Lake Okeechobee Ecosystem Health

2-26-2025

EXECUTIVE SUMMARY

The Florida legislature funded a study of Lake Okeechobee ecosystem health in Senate Bill 1638 – Environmental Resource Management, Chapter 2024-58 Laws of Florida, Section 15, and the work was to be coordinated by the South Florida Water Management District (District) and led by the Water School at Florida Gulf Coast University (FGCU). Subsequently, FGCU engaged the Consensus Center at Florida State University (FSU-in cooperation with the Orthon Group), the University of South Florida (USF), and Harbor Branch Oceanographic Institute at Florida Atlantic University (FAU) to collaborate on this report. The FSU and Orthon Group partnership conducted outreach and stakeholder engagement; the USF effort gathered available information and expert opinions on lake health and options for improvements; and FAU/FGCU examined current conditions related to the decline in important plant communities. The Florida Fish and Wildlife Conservation Commission (FWC) also played a vital role in this effort.

Background

Lake Okeechobee has a surface area of 730 square miles (~451,200 acres), the second largest in surface area of the freshwater lakes in the United States. The lake is very shallow, with an open water area that averages less than 10 feet in depth, making wind-driven bottom sediment resuspension a major issue that impacts the 100,000 acres of littoral zone, the shallowest part of the lake with submerged, emergent and floating plants, that supports fish and wildlife communities. The lake is surrounded by approximately 143 miles of levee forming the Herbert Hoover Dike (HHD), that was built as part of the Central and Southern Florida Project in response to damage from hurricanes. Rainfall and evaporation are the main divers of water levels in the lake, with an average of 50 inches per year and roughly an equivalent amount of evaporation. In addition, there are significant inflows from tributaries such as the Kissimmee River and Fisheating Creek.

The lake is an essential part of the Everglades, provides water for irrigation in areas around the lake, serves as backup water supply for the Lower East Coast, connects the Atlantic Ocean to the Gulf of America via the Okeechobee Waterway, host vibrant fish and wildlife communities and protects the surrounding areas from flooding. The US Army Corps of Engineers (USACE) underwent a detailed study of these potential conflicts among these management objectives and replaced the Lake Regulation Schedule with the Lake Okeechobee Systems Operating Manual (LOSOM), which took effect on August 12th, 2024.

Nutrient loading from the watershed is also problematic because these nutrients feed the growth of blue-green algae (cyanobacteria), that often form expansive blooms on the lake. Multiple efforts are underway to address external loads of nitrogen and phosphorus via construction and operation of various projects that treat incoming water. Efforts include implementation of Best Management Practices by agricultural facilities, the Northern Everglades and Estuaries Protection Plan, the Lake Okeechobee Watershed Protection Plan, and the combination of the Lake Okeechobee Total Maximum Daily Load and Lake Okeechobee Basin Management Action Plan.

Current Status of the Ecology of Lake Okeechobee

One of the main stresses on the ecology of the lake is the depth of the water. Rainfall, evaporation and inflow from the watershed, drive lake water levels, while releases west Caloosahatchee River, east the St. Lucie River and south for agriculture can lower the water levels, but a limited extent. Deep water prevents light penetration in the littoral zone because suspended sediments are transported from the deeper, central “legacy” mud-rich area of the lake. Light reaching to the bottom of the littoral zone is essential for aquatic plant growth and gemination. High water levels over the past 5 years, as well as the impact of hurricanes, have greatly diminished the littoral zone vegetation and the subsequent loss of fish and wildlife habitats. Recognizing this impact, On December 7th, 2024, the USACE implemented Lake Okeechobee Recovery Operations, with the goal of allowing light to penetrate to the bottom and allow the submerged aquatic vegetation (SAV) to regrow during the April-July period. They anticipate the lower water levels will “reduce water turbidity and nutrient concentrations” and the regrowth of the SAV will start the restoration of the fish and wildlife communities. **In the short term, observations of recovery from seed banks at key locations, such as Tin House Cove, Fisheating Bay, Pelican Bay, Turners Cove and First Point Cut, could be undertaken as water levels are lowered.**

The second main stress on the ecology of the lake is nutrients, nitrogen and phosphorus, from the watershed and resuspension from accumulated bottom sediments. These nutrients feed blue-green algae (cyanobacteria) blooms, large floating colonies that can rapidly cover the lake from late spring through the summer. They can cause oxygen depletion that can lead to fish kills, shade the SAV, sometimes produce cyanotoxins, and have a significant impact if they flow into the Caloosahatchee and St. Lucie.

The final stress on the ecology of the lake is nuisance aquatic plants. These are mostly non-native, invasive species, fueled by the nutrients described above, that can form dense monocultures, often crowding out native species, and these monocultures tend to be less suitable habitat for fish and wildlife. Active management programs operated by the District, FWC and USACE are coordinated by the Lake Okeechobee Aquatic Plant Management Task Force. Overall, herbicide applications are carefully evaluated and have been significantly reduced since 2015.

Stakeholder Perceptions of the Health of the Lake

The Consensus Center and the Orthon Group undertook three lines of outreach activity: interviews with individuals; two rounds of stakeholder input workshops; and an online comment portal to allow the broadest practicable range of individuals to offer their opinions and ideas. Over 500 stakeholders provided input: 1) Thirty-six individuals (*interviewees*) representing fishing, recreational, environmental, agricultural, and business groups, communities around the lake, scientific organizations and state and federal agencies participated in 31 interviews; 2) Almost 400 individuals (*online commenters*) offered ideas and suggestions through the online portal. Many of these stakeholders had over 20 years of experience on the lake, and a wide range of affiliations and backgrounds in the surrounding communities and throughout the state; 3) More than 100 people (*workshop participants*) attended one or more of the workshops.

- The stakeholders have observed and are concerned about declines in conditions within the lake that include loss of submerged aquatic vegetation, both native vegetation and non-native *Hydrilla;* changes in the location, extent, composition, and structure of shoreline marshes; decreased water clarity; increased blooms of algae; and declines in numbers of wading birds and waterfowl, fishes and wildlife.
- The stakeholders have experienced or are concerned about detrimental economic changes, especially in communities north of the lake.
- The stakeholders listed higher water levels, poor conditions in the lake's sediments, unintended consequences from management of vegetation, nutrient loads, detrimental effects from activities in the watershed, and changes in climate as potential drivers of recent changes.
- Among other potential actions, the stakeholders suggested, rehabilitating sediments, circulating water, revising management of vegetation, mitigating turbidity, restoring lost submerged aquatic vegetation, expanding the capacity to store water, and establishing an interagency coordinating body and contingency fund focused on Lake Okeechobee.
- Expert Response: Attempts to reduce concentrations of nutrients and capture particles by pumping water through existing wetlands or offline treatment facilities is logistically challenging, and the approach carries substantial risk of degrading those wetlands.

Water Clarity and Submerged Aquatic Vegetation

Because submerged aquatic vegetation (SAV) plays such an important role in the health of Lake Okeechobee (e.g., nutrient uptake, fish and wildlife habitat, shoreline stabilization), it is crucial to fully understand the various factors that impact SAV health, including water transparency. SAV is negatively impacted by high concentrations of suspended solids (referred to as turbidity) that block light needed for photosynthesis. Furthermore, hurricanes can resuspend large amounts of sediment in the Lake, thereby increasing turbidity, and can uproot SAV beds. This project therefore took advantage of an unusually active hurricane season to examine the impacts of

Hurricane Milton on turbidity through repeated sampling at two sites in the Lake over a period of 1-6 weeks.

At the time of sampling, light penetration in the Lake was insufficient for SAV growth on the bottom. These conditions persisted for one month following Hurricane Milton, with light limitation preventing the growth of aquatic plants in deeper water, creating a significant challenge for the recovery of SAV. Most of the resuspended sediments responsible for this lack of light penetration were of very small particle size and, based on their chemical signature, likely originating from the deep, mud-rich areas of the Lake. These smaller particle sizes take longer to settle out of the water column, further impacting SAV recovery and restoration efforts.

A new technology for the reduction of turbidity in the lake is under development at FGCU. It is a microencapsulated product that floats and slowly dissolves as a function of pH in aquatic environments for the flocculation, sequestration, and safe degradation of suspended solids, harmful algal blooms and excess phosphorus. We are “barrowing” technology from the drinking water industry for the core materials we are testing, as well as Bauxol ViroPhos™.

Appendices

In addition to this Executive Summary, Appendices articulate the relevant issues in greater detail and point to potential considerations that may lead to short-term benefits. These appendices include contributions from the FCRC Consensus Center at FSU; the Center for Analysis, Synthesis, and Application at USF; the Harbor Branch Oceanographic Institute at FAU; and The Water School at FGCU.

APPENDICES

Appendix 1: Health of Lake Okeechobee Literature Review

Prepared by: Florida Gulf Coast University Water School: Megan Feeney and Barry Rosen

INTRODUCTION

Lake Okeechobee is a large, shallow, nutrient rich, freshwater subtropical lake that is subject to frequent blooms of cyanobacteria (Dang et al., 2023). Lake Okeechobee provides many ecosystem services including drinking water supply, flood protection, navigation, recreational and commercial fishing, and wildlife habitat (Aumen, 1995; K. E. Havens & James, 2005). Lake Okeechobee is encircled by the Herbert Hoover dike, and the inflows, outflows, and water levels of the lake are managed for water supply, flood control, and environmental concerns (K. E. Havens et al., 1996). All but one of the lake's inflows and outflows pass through water control structures (K. E. Havens & James, 2005). The lake receives inflows from six tributaries in the northern region, including lake Kissimmee and Lake Istokpoga, inflows from the east from the L-8 basin and reverse flow from the St. Lucie Canal, inflows from the west from Nicodemus Slough and reverse flows from the Caloosahatchee River, and inflows from the south from reverse flows and back-pumping from the Everglades Agricultural Area and the S4 basin (Faridmarandi et al., 2020). Back-pumping occurs as flood control during extreme weather events (Faridmarandi et al., 2020). Excessive phosphorus (P) loads from the surrounding watershed have led to increased eutrophication and harmful algal blooms (K. E. Havens, 1995; K. E. Havens et al., 1996). Land uses in the surrounding watershed include beef cattle pasture, dairy farming, citrus, vegetable crops, and urban areas (Flaig & Havens, 1995). High net imports of P results from animal feed, fertilizer, agricultural land runoff, and high levels of P in soils and tributary sediments (K. E. Havens & James, 2005). P also enters the system through atmospheric deposition, and internal loading (decomposing plant material, sediment resuspension) (Faridmarandi et al., 2020).

LITERATURE REVIEW

Changes in nutrient loads. Changes in land use and drainage patterns have led to recent accelerated eutrophication (K. E. Havens et al., 1996). Periods of high P inputs can change the sediment-water P dynamics, where decades of high P loading can decrease the capacity of sediment to assimilate P as they become saturated (K. E. Havens & James, 2005). Inflow total phosphorus (TP) increased in the 1970s from 150 to >200 µg/L with changes in land use and then declined in the 1980s and 1990s to ~150 µg/L with better management (K. E. Havens & James, 2005). The removal of some dairy farms, agricultural runoff best management practices, and the restoration of meanders in the Kissimmee River to lessen the degree of P loading in Lake Okeechobee (Missimer et al., 2020). To meet the goal of a mandated total maximum daily load (TMDL) of 140 metric tons per year, average inflow TP concentrations would need to be further reduced to the range of 40 to 50 µg/L (K. E. Havens & James, 2005). Additionally, high inflow TP concentrations still occur in certain years, possibly driven by dry followed by very wet years transporting accumulated P downstream (K. E. Havens & James, 2005). Lake water TP stabilized in the 1980s and 1990s but increased in recent years possibly due to sediment saturation with P

(K. E. Havens & James, 2005). Internal loading, P transported from the lake sediments back into the water column, results in elevated lake water P concentrations when external loading from inflows is reduced (K. E. Havens & James, 2005). A change in P assimilation could indicate a new equilibrium in response to reduced inflow P concentrations or could indicate that sediments are becoming saturated with P (K. E. Havens & James, 2005). An observed decreasing assimilative capacity of the lake with increasing lake water P concentrations has the potential to export large amounts of P rich water in certain years and indicates the lake's ecosystem is at risk for worsened eutrophication under current P loading conditions (K. E. Havens & James, 2005). Fluxes of P in the lake are predominantly internal, rather than external, with internal releases exceeding external input by a factor of 3 (Pollman & James, 2011). Based on modeling simulation results, internal loading from sediments has increased between 1972 and 2000 and then stabilized (Pollman & James, 2011). External load reductions would reduce the trend of sediments absorbing less P (Pollman & James, 2011).

In recent years (2018-2023), the TP TMDL has averaged 402 metric tones per year, much higher than the goal of 140 metric tones per year (Betts et al., 2024). Hurricanes Irma, Ian and Nicole have resulted in spikes in TP concentrations as well as P load increases (Betts et al., 2024; Welch et al., 2019). These spikes in P resulting from hurricanes will impede efforts to attain target lake TP concentrations of 40 µg/L (Canfield Jr et al., 2020). The highest TP concentrations between 2013 and 2023 was 203 µg/L due to hurricane Irma in 2018 (Betts et al., 2024). Within the same time frame, the lowest TP concentrations were measured at 118 µg/L in 2014, still higher than the goal of 40 µg/L (Betts et al., 2024). The current five-year (2018-2023) moving average TP concentrations is 151 µg/L, higher than the pre-hurricane (pre-2004) TP concentrations of 57-127 µg/L (Betts et al., 2024). The current five-year average for the net sedimentation coefficient, the amount of TP that accumulates in the sediment divided by the average lake water TP mass, ranged between 0.2 and 0.5, with positive values indicating net accumulation in the sediment (Betts et al., 2024). In 2023, the net sedimentation coefficient was negative (-0.10), where an estimated 75 t of TP was released from the sediments (Betts et al., 2024). For the past three years (2021-2023) the P budget was below 0.2, suggesting the lake is close to capacity in terms of TP absorption (Betts et al., 2024).

Lake Okeechobee is not listed as impaired for total nitrogen (TN), though TN loads and concentrations contribute to the lake's eutrophication and algal blooms (Betts et al., 2024). The mean annual lake pelagic zone total nitrogen to total phosphorus (TN:TP) ratios suggest the ratios have declined since 1975 with increasing TN-limitation for phytoplankton growth (Betts et al., 2024). This gives a competitive advantage to cyanobacteria that can fix atmospheric nitrogen and increases the likelihood for cyanobacteria blooms (Betts et al., 2024). Minimizing TP loading and maximizing TN:TP loading ratios and in-lake ratios would help minimize the frequency and intensity of nitrogen-fixing cyanobacterial blooms (Betts et al., 2024).

Despite further management efforts, and early reductions in inflow TP in the 1980s to 1990s, inflow TP concentrations have not significantly declined further (Canfield Jr et al., 2020; K. E. Havens & James, 2005). The decline in inflow TP coincides with TP declines in major tributaries and the implementation of programs to reduce P export from dairy farms and agricultural land uses (K. E. Havens & James, 2005). TP concentrations stabilize at ~150 µg/L between 1996 and

2002 in inflows (K. E. Havens & James, 2005). It would take a further 65% reduction in the TP TMDL (402 metric tons per year between 2018 and 2023) to meet the mandated TP TMDL of 140 metric tons per year. While there were declines in TP concentrations, there was no statistically significant downward trend in P loads between 1973 and 2019, due to the overriding influence of flow on P loading (Canfield Jr et al., 2020; K. E. Havens & James, 2005). TP concentrations in the lake have gradually increased in recent years, which does not correlate to inflow TP concentrations (Canfield Jr et al., 2020; K. E. Havens & James, 2005). With the resuspension of sediments being the source of elevated TP in Lake Okeechobee, the legally mandated TP concentrations for the pelagic zone cannot be met without somehow removing the effect of unconsolidated sediments (Canfield Jr et al., 2020).

Harmful algal blooms. Extensive cyanobacterial blooms have occurred in Lake Okeechobee since the mid-1980s, impairing the recreational value of the lake and threatening the quality of drinking water (K. E. Havens et al., 1994). Predominant bloom-forming cyanobacteria, such as *Microcystis aeruginosa*, produce harmful cyanotoxins (K. E. Havens et al., 1994; Missimer et al., 2020). There are seasonal and spatial variations in algal blooms for Lake Okeechobee. Algal bloom frequencies positively correlate with water temperatures and water transparency (Secchi transparencies) (K. E. Havens et al., 1994). Blooms are less frequent when wind-driven sediment resuspension limits light availability for cyanobacterial growth, and more frequent when warmer temperatures and improved Secchi transparencies promote cyanobacteria growth (K. E. Havens et al., 1994). Historically, blooms were most frequent in May-June and August-December and in the northern and western pelagic regions (K. E. Havens et al., 1994). Blooms are the least frequent in the central pelagic region, overlying mud sediments (K. E. Havens et al., 1994). The frequency of algal blooms has increased since the 1980s, blooms occur every month where previously they only occurred for 8 months of the year (K. E. Havens et al., 1994). In Lake Okeechobee algal blooms are primarily nitrogen (N) limited (Betts et al., 2024; Welch et al., 2019). N limitation can support the growth of nitrogen-fixing cyanobacteria but can limit the growth and toxin production of some genera (including *Microcystis* and *Planktothrix*) (Kramer et al., 2018). High levels of nitrogen (N) support *M. aeruginosa* blooms, and there are significant correlations between TN and microcystin production (Kramer et al., 2018). N concentrations should be better monitored and controlled to better manage future microcystin producing cyanobacterial blooms (Kramer et al., 2018).

Previous hurricanes in 2004 and 2005 caused initial three-fold reductions in phytoplankton biomass, two-fold reductions in water transparency (Secchi transparency), and three-fold increases in the amounts of dissolved inorganic nitrogen and soluble reactive phosphorus (K. Havens et al., 2016). Following drops in suspended solids in summer of 2006 there was one of the most intense blooms observed in Lake Okeechobee; the bloom was dominated by *M. aeruginosa* and produced very high levels of the cyanotoxin microcystin (K. Havens et al., 2016). The hurricane following this event increased turbidity by reducing algal biomass and was not followed by another major bloom event (K. Havens et al., 2016).

Between 2013 and 2023, 106 occurrences of algal blooms (where chlorophyll *a* concentrations are 40 µg/L or greater) was recorded at field stations (Betts et al., 2024). 2013 experienced the fewest number of algal blooms, while 2023 had the highest frequency (Betts et al., 2024). This frequency of 14% of all samples collected is higher than the Comprehensive Everglades

Restoration Plan Restoration Coordination and Verification program target of fewer than 5% of samples (Betts et al., 2024). Bloom activity was typically correlated with high water levels, thanks to a combination of internal nutrient transport and high nutrient inflows (Betts et al., 2024). High water levels in the winter of 2021 and 2022, which corresponds with high bloom frequencies in 2022 (Betts et al., 2024). Blooms were most frequent during the wet season (Betts et al., 2024). The highest microcystin toxin detection frequencies occurred in 2019 and 2022; 2019 also had a much lower bloom frequency, showing toxin production is variable (Betts et al., 2024).

