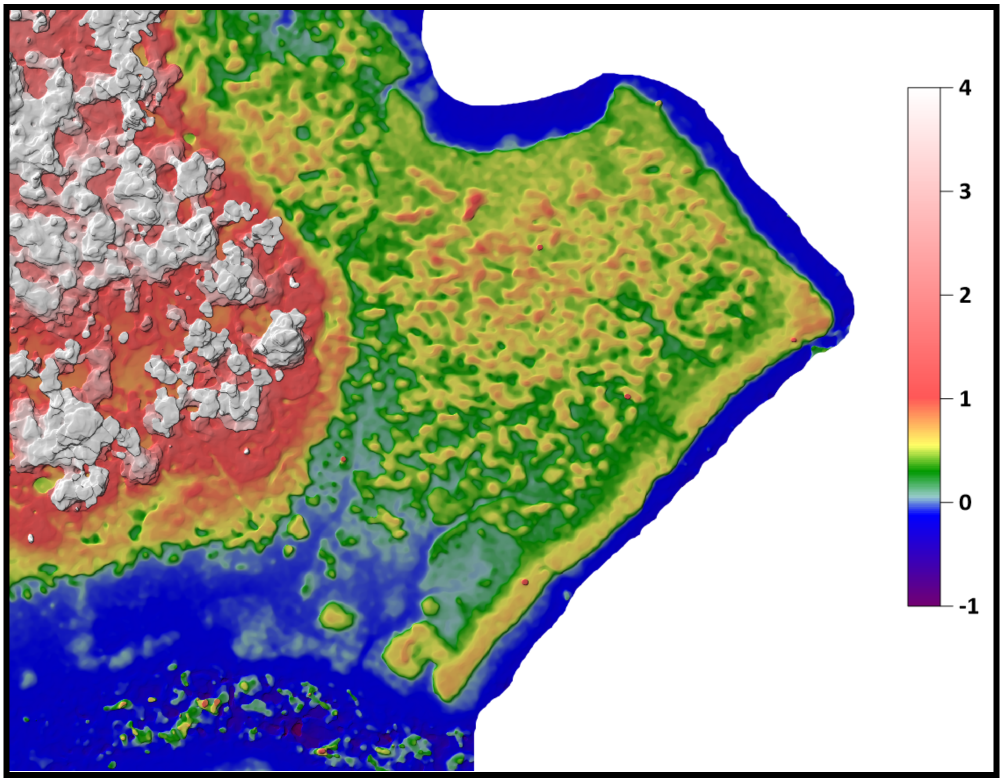


Figure 8: Example of Georectified Digital Surface Map of Gales Creek, NC. Units are in meters NAVD88.

Results: (What were the findings of your project?)

The results section below contains a subset of the datasets produced for this project. More data will be provided upon request and ultimately with the final data release as described in the Data Management Plan section.

Transects

Transects were collected at sites to identify the presence and prominence of levees using an RTK GPS. Points were taken approximately every meter to produce the transects seen here, starting from the mudflats on the left and moving up onto the marsh as distance increases.

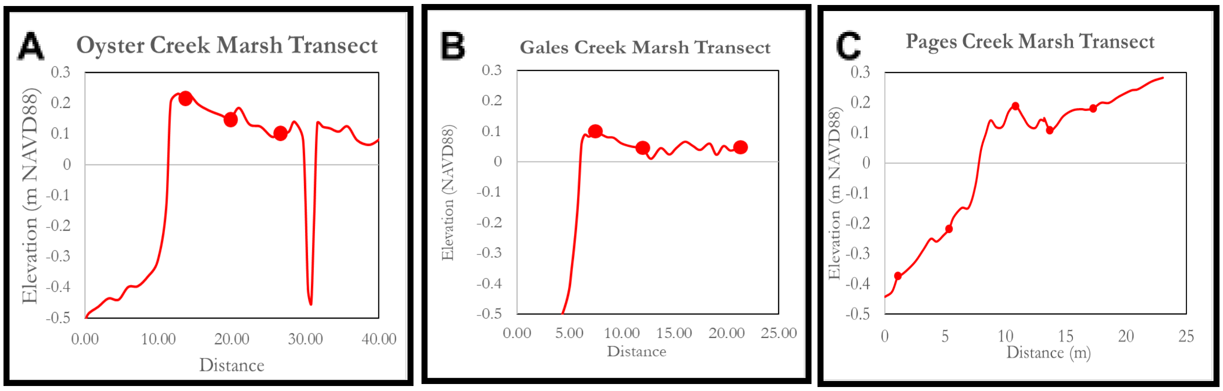


Figure 9: Transects from 3 of the sites where Turbidity sensors were deployed. Large markers on the figures represent the location of an RBR and/or OpenOBS sensor.