Changes in lake sediments. The first evaluation of Lake Okeechobee bottom characteristics was conducted in 1975 (Missimer et al., 2020). One-third of the lake bottom was covered with a stiff organic mud, the western half of the lake had a sandy bottom, and the eastern and southern part was rock or calcareous marl, with peat deposits at the southern margin of the lake (Missimer et al., 2020). The mud was 80 cm at its deepest and located in the center of the lake and near the inflow of the Kissimmee River and Nubbin Slough (Missimer et al., 2020). Currently, the lake has an unconsolidated floc layer consisting of a thixotrophic, fluid like organic mud above the consolidated mud layers, 0-8 cm thick that is easy to resuspend and transport with little energy (Missimer et al., 2020). This unconsolidated floc layer varies in thickness throughout the lake and is known to occur near the inflow of Nubbin Slough (Missimer et al., 2020). This thixotrophic mud can be resuspended with normal wind and wave activity and supplies excess nutrients supporting algal blooms (Missimer et al., 2020). The thixotrophic mud contains higher nutrient concentrations than the immobile consolidated mud (Missimer et al., 2020).

In the last decades, high nutrient loading has transitioned the lake from a sandy bottom and macrophyte dominated mesoeutrophic waterbody to a phytoplankton-dominated, eutrophic lake with organic mud sediments (Brezonik & Engstrom, 1998; Faridmarandi et al., 2020). Fine grained mud sediments have accumulated only in recent times since roughly 1900 (Brezonik & Engstrom, 1998). Sediment accumulation rates have increased by a factor of two between 1860 and 1980 (Brezonik & Engstrom, 1998). This could be due to either increased organic production that outpaced the rate of sediment loss, and the enhanced retention of sediments from dike construction, especially along the southern margin (Brezonik & Engstrom, 1998). It is more likely that increased organic production resulted in increased sedimentation rates, as dike construction did not increase the lake depth (Brezonik & Engstrom, 1998). The spatial extent of mud sediments in the middle of the lake has expanded, especially in the southern direction between 1975 and 1988 (K. E. Havens & James, 1999). P accumulation rates increased in association with increasing sedimentation rates (Brezonik & Engstrom, 1998). The construction of the Herbert Hoover Dike prevents the natural lateral expansion of the lake into riparian wetlands where nutrient rich suspended sediments were previously deposited (Lodge, 2016; Missimer et al., 2020). A solution to effectively remove the thixotrophic mud in Lake Okeechobee is needed in order to control issues with legacy nutrients (Missimer et al., 2020). A combination of nutrient influx management, water budget management and the elimination of legacy nutrients is needed (Missimer et al., 2020).

Water transparency and resuspended sediments. Water transparency is a determining factor for the colonization of submerged aquatic vegetation (SAV) (Chambers & Kaiff, 1985; Sand-Jensen & Madsen, 1991). Water transparency is depth dependent and influenced by chlorophyll *a,* colored dissolved organic matter (CDOM), and suspended solids (Sathyendranath, 2000; Saulquin et al., 2013). For Lake Okeechobee, the majority of light reduction in the water column is due to organic and inorganic suspended solids (K. E. Havens, 2003). There is natural variation in water transparency for Lake Okeechobee, which is typically lower during the winter season due to high winds and cold fronts, and higher during the summer season (K. E. Havens, 1995; K. E. Havens & James, 1999; R. T. James et al., 2009; Xu et al., 2022). The long fetch of the lake generates relatively high wind induced waves with even modest wind events, and its shallow depth results in sediment resuspension (Chimney, 2005; Jin et al., 2011). In addition to natural variation there has been a decline in transparency for some areas of the lake (K. E. Havens & James, 1999). Following 1989, water transparency was significantly lower for stations in the southwestern portions of the lake (K. E. Havens & James, 1999). Declines in transparency were associated with the redistribution of mud sediments to southern portions of the lake between 1975 and 1988 (K. E. Havens & James, 1999). Prior to this new stable state, light may have often reached the lake bottom in the southwestern pelagic regions but never reached the bottom of the lake following the expansion of mud sediments (K. E. Havens & James, 1999). The altered hydrology of Lake Okeechobee prevents the natural expansion of the lake into surrounding wetlands, which used to sequester the nutrient rich resuspended sediment (Lodge, 2016; Missimer et al., 2020).

Hurricanes have exasperated water transparency issues, with high wind speeds and wave action causing sediment resuspension events (T. R. James et al., 2008; Jin et al., 2011). Hurricanes Frances and Jeanne in 2004, and Wilma in 2005 scoured the lakebed and resuspended large quantities of sediment, releasing nutrients into the water column, resulting in total suspended solids (TSS) six times higher than pre-hurricane conditions (Jin et al., 2011). TSS remained two to four times higher than pre-hurricane conditions through the winter following these hurricane events (Jin et al., 2011). These changes in suspended solids persisted for two years following the hurricanes (T. R. James et al., 2008). This is because these hurricanes loosened deep consolidated layers of sediments, resulting in unconsolidated sediments that were easier to resuspend even under calm wind conditions (T. R. James et al., 2008; Jin et al., 2011). These resuspension events resulted in the northward migration of sediments in the lake and two-fold and four-fold increases in water column TP and TN concentrations following, from both internal loading (sediment resuspension, plant decomposition) and external loading (increased inflows due to rainfall) (T. R. James et al., 2008; Jin et al., 2011). Light limitation, due to high levels of resuspended solids, may have reduced nutrient uptake by aquatic vegetation and phytoplankton allowing high nutrient concentrations to persist (T. R. James et al., 2008). These light limited conditions are unfavorable for bloom-forming Cyanobacteria, reducing Cyanobacteria biovolume which is dominated by small celled Cyanobacteria and diatoms (T. R. James et al., 2008). Bottom critical stresses, the energy needed to resuspend sediments from the bottom, indicated that wind speeds over 100 miles/hr are large enough to resuspend all accumulated sediment in the lakebed (Jin et al., 2011).

In recent years hurricanes Irma in 2017 and hurricanes Ian and Nicole in 2022 resulted in sediment resuspension events in Lake Okeechobee (Betts et al., 2024; Welch et al., 2019). Strong winds following hurricane Irma caused further sediment resuspension, resulting in the highest average pelagic turbidity levels since the 2004-2005 hurricanes which remained elevated until April 2018 (Welch et al., 2019). This resulted in the loss of more than 15,000 acres or 57% of SAV following Irma (Welch et al., 2019). Hurricanes Ian and Nicole caused elevated turbidity in the lake for six months from October 2022 through April 2023 (Welch et al., 2019). As for other hurricanes, turbidity peaked several months after the storm's passing due to sustained winds from cold fronts resuspending sediments (Welch et al., 2019). Turbidity levels were slightly lower following Ian and Nicole compared to hurricane Irma (Welch et al., 2019). Increased turbidity and high-water levels in the months following these hurricanes resulted in poor water quality conditions (Betts et al., 2024; Welch et al., 2019).

Submerged aquatic vegetation. SAV plays an important role in sediment retention and nutrient reduction in freshwater lakes (Dierberg et al., 2002; Knight et al., 2003; Vermaat et al., 2000). In freshwater treatment wetlands, SAV supports greater P removal rates compared to rooted, emergent aquatic vegetation (EAV) (Dierberg et al., 2002; Knight et al., 2003). SAV serves as an important habitat for zooplankton, invertebrates, and other communities; affecting higher tropic levels including fish populations (Deosti et al., 2021; Dibble & Thomaz, 2009; Gomes et al., 2012; Thomaz, 2023). SAV coverage can be influenced by a variety of factors including sediment type, water depth, transparency, wave disturbance (K. E. Havens, 2003; Hudon et al., 2000; Schwarz et al., 2002; Wallsten & Forsgren, 1989). SAV biomass in Lake Okeechobee is relatively low; of all SAV species present (including *Hydrilla verticillata,* eelgrass *Vallisneria americana,* and pondweed *Potamogeton illinoinensis*), *Chara* spp. was reported to have the highest biomass (K. E. Havens, 2003).

Water transparency and depth are key environmental variables for SAV coverage in Lake Okeechobee (K. E. Havens, 2003; Johnson et al., 2007; Steinman et al., 2002). *Chara* spp. biomass was strongly negatively correlated with total suspended solids (TSS) and inorganic suspended solids, which are responsible for reducing transparency (K. E. Havens, 2003). SAV biomass is also negatively correlated with water depth, with SAV occurring at maximum depths of 2.3-6.6 ft (Hopson & Zimba, 1993; Johnson et al., 2007; Steinman et al., 1997, 2002). Increases in water depth further reduces the light that can reach the bottom of the lake and can also result in winds and nutrient-rich, sediment-rich waters to be transported into the near-shore zone, further reducing light availability (K. E. Havens, 2002; Johnson et al., 2007). Lake stages exceeding 16.7 ft msl (mean sea level) will cause substantial loss of aquatic and wetland plants in Lake Okeechobee (Johnson et al., 2007). When the lake stage is less than 15 ft msl, an underwater ridge helps prevent the transport of sediment and nutrient-rich water into the near-shore zone (K. E. Havens, 2002; Johnson et al., 2007). This reduces suspended solids, increasing light availability and promoting the expansion of SAV (Johnson et al., 2007). If the lake stage regularly varies between 12.1 ft msl and 15 ft msl most years, littoral and near-shore zones should be expected to develop diverse and widespread stands of aquatic vegetation (Johnson et al., 2007). SAV recovery takes time, previously it took two years following a drought period of reduced lake stage for moderate SAV biomass to reoccur (K. E. Havens et al., 2004; Johnson et al., 2007). *Chara* spp. is the quickest to recover of SAV present in Lake Okeechobee, with the recovery of vascular SAV occurring after (K. E. Havens et al., 2004). SAV dominated by *Chara* spp. recovered within months of the initial drawdown, with vascular SAV species recovering over a year later, possibly due to changes in physical and meteorological conditions (K. E. Havens et al., 2004). *Chara* spp. can germinate with less light than vascular plants (eelgrass *Vallisneria americana*), aiding to its quick recovery (K. E. Havens et al., 2004). Dense beds of *Chara* spp. likely helped improve water clarity and growing conditions for vascular SAV plants, followed by wind events that allowed vascular plants to replace *Chara* spp. populations (K. E. Havens et al., 2004).

Hurricanes have damaged SAV communities in Lake Okeechobee. SAV coverage was devastated by hurricane Irma in 2017 and again by hurricane Ian in 2022 (Betts et al., 2024; Welch et al., 2019). Hurricanes Ian and Nicole in 2022 both resulted in lowest coverage of SAV following Hurricanes Frances and Jeanne in 2004, and Wilma in 2005 (Betts et al., 2024). These hurricanes both physically uprooted SAV and EAV communities and resulted in unfavorable conditions for growth (Betts et al., 2024; T. R. James et al., 2008). These hurricanes increased turbidity, reducing light penetration for months following the hurricanes (Betts et al., 2024; Welch et al., 2019). Following hurricanes Frances, Jeanne, and Wilma, SAV started to regrow one year after water levels reached an optimal level (12 ft NGVD) (T. R. James et al., 2008). *Chara* coverage is dependent on lake stage, with SAV coverage peaking one to two years after low lake levels which leads to increased light penetration (Betts et al., 2024). Following hurricane Irma in 2019, vascular species (eelgrass, *Vallisneria americana*) were reduced by 35% and non-vascular species (the macroalgae *Chara* spp.) were essentially nonexistent (Betts et al., 2024). *Chara* spp. populations started to recover in the years following Irma due to low water levels (Betts et al., 2024). Any recovery of coverage was eliminated with hurricane Ian (Betts et al., 2024).

Emergent aquatic vegetation. EAV provides important habitat for fish wading birds and other wildlife (Betts et al., 2024). EAV supports higher rates of photosynthesis and primary production compared to other primary producers (Thomaz, 2023). Rooted EAV traps sediment and reduces erosion, stabilizing shorelines and providing a physical barrier that reduces wave energy (Thomaz, 2023). In Lake Okeechobee EAV species composition and coverage is affected by water levels, management actions, hurricanes and invasive plant species (Betts et al., 2024). EAV in Lake Okeechobee consists of herbaceous vegetation (grasses, sedges, smartweed *Polygonum* spp., and water pennywort *Hydrocotyle* spp.), woody vegetation (willow *Salix caroliniana*, buttonbush *Cephalanthus occidentalis*, hibiscus *Hibiscus* spp., pond apple *Annona glabra* and other trees) cattail (*Typha* spp.) and alligator flag (*Thalia geniculata*). Some species like giant bulrush (*Scirpus californicus*) in Lake Okeechobee can act as a protective barrier along the near-shore zone that protects submerged plants from wave action (Johnson et al., 2007).

Water levels are important to both SAV and EAV communities in the littoral zone, the shallow nearshore environment where light reaches the lake bottom to support photosynthesis. Low stages can dry out marshes, while high lake stages shift littoral communities upslope, reducing the spatial extent of the littoral ecosystem (Johnson et al., 2007; Julian & Welch, 2022). Elevated nutrients can cause cascading effects shifting the basal food web structure in this zone (Julian & Welch, 2022). Some emergent plants, such as sawgrass (*Cladium jamaicense*) and giant bulrush, are stressed by prolonged periods of deep flooding (Johnson et al., 2007). Periods of high-water levels allow sediments and nutrients to be transported into the littoral zone, helping facilitate the spread of nutrient tolerant nuisance (such as cattail, *Typha* spp.) or invasive plants (such as torpedo grass, *Panicum repens*) (Johnson et al., 2007; Julian & Welch, 2022). Cattails are adapted to deep water (over 3.9 feet), and prolonged periods of deep flooding in Lake Okeechobee can lead to the spread of cattail (Johnson et al., 2007). During the spring periods of drought or near-drought water levels could also promote the spread of cattails, allowing cattail seeds to germinate in shallow water (Johnson et al., 2007). Torpedograss cannot establish in water depths greater than 9.8 in; lower lake stages would likely promote the invasion of torpedograss but are needed for the growth of SAV and other EAV species (Johnson et al., 2007). Many emergent native plants expand in coverage with low water levels, including spikerush (*Elocharis cellulosa*), Egyptian paspalidium (*Paspalidium geminatum*), beakrush (*Rhynchospora tracyi*) and fragrant water lily (*Nymphaea odorata*) (Johnson et al., 2007).

Hurricane disturbances have also resulted in the loss of EAV coverage. High wind and wave energy uprooted and washed away emergent and floating vegetation on the exposed edges of the marsh (Betts et al., 2024). Hurricane Irma in 2017 caused an estimated loss of 5,200 acres of EAV (Betts et al., 2024; Welch et al., 2019). Following hurricane Irma, Lake Okeechobee saw increased open water habitat with increased water lily (*Nymphaea* spp.), American lotus (*Nelumbo lutea*), and willow (*Salix* spp.) coverage due to vegetation management activity (Welch et al., 2019). Irma also increased flooding depth, and uprooted vegetation on the outer edge of the marsh (Welch et al., 2019). This included declines woody shrubs and cattail (*Typha* spp.) and torpedo grass (*Panicum repens*) (Welch et al., 2019).

Fisheries and habitat in Lake Okeechobee. SAV provides important habitat for zooplankton, macroinvertebrates, and small fish as well as protective cover from predation (Hanlon & Jordan, 2023 and references therein). SAV serves as foraging habitat and protective cover for young largemouth bass (*Micropterus salmoides*), increasing their abundance and survival rate (Hanlon & Jordan, 2023 and references therein). Largemouth bass is the most popular and targeted freshwater game fish in the United States, hundreds of millions of dollars are spent annually by anglers targeting this species (Hanlon & Jordan, 2023; U.S. Fish and Wildlife Service and U.S. Bureau of the Census, 2016).

Fish are unevenly distributed throughout the lake, and fish populations show seasonal distribution patterns (Bull et al., 1995). The abundance of threadfin shad, an important forage fish to sport fish such as black crappie, is inversely related to turbidity and positively associated to phytoplankton standing crops in Lake Okeechobee (Bull et al., 1995). Periods of reduced SAV cover have caused low population densities of largemouth bass and failure to recruit young fish into the population (Havens et al., 2005). The abundance of all largemouth bass age groups positively correlates to SAV cover in Lake Okeechobee (Hanlon & Jordan, 2023). Age 0, juvenile, and all-ages largemouth bass tend to be most abundant where vascular SAV coverage exceeded 20% of the littoral and near-shore area (Hanlon & Jordan, 2023). The increase in cover of vascular SAV was associated with the strong recruitment of young largemouth bass (Havens et al., 2005). Giant bulrush, hydrilla, and Illinois pondweed are the most valuable vegetation communities to fisheries in Lake Okeechobee, with eelgrass and Illinois pondweed providing the most valuable habitat for juvenile sport and forage fishes (Furse & Fox, 1994).

Largemouth bass catch rates have declined by 76% between 2014 to 2019, following declining trends in SAV cover (Betts et al., 2024). Catch rates increased starting in 2020, where a slight increase in vascular SAV coverage resulted in a five-fold increase in largemouth bass catch rate (Betts et al., 2024). Improving environmental conditions in 2019, where low lake stage improved *Chara* coverage and dense beds of vascular SAV began to form, resulted in a large increase in young of the year largemouth bass (Betts et al., 2024). Following late 2020 and 2021 lake stages were high, resulting in the loss of SAV habitat and a large decline in the catch rate of largemouth bass (Betts et al., 2024). Largemouth bass catch rates were still declining in 2022 (Betts et al., 2024). Total fish abundance has also followed a declining trend between 2014 and 2017, thanks to annual reductions in threadfin shad, an important forage fish (Betts et al., 2024). Black crappie and threadfin shad abundances were low most years between 2017 and 2022, with some population spikes in 2018 and 2021, primarily due to increases in young of year fish and increases in threadfin shad (Betts et al., 2024). Hurricane Irma was possibly less damaging than previous hurricanes in 2004 and 2005, however the survival rate of black crappie in 2018 and 2021 was low. The continuous lack of favorable environmental conditions (clear water, spawning habitat, and forage) has made it difficult for black crappie populations to thrive for extended periods (Betts et al., 2024).

Climate change and Lake Okeechobee. Global climate change will significantly warm the atmosphere and hydrosphere, resulting in an increase in extreme precipitation events, increases in drought duration, and likely increase peak wind velocities during tropical cyclones (Knutson et al., 2010; O'Gorman, 2015; Rummukainen, 2012). Climate change will likely result in negative impacts to the health of Lake Okeechobee. Increases in precipitation and intense rainfall events would bring greater loads of nutrients to an already impaired lake and raise lake stages to the detriment of SAV growth and recovery (K. Havens et al., 2016; Hopson & Zimba, 1993; Johnson et al., 2007; Steinman et al., 1997, 2002). Climate change could alter rainfall and alter the dynamics of lake ecosystems and their response to management actions (K. Havens et al., 2016). The intensification of wind velocities in tropical cyclones would likely exacerbate documented water quality issues associated with sediment resuspension in Lake Okeechobee (K. Havens et al., 2016). If future storms are more intense or occur in close sequence, the lake may not have enough time to recover from their impacts (K. Havens et al., 2016). Because of the correlation between algal blooms and temperature in Lake Okeechobee, increasing atmospheric temperatures could increase the possibility for algal blooms in the future, provided water transparency remains low (K. E. Havens et al., 1994). Increases in the input or resuspension of N or P, and changes in water depth could also simulate cyanobacterial blooms (K. Havens et al., 2016). These considerations need to be incorporated into long-term lake management plans (K. Havens et al., 2016). Current rehabilitation methods may not be enough to restore health to the lake if the various effects of global climate change may amplify the effects of nutrients (K. Havens et al., 2016).

CONCLUSIONS

Lake Okeechobee is a eutrophic lake heavily impacted by anthropogenic stressors. Changes in land use have led to increases in TP loading and concentrations and the accumulation of mud sediments that have resulted in water quality issues. Lake Okeechobee continues to be impaired for P, and concentrations of TP are increasing in lake waters. Management efforts have failed to meet mandated TMDL values for TP, and further action is needed to reduce TP loading in the lake. Better management of TN concentrations is needed as TN can contribute to harmful algal blooms. TP loading has resulted in increased frequency of algal blooms, and in the accumulation of carbon-rich mud sediments over time. The accumulation of mud sediments has resulted in increased suspended solids, resulting in decreased light penetration affecting the growth of SAV.

Accumulated mud sediments are frequently resuspended by wind action, releasing TN and TP associated with them, and continue to serve as a challenge to restoration.

SAV cover, and subsequently fish populations, have been declining in Lake Okeechobee. This can be attributed to declining water transparency, periods of high lake stages, and hurricane stressors. Hurricanes have further exacerbated water quality issues, resuspending greater volumes of sediment into the water column, increasing nutrient concentrations, and both physically uprooting aquatic vegetation and reducing light penetration for plant growth, resulting in the loss of vital habitat. In recent years, hurricanes Irma, Ian and Nicole have resulted in high nutrient concentrations, the loss of SAV and EAV habitat, and declines in fish populations. Largemouth bass populations and black crappie populations are both economically important fisheries for the lake. Reductions in lake stage are critical following hurricane impacts and can help improve light penetration and promote SAV recovery.

A combination of improved nutrient influx management, water budget management and the elimination of legacy nutrients is needed. Current restoration measures are not enough to improve water quality in Lake Okeechobee. Inflow P concentrations and loads need to be further reduced. Management plans also need to consider climate change, as the effects of climate change may amplify the effects of nutrients in the lake.

Additional literature review can be found in Appendix 2, Appendix 3, and Appendix 4.

References

Aumen, N. G. (1995). The history of human impacts, lake management, and limnological research on Lake Okeechobee, Florida (USA). *Advances in Limnology [ERGEB. LIMNOL./ADV. LIMNOL.]. 1995.*

Betts, A., Welch, Z., & Jones, P. (2024). Chapter 8B: Lake Okeechobee Watershed Protection Plan Annual Progress Report. In *2024 South Florida Environmental Report* (Vol. 1, pp. 8B 1-8B 2 42). South Florida Water Management District.

Brezonik, P. L., & Engstrom, D. R. (1998). Modern and historic accumulation rates of phosphorus in Lake Okeechobee, Florida. *Journal of Paleolimnology*, *20*, 31–46.

Bull, L. A., Fox, D. D., Brown, D. W., Davis, L. J., Miller, S. J., & Wullschleger, J. G. (1995). Fish distribution in limnetic areas of Lake Okeechobee, Florida. *Archiv Fur Hydrobiologie, Advances in Limnology*, *45*, 333–342.

Canfield Jr, D. E., Bachmann, R. W., & Hoyer, M. V. (2020). Restoration of Lake Okeechobee, Florida: mission impossible? *Lake and Reservoir Management*, *37*(1), 95–111.

Chambers, P. A., & Kaiff, J. (1985). Depth distribution and biomass of submersed aquatic macrophyte communities in relation to Secchi depth. *Canadian Journal of Fisheries and Aquatic Sciences*, *42*(4), 701–709.

Chimney, M. J. (2005). Surface seiche and wind set-up on Lake Okeechobee (Florida, USA) during hurricanes Frances and Jeanne. *Lake and Reservoir Management*, *21*(4), 465–473.

Dang, T. D., Arias, M. E., Tarabih, O., Phlips, E. J., Ergas, S. J., Rains, M. C., & Zhang, Q. (2023). Modeling temporal and spatial variations of biogeochemical processes in a large subtropical lake: Assessing alternative solutions to algal blooms in Lake Okeechobee, Florida. *Journal of Hydrology: Regional Studies*, *47*, 101441.

Deosti, S., de Fátima Bomfim, F., Lansac-Tôha, F. M., Quirino, B. A., Bonecker, C. C., & Lansac-Tôha, F. A. (2021). Zooplankton taxonomic and functional structure is determined by macrophytes and fish predation in a neotropical river. *Hydrobiologia*, *848*, 1475–1490.

Dibble, E. D., & Thomaz, S. M. (2009). Use of fractal dimension to assess habitat complexity and its influence on dominant invertebrates inhabiting tropical and temperate macrophytes. *Journal of Freshwater Ecology*, *24*(1), 93–102.

Dierberg, F. E., DeBusk, T. A., Jackson, S. D., Chimney, M. J., & Pietro, K. (2002). Submerged aquatic vegetation-based treatment wetlands for removing phosphorus from agricultural runoff: response to hydraulic and nutrient loading. *Water Research*, *36*(6), 1409–1422.

Faridmarandi, S., Khare, Y. P., & Naja, G. M. (2020). Long-term regional nutrient contributions and in-lake water quality trends for Lake Okeechobee. *Lake and Reservoir Management*, *37*(1), 77–94.

Flaig, E. G., & Havens, K. E. (1995). Historical trends in the Lake Okeechobee ecosystem. I. Land use and nutrient loading. *Arch Hydrobiol*, *107*, 1–24.

Furse, J. B., & Fox, D. D. (1994). Economic fishery valuation of five vegetation communities in Lake Okeechobee, Florida. *Proceedings of the Annual Conference of Southeastern Association of Fish and Wildlife Agencies*, *48*, 575–591.

Gomes, L. C., Bulla, C. K., Agostinho, A. A., Vasconcelos, L. P., & Miranda, L. E. (2012). Fish assemblage dynamics in a Neotropical floodplain relative to aquatic macrophytes and the homogenizing effect of a flood pulse. *Hydrobiologia*, *685*, 97–107.

Hanlon, C. G., & Jordan, A. (2023). Influence of habitat and other factors on Largemouth Bass abundance in Lake Okeechobee, Florida. *Transactions of the American Fisheries Society*, *152*(4), 429–442.

Havens, K. E. (1995). Particulate light attenuation in a large subtropical lake. *Canadian Journal of Fisheries and Aquatic Sciences*, *52*(8), 1803–1811.

Havens, K. E. (2002). Development and application of hydrologic restoration goals for a large subtropical lake. *Lake and Reservoir Management*, *18*(4), 285–292.

Havens, K. E. (2003). Submerged aquatic vegetation correlations with depth and light attenuating materials in a shallow subtropical lake. *Hydrobiologia*, *493*, 173–186.

Havens, K. E., Aumen, N. G., James, R. T., & Smith, V. H. (1996). *Rapid ecological changes in a large subtropical lake undergoing cultural eutrophication.*

Havens, K. E., Fox, D., Gornak, S., & Hanlon, C. (2005). Aquatic vegetation and largemouth bass population responses to water-level variations in Lake Okeechobee, Florida (USA). *Hydrobiologia*, *539*, 225–237.

Havens, K. E., Hanlon, C., & James, R. T. (1994). Seasonal and spatial variation in algal bloom frequencies in Lake Okeechobee, Florida, USA. *Lake and Reservoir Management*, *10*(2), 139–148.

Havens, K. E., & James, R. T. (1999). Localized changes in transparency linked to mud sediment expansion in Lake Okeechobee, Florida: ecological and management implications. *Lake and Reservoir Management*, *15*(1), 54–69.

Havens, K. E., & James, R. T. (2005). The phosphorus mass balance of Lake Okeechobee, Florida: implications for eutrophication management. *Lake and Reservoir Management*, *21*(2), 139–148.

Havens, K. E., Sharfstein, B., Brady, M. A., East, T. L., Harwell, M. C., Maki, R. P., & Rodusky, A. J. (2004). Recovery of submerged plants from high water stress in a large subtropical lake in Florida, USA. *Aquatic Botany*, *78*(1), 67–82.

Havens, K., Paerl, H., Phlips, E., Zhu, M., Beaver, J., & Srifa, A. (2016). Extreme weather events and climate variability provide a lens to how shallow lakes may respond to climate change. *Water*, *8*(6), 229.

Hopson, M. S., & Zimba, P. V. (1993). Temporal variation in the biomass of submersed macrophytes in Lake Okeechobee, Florida. *Journal of Aquatic Plant Management*, *31*, 76.

Hudon, C., Lalonde, S., & Gagnon, P. (2000). Ranking the effects of site exposure, plant growth form, water depth, and transparency on aquatic plant biomass. *Canadian Journal of Fisheries and Aquatic Sciences*, *57*(S1), 31–42.

James, R. T., Havens, K., Zhu, G., & Qin, B. (2009). Comparative analysis of nutrients, chlorophyll and transparency in two large shallow lakes (Lake Taihu, PR China and Lake Okeechobee, USA). *Hydrobiologia*, *627*, 211–231.

James, T. R., Chimney, M. J., Sharfstein, B., Engstrom, D. R., Schottler, S. P., East, T., & Jin, K.-R. (2008). Hurricane effects on a shallow lake ecosystem, Lake Okeechobee, Florida (USA). *Fundamental and Applied Limnology*, *172*(4), 273.

Jin, K.-R., Chang, N.-B., Ji, Z.-G., & James, R. T. (2011). Hurricanes affect the sediment and environment in Lake Okeechobee. *Critical Reviews in Environmental Science and Technology*, *41*(S1), 382–394.

Johnson, K. G., Allen, M. S., & Havens, K. E. (2007). A review of littoral vegetation, fisheries, and wildlife responses to hydrologic variation at Lake Okeechobee. *Wetlands*, *27*(1), 110–126.

Julian, P., & Welch, Z. (2022). Understanding the ups and downs: application of hydrologic restoration measures for a large subtropical lake. *Lake and Reservoir Management*, *38*(4), 304–317.

Knight, R. L., Gu, B., Clarke, R. A., & Newman, J. M. (2003). Long-term phosphorus removal in Florida aquatic systems dominated by submerged aquatic vegetation. *Ecological Engineering*, *20*(1), 45–63.

Knutson, T. R., McBride, J. L., Chan, J., Emanuel, K., Holland, G., Landsea, C., Held, I., Kossin, J. P., Srivastava, A. K., & Sugi, M. (2010). Tropical cyclones and climate change. *Nature Geoscience*, *3*(3), 157–163.

Kramer, B. J., Davis, T. W., Meyer, K. A., Rosen, B. H., Goleski, J. A., Dick, G. J., Oh, G., & Gobler, C. J. (2018). Nitrogen limitation, toxin synthesis potential, and toxicity of cyanobacterial populations in Lake Okeechobee and the St. Lucie River Estuary, Florida, during the 2016 state of emergency event. *PLoS One*, *13*(5), e0196278.

Lodge, T. E. (2016). *The Everglades handbook: understanding the ecosystem*. Crc Press.

Missimer, T. M., Thomas, S., & Rosen, B. H. (2020). Legacy phosphorus in Lake Okeechobee (Florida, USA) sediments: A review and new perspective. *Water*, *13*(1), 39.

O'Gorman, P. A. (2015). Precipitation extremes under climate change. *Current Climate Change Reports*, *1*, 49–59.

Pollman, C. D., & James, R. T. (2011). A simple model of internal loading of phosphorus in Lake Okeechobee. *Lake and Reservoir Management*, *27*(1), 15–27.

Rummukainen, M. (2012). Changes in climate and weather extremes in the 21st century. *Wiley Interdisciplinary Reviews: Climate Change*, *3*(2), 115–129.

Sand-Jensen, K., & Madsen, T. V. (1991). Minimum light requirements of submerged freshwater macrophytes in laboratory growth experiments. *The Journal of Ecology*, 749–764.

Sathyendranath, S. (2000). *Remote sensing of ocean colour in coastal, and other optically-complex, waters.*

Saulquin, B., Hamdi, A., Gohin, F., Populus, J., Mangin, A., & d'Andon, O. F. (2013). Estimation of the diffuse attenuation coefficient KdPAR using MERIS and application to seabed habitat mapping. *Remote Sensing of Environment*, *128*, 224–233.

Schwarz, A.-M., de Winton, M., & Hawes, I. (2002). Species-specific depth zonation in New Zealand charophytes as a function of light availability. *Aquatic Botany*, *72*(3–4), 209–217.

Steinman, A. D., Havens, K. E., Rodusky, A. J., Sharfstein, B., James, R. T., & Harwell, M. C. (2002). The influence of environmental variables and a managed water recession on the growth of charophytes in a large, subtropical lake. *Aquatic Botany*, *72*(3–4), 297–313.

Steinman, A. D., Meeker, R. H., Rodusky, A. J., Davis, W. P., & Hwang, S.-J. (1997). Ecological properties of charophytes in a large subtropical lake. *Journal of the North American Benthological Society*, *16*(4), 781–793.

Thomaz, S. M. (2023). Ecosystem services provided by freshwater macrophytes. *Hydrobiologia*, *850*(12), 2757–2777.

U.S. Fish and Wildlife Service and U.S. Bureau of the Census. (2016). *National survey of fishing, hunting, and wildlife-associated recreation*.

Vermaat, J. E., Santamaria, L., & Roos, P. J. (2000). Water flow across and sediment trapping in submerged macrophyte beds of contrasting growth form. *Archiv Für Hydrobiologie*, *148*(4), 549–562.

Wallsten, M., & Forsgren, P. O. (1989). *The effects of increased water level on aquatic macrophytes.*

Welch, Z., Zhang, J., & Jones, P. (2019). Chapter 8B: Lake Okeechobee Watershed Annual Report. In *2019 South Florida Environmental Report* (Vol. 1, pp. 8B 1-8B 83). South Florida Water Management District.

Xu, T., Yang, T., Zheng, X., Li, Z., & Qin, Y. (2022). Growth limitation status and its role in interpreting chlorophyll a response in large and shallow lakes: A case study in Lake Okeechobee. *Journal of Environmental Management*, *302*, 114071.

Appendix 2: Evaluation of Potential Actions Using Available Information and Expert Opinion

Prepared by: The Center for Analysis, Synthesis, and Application,
University of South Florida: Thomas K. Frazer & Charles A. Jacoby

Summary

Major, ongoing efforts to restore the health of Lake Okeechobee focus on adding flexibility to control of water levels in the lake and reducing external loads of nutrients. These efforts include the Comprehensive Everglades Restoration Plan, Lake Okeechobee System Operating Manual, Lake Okeechobee Total Maximum Daily Load, Lake Okeechobee Basin Management Action Plan, agricultural best management practices, Northern Everglades and Estuaries Protection Plan, and Lake Okeechobee Watershed Protection Plan.

With the existing efforts as critical context, additional, complementary actions were evaluated by 1) defining key issues and associated concerns, with a focus on input from stakeholders; 2) presenting recent guidance for implementing projects at various scales, and 3) identifying caveats, knowledge gaps, and potential challenges to success. Three issues were targeted: 1) accumulation of "mud," 2) spread of nuisance plants, and 3) loss of submerged aquatic vegetation. In addition, comments from reviews were addressed in an addendum.

Addressing mud will promote a healthier lake by reducing the internal load of nutrients, especially phosphorus, that fuel harmful blooms of Cyanobacteria, decreasing turbidity, and promoting growth of submerged aquatic vegetation. Dredging the center of the lake will take a significant investment and more than a decade to complete. Smaller scale dredging may yield value, but its ultimate efficacy remains to be proven. All approaches to addressing mud have associated risks that should be explored. In particular, altered interactions with groundwater after dredging has proven to be a concern that may warrant exploration for Lake Okeechobee.

Submerged aquatic vegetation and fish and wildlife also are threatened by the spread of nuisance plants that form dense monocultures of lower quality habitat. For Lake Okeechobee, plant

management is a cooperative operation coordinated by an interagency task force. Relative to maintenance control with herbicides, harvesting is a relatively expensive and non-selective approach to controlling invasive plants that may detrimentally affect aquatic animals. Multiple precautions are taken to ensure safe, effective, and efficient use of herbicides, and promulgating that information will be valuable.

Overall, the acreage covered by submerged aquatic vegetation has decreased substantially since 2012, which reduces suitable habitat for fish and wildlife. Planting throughout the lake would be an unprecedented investment that will be affected by unfavorable or unstable conditions, especially penetration of light. When available, data from planting in Lake Apopka my yield useful insights into establishing submerged aquatic vegetation in a turbid lake. In many cases, natural recovery from seed banks occurs within decades of the key stressors being reduced or removed. Pilot projects to refine techniques associated with planting, assess the health of seed banks, and evaluate the possibility of harvesting and scattering seeds represent three potentially useful approaches that avoid the risks associated with large-scale planting before water quality is suitable.

Sampling to elucidate interactions between the pelagic and littoral zones in Lake Okeechobee should be continued. The resulting data can be used to identify conditions when phytoplankton blooms in the littoral zone are fueled by nutrients from the pelagic zone and when turbidity from the pelagic zone reduces the amount of light reaching the substrate in the littoral zone. In both cases, less light is available to support submerged aquatic vegetation in the littoral zone.

Pumping water through a facility designed to reduce turbidity or concentrations of nitrogen and phosphorus is underway elsewhere or has been investigated in pilot studies. A major concern would be the commitment to scaling such efforts to yield a lakewide effect in a suitable timeframe. Additional pilot efforts may yield valuable insights.

Pumping water through existing wetlands has a high potential to adversely affect their structure and function. In addition, plants may need to be harvested to maintain high rates of uptake. Furthermore, conditions in the littoral zone may deteriorate following increased interaction with the pelagic zone of the lake.

Lake Okeechobee is a valuable resource exhibiting clear signs of ecological stress, but evidence from the lake and other ecological systems indicates that recovery is possible once stresses are reduced sufficiently. The lake is large, and current conditions have developed over decades, so restoring the health of Lake Okeechobee is expected to require substantial, sustained investment.

Introduction

This portion of the study focused on using available information and expert opinion to evaluate potential actions, especially actions proposed by local stakeholders. Potential actions were considered in the context of the major, ongoing efforts to restore the health of Lake Okeechobee by adding flexibility to control of water levels in the lake and by reducing external loads of nutrients. Thus, the focus of this report was on additional actions that could complement or augment full implementation of the Comprehensive Everglades Restoration Plan, Lake Okeechobee System Operating Manual, Lake Okeechobee Total Maximum Daily Load, Lake Okeechobee Basin Management Action Plan, agricultural best management practices, Northern Everglades and Estuaries Protection Plan, Lake Okeechobee Watershed Protection Plan, and other ongoing efforts.

Evaluations of proposed actions included 1) defining key issues and relevant concerns, with the realization that issues often are interrelated; 2) presenting recent guidance for implementing projects at different scales, and 3) identifying caveats, knowledge gaps, and potential challenges to success. The report is meant to add value during discussions of additional actions to restore the health of Lake Okeechobee.

Historical system

Lake Okeechobee formed in a shallow depression in the Pamlico Terrace after the ocean receded about 6,000 years ago. Rainfall provided over half of the water in the newly formed lake, and evapotranspiration, rather than outflow, was responsible for over 70% of the water lost.

By about 4,000 years ago, a berm of organic matter had formed along the southern edge of the lake resulting in a larger and deeper lake with few natural outlets. Organic matter contains carbon and comes from plants and animals, and in this case, the bulk of the material was from plants. At this time, the lake extended further to the south and west than it does today, its open water zone was deeper, and the current shallow water fringing marsh, also was under deeper water. Most inflow came from a meandering Kissimmee River, and a large proportion of the outflow exited to the south either through breaks in the organic berm during low water or as wide swath of sheet flow over the berm during high water. If water levels remained sufficiently high, the outflow passed through the Everglades and ultimately reached Florida Bay. During high water, sheet flow also linked Lake Okeechobee to Lake Hicpochee to the southwest, with sufficiently high water leading to discharge through the Caloosahatchee River. Overall, water moved into and out of Lake Okeechobee slowly, and it was filtered by the floodplains.