Turbidity Data

Turbidity data are presented as a time series of readings. These data were processed and displayed all together for a single site, making for rich figures with many signals to detect. The first figure caption in this section will detail the components of the figure. Turbidity measurements were resampled into 10-minute averages and only shown when sensors were submerged under 10 cm of water or more to standardize measurement conditions across sensors and minimize the effect of surface bubbles on readings during the initial flooding phase.

The data show large deviations from the mean at each of the sensors, but with generally low NTU readings that indicate low turbidity waters. At Gales Creek, the channel contained just under two times the turbidity of the marsh platform. The innermost sensor recorded the lowest turbidity, while the levee and second marsh sensor (8 m in from the marsh edge) carried similar averages for the deployment.

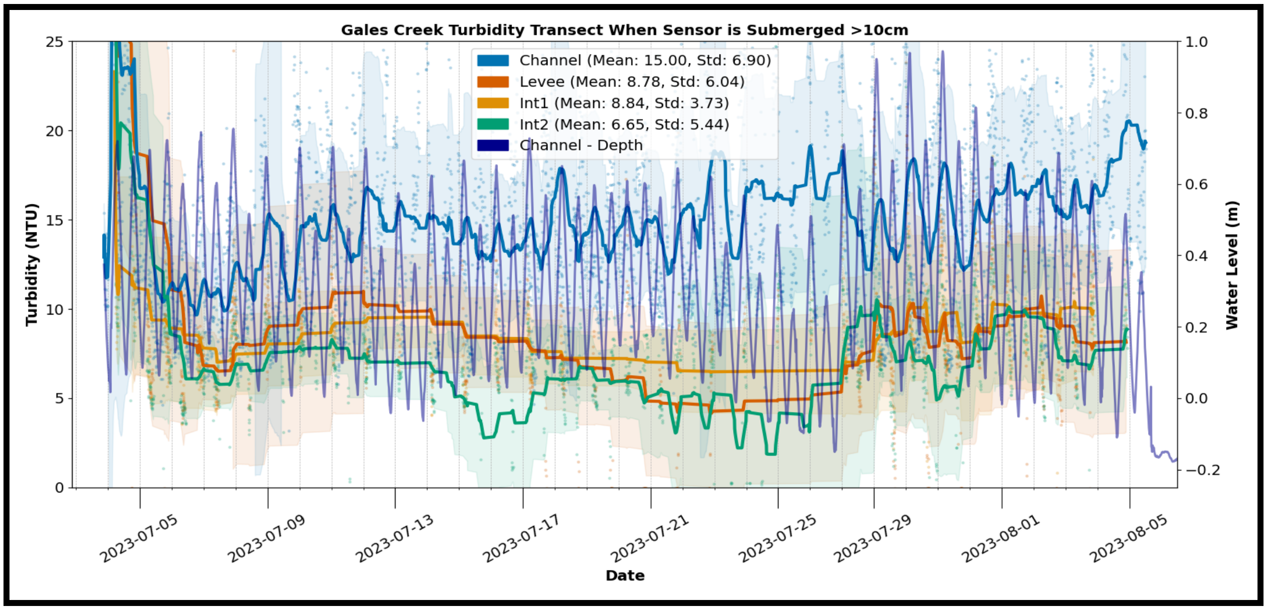


Figure 10: Gales Creek in July of 2023- Turbidity is shown as the first 4 items in the legend, with the mean and standard deviation of all measurements considered in the plot. Dots represent the resampled measurements, Solid lines represent a 100-measurement moving average for each sensor. The transparent shading around lines represents the standard deviation for the same 100-measurement windows. Water level (Channel - Depth) is the last item in the legend and corresponds to the Y-axis on the right. It appears as a sinusoidal thinner line behind the turbidity moving averages and can be followed starting from the right y-axis backward.

Turbidities across Oyster Creek sensors (mean of ~ 4.5 NTU) were lower than those measured at Gales Creek (mean ~10 NTU). They decayed from the channel into the marsh. For non-creek sensors, there were long periods of this deployment where the quality threshold of sensor submersion over 10cm was not met, thus no data is shown for those periods. Instead, the moving average appears as a flat line, which indicates the bounding measurements before the data-deprived time period. Oyster Creek exhibits a tidal range of ~0.4m, illustrated by the difference between consecutive high and low water levels.

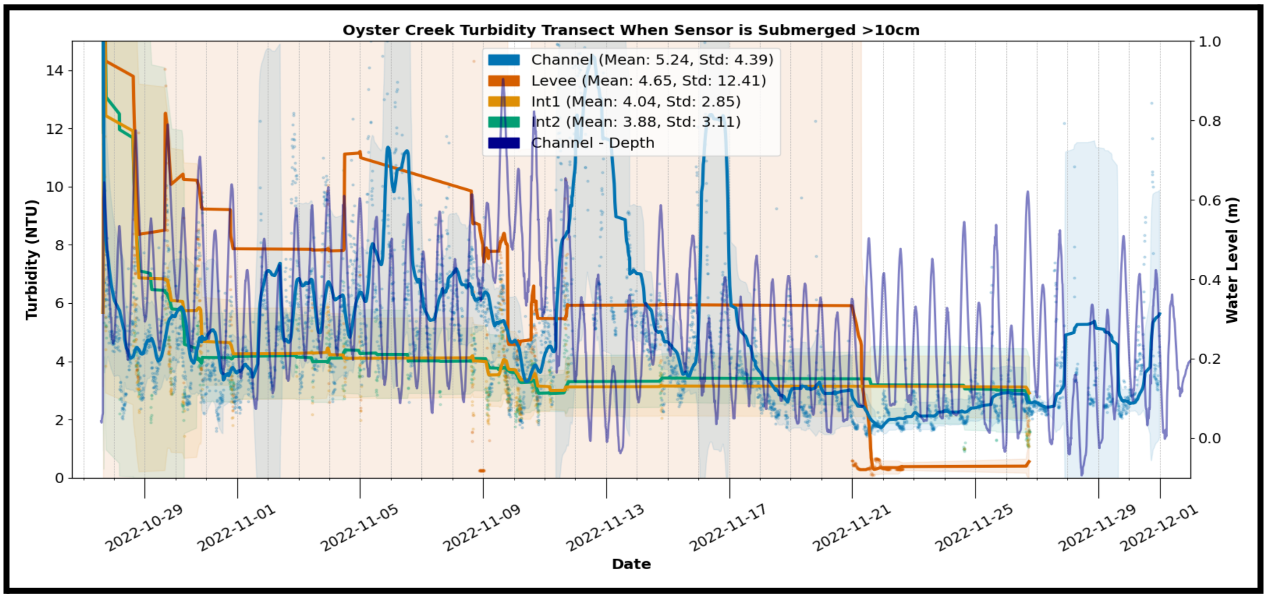


Figure 11 - Oyster Creek Deployment from November of 2022. All descriptors from the figure caption above apply here.

Another Oyster Creek Deployment in May of 2022 yielded a shorter duration of usable data, as RBR sensors were not equipped with wipers similar to the OpenOBS units, to try and expose paired sensors to similar fouling signals and compare the observable difference. The fouling masses on paired sensor faces were similar but did not yield similar signal disturbances. The below data shows the first two full days of the deployment before fouling began to hike up measurement values. This happened quickly during this deployment, likely due to warm, productive waters in May.

In this deployment at Oyster Creek, we aimed to explore sediment transport in a tidal channel behind the marsh (seen in Figure 8b). This back channel had a low concentration of sediment relative to the marsh and the embayed portion of Oyster Creek shown as "channel". Both resembled the concentrations found at Oyster Creek in November of that year, but the marsh platform itself recorded higher concentrations than the channels.