Changes and subsequent stresses

Deadly and damaging floods in the early 1920s prompted engineering that altered the nature of Lake Okeechobee. The United States Army Corps of Engineers led construction of a flood control system comprising dikes, gates, pumps, and canals that changed outflow from a combination of small discharges through natural low points during low water and acres of sheet flow during high water to discharge to canals governed by control structures. One of the major canals expanded the lake's connection to the Caloosahatchee River and Florida's west coast, and a second major canal linked the lake to the St. Lucie River and estuary on the Atlantic coast. In addition, the Kissimmee River and other inflows were channelized, which meant more water from the adjacent catchments flowed into the lake quickly rather than spreading out over a floodplain and evaporating or moving slowly into the lake. Currently, Lake Okeechobee has a surface area of nearly 730 square miles and a mean depth of less than ten feet. Interestingly, rainfall on the lake's surface and evapotranspiration remain the major source and loss of water for the lake.

Beyond altering the hydrology of Lake Okeechobee, human activities have affected its ecology. This portion of the study addresses five interrelated changes: 1) controlled water levels, 2) increased external loads of nitrogen and phosphorus that fuel blooms of single-celled algae, including harmful blue-green algae (cyanobacteria), 3) accumulation of "mud," 4) spread of nuisance plants, and 5) loss of submerged aquatic vegetation, which comprises plants and attached algae (macroalgae) that live on the bottom of the lake.

Water levels – Storing water in the lake to supply local communities or to prevent flooding stresses parts of the system. For example, submerged aquatic vegetation receives less light to support its growth because less light penetrates the deeper water, the endangered Florida snail kite (*Rostrhamus sociabilis*) cannot access the apple snails that are its preferred prey, and birds that forage successfully in water less than six inches deep struggle to find food (Table 1).

Table 1. Examples of birds that rely on shallow water for successful foraging (provided by Dr. Paul Gray).

Shorebirds		**Waterfowl (dabblers)**	**Rails**	**Wading birds**
Black-bellied plover	Western sandpiper	Fulvous whistling duck	Yellow rail	American bittern
Semipalmated plover	Least sandpiper	Black-bellied whistling duck	Black rail	Snowy egret
Killdeer	White-rumped sandpiper	Wood duck	King rail	Little blue heron
Black-necked stilt	Pectoral sandpiper	Gadwall	Virginia rail	Black-crowned night heron
American avocet	Dunlin	American wigeon	Sora	White ibis
Greater yellowlegs	Stilt sandpiper	Mottled puck		Glossy ibis
Lesser yellowlegs	Long-billed dowitcher	Blue-winged peal		Roseate spoonbill
Solitary sandpiper	Wilson's snipe	Northern pintail		Limpkin
Spotted sandpiper	Wilsons's phalarope	Green-winged teal		
Semipalmated sandpiper				

Loads of nutrients – Loads of nitrogen and phosphorus entering Lake Okeechobee increased, due in large part to more intensive use of the land in the lake's watershed and channelization of the Kissimmee River and other tributaries. Fertilizers, animal waste, discharges from wastewater treatment plants, and effluent from septic tanks all contribute to the loads, and channelization moves larger quantities of water and nutrients to the lake quickly and without the evaporation and filtration that would have occurred in the floodplains following rainstorms. Increased loads of nitrogen and phosphorus, two key nutrients that support all life, have shifted conditions in the lake away from submerged aquatic vegetation and toward dominance by single-celled algae. These algae obtain and use nutrients in the water column more effectively than submerged aquatic vegetation, and shading from the subsequent blooms causes submerged aquatic vegetation to regress, which further shifts competition for nutrients in favor of single-celled algae. An excess of phosphorus relative to nitrogen has been documented in the lake, and this skewed ratio can trigger a shift to blue-green algae that can draw nitrogen from the atmosphere. These algae may be less palatable to zooplanktonic grazers so they can form more intense blooms, and some can produce toxins that harm animals and people.

Accumulation of mud – Organic matter generated by single-celled algae and by other plants that proliferate in response to the increased concentrations of nutrients have combined with fine particles of sediment that come off land when it is developed or farmed to create "mud." An estimated 2.5 feet of mud has accumulated in the deepest portions of the lake (Figure 1).

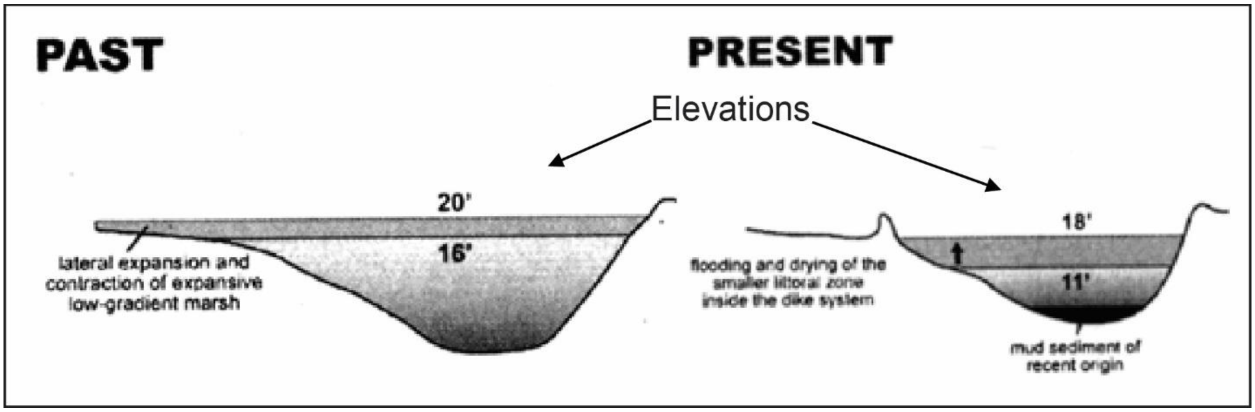


Figure 1. Diagram of past and present conditions in Lake Okeechobee. Adapted from Havens, K.E., and D.E. Gawlik. 2005. Lake Okeechobee Conceptual Ecological Model, Wetlands 25: 908–925.

The accumulated mud creates several issues. The mud reduces the lake's capacity to store water. The mud also produces an internal load of nitrogen and phosphorus because bacterial decomposition of organic matter generates these nutrients. The resulting internal loads of nutrients have been estimated to equal external loads originating in the lake's watershed, and they create the same detrimental effects. Lastly, resuspension of the mud by wind-driven waves reduces water clarity, and the resultant turbidity (scattering and absorption of light) reduces the amount of light reaching the lake's bottom and submerged aquatic vegetation. The turbidity from resuspended particles can exceed that caused by blooms of single-celled algae (Figure 2). Sufficiently turbid water leads to a loss of submerged aquatic vegetation due to excessive shading that reduces photosynthetic output below the metabolic needs of the vegetation. Loss of submerged aquatic vegetation eliminates its stabilizing effect on sediment and reduces competition for nutrients. These changes promote resuspension of particles and blooms of single-celled algae, which further stress any remaining submerged aquatic vegetation.

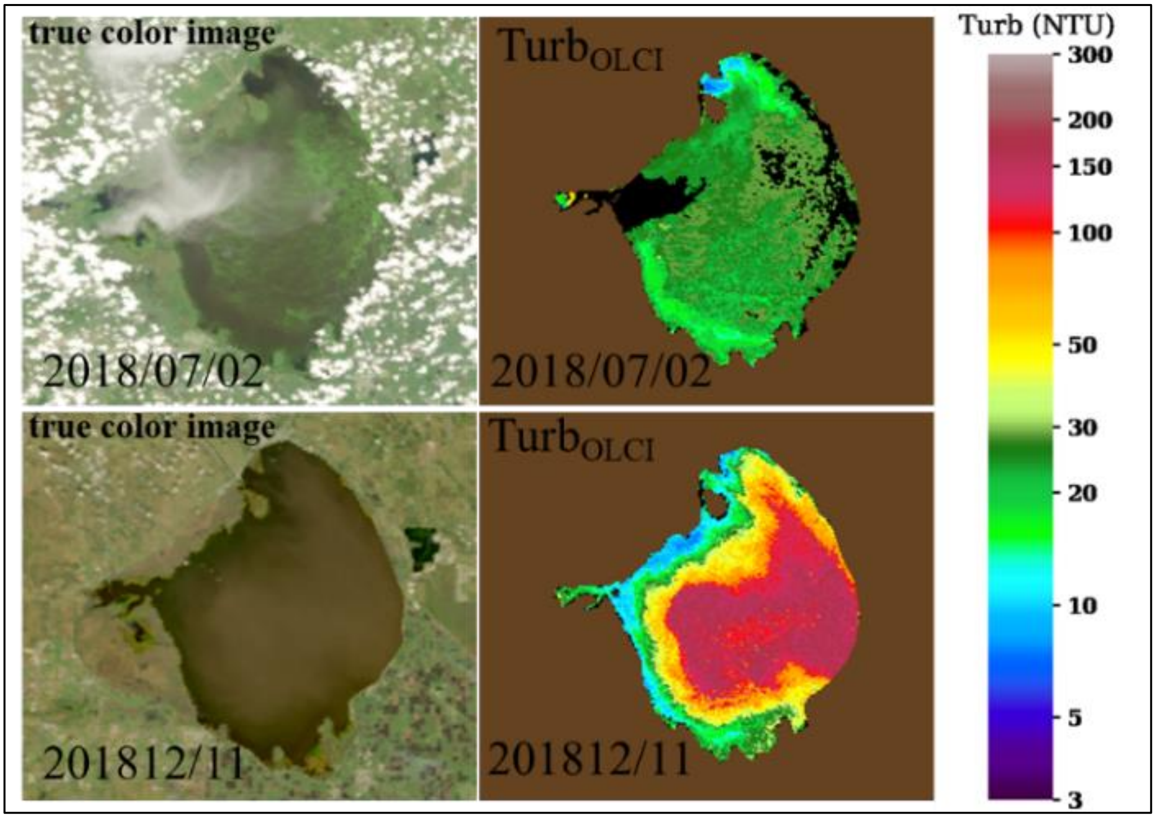


Figure 2. Comparison of satellite imagery and modeled turbidity during a bloom (top) and during an event not associated with a bloom (bottom). True color images are in the left column, modeled values for turbidity are in the right column, and a scale for turbidity is on the right. Figure provided by College of Marine Science, University of South Florida.

Spread of nuisance plants – In addition to reduced light, submerged aquatic vegetation also is threatened by the spread of nuisance plants that form dense monocultures. Both native and non-native plants contribute to this stress. Whereas high water levels stress submerged aquatic vegetation by reducing the light they receive, low water levels can stress submerged aquatic vegetation and other desirable species by exposing them to heat and desiccation. In addition, low water levels combined with high concentrations of nutrients can accelerate the spread of nuisance plants that form dense monocultures and exclude more favorable species. In general, dense monocultures provide lower quality habitat for fish and wildlife than mixed assemblages of submerged aquatic vegetation because there are fewer suitably sized refuges for fish and access to prey is more difficult.

Loss of submerged aquatic vegetation – The acreage covered by vascular plants (e.g., *Vallisneria* or tapegrass) and non-vascular, attached macroalgae (e.g., *Chara* or muskgrass) tends to increase during periods of drought and low water levels and decrease when hurricanes deliver rain and wind that result in higher water levels and higher turbidity (Figure 3). A persistent decrease in acreage has been recorded since 2012 (Figure 3). Large changes in the vegetative assemblage reduce suitable habitat for fish and wildlife, with changes in the numbers of largemouth bass exemplifying this effect (Figure 4). The complexity of the relationship is highlighted by the absence of an increase in catches of bass following an increase in the extent of submerged aquatic vegetation in 2017, and the 2020 increase in catches that lagged an increase in submerged aquatic vegetation in 2019.

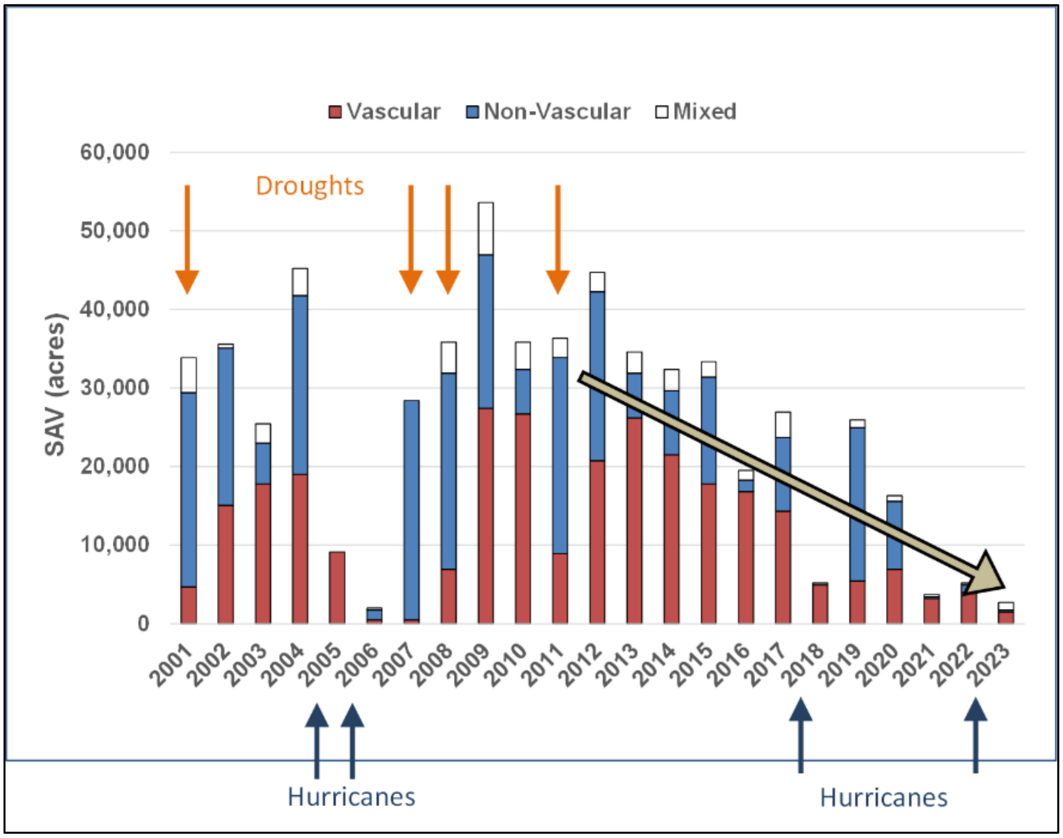


Figure 3. Acres of submerged aquatic vegetation present in Lake Okeechobee through time. Assemblages were classified as primarily vascular plants, primarily non-vascular plants or algae, and a mixture of the two types of vegetation. Droughts indicated by red arrows, hurricanes indicated by blue arrows, and the recent trend indicated by the brown arrow. Figure provided by the South Florida Water Management District.

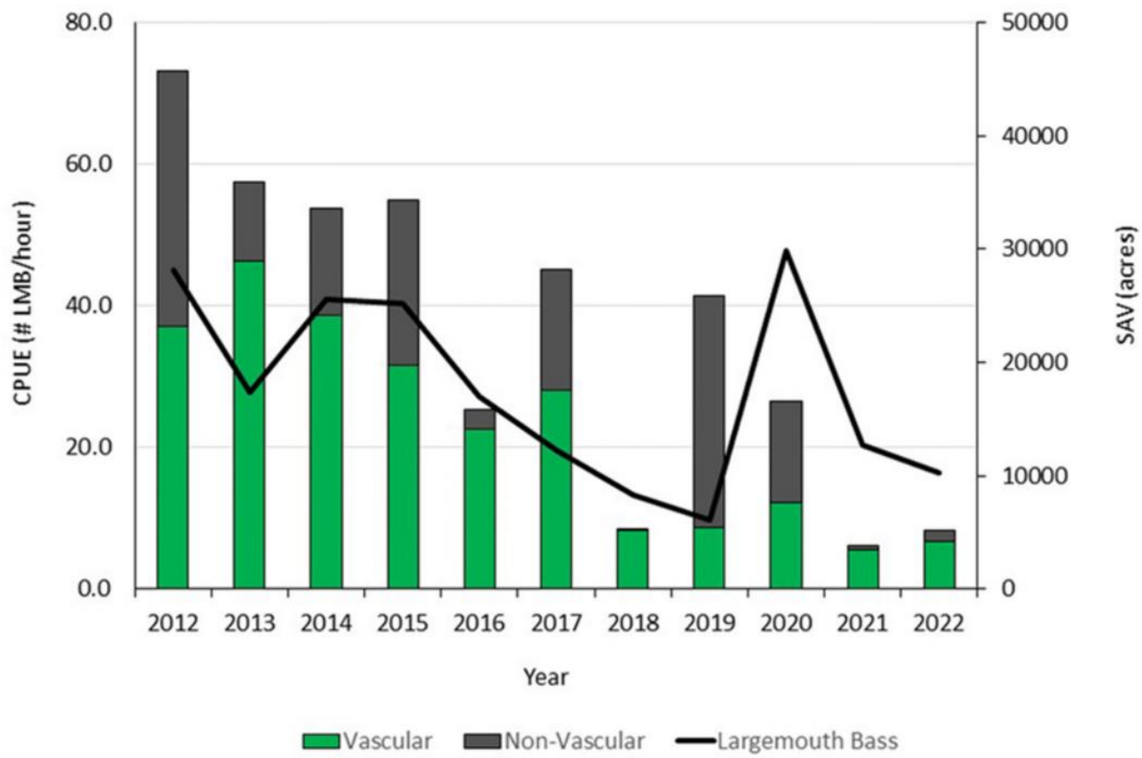


Figure 4. Relationship between number of bass caught per hour (catch per unit effort or CPUE) and acres of vascular and non-vascular submerged aquatic vegetation in Lake Okeechobee. Figure provided by the South Florida Water Management District.

Existing and potential management of stresses

The five key elements in restoring the health of Lake Okeechobee are all important. Control of water levels and increased external loads of nitrogen and phosphorus are being addressed by major, long-term investments, which will be described briefly. Those efforts form a critical context when considering accumulation of mud, spread of nuisance plants, and loss of submerged aquatic vegetation.

Managing water levels – Water levels in Lake Okeechobee are managed to serve multiple, and sometimes competing, purposes. Primary reasons for controlling water levels include flood control, water supply, navigation, recreation, enhancement of fish and wildlife, drainage, and preventing intrusion of saline water into aquifers. Changes in water levels are driven by the weather, with intense rainfall causing higher water levels and drought leading to lower water levels.

Managers must base their actions on predicted weather, along with the associated uncertainties, because structural constraints limit the amount of water that can be held in Lake Okeechobee and the rate at which it can be discharged safely. Structural constraints include the integrity of the Herber Hoover Dike; the integrity and capacity of control structures; the integrity and available capacity in conveyances; and the integrity and available capacity in storage and treatment facilities. The flexibility to manage water levels will be increased substantially by ongoing efforts to increase storage, treatment, and conveyance of water both upstream and downstream of Lake Okeechobee. By 2032, tens of billions of dollars will have been invested in projects comprising the Comprehensive Everglades Restoration Plan and allied efforts (Table 2).

Table 2. Estimated timelines (gray cells) for examples of projects that will increase the flexibility to manage water levels in Lake Okeechobee.

Project	Fiscal year										
	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
Herbert Hoover Dike											
Lake Okeechobee System Operating Manual											
C-44 reservoir testing											
C-44 stormwater treatment area testing											
C-23/24 reservoirs											
C-23/24 stormwater treatment area											
C-25 reservoir & stormwater treatment area											
C-43 reservoir											
Everglades Agricultural Area reservoir & stormwater treatment area											

In addition, the Lake Okeechobee System Operating Manual recognizes the need to address conflicts among the purposes for managing water levels via collaborative decision-making. An example of adaptation is the change to pulsed releases of water to the estuaries located east and west of the lake because pulses mimic the natural stress/recovery cycle associated with short-term increases in the flow of fresh water following intense rainfall. Given the ongoing efforts to enhance management of water levels in Lake Okeechobee, this report focuses on other actions that may improve the ecological health of Lake Okeechobee in the interim.

Managing external loads of nutrients – A second major factor affecting the ecology of Lake Okeechobee are loads of nutrients generated by people's activities in the watershed. Key nutrients are nitrogen and phosphorus, with concentrations of phosphorus in the lake being a primary concern. Concentrations of phosphorus in the water column of the lake doubled between the early 1970s and the early 1980s (50 µg per liter to 100 µg per liter), with the change being attributed to higher loads that exceeded the assimilative capacity of the lake. A major pathway for assimilation is binding of phosphorus to particles that are "stored" in the sediment. Thus, changes in the concentrations of phosphorus in the water column are related to the changes in the influence of mud, with this relationship being discussed later.

Multiple efforts are underway to address external loads of nitrogen and phosphorus via construction and operation of various projects that treat incoming water. Efforts include implementation of Best Management Practices (BMPs) by agricultural facilities, the Northern

Everglades and Estuaries Protection Plan (NEEPP), the Lake Okeechobee Watershed Protection Plan (LOWPP), and the combination of the Lake Okeechobee Total Maximum Daily Load (TMDL) and Lake Okeechobee Basin Management Action Plan (BMAP).

Setting a total maximum daily load and implementing a basin management action plan to achieve the necessary reductions in loads represent key regulatory instruments. The objective is to reduce external loads of phosphorus to a level that yields 40 µg per liter of phosphorus in Lake Okeechobee, with this goal to be reached by 2032. As of the last evaluation (2011–2017), annual geometric mean concentrations of nitrogen in Lake Okeechobee have been meeting standards, but concentrations of phosphorus have exceeded targets that have been set at various locations (Figure 5).

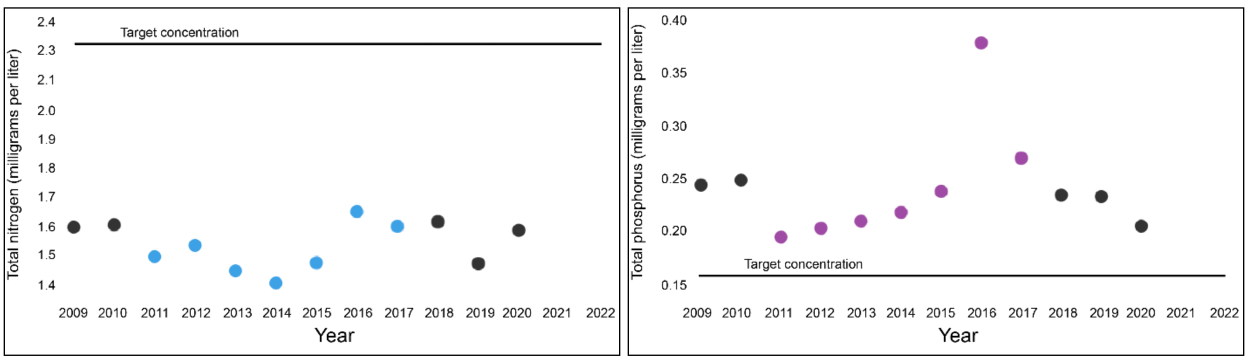


Figure 5. Annual geometric mean concentrations of all forms of nitrogen and phosphorus in the water column at one location in Lake Okeechobee through time. Black lines are target concentrations converted to milligrams per liter, dots are annual geometric mean concentrations, and colored dots are values used in the most recent assessment of progress.
Adapted from the Statewide Annual Report produced by the Florida Department of Environmental Protection.

Targets for external loads of nutrients and the response of the system once the targets are achieved are surrounded by uncertainty; therefore, the process is adaptive. Thus, evaluation may reveal the need for additional reductions in external loads and an adjusted timeline. Nevertheless, efforts to reduce external loads of nutrients are ongoing, so this report focuses on other issues that may improve the ecological health of Lake Okeechobee in the interim.

Managing "mud" – One potential interim action that could improve the health of Lake Okeechobee is managing mud. When the lake was in its natural state, higher water levels and strong winds likely forced organic and inorganic particles out into the surrounding floodplains, with much of the material settling outside of the lake as the water slowly receded.

The Herbert Hoover Dike impeded this natural cleansing, and in combination with increasingly intense use of land in the lake's watershed, led to an accumulation of mud. Most of the mud has accumulated since the 1940s. Available estimates state that the depth of mud varies from one inch to ~2.5 feet, it covers approximately 44% of the lake's bottom, and it consists of approximately 252,000,000 cubic yards of material. The mud contains up to 34% organic matter on average, and the inorganic matter is a mix of 30% silt, 40% clay, and 30% sand.

Considerable work indicates that addressing mud should promote a healthier lake. The load of phosphorus moving from the sediment to the water column can equal the load from the watersheds, so eliminating this internal load would accelerate recovery once external loads are reduced. In addition to reducing harmful blooms of cyanobacteria and single-celled algae, preventing resuspension of the mud should reduce the magnitude and duration of turbidity that also can shade and detrimentally affect submerged aquatic vegetation. Three primary methods to manage mud and the loads of nutrients it generates have been considered. Mud can be removed by dredging or it can be excavated if exposed during very low water levels. Mud can be treated with chemicals (e.g., alum (aluminum sulfate)) to bind the phosphorus and keep it from being biologically available. The pH ranges in Lake Okeechobee and other toxicity issues may eliminate this solution. A third approach would involve capping the mud with clean clay or other material to keep it from interacting with the water column directly. To be successful, the latter approach must prevent resuspension during storms, which is a time when considerable phosphorus is introduced into the water column. The efficacy of chemical treatment wanes over time, and an available estimate projected approximately a 15-year cycle for repeated treatment. Beyond the limited effective life of chemical treatment, there are concerns about toxicity to animals, especially under acidic conditions that release aluminum from alum. Given its long-term efficacy (mud and the associated nitrogen and phosphorus are removed), reduced concerns about toxicity, and the availability of information from recent projects, dredging is explored as an option.

Evaluations have noted that it will take repeated dredging to garner the maximum reduction in concentrations of phosphorus and turbidity. In addition, mud contains a substantial amount of water so treatment of this interstitial water will reduce the likelihood of stimulating blooms of single-celled algae by returning biologically available nitrogen and phosphorus to the lake. One estimate stated that ten dredges operating full-time would take about 15 years to complete a cycle of dredging. Dredging a sump in the deeper portion of the lake could collect mud and make subsequent projects more efficient.

Dredging the center of Lake Okeechobee would parallel recent dredging in the Indian River Lagoon. The material is similar in composition and the projected benefits and concerns are the same. Hydraulic dredging is the most effective at removing the fine material without causing excessive turbidity, and dredging in the lagoon has occurred in residential canals without detrimental effects on turbidity, dissolved oxygen, or other parameters related to water quality. Geotextile tubes have proven to be beneficial for dewatering the spoil from dredging. Treating the interstitial water was challenging due to the need to adjust concentrations of key chemicals as salinity varied, but treatment may be simpler because Lake Okeechobee is a freshwater lake. Treatment of interstitial water with a proprietary mix of chemicals, including a flocculant, was most effective at reducing concentrations of phosphorus and moderately effective at reducing concentrations of nitrogen. Based on the most recent contract for the Indian River Lagoon, the cost would be at least $100 per cubic yard. Costs will rise if the management area for the dredged material is far from where the dredge is working due to the need for additional booster pumps at the rate of about one per mile. The material dredged from the Indian River Lagoon is not suitable for building berms or other structures because the particles are too fine, which also is likely for mud from Lake Okeechobee. Currently, the material dredged from the lagoon is used as an amendment for soil, and this beneficial use may be even more suitable for mud from Lake Okeechobee because of its reduced salt content. Testing would be needed to ensure that the material does not contain contaminants, especially metals or pesticides, at levels that exceed regulatory guidelines for disposal or beneficial use. For Lake Okeechobee, there is evidence that arsenic could be an issue, and various pesticides have been found near inflows and the shoreline of the lake.

The investment needed to dredge the whole of Lake Okeechobee is large, so targeting smaller areas may be a worthwhile consideration. In fact, the South Florida Water Management District conducted a pilot project in Eagle Bay. Dredging sent 4,000 cubic yards of mud and 11,000 pounds of phosphorus to a containment area, there were no substantial reductions in water quality near the dredge, and interstitial water treated with chemicals met the 40 µg per liter target for concentrations of total phosphorus in Lake Okeechobee. The broader and longer-term effects on water quality from small-scale dredging remain to be evaluated.

Managing nuisance plants – In essence, nuisance plants are those that form dense monocultures, which tend to be less suitable habitat for fish and wildlife. Nuisance plants are typically non-native, invasive species, but native plants can pose issues as well, especially when their growth is fueled by excess nitrogen and phosphorus. Key concerns regarding management of aquatic nuisance plants revolve around oversight and compensation for applicators of chemicals, the creation of additional organic matter that contributes to mud, and potential unintended effects of chemicals on desirable submerged aquatic vegetation, fish, and wildlife.

For Lake Okeechobee, plant management is a cooperative operation primarily involving the South Florida Water Management District, the Florida Fish and Wildlife Conservation Commission, and the United States Army Corps of Engineers. An interagency task force supports coordination of efforts, and there are two main branches to operations (Figure 6). The Invasive Plant Management Program of the Florida Fish and Wildlife Conservation Commission and the United States Army Corps of Engineers conduct the bulk of the management of aquatic plants. They each focus on a different section of the lake. The Aquatic Habitat Restoration and Enhancement Program focuses on projects that restore habitats using funds in the budget of the Florida Fish and Wildlife Conservation Commission.

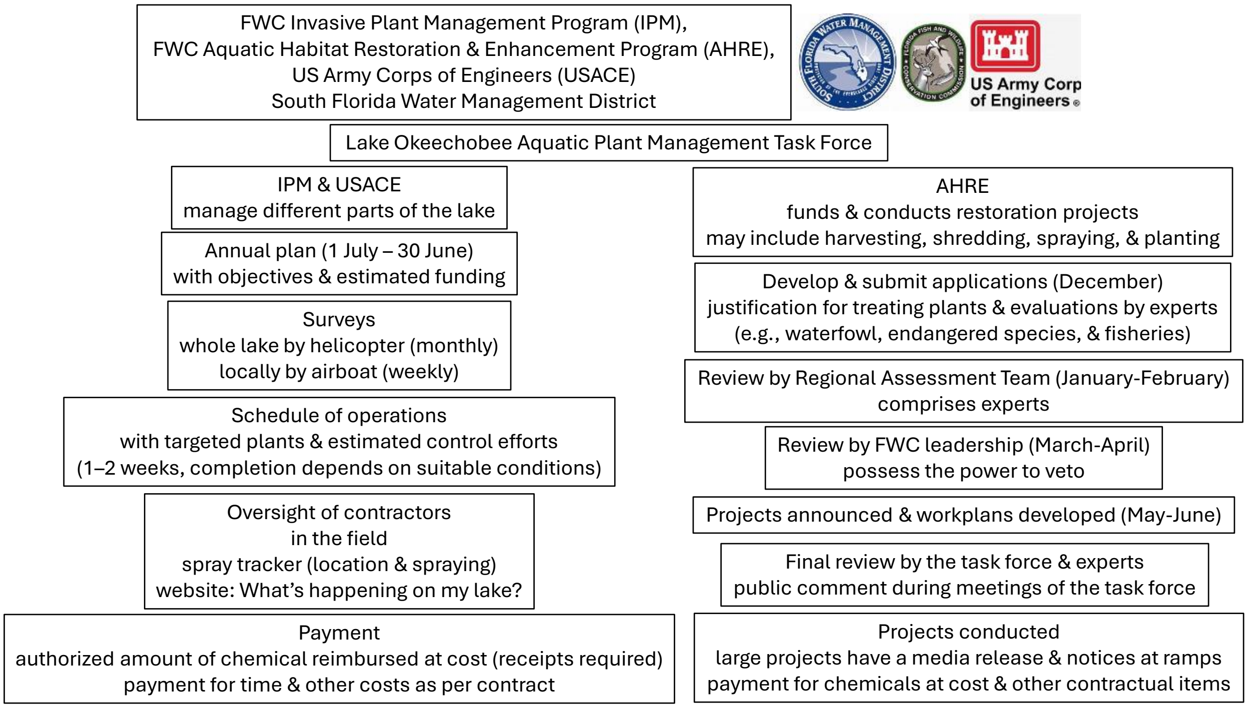


Figure 6. Diagram outlining the process for managing plants in and around Lake Okeechobee.

Projects funded and implemented via the Aquatic Habitat Restoration and Enhancement Program may involve managing plants using mechanical harvesting, fire, and treatment with chemicals. All proposed efforts undergo multiple reviews by a broad suite of experts to reduce potential issues related to other components of the lake's ecology and use. The public can comment on projects during their final review. Projects are managed by staff of the Florida Fish and Wildlife Conservation Commission, and the public is notified of activities in advance via media releases and notices at boat ramps. Projects, such as treating cattails with chemicals followed by controlled burning, have yielded positive results that include a record number of successful nests for the endangered snail kite.

The Invasive Plant Management Program of the Florida Fish and Wildlife Conservation Commission and the United States Army Corps of Engineers conduct the bulk of management of aquatic plants, with responsibilities being separated by location in the lake. The process involves monthly surveys of the lake via helicopter and weekly surveys via airboat to identify areas where vegetation is visibly problematic. A plan is prepared that directs contractors where to spray and with what chemical. All contractors have global positioning systems that allow them to be tracked to confirm they are operating in the agreed areas, and a system that records when spraying occurs. Contractors are paid for their field time and other agreed costs, and they are reimbursed for the actual cost of chemicals. The reimbursement is based on the amount of chemical needed to achieve the desired application rate across the targeted area, with receipts for purchases of chemicals being submitted to confirm actual prices. A maximum of eight applicators is operating on the lake at any one time, operations are not conducted in buffer zones around nesting birds, including snail kites, or other sensitive areas, and operations are suspended for fishing tournaments and other events. All chemicals are approved for use in aquatic systems, which includes evaluating toxicity to animals. Solutions are sprayed onto the emergent structures of plants, and those solutions contain less than 1% active ingredient, which makes the likelihood of achieving a concentration that would affect submerged aquatic vegetation very unlikely. The two agencies strive to achieve maintenance control over nuisance plants, which substantially reduces the amount of chemicals that are applied. Maintenance control in Lake Okeechobee has been achieved since 2019, with the increase in application during 2018 being related to reestablishing maintenance control after a pause in spraying (Figure 7). Similar increases in spraying have followed mechanical harvesting that can spread plants and harm animals taken as bycatch. In addition to requiring less chemicals, maintenance control helps alleviate concerns about decomposition of dead plants leading to low dissolved oxygen levels and higher nutrient loads. The amount of material generated during maintenance control more closely resembles the amount of material generated by replacement of leaves each 1–2 weeks. Overall, it will be beneficial to clearly communicate procedures that address the public's existing concerns.

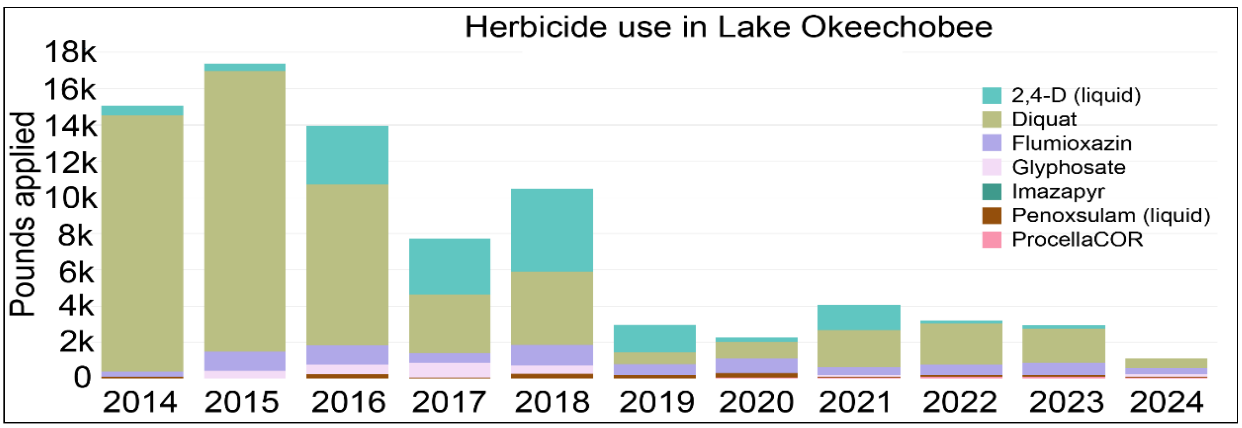


Figure 7. Pounds of herbicide applied in Lake Okeechobee. k = thousands.
Figure provided by the Florida Fish and Wildlife Conservation Commission.

Planting submerged aquatic vegetation – Another potential interim action would be planting submerged aquatic vegetation. Most efforts to plant submerged aquatic vegetation cover acres rather than the thousands of acres lost in Lake Okeechobee, and all restoration of submerged aquatic vegetation requires suitable conditions for establishment, growth, and expansion. Suitable conditions include protection from waves during the time that roots and rhizomes are establishing a firm hold on sediment and sufficient light to support survival, growth, and spread. In general, experts agree that replanting vegetation is risky unless the cause of the initial loss has been addressed.

In Lake Okeechobee, the likely cause for loss of submerged aquatic vegetation was reduction in the amount of light reaching vegetation on the bottom. Availability of light at the bottom will be reduced if water levels rise after major rainfall, and recent data for levels of turbidity and the amount of light reaching the bottom indicate that conditions have not been consistently favorable. Evaluation of satellite imagery from May 2016 through December 2023 detected increases in turbidity each winter, with values above the long-term mean lasting for 3–9 months each winter, and a maximum average value of ~90 nephelometric turbidity units (ntu) in February 2018 (Figure 8). Furthermore, sufficient light to sustain healthy *Vallisneria* (i.e., over 20% of incident light) reached the bottom in less than five feet of water on only 45% of the 1,449 days when measurements were made in July, August, September, or October from 2008 to 2023. Maintaining sufficient light to support growth and spread of *Vallisneria* will be challenging until increased control of water levels is possible, algal blooms are no longer exacerbated by excess loads of nutrients, and turbidity from resuspended sediment is reduced. Other submerged aquatic vegetation, such as the alga *Chara*, may survive better in low light, but information from a restoration project that employed macroalgae was not available.