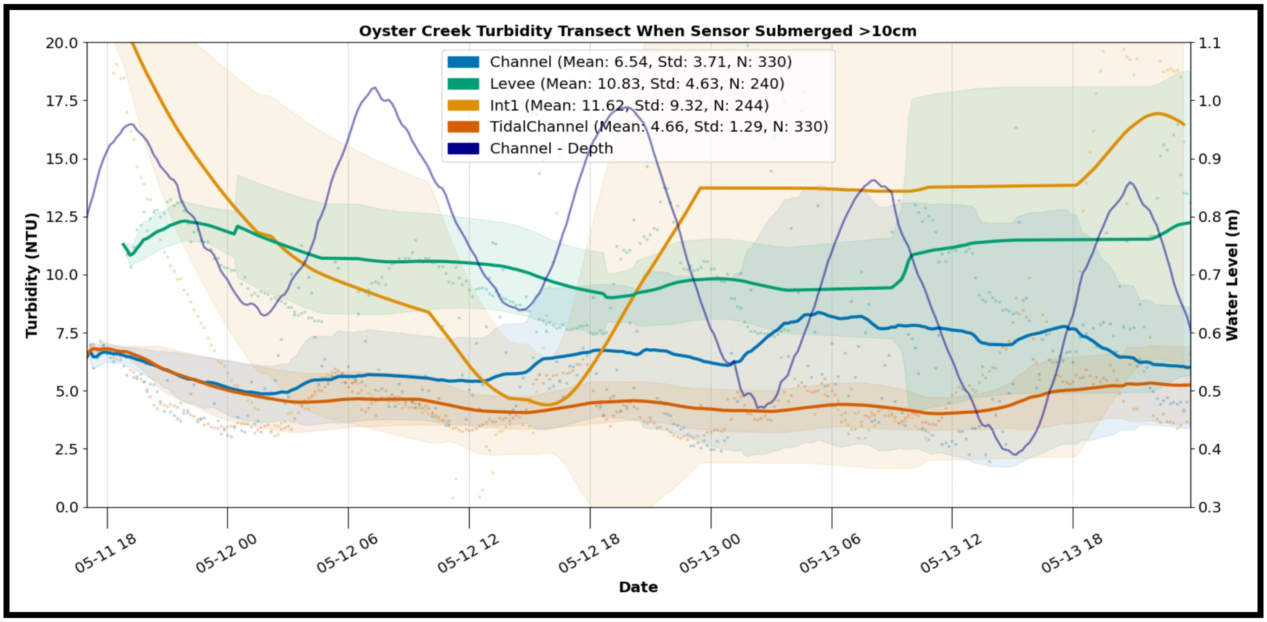


Figure 12 - Oyster Creek Deployment from May of 2022. All descriptors from the figure caption above apply here.

Data from the OpenOBS deployment at Pages Creek in New Hanover County, NC represented the most successful time-series of OpenOBS data produced for this project. Fouling stress was minimal here, allowing a full monthlong deployment. Similar to the previously presented datasets, the time series of data is presented as 10-minute averages when all sensors were simultaneously submerged in 8 cm (rather than 10 cm) of water. The tidal range here is the highest of any of the sites, around 0.9 m. The high mg/L readings seen here may relate to the larger tidal range of the site, which generally increases the tidal prism or volume of water moving in and out of the creek in a fixed tidal time. That being said, tidal prism is not known explicitly as it requires knowledge of bathymetry and tidal excursion.