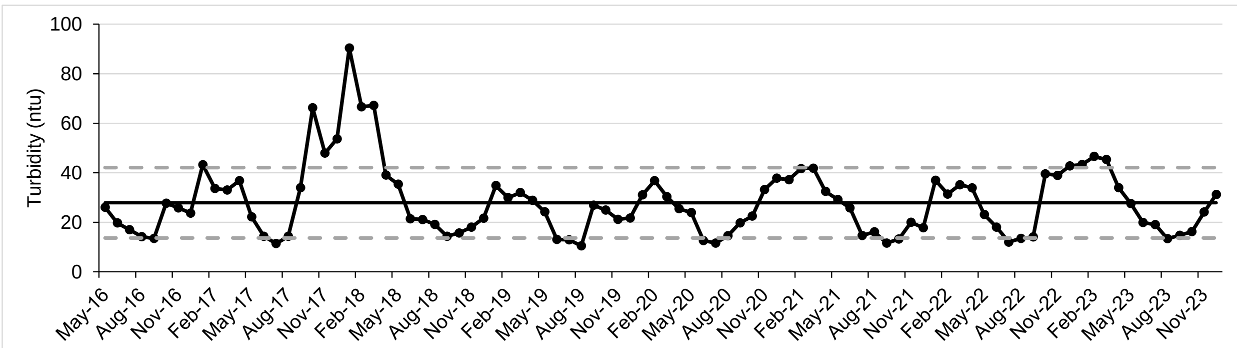


Figure 8. Mean values for turbidity (in nephelometric turbidity units or ntu) across the pelagic zone of Lake Okeechobee through time. Long-term mean value is the solid line, and the dashed lines are one standard deviation around the long-term mean.
Figure provided by the University of South Florida.

Disturbance is another concern because the fetch across Lake Okeechobee leads to formation of waves that can uproot newly planted submerged aquatic vegetation. Some efforts to plant submerged aquatic vegetation in areas subject to wave action have deployed devices to protect the plants. The most recent evaluation of this approach comes from the Indian River Lagoon. Although this project involves seagrass rather than freshwater plants, its approach should be applicable. The project will include installation of devices to attenuate waves, submerged aquatic vegetation planted shoreward of the devices, renourishment of the shoreline, and terrestrial plants to create a living shoreline (Figure 9).

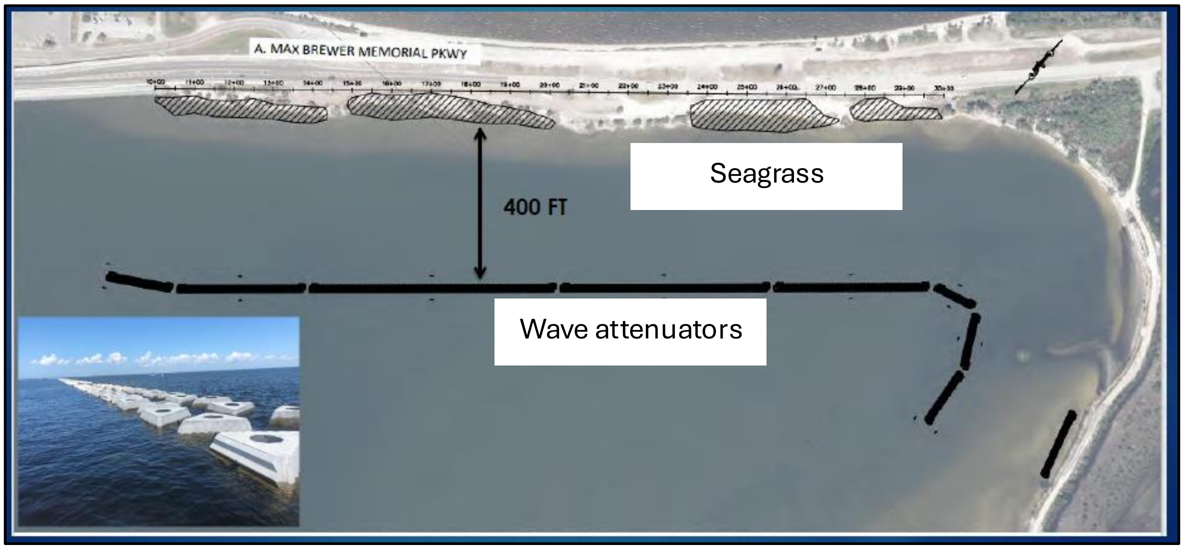


Figure 9. Plans for a project in the Indian River Lagoon, with wave attenuators in the inset.
Modified from a figure produced for Brevard County.

Another example of planting submerged aquatic vegetation is underway in Lake Apopka, which is a lake with limited water clarity like Lake Okeechobee. Wave attenuators are not used, and plants cost approximately $23,000 per acre. These costs include planting a combination of *Vallisneria* and *Potamogeton* with multiple blades that are at least six inches long. The specifications were designed to ensure a mixed assemblage of plants with photosynthetically active blades that are up in the water column where light should support growth. As yet, there are no data on survival of the plants. This was also true in a project on Lake Trafford.

The spatial scale associated with replanting submerged aquatic vegetation throughout Lake Okeechobee suggests there may be more value in smaller scale efforts. Miles of attenuators and tens of thousands of acres of plants would be required to protect the length of the zone where submerged aquatic vegetation has grown in the past (potential sites for submerged aquatic vegetation indicated by the gray squares in Figure 10). Even an attempt to plant the 8,000–10,000 hectares (ha) or 20,000–25,000 acres that support the maximum number of bass will require a major investment (Figure 11).

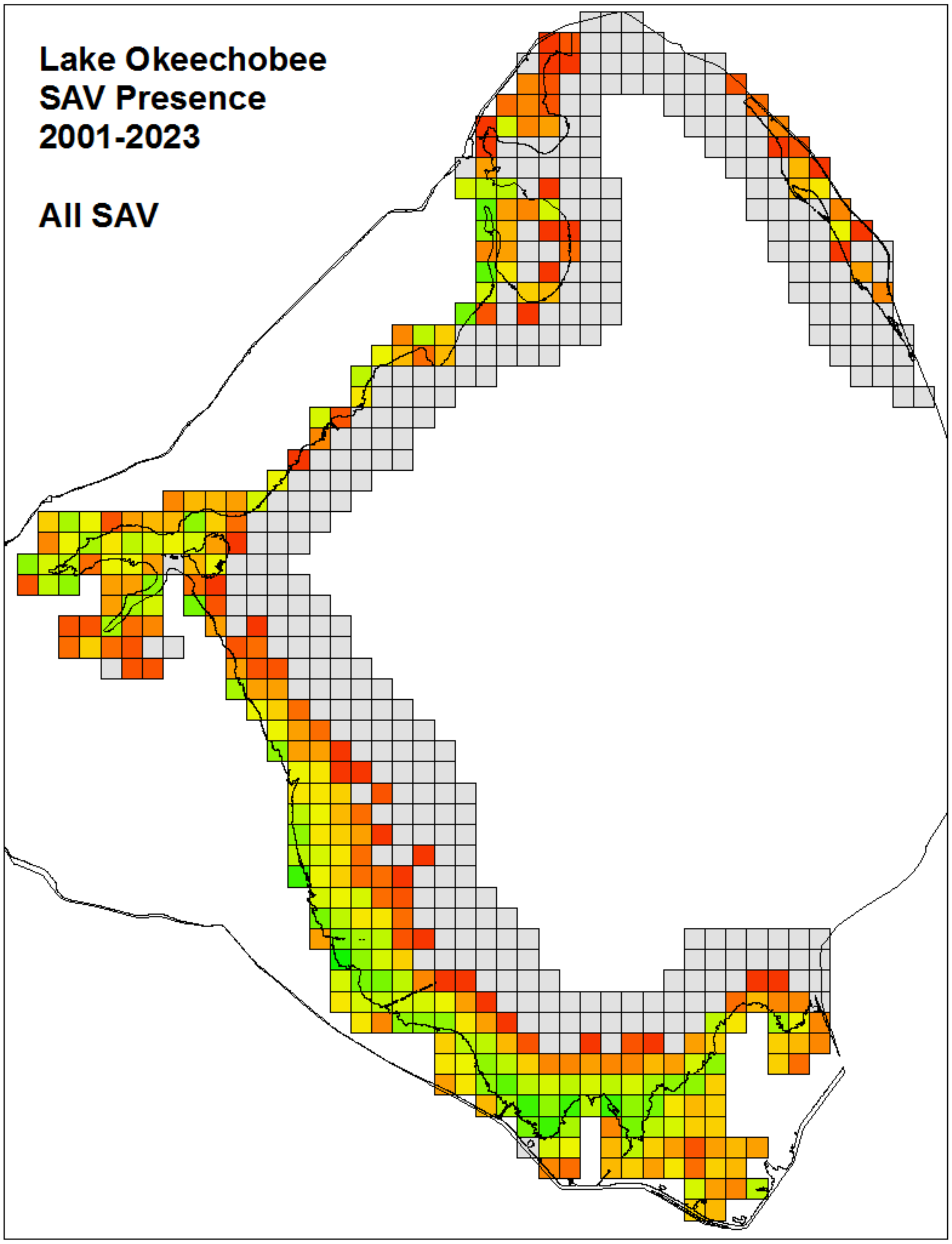


Figure 10. A map with colored squares indicating the presence of submerged aquatic vegetation (SAV) from 2001 to 2023 and gray squares indicating locations that could support vegetation. Figure provided by the South Florida Water Management District.

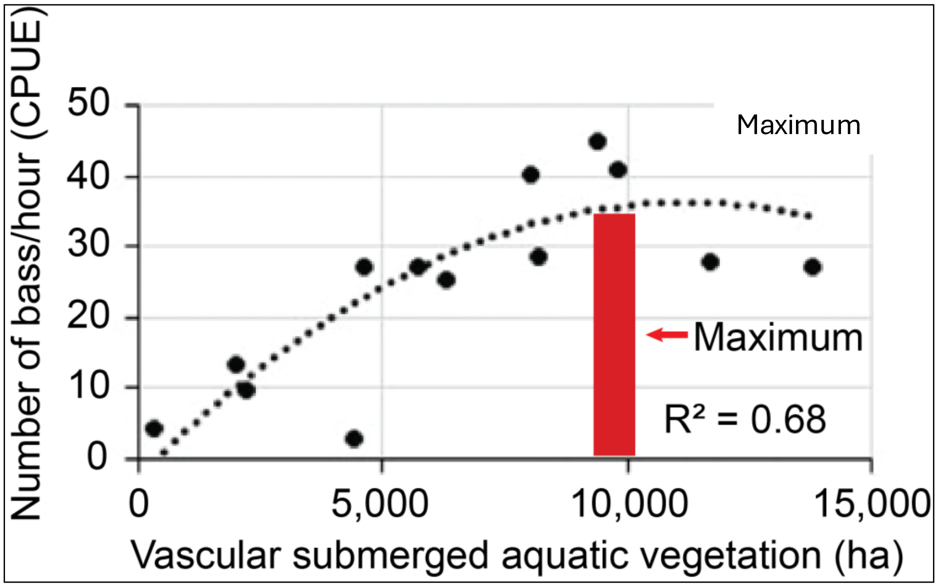


Figure 11. Relationship between number of bass caught per hour (catch per unit effort or CPUE) and hectares (ha) of vascular submerged aquatic vegetation.

Figure modified from Hanlon, C.G., and A. Jordan. 2022. Influence of habitat and other factors on largemouth bass abundance in Lake Okeechobee, Florida. Transactions of the American Fisheries Society 152: 429–442.

Overall, planting submerged aquatic vegetation faces substantial challenges if environmental conditions are not favorable or unstable, and there is no example of planting at the scale of tens of thousands of acres to use as a guide. The presence of sufficient light is a highly influential condition, and planting can fail if water levels in the lake rise or turbidity becomes too high for too long. In addition, the need to protect newly planted vegetation from grazing may prove to be an additional cost. Pilot studies in regions that are protected could help refine an understanding of water clarity and other conditions needed for large-scale, long-term success. Furthermore, evidence from other freshwater systems indicates that seeds stored in the sediment, termed seed banks, can germinate and revegetate denuded areas. Thus, there may be value in directly assessing the health of seed banks to identify areas that may or may not recover naturally when conditions are suitable and to prevent dredging from damaging a viable seed bank.

Engagements

Affiliation	Surname	Forename
Audubon Florida	Gray	Paul
Brevard County	Allen	Jeanne
	Alvarez	Carolina
	Barker	Virginia
	Culver	Matt
	Gering	Abigail
Florida Fish and Wildlife Conservation Commission	Agoora	Leila
	Erskine	James
	Fox	Donald
	Furse	Beacham
	Johnson	Kevin
	Jordan	Alyssa
	Kipker	Robert
	Kirkland	Danielle
	Paladino	Sarah
	Phillips	Matthew
Florida Institute of Technology	Fox	Austin
Harbor Branch Oceanographic Institute at Florida Atlantic University	Beckler	Jordon
Indian River Lagoon National Estuary Program	De Freese	Duane
Private citizen	Watt	Jim
South Florida Water Management District	Rodgers	LeRoy
	Welch	Zachariah
St. Johns River Water Management District	Slater	Jodi
United States Army Corps of Engineers	Fair	Jessica
University of Florida	Aguilar	Trenton
	Allen	Michael
University of South Florida	Barnes	Brian
	Hu	Chuanmin
	Xue	Cheng

References

Adams, C.A., L. Reynolds, C.W. Martin, C. Rohal, R. Goebel, and J. Slater. 2023. Common wetland and aquatic plant of Lake Apopka, Florida (USA). EDIS 2023 (1). https://doi.org/10.32473/edis-EP627-2023.

Allen, M.S., K.I. Tugend, and M.J. Mann. 2003. Largemouth bass abundance and angler catch rates following a habitat enhancement project at Lake Kissimmee, Florida. North American Journal of Fisheries Management 23: 845–855.

Atkins. 2015. Sediment report Grand Canal muck removal project, Brevard County. Brevard County, Viera, Florida.

Audubon Florida. 2014. A brief history of Lake Okeechobee ecosystem responses to water level management. Audubon Florida, Miami, Florida.

Aumen, N.G., and K.E. Havens. 1998. Okeechobee Lake, Florida, USA: human impacts, research and lake restoration. In: Herschy, R.W., and R.W. Fairbridge, eds. Encyclopedia of Hydrology and Water Resources. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Bachmann, R.W., C.A. Horsburgh, M.V. Hoyer, L.K. Mataraza, and D.E. Canfield, Jr. 2002. Relations between trophic state indicators and plant biomass in Florida lakes. Hydrobiologia 470: 219–234.

Bachmann, R.W., M.V. Hoyer, C. Fernandez, and D.E. Canfield Jr. 2003. An alternative to proposed phosphorus TMDLs for the management of Lake Okeechobee. Lake and Reservoir Management 19: 251–264.

BCI Engineers & Scientists. 2007. Rapid dewatering techniques for dredged lake sediments, literature review and summary report. Special Publication SJ2008-SP11, St. Johns River Water Management District, Palatka, Florida.

Beaver, J.R., D.A. Casamatta, T.L. East, K.E. Havens, A.J. Rodusky, R.T. James, C.E. Tauz, and Buccier, K.M. 2013. Extreme weather events influence the phytoplankton community structure in a large lowland subtropical lake (Lake Okeechobee, Florida, USA). Hydrobiologia 709: 213-226.

Beckler, J., V. Ruiz-Xomchuk, M. Jiang, Y. Tang, M. McFarland, A. Nayak, T. Moore, D. Hanisak, M. Parsons, S. Duncan, and B. Kirkpatrick. 2022. Harmful algal bloom innovative technology: the Harmful Algal Bloom Assessment of Lake Okeechobee System (HALO). Report on project FDEP MN016. Florida Department of Environmental Protection, Tallahassee, Florida.

Bell, F.W. 2006. The economic importance of recreational and commercial uses of Lake Okeechobee for Okeechobee and Glades Counties, Florida 2004–2005. Report on Contract Number OT040050. South Florida Water Management District, Palm Beach, Florida

BEM Systems Inc. 2006. Lake Okeechobee sediment mapping. South Florida Water Management District, West Palm Beach, Florida.

BEM Systems Inc. 2007. Lake Okeechobee sediment quality mapping project. South Florida Water Management District, West Palm Beach, Florida.

Blasland, Bouck & Lee. 2003. Evaluation of alternatives for the Lake Okeechobee sediment management feasibility study. South Florida Water Management District, West Palm Beach, Florida.

Bowling, A.C., J. Martin, and W.M. Kitchens. 2012. The effect of changes in habitat conditions on the movement of juvenile snail kites, *Rostrhamus sociabilis*. Ibis 154: 554–565.

Brezonik, P.L., and D.R. Engstrom. 1998. Modern and historic accumulation rates of phosphorus in Lake Okeechobee, Florida. Journal of Paleolimnology 20: 31–46.

Canfield D.E. Jr, R.W. Bachmann, and M.V. Hoyer. 2020. Restoration of Lake Okeechobee, Florida: mission impossible? Lake Reservoir Management 37: 95–111.

Canfield, D.E. Jr., R.W. Bachmann, R.W., and M.V. Hoyer. 2023. The Florida experience: time for a revitalized and restructured Clean Lakes Program. Lake and Reservoir Management 39: 191–212.

Canfield, D.E. Jr., and M.V. Hoyer. The eutrophication of Lake Okeechobee. Lake and Reservoir Management 4: 91–99.

Carrick, H.J., D. Worth, and M.L. Marshall. The influence of water circulation on chlorophyll–turbidity relationships in Lake Okeechobee as determined by remote sensing. Journal of Plankton Research 16: 1117–1135.

Chastant, J.E., M.L. Petersen, and D.E. Gawlik. Nesting substrate and water-level fluctuations influence wading bird nesting patterns in a large shallow eutrophic lake. Hydrobiologia 788: 371–383.

Chimney, M.J. 2005. Surface seiche and wind set-up on Lake Okeechobee (Florida, USA) during hurricanes Frances and Jeanne. Lake and Reservoir Management 21: 465–473.

Comprehensive Everglades Restoration Plan. 2018. Lake Okeechobee performance measure littoral zone emergent vegetation mosaic. United States Army Corps of Engineers, Jacksonville, Florida.

Comprehensive Everglades Restoration Plan. 2020. Lake Okeechobee performance measure lake stage. United States Army Corps of Engineers, Jacksonville, Florida.

Comprehensive Everglades Restoration Plan. RECOVER 2024 System Status Report. South Florida Water Management District, West Palm Beach, Florida.

David, P.G. 1994. Wading bird use of Lake Okeechobee relative to fluctuating water levels. Wilson Bulletin 106: 719–732.

Dotson, J.R., K.I. Bonvechio, B.C. Thompson, W.E. Johnson, and N.A. Trippel, J.B. Furse, S. Gornak. C.K. McDaniel, W.F. Pouder, and E.H. Leone. 2014. Effects of large-scale habitat enhancement strategies on Florida bass fisheries. In M.D. Tringali, J.M. Long, T.W. Birdsong, and M.S. Allen, eds. Black Bass Diversity: Multidisciplinary Science for Conservation. American Fisheries Society Symposium Volume 82. American Fisheries Society, Bethesda, Maryland.

Evans, J.M. 2013. *Pistia stratiotes* L. in the Florida peninsula: biogeographic evidence and conservation implications of native tenure for an 'invasive' aquatic plant. Conservation and Society 11: 233–246.

Fisher, M.M., K.R. Reddy, and R.T. James. 2001. Long-term changes in the sediment chemistry of a large shallow subtropical lake. Journal of Lake and Reservoir Management 17: 217–232.