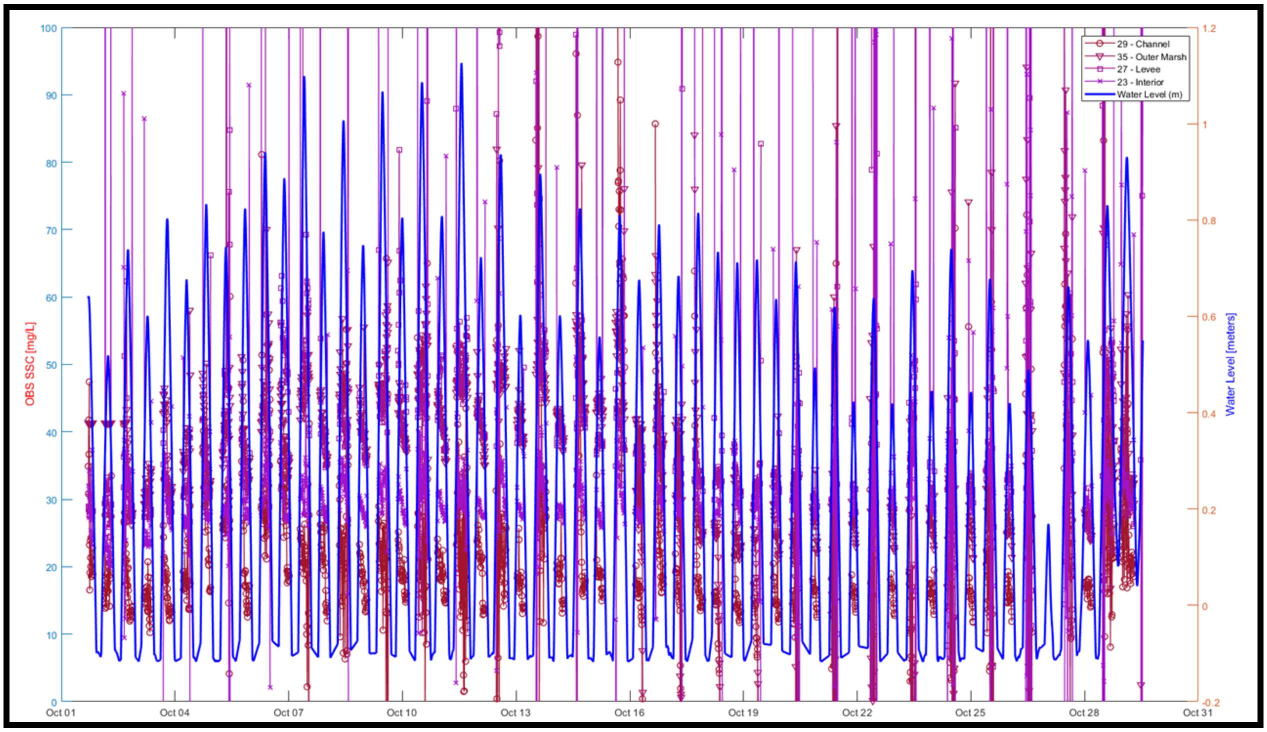


Figure 13 - Pages Creek Deployment from October. Raw voltage readings from the OpenOBS sensors were lab-calibrated using local sediment to display concentrations in mg/L. The water level is shown as a bright blue line.

When aggregating the data from Pages Creek into averages for the entire deployment, a small but clear flood-ebb suspended sediment concentration differential becomes evident. As water carrying sediment flows onto the marsh as the tide rises, some deposits out onto the marsh surface, and so long as the material is not being net sourced from within the marsh, the falling tide should carry a smaller suspended sediment concentration. Displayed as the lower red bar adjacent to the blue bar, falling tides do indeed exhibit lower SSCs at Pages Creek. Similar summary analyses have yet to be conducted for the remaining study sites.

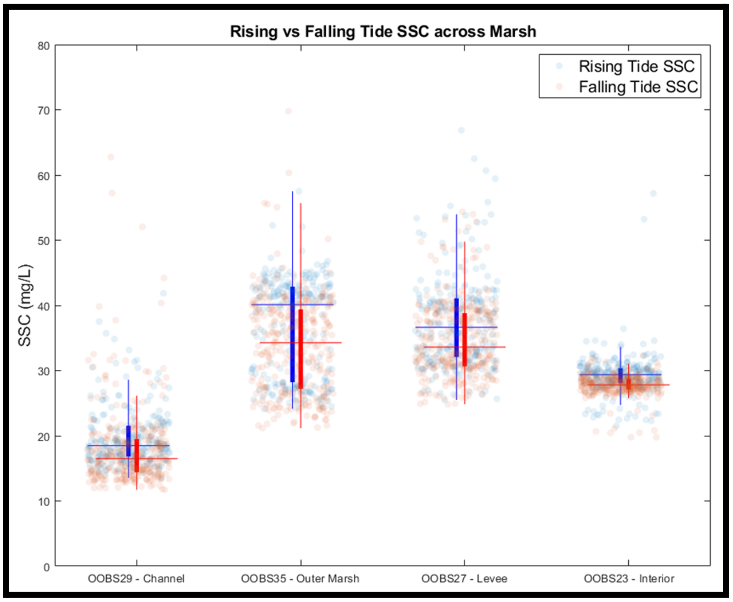


Figure 14 - Averages, interquartile, and 10%-90% ranges for each sensor from the month deployment at Pages Creek. Points represent 10-minute averages. Blues represent water level rising, while red represents water falling.

Both Gales Creek and Oyster Creek monthlong deployments exhibited decays of sediment going into the marsh. Oyster Creek, with the slightly more prominent levee, shows a slower decay rate (-0.02) in measured turbidity going into the marsh than found at Gales Creek (-0.05). Additionally, Oyster Creek began with lower turbidity, perhaps indicating that most of the sediment in suspension was within the competence of the flow even as it slows over the vegetated marsh and unlikely to be deposited during the time of one tidal cycle on the platform.

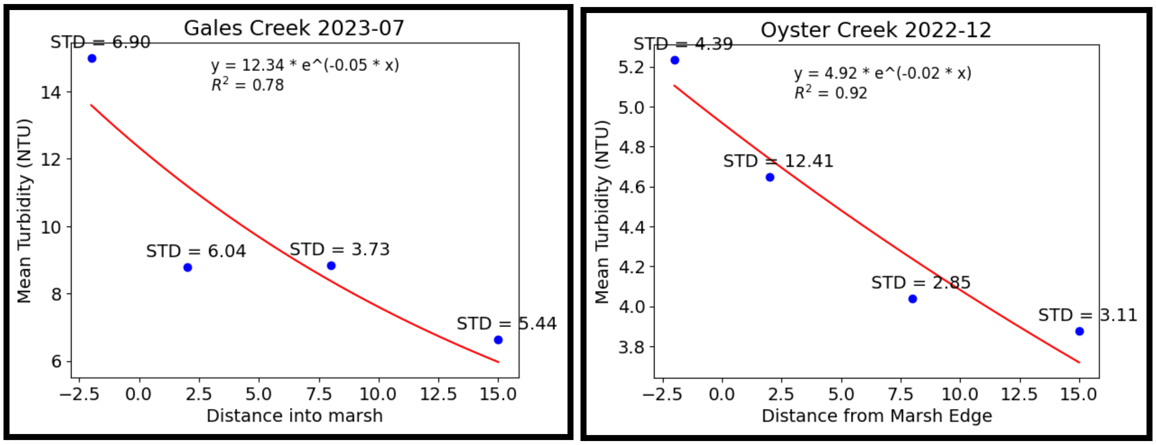


Figure 15 - Average turbidities at each sensor represented as blue dots, with standard deviation annotated. Distance from the marsh edge is shown on the x-axis, with 0 being the marsh edge itself. Red lines show the exponential fit of the functions.

Discussion: (How do the results of your project relate to the problem you were trying to address? How do they relate to the greater body of work on this question? What are the final takeaway implications from your project?)

The results of this project reveal several things. First, I found that low-cost open-source turbidity sensors are, in their current state, not a reliable replacement for commercial sensors. Due to the intense fouling pressures in the waters of the APNEP management region, shallow waters with large sunlight signals, and ambiently low suspended sediment concentrations, the OpenOBS produces noisy and non-turbidity-trended datasets. Despite this, the sensors do have some utility for short deployments with and during low photic intensity periods. For monitoring the outflow of sediment-laden waters post-storm event, for example, these sensors offer a low-cost and thus low-risk instrument.

Second, I found generally low suspended solids at most sites, with decay to a non-zero background concentration rather rapidly onto the marsh. Perhaps due to the low initial sediment concentrations and low competence of flow as it nears the marsh, there is only a small amount of material in suspension, much of which may have settling velocities too low to settle upon the marsh within a single tidal cycle - thus the non-zero background turbidity. Additionally, the findings suggest that marshes are indeed sediment-poor during fair weather conditions observed, corroborating decadal-scale sedimentation rates below local rates of sea-level rise found by Bost et al., 2023.

The sediment loading which is known to have adverse effects on nursery habitats, fish abundance, and subaqueous vegetation (e.g. Hauer et al., 2018) may be a thing of the past as development in most of the watersheds analyzed has stabilized in recent decades. Species that depend on clear and clean water are threatened by turbid waters that limit photosynthesis, visibility, and trophic interactions. Still, sediment coring reveals a disconnect between high sedimentation in subtidal environments and accretionary deficits on salt marsh platforms which must be addressed before watershed management modifications are made to reduce future sediment loads, which could unintentionally impact the sustainability of wetlands.