Fisher, M.M., K.R. Reddy, and R.T. James. 2005. Internal nutrient loads from sediments in a shallow, subtropical lake. Lake and Reservoir Management 21: 338–349.

Flaig, E.G., and K.E. Havens. 1995. Historical trends in the Lake Okeechobee ecosystem I. Land use and nutrient loading. Archiv für Hydrobiologie Supplement 107: 1–24.

Florida Department of Environmental Protection. 2001. Total Maximum Daily Load for Total Phosphorus Lake Okeechobee, Florida. Florida Department of Environmental Protection, Tallahassee, Florida.

Florida Department of Environmental Protection. 2008. Lake Okeechobee Watershed Construction Project Phase II Technical Plan. Florida Department of Environmental Protection, Tallahassee, Florida.

Florida Department of Environmental Protection. 2020. Lake Okeechobee basin management action plan. Florida Department of Environmental Protection, Tallahassee, Florida.

Florida Fish and Wildlife Conservation Commission. 2011. Black bass management plan. Florida Fish and Wildlife Conservation Commission, Tallahassee, Florida.

Florida Fish and Wildlife Conservation Commission. 2022. Fish, wildlife, and habitat management plan, Lake Okeechobee. Florida Fish and Wildlife Conservation Commission, Tallahassee, Florida.

Fox, A.L., and J.H. Trefry. 2023. Nutrient fluxes from recent deposits of fine-grained, organic-rich sediments in a Florida estuary. Frontiers in Marine Science 10: 1305990.

Furse, J.B., and D.D. Fox. 1994. Economic fishery valuation of five vegetation communities in Lake Okeechobee, Florida. Proceedings of the Annual Conference of the Southeastern Association of Fish and Wildlife Agencies 48: 575–591.

Geosyntec Consultants. 2019. Sediment sampling report, Brevard County Grand Canal and Banana River Muck Removal Dredge Material Management Area. Florida Department of Environmental Protection, Tallahassee, Florida.

Golder Associates Inc. 2007. Assessment for the feasibility of using chemical inactivation to reduce internal phosphorus loading from Lake Okeechobee pelagic sediments. South Florida Water Management District, West Palm Beach, Florida.

Graham, W.D., M.J. Angelo, T.K. Frazer, P.C. Frederick, K.E. Havens, and K.R. Reddy. 2015. Options to reduce high volume freshwater flows to the St. Lucie and Caloosahatchee estuaries and move more water from Lake Okeechobee to the southern Everglades. University of Florida, Gainesville, Florida.

Graham, W.D., M. Brenner, J.W. Fourqurean, C. Jacoby, and J. Obysekera. 2020. Scientific synthesis to inform development of the new Lake Okeechobee System Operating Manual. University of Florida, Gainesville, Florida.

Gray, P.N. 2017. A brief history of Lake Okeechobee ecosystem responses to water level management. Audubon Florida publication.

Gray, P.N., B. Pranty, and G.R. Schrott. 2009. Shorebird and larid use of mudflats at Okeechobee, Florida, during drought conditions. Florida Field Naturalist 37: 33–73.

Gray, S., J. Brooks, and C. Aller. 2004. Lake Okeechobee Protection Program: Lake Okeechobee Protection Plan. South Florida Water Management District, West Palm Beach, Florida.

Gray, S., J. Brooks, and C. Aller. 2007. Lake Okeechobee Protection Program: Lake Okeechobee Protection Plan Evaluation Report. South Florida Water Management District, West Palm Beach, Florida.

Grimshaw, H.J., K. Havens, B. Sharfstein, A. Steinman, D. Anson, T. East, R.P. Maki, A. Rodusky, and K-R. Jin. 2002. The effects of shading on morphometric and meristic characteristics of wild celery, *Vallisneria americana* Michx., transplants from Lake Okeechobee, Florida. Archiv für Hydrobiologie 155: 65–81.

Guan, J., C.A. Jacoby, and T.K. Frazer. 2020a. Light attenuation by periphyton on *Vallisneria americana*. Ecological Indicators 116: 106498.

Guan, J., C.A. Jacoby, and T.K. Frazer. 2020b. *In-situ* assessment of the effects of periphyton on the growth of *Vallisneria americana*. Ecological Indicators 119: 106775.

Hanlon, C.G., and M. Brady. 2005. Mapping the distribution of torpedograss and evaluating the effectiveness of torpedograss management activities in Lake Okeechobee, Florida. Journal of Aquatic Plant Management 43: 24–29.

Hanlon, C.G., and A. Jordan. 2022. Influence of habitat and other factors on largemouth bass abundance in Lake Okeechobee, Florida. Transactions of the American Fisheries Society 152: 429–442.

Hanlon, C.G., R.L. Miller, and B.F. McPherson. 1998. Relationships between wind velocity and underwater irradiance in a shallow lake (Lake Okeechobee, Florida, USA). Journal of the American Water Resources Association 34: 951–961.

Harwell, M.C., and K.E. Havens. 2003. Experimental studies on the recovery potential of submerged aquatic vegetation after flooding and desiccation in a large subtropical lake. Aquatic Botany 77: 135–151.

Harwell, M.C., and B. Sharfstein. 2009. Submerged aquatic vegetation and bulrush in Lake Okeechobee as indicators of greater Everglades ecosystem restoration. Ecological Indicators 9S: S46–S55.

Havens, K.E. 1994. Seasonal and spatial variation in nutrient limitation in shallow sub-tropical lake (Lake Okeechobee, Florida) as evidenced by trophic state deviations. Archiv für Hydrobiologie Supplement 131: 39–53.

Havens, K.E. 1995. Particulate light attenuation in a large subtropical lake. Canadian Journal of Fisheries and Aquatic Sciences 52: 1803–1811.

Havens, K.E. 1997. Water levels and total phosphorus in Lake Okeechobee. Journal of Lake and Reservoir Management 13: 16–25.

Havens, K.E. 2003. Phosphorus-algal bloom relationships in large lakes of south Florida: implications for establishing nutrient criteria. Lake and Reservoir Management 19: 222–228.

Havens, K.E. 2003. Submerged aquatic vegetation correlations with depth and light attenuating materials in a shallow subtropical lake. Hydrobiologia 493: 173–186.

Havens, K. 2005. L. Okeechobee: hurricanes & fisheries. Lakeline Fall 2005: 25–28.

Havens, K.E. 2018. Managing high water levels in Florida’s largest lake: Lake Okeechobee. EDIS TP-232.

Havens, K.E., N.G. Aumen, R.T. James, and V.H. Smith. 1996. Rapid ecological changes in a large subtropical lake undergoing cultural eutrophication. Ambio 25: 150–155.

Havens, K.E., J.R. Beaver, D.A. Casamatta, T.L. East, R.T. James, P. McCormick, E.J. Phlips, and A.J. Rodusky. 2011. Hurricane effects on the planktonic food web of a large subtropical lake. Journal of Plankton Research 33: 1081–1094.

Havens, K.E., V.J. Bierman Jr., E.G. Flaig, C. Hanlon, R.T. James, B.L. Jones, and V.H. Smith. 1995. Historical trends in the Lake Okeechobee ecosystem VI. Synthesis. Archiv für Hydrobiologie Supplement 107: 101–111.

Havens, K.E., H.J. Carrick, E.F. Lowe, and M.F. Coveney. 1999. Contrasting relationships between nutrients, chlorophyll *a* and Secchi transparency in two shallow subtropical lakes: lakes Okeechobee and Apopka (Florida, USA). Journal of Lake and Reservoir Management 15: 298–309.

Havens, K.E., and T.L. East. 2006. Plankton food web responses to experimental nutrient additions in a subtropical lake. The Scientific World Journal 6: 827–833.

Havens, K.E., D. Fox, S. Gornak, and C. Hanlon. 2005. Aquatic vegetation and largemouth bass population responses to water-level variations in Lake Okeechobee, Florida (USA). Hydrobiologia 539: 225–237.

Havens, K.E., and D.E. Gawlik. 2005. Lake Okeechobee Conceptual Ecological Model, Wetlands 25: 908–925.

Havens, K.E., M.C. Harwell, M.A. Brady, B. Sharfstein, T.L. East, A.J. Rodusky, D. Anson, and R.P. Maki. 2002. Large-Scale Mapping and Predictive Modeling of Submerged Aquatic Vegetation in a Shallow Eutrophic Lake. The Scientific World Journal 2: 949–965.

Havens, K.E., and R.T. James. 1999. Localized changes in transparency linked to mud sediment expansion in Lake Okeechobee, Florida: ecological and management implications. Lake and Reservoir Management 15: 54–69.

Havens, K.E., K-R. Jin, N. Iricanin, and R.T. James. 2007. Phosphorus dynamics at multiple time scales in the pelagic zone of a large shallow lake in Florida, USA. Hydrobiologia 581: 25–42.

Havens, K.E., K-R. Jin, A.J. Rodusky, B. Sharfstein, M.A. Brady, T.L. East, N. Iricanin, R.T. James, M.C. Harwell, and A.D. Steinman. 2001. Hurricane effects on a shallow lake ecosystem and its response to a controlled manipulation of water level. The Scientific World 1: 44–70.

Havens, K.E., E.J. Phlips, M.F. Cichra, and B-L. Li. Light availability as a possible regulator of cyanobacteria species composition in a shallow subtropical lake. Freshwater Biology 39: 547–556.

Havens, K.E., and C.L. Schelske. 2001. The importance of considering biological processes when setting total maximum daily loads (TMDL) for phosphorus in shallow lakes and reservoirs. Environmental Pollution 113: 1–9.

Havens, K.E., B. Sharfstein, M.A. Brady, T.L. East, M.C. Harwell, R.P. Maki, and A.J. Rodusky. 2002. Recovery of submerged plants from high water stress in a large subtropical lake in Florida, USA. Aquatic Botany 78: 67–82.

Hopson, M.S., and P.V. Zimba. 1993. Temporal variation in the biomass of submersed macrophytes in Lake Okeechobee, Florida. Journal of Aquatic Plant Management 31: 76–81.

Hoyer, M.V., and D.E. Canfield Jr. 1996. Largemouth bass abundance and aquatic vegetation in Florida lakes: an empirical analysis. Journal of Aquatic Plant Management 34: 23–32.

James, R.T., V.J. Bierman Jr., M.J. Erickson, and S.C. Hinz. 2005. The Lake Okeechobee Water Quality Model (LOWQM) enhancements, calibration, validation and analysis. Lake Reservoir Management 21: 23–260.

James, R.T., M.J. Chimney, B. Sharfstein, D.R. Engstrom, S.P. Schottler, T. East, and K-R. Jin. Hurricane effects on a shallow lake ecosystem, Lake Okeechobee, Florida (USA). Archiv für Hydrobiologie 172: 273–287.

James, R.T., W.S. Gardner, M.J. McCarthy, and S.A. Carini. 2011. Nitrogen dynamics in Lake Okeechobee: forms, functions, and changes. Hydrobiologia 669: 199–212.

James, R.T, and K.E. Havens. 2005. Outcomes of extreme water levels on water quality of offshore and nearshore regions in a large shallow subtropical lake. Archiv für Hydrobiologie 163: 225–239.

James, R.T., and C.D. Pollman. 2011. Sediment and nutrient management solutions to improve the water quality of Lake Okeechobee. Lake and Reservoir Management 27: 28–40.

Ji, Z-R., and K-R. Jin. 2006. Gyres and seiches in a large and shallow lake. Journal of Great Lakes Research 32: 764–775.

Jin, K-R., N-B. Chang, Z-G. Ji, and R.T. James. 2011. Hurricanes affect the sediment and environment in Lake Okeechobee. Critical Reviews in Environmental Science and Technology, 41(S1): 382–394.

Jin, K-R., and Z-G. Ji. 2013. A long term calibration and verification of a submerged aquatic vegetation model for Lake Okeechobee. Ecological Processes 2 (1): 1–13.

Johnson, K.G., M.S. Allen, and K.E. Havens. 2007. A review of littoral vegetation, fisheries, and wildlife responses to hydrologic variation at Lake Okeechobee. Wetlands 27: 110–126.

Julian II, P., and Z. Welch. 2022. Understanding the ups and downs: application of hydrologic restoration measures for a large subtropical lake. Lake and Reservoir Management 38: 304–317.

Khan, A. 2010. Lake Okeechobee sediment management. Presentation at the Greater Everglades Restoration Conference.

Kramer, B.J., T.W. Davis, K.A. Meyer, B.H. Rosen, J.A. Goleski, G.J. Dick, G. Oh, and C.J. Gobler. 2018. Nitrogen limitation, toxin synthesis potential, and toxicity of cyanobacterial populations in Lake Okeechobee and the St. Lucie River Estuary, Florida, during the 2016 state of emergency event. PLoS ONE 13: e0196278.

Langeland, K.A., and C.C. Jacono. 2012. Common aquatic plants of Lake Okeechobee: identification, value, and management. EDIS SS-AGR-362.

Lecher, A.L. 2021. A brief history of Lake Okeechobee: a narrative of conflict. Journal of Florida Studies Volume 1 Issue 9.

Lee, Z., S. Shang, K. Du, and J. Wei. 2018. Resolving the long-standing puzzles about the observed Secchi depth relationships. Limnology and Oceanography 63: 2321–2336.

Ma, C., Z. Li, P.C. Mwagona, A. Rabbany, and J.H. Bhadha. 2022. Spatial and seasonal dynamics of phytoplankton groups and its relationship with environmental variables in Lake Okeechobee, USA. Journal of Freshwater Ecology 37: 173–187.

Maceina, M.J. 1996. Largemouth bass abundance and aquatic vegetation in Florida lakes: an alternative interpretation. Journal of Aquatic Plant Management 34: 43–47.

Maderia, P.T., F.A. Dray Jr., and P.W. Tipping. 2022. The phytogeography and genetic diversity of the weedy hydrophyte, *Pistia stratiotes* L. Biological Invasions 24: 2613–2634.

McCarthy, M.J., R.T. James, Y. Chen, T.L. East, and W.S. Gardner. 2009. Nutrient ratios and phytoplankton community structure in the large, shallow, eutrophic, subtropical lakes Okeechobee (Florida, USA) and Taihu (China). Limnology 10: 215–227.

Missimer, T.M., S. Thomas, and B.H. Rosen. Legacy phosphorus in Lake Okeechobee (Florida, USA) sediments: a review and new perspective. Water 13: 39.

Moore, P.A. Jr., K.R. Reddy, and M.M. Fisher. 1998. Phosphorus flux between sediment and overlying water in Lake Okeechobee, Florida: spatial and temporal variations. Journal of Environmental Quality 27: 1428–1439.

Olexa, M.T., T. Borisova, and J. Caracciolo. 2021. 2021 Handbook of Florida Water Regulation: Northern Everglades and Estuaries Protection Program. EDIS FE610.

Phlips, E.J., M. Cichra, K. Havens, C. Hanlon, S. Badylak, B. Rueter, M. Randall, and P. Hansen. 1997. Relationships between phytoplankton dynamics and the availability of light and nutrients in a shallow sub-tropical lake. Journal of Plankton Research 19: 319–342.

Project Seagrass. 2024. Scientists outline 10 golden rules for seagrass restoration. https://www.projectseagrass.org.

Reddy, K.R., M.M. Fisher, Y. Wang, J.R. White, and J.R. Thomas. 2007. Potential effects of sediment dredging on internal phosphorus loading in a shallow, subtropical lake. Lake and Reservoir Management 23: 27–38.

Reddy, K.R., J.R. White, M.M. Fisher, H.K. Pant, Y. Wang, K. Grace, and W.G. Harris. 2002. Potential impacts of sediment dredging on internal phosphorus load in Lake Okeechobee. South Florida Water Management District, West Palm Beach, Florida.

Reynolds, L., C.R. Adams, E. Latimer, C.W. Martin, C. Rohal, and J. Slater. 2020. A comparison of planting techniques for submerged aquatic vegetation. EDIS 2020 (4). https://doi.org/10.32473/edis-ss685-2020

Reynolds, L.K., C.B. Rohal, W.A. Scheffel, C.R. Adams, C.W. Martin, and J. Slater. 2021. Submerged aquatic vegetation species and populations within species respond differently to environmental stressors common in restorations. Environmental Management 68: 477–490.

Rodusky, A.J., B. Sharfstein, K-R. Jin, and T.L. East. Thermal stratification and the potential for enhanced phosphorus release from the sediments in Lake Okeechobee, USA. Lake and Reservoir Management 21: 330–337.

Rodgers, J.A. Jr., H.T. Smith, and D.D. Thayer. 2001. Integrating nonindigenous aquatic plant control with protection of snail kite nests in Florida. Environmental Management 28: 31–37.

Rodgers, J.A. Jr., and S.T. Schwikert. 2003. Breeding chronology of snail kites (*Rostrhamus sociabilis plumbeus*) in central and south Florida wetlands. Southeastern Naturalist 2: 293–300.

Rogers, M.W., and M.S. Allen. 2008. Hurricane impacts to Lake Okeechobee: altered hydrology creates difficult management trade offs. Fisheries 33: 11–17.

Rogers, M.W., and M.S. Allen. 2012. An ecosystem model for exploring lake restoration effects on fish communities and fisheries in Florida. Restoration Ecology 20: 612–622.

Rohal, C.B., C.R. Adams, C.W. Martin, S. Tevlin, and L.K. Reynolds. 2022. Intraspecific variation in *Potamogeton illinoensis* life history and seed germination has implications for restoration in eutrophic lakes. Hydrobiologia 849: 3481–3500.

Rohal, C. B., L.K. Reynolds, C.R. Adams, C.W. Martin, E. Latimer, S.J. Walsh, and J. Slater. 2021. Biological and practical tradeoffs in planting techniques for submerged aquatic vegetation. Aquatic Botany, 170: 103347.

Schelske, C.L. 1989. Assessment of nutrient effects and nutrient limitation in Lake Okeechobee. Water Resources Bulletin 25: 1119–1130.

Slagle, Z.K., and M.S. Allen. 2018. Should we plant macrophytes? Restored habitat use by the fish community of Lake Apopka, Florida. Lake and Reservoir Management 34: 296–305.

Smith, M.J. 2021. Influence of lake stage on the recruitment of Florida bass in Lake Okeechobee. Fisheries Management and Ecology 29: 319–322.

South Florida Water Management District. 2010. Final adaptive protocols for Lake Okeechobee operations. South Florida Water Management District, West Palm Beach, Florida.

South Florida Water Management District. 2011. Executive Summary Lake Okeechobee Protection Plan. South Florida Water Management District, West Palm Beach, Florida.

Steinman, A., K. Havens, and L. Hornung. 2002. The managed recession of Lake Okeechobee, Florida: integrating science and natural resource management. Conservation Ecology 6: 17.

Steinman, A.D., R.H. Meeker, A.J. Rodusky, W.P. Davis, and S-J. Hwang. 1997. Ecological properties of charophytes in a large subtropical lake. Journal of the North American Benthological Society 16: 781–793.

Tan, Y.M., O. Dalby, G.A. Kendrick, J. Statton, E.A. Sinclair, M.W. Fraser, P.I. Macreadie, C.L. Gillies, R.A. Coleman, M. Waycott, K. van Dijk, A. Vergés, J.D. Ross, M.L. Campbell, F.E. Matheson, E.L. Jackson, A.D. Irving, L.L. Govers, R.M. Connolly, I.M. McLeod, M.A. Rasheed, H. Kirkman, M.R. Flindt, T. Lange, A.D. Miller, and C.D.H. Sherman. 2020. Seagrass restoration is possible: insights and lessons from Australia and New Zealand. Frontiers in Marine Science 7: 617.

United States Army Corps of Engineers. 2002. Central and Southern Florida Project, Comprehensive Everglades Restoration Plan Section 2.0 Evaluation Criteria, Draft Watershed Assessment Report, Lake Okeechobee Watershed Project. United States Army Corps of Engineers, Jacksonville, Florida.

United States Army Corps of Engineers. 2024. Final Environmental Impact Statement Lake Okeechobee System Operating Manual. United States Army Corps of Engineers, Jacksonville, Florida.

Walker, W.W., and K.E. Havens. 1995. Relating algal bloom frequencies to phosphorus concentrations in Lake Okeechobee. Lake and Reservoir Management 11: 77–83.

Xue, C., H. Chuamin, B. Barnes, Y. Xie, L. Qi, C. Armstrong, Z. Chen, and P. Jones. Long-term changes of chlorophyll-a in Lake Okeechobee: combining the strengths of *in situ* observations, multi-sensor remote sensing, and machine learning. Submitted to Transactions on Geoscience and Remote Sensing.

Zaffke, M. 1984. Wading bird utilization of Lake Okeechobee marshes 1977–1981. South Florida Water Management District Technical Publication 84-9. South Florida Water Management District, West Palm Beach, Florida.

Zhang, J., P. Jones, and A. Betts. 2022. Chapter 8b: Lake Okeechobee Watershed Protection Plan annual progress report. In: 2022 South Florida Environmental Report – Volume I. South Florida Water Management District, West Palm Beach, Florida.

Addendum

1) *Knowledge gaps - One outcome of a thorough review of the system and the collective knowledge gained over the past half century could be to identify some key unknowns, and specify an approach(es) to find answers, if possible. Were there some that could be pointed out? You did mention some unknowns with projects, like dredging or planting, but some others for me are –*

    - *There's talk in the literature about a non-linear relationship between water quality and stage in the nearshore, with worsening conditions starting at a stage of roughly >13-14ft. Is this true today? That was based on a 1991 paper. What is the stage threshold? Where is this evident? Probably different in the south than the SW or NW. Implications on stage management, SAV habitat suitability at different stages.*

      Some relevant past work focused on concentrations of phosphorus in the littoral zone. In one study, concentrations of phosphorus were measured at varying distances from the littoral zone during periods with different water levels. Higher water levels resulted in a weaker relationship, but the data, which were parsed into three "stages" (< 3.95 m, 3.96–4.49 m, and > 4.50 m), did not support identification of non-linearity. The weaker relationship of increasing concentrations of phosphorus further from shore was attributed to heterogeneous mixing of water with differing concentrations of phosphorus during periods of high water. Another evaluation reinforced the concept that wind was a major factor in determining concentrations of phosphorus in the littoral zone and wind was also a major factor in determining turbidity and its subsequent effect on penetration of sunlight to submerged aquatic vegetation. High winds, e.g., during winter, created turbidity that shaded submerged aquatic vegetation to the point where its decline resulted in less uptake of phosphorus and subsequently more phosphorus being available to phytoplankton, which led to blooms. Overall, interactions among high water levels, turbidity, availability of nutrients, and phytoplankton blooms remain key issues that affect the health of submerged aquatic vegetation in the littoral zone. Recently expanded sampling of water quality highlighted small-scale spatial variation in concentrations of nitrogen, phosphorus, and chlorophyll-*a* along transects extending from the shore into the lake, as well as temporal variation likely linked to the effects of rainfall and wind on loads of nutrients and light availability. A concerted effort to collect and analyze samples along these transects across additional periods of high, moderately high, and low water levels should yield valuable insights into the dynamic responses of the lake.

- *If higher water conditions exist, plants eventually move up slope. We can see in satellite imagery, areas that are now emergent, or were, used to be open water/possibly SAV in the 90s. South Bay, Eagle Bay Island, north side of Fisheating Bay. What is the process of pushing emergent marsh back and replacing with SAV as stages rise? Storms speed it up, but is seed bank there? How can we expedite the process? Perfect opportunity next to Harney Pond canal where cattail and floating leaf marsh has disappeared over the past 5-10 years.*

In general, multiple species of submerged aquatic vegetation can colonize areas fairly rapidly. For example, dating of fossils indicated that macrophytes colonized a lake in Norway within decades of temperatures becoming suitable, and sampling of seeds in Chesapeake Bay also indicated changes in submerged aquatic vegetation on the decadal timescale over a total period of ~900 years. Initially, freshwater vegetation expanded seaward probably due to increased inputs of fresh water following clearing of large areas of land. Eventually, loads of nutrients that fueled blooms of phytoplankton and loads of sediment reduced water clarity to the point where submerged aquatic vegetation was lost.

Often, seed banks play an important role in colonization of "vacant space," so gaining an understanding of the presence and viability of seed banks throughout the lake would be valuable when planning restoration. Expediting sprouting of seeds or other means of colonization may be a challenge, but collecting, culturing, and broadcasting seeds over twenty years has been deemed successful for restoring *Zostera marina* to coastal bays of Virginia. The effort involved over 3,500 hours and more than 10 million seeds. It is worth noting that *Z. marina* is among the most prolific producers of seeds, so replicating this success with other species may involve additional time and effort. For Lake Okeechobee, local concern regarding the health of lake increases the likelihood that volunteers will be available to assist.

Selection of sites for experimentation or restoration related to submerged aquatic vegetation benefits greatly from an understanding of the underlying cause(s) for its absence or loss. Success is more likely if this understanding is based on a historical record of conditions and evidence of consistent relationships between the abundance of submerged aquatic vegetation and potential stressors, including light, temperature, and salinity. In turn, restoration is more likely to succeed if detrimental conditions no longer exist. A valuable initial step for Lake Okeechobee would be to "mine" existing data to assess current knowledge of habitat suitability and gaps in our understanding of this important characteristic.

2) *Dredging - More info on risks, possibilities, prior efforts, how to proceed if desired. Lake Trafford, for example, was completely dredged but had blooms afterwards and increased groundwater interaction. There may be substantial short-term impacts during dredging… which of course become long-term if doing the whole lake over 15 years*

Dredging does involve some risk, and dredging in Lake Trafford exposed a potential concern for many shallow lakes in Florida: an altered interaction with groundwater. Removing sediment apparently promoted greater inflows, especially in the deeper portions of the lake. The groundwater delivered nitrogen and phosphorus to the lake, and these loads were considered responsible for continuing blooms of phytoplankton and expansion of invasive plants. It is worth noting that the dredging did lower the loads of nutrients coming from the sediment, and it also is worth noting that excess nutrients in groundwater are being addressed in Florida. Thus, interactions with groundwater may become less of an issue once planned environmental restoration is more complete, but an effort to understand past, present, and current influences of groundwater on Lake Okeechobee would be a valuable contribution. In addition, available evidence indicates that short-term impacts on water quality from dredging need not be extreme. For example, median turbidity values during dredging of two areas in the Indian River Lagoon were no more than 1.2 nephelometric turbidity units higher than medians in the preceding 18–26 years, and medians for 4-5 years after dredging were approximately 1–3 nephelometric turbidity units lower. Of course, rainfall, wind and other factors influence turbidity, but these data do show that dredging did not substantially increase turbidity.

- *May mention issues like blooms are light limited in the center of the lake right now, and there's sufficient inflow of nutrients to cause blooms even without the sediment internal loading. If we improve light conditions in the middle, there's a chance we'd have substantial increases in blooms as well, at least for some period.*

Fully restoring the health of Lake Okeechobee will require sustained effort to overcome interacting challenges. The interaction between availability of light and availability of nutrients as causes for blooms of phytoplankton illustrates this issue. Currently, blooms of phytoplankton tend to be most intense nearer the shoreline in large part because turbidity is lower and light penetrates further into the water column. Removing the fine sediment that both generates an internal load of nutrients and creates turbidity in the pelagic portion of the lake may reduce the availability of nutrients and increase the availability of light, but if external loads of nutrients are not reduced sufficiently, those loads may fuel blooms because light is no longer a limiting factor. In other words, full restoration requires addressing external loads of nutrients and internal or "legacy" loads of nutrients. Simultaneous reductions may not be feasible, so there may be a tradeoff of "short-term pain" for "long-term gain."

- *Could mention more about the feasibility of chemical additives, beyond potential toxicity or temporary effect issues; like how you might need an actual alum factory on the shoreline to provide the quantities required to bind Lake O sediments.*

- *Regarding treating the porewater from dredged spoil, is it possible to treat water with an industrial scale water treatment plant on the lake shores, as an alternative or supplementary to dredging, as has been suggested? The city of Lake O, for example,* *treats lake water to drinking standards. Would building more of those be feasible, or be prohibitively expensive per pound of P removed?*

Treating water from the lake to standards for drinking water may be unnecessary but treating both water and porewater are approaches worth considering. As a guide, Brevard County recently estimated that interstitial water can be treated to yield return water containing approximately 2–3 milligrams per liter of total nitrogen and approximately 0.08–0.10 milligrams per liter of total phosphorus. Costs depend on the initial concentrations of nutrients, but they averaged $78 per pound for total nitrogen and $1,310 per pound for total phosphorus over 16 projects. An example of treating water that is not interstitial water is provided by the Nutrient Reduction Facility (NuRF) operated by Lake County. It treats all of the regulated outflow from Lake Apopka, which can be over 400,000 gallons per month, and it feeds treated water into Lake Beauclair, which is the first in the series of lakes comprising the Harris Chain of Lakes. The facility introduces alum to bind and precipitate phosphorus into two, 9-acre settling ponds. The "floc" produced by alum is removed from the ponds by a remotely controlled dredge that pumps it to a centrifuge for dewatering. The process removes approximately 50%–60% of the 0.1 milligrams per liter of phosphorus in the inflow, and it reduces turbidity by approximately 2 nephelometric turbidity units. The facility cost $7.4 million to construct in 2023, with the land being provided by the St. Johns River Management District. The operational costs run about $1 million per year, but those costs vary with the volume of water treated. Overall, costs average about $300–$350 per pound of phosphorus removed. Dewatering the sludge dredged from the ponds and extraneous material that interferes with the dredge are two ongoing challenges. As with any other lakewide effort, scaling the approach used at the NuRF to affect Lake Okeechobee results in a substantial investment. For example, if the lake were isolated from inflows and outflows, a single facility would require hundreds of thousands of years to treat the resulting 1 trillion gallons of water. If the goal was to treat the "isolated" lake over a decade, it would require the construction and operation of over 16,000 facilities.

- *More expert advice on*
  - *How to target smaller areas if muck removal was desired. Littoral reaches have been scraped before at low water, but where would be most beneficial in the lake. A sump in the center?*
  - *Providing info about how to approach the projects in order to maximize knowledge gained and efficacy. What approach do we use to ensure it scales up, how do we monitor?*
  - *What risks may need to be mitigated for with projects like dredging or chemical capping, and how might that happen*

Designing projects, including pilot projects, benefits from having clear objectives. Dredging, capping, and chemical treatment of fine sediments have all been used to improve water quality. Each technique has its benefits, costs, and associated risks as have been outlined in the appendix and this addendum. Clear objectives are also important for designing monitoring. Improved water quality is the primary target for the projects under discussion, which is a departure from the goal of removing sediment to improve navigation, and that shift makes the composition of the water returned to the system more important and the need for treating interstitial water more critical. Establishing a baseline for water quality before initiating a project will provide a valuable point of reference for assessing changes due to the project. Multiple locations that are not affected by the project will provide valuable controls and a means of avoiding pseudoreplication, which confounds attempts to attribute changes to the project if there is only one perturbed location and one unperturbed or control location. Perhaps, the biggest challenge will always be scaling any effort to yield a lakewide effect in a relatively short time.

3) *A brief review a few of the suggestions from stakeholders, like using the marsh as an STA, or increasing connectivity between nearshore and interior marsh.*
    - *Caution against using littoral zone as an STA*
    - *Review phenomenon of nearshore vs pelagic WQ, connecting the 2 more may have long-term impacts to littoral areas.*

      Pumping water is a challenge, especially in volumes large enough to have a widespread effect. The information for the NuRF illustrates this issue. Treating natural systems as a filter ultimately yields reduced return on investment as the capacity to uptake or bind nitrogen and phosphorus decreases. Harvesting plants to promote uptake that supports new growth is possible, but such "managed" systems are unlikely to yield the same benefits as systems that are not disturbed, with lost benefits including less suitable habitat for birds and wildlife. Another consideration is the results of moving water from the pelagic zone of the lake into its littoral zone. As detailed above, evidence suggests that a stronger connection may stimulate blooms of phytoplankton, loss of water clarity, and loss of valuable submerged aquatic vegetation.

    - *General estimates of efficacy of vegetation harvest or algae harvest as a nutrient removal tool. Previous hyacinth/algae project on north side of lake, for example.*

      Harvesting plants in the wild is expensive, easily several thousands of dollars per acre, and its lack of selectivity can cause detrimental effects on aquatic plants and animals, such as removal of up to 32% of young-of-the-year sportfish. Furthermore, vegetation is mostly water, so costs per pound of nitrogen and phosphorus are even higher than costs per acre harvested. Additional considerations can be found at: https://plants.ifas.ufl.edu/management-plans/mechanical-control-considerations/harvesters/.

      "Offline" systems that rely on uptake of nutrients by plants or algae as a means of reducing loads can be constructed. These systems rely on harvesting the plants or algae to "reset" the system and maintain relatively high growth rates. The efficacy of such an approach was documented in a pilot study that initially treated water by sending it through two types of scrubbers: one containing water hyacinth and others containing periphyton. Eventually, the focus shifted to the algal scrubbers. Depending on the rate of inflow, the algal scrubbers removed 20–77 times as much phosphorus per unit area as a typical stormwater treatment area. Thus, less land is needed to yield a similar reduction in loads of phosphorus. The plant and algal material that was harvested from the facility was used as feed for cattle and as an addition to compost. The algal scrubber system had an active area of ~0.03 acres, and over 139 days, it processed ~34,000 gallons of water per day. Again, scaling to process a substantial amount of the 1 trillion gallons of water in Lake Okeechobee will require a significant investment.

- *Whether using hydrilla or a non-native phenotype of Val (rockstar) might be useful as an approach in some areas. Could review situation on Apopka, for example, where restoration may lead to increased invasive plant mgmt.*

  Data from Lake Apopka are likely to be valuable when they become available. Managers should consider the tradeoffs associated with planting "non-native" species, and development of a set of metrics for evaluating tradeoffs would be a valuable approach. Such an evaluation is likely to comprise some broadly applicable considerations and some "project specific" considerations.

4) *Plant management*
   Considerable confusion appears to surround management of vegetation in Lake Okeechobee. For example, costs that are mistakenly treated as only covering purchase of chemicals actually include labor, administration of contracts, and other expenditures. Thus, calculating a cost per acre and attributing it solely to chemicals is misleading. A valuable approach would be to design and implement a strategy to address existing misunderstandings and miscommunications.

References

Birks, H. 2000. Aquatic macrophyte vegetation development in Kråkenes Lake, western Norway, during the late-glacial and early-Holocene. Journal of Paleolimnology 23: 7–19.

Brush, G.S., and W.B. Hilgartner. 2000. Paleoecology of submerged macrophytes in the upper Chesapeake Bay. Ecological Monographs 70: 645–667.

Havens, K.E. 1997. Water levels and total phosphorus in Lake Okeechobee. Lake and Reservoir Management 13: 16–25.

Hydromentia, Inc. 2005a. S-154 pilot ATS™–WHS™ aquatic plant treatment system. Final report to the South Florida Water Management District. https://hydromentia.com/resources/ats-library/

Hydromentia, Inc. 2005b. S-154 pilot single stage algal turf scrubber® (ATS™). Final report to the South Florida Water Management District. https://hydromentia.com/resources/ats-library/

Maceina, M.J. 1993. Summer fluctuations in planktonic chlorophyll *a* concentrations in Lake Okeechobee, Florida: the influence of lake levels. Lake and Reservoir Management 8: 1–11.

Orth, R.J., J.S. Lefcheck, K.S. McGlathery, L. Aoki, M.W. Luckenbach, K.A. Moore, M.P.J. Oreska, R. Snyder, D.J. Wilcox, and B. Lusk. Restoration of seagrass habitat leads to rapid recovery of coastal ecosystem services. Science Advances 6: eabc6434.

Tan, Y.M., O. Dalby, G.A. Kendrick, J. Statton, E.A. Sinclair, M.W. Fraser, P.I. Macreadie, C.L. Gillies, R.A. Coleman, M. Waycott, K. van Dijk, A. Vergés, J.D. Ross, M.L. Campbell, F.E. Matheson, E.L. Jackson, A.D. Irving, L.L. Govers, R.M. Connolly, I.M. McLeod, M.A. Rasheed, H. Kirkman, M.R. Flindt, T. Lange, A.D. Miller, and C.D.H. Sherman. 2020. Seagrass restoration is possible: insights and lessons from Australia and New Zealand. Frontiers in Marine Science 7: 617.

Tetra Tech, Inc. 2025. Save our Indian River Lagoon project plan 2025 update for Brevard County. https://www.brevardfl.gov/SaveOurLagoon/ProjectPlan

Underwood, A.J. 1994. On beyond BACI: sampling designs that might reliably detect environmental disturbances. Ecological Applications 4: 3–15.

Van Katwijk, M.M. A. Thorhaug, N. Marbà, R.J. Orth, C.M. Duarte, G.A. Kendrick, I.H.J. Althuizen, E. Balestri, G. Bernard, M.L. Cambridge, A. Cunha, C. Durance, W. Giesen, Q. Han, S. Hosokawa, W. Kiswara, T. Komatsu, C. Lardicci, K-S. Lee, A. Meinesz, M. Nakaoka, K.R. O'Brien, E.I. Paling, C. Pickerell, A.M.A. Ransijn, and J.J. Verduin. Global analysis of seagrass restoration: the importance of large-scale planting. Journal of Applied Ecology 53: 567–578.

Additional engagements

Affiliation	Surname	Forename
Brevard County	Gering	Abigail
Florida Fish and Wildlife Conservation Commission	Phillips	Matthew
St. Johns River Water Management District	Mitchell	Jennifer
Woodard & Curran	Stanley	Sam

Appendix 3: Summary of Stakeholder Input

Prepared by: Consensus Center at Florida State University: Hal Beardall and Rafael Montalvo, and the Orthon Group: Steve Smallpage.

Introduction

The Consensus Center and the Orthon Group undertook three lines of outreach activity: interviews with individuals; two rounds of stakeholder input workshops; and an online comment portal to allow the broadest practicable range of individuals to offer their opinions and ideas. Over 500 stakeholders provided input:

- Thirty-six individuals (*interviewees*) representing fishing, recreational, environmental, agricultural, and business groups, communities around the lake, scientific organizations and state and federal agencies participated in 31 interviews.
- Almost 400 individuals (*online commenters*) offered ideas and suggestions through the online portal. Many of these stakeholders had over 20 years of experience on the lake, and a wide range of affiliations and backgrounds in the surrounding communities and throughout the state.
- More than 100 people (*workshop participants*) attended one or more of the workshops.

In all of the outreach activities, the team posed versions of the following three questions:

- What changes have you observed in the ecosystem of the littoral zone in recent years?
- What factors do you think may be contributing to any changes