Sea Grant NC set its first priority for the 2018-23 Strategic Plan to ensure that upstream outputs including sediment are coupled to their downstream effects like marsh deposition (NCSG, 2018). Autochthonous organic production and allochthonous sediment delivery, the two components of accretion, are mediated by the connectivity of a marsh. Nutrient availability and porewater quality, flow velocities, and tidal range, and distance to high-concentration sediment sources all influence resilience and are related to connectivity. For example, reduced tidal exchange may exacerbate interior marsh die-off through the buildup of waterlogged and sometimes phytotoxic waters (Mendehlson and Mckee, 1988; Spivak et al., 2017; Himmelstein et al., 2021). A better understanding of marsh connectivity across timescales can inform managers' efforts, whether they are promoting drainage density by ditching or infilling marsh platforms through thin-layer placements. Currently, the existing datasets are not robust enough to statistically differentiate suspended sediment decay functions going into the marsh between small and large leveed sites. However, to further explore levees as a cause for marsh disconnectivity, continuing work will add sites to this project and use the work completed here as a foundation to refine best practices for collecting such data.

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Outreach: (How did you convey the results of your project to a broad and diverse audience? How are they using the results of your project?)

In June of 2023, I presented to French scientists and American PhD students from across the states at the Universite Bretagne Sud in Vannes, France as part of NSF Advanced Studies Institute. The students were excited to learn about the sensors and how coastal geomorphologists use turbidity as a tool to explore marsh resilience.

Additionally, I presented some preliminary findings of this research at the NC Coastal Conference in Raleigh in November of 2022. There I discussed my work with non-geomorphologists.

I will continue my role as the Researcher-Educator Liaison with the Scientific Research Educators Network (SciREN), an initiative started in the Rodriguez lab. Via in-person workshops, I will help researchers distribute novel science lesson plans to K-12 educators. The Rodriguez Lab will create a lesson emphasizing the relation of sediment supply to landscape change and social-ecological problems. I will continue to work as a group leader for the Growing Equity in Science and Technology (GEST) weekend events for Carteret County middle schoolers with the goal of increasing diverse representations in the geosciences. Finally, I will continue to discuss coastal geomorphology topics with media outlets whose audience ideally benefits from this work.

Students supported: (What type and how many students were trained as a result of this project?)

Graduate: Josh Himmelstein
Undergraduate: David Go (UNC ‘24)
Undergraduate: Lillian Cooper (UNC ‘23)
Undergraduate: McKenzie MacLean (UNC ‘22)

News/Media coverage of this project:

- UNC Endeavors (Research Magazine) covered the research and produced a video / and written article in late August 2022.
    - Link https://endeavors.unc.edu/mucking-in-the-marshes/

Data Management Plan Progress: (Please document that you have completed the steps outlined in your project's initial data management plan. Has your data management plan changed? If the data management plan is not finalized, please include a timeline for its completion.)

The "Distribution of suspended-sediment loads across North Carolina's saltmarshes; wetland stability explored through modern measurement systems" project implemented by Joshua Himmelstein (graduate student) and Antonio Rodriguez (Faculty Advisor), generated and will continue generating novel environmental data.

These data will include the following: suspended sediment concentrations sensors across four + research locations within the APNEP management boundary, water-level and temperature logger readings at each site, repeat RTK GPS elevation measurements across marsh platforms,and drone imagery. **Completed.**

Turbidity sensor data will be collected by the Rodriguez Lab and processed according to the workflow conducted and shared with us by the researchers who developed the OpenOBS sensors (Eidam et al., *accepted*). Field observations will be recorded in a "Rite in the Rain" all-weather field notebook and digitized within a week of collection. **Completed**

Data files will be offloaded at the UNC-CH Institute of Marine Science, parsed in Matlab R2021b and Python 3.x. **Completed**

And uploaded to a public Github repository (https://github.com/joshimmel) as .csv files. **To Be Completed**

Elevation measurements in NAVD 88 will also be reported in .csv format. Hobo Water level logger data will be corrected for fluctuations in atmospheric pressure within the HOBOWare Pro software, then exported as .csv files for use in Matlab and by other interested parties. **Partially Completed**

Files will be backed up cloud storage through a 2TB Dropbox. They will also be kept locally on a "cold storage" hard-drive. **Completed**

Data will be openly distributed with the Creative Commons By Share Alike License (CC BY-SA) to support open access and increase research impact. **These data and the remainder generated will be publicly released by May 1st, 2025.**

APNEP and NCSG officials will be provided access upon request before the public release date.

Requests for data should be directed to Joshua Himmelstein (252-726-6841 x JH) or himmelstein@unc.edu. Preprints of our derivative journal articles will be made available on the EarthArXiv server. All future works by sub-awardees not herein identified will agree to this data sharing plan as a condition of their contract acceptance. Any additional data sharing stipulations for future sub-awardees may be outlined at that time and described in their contract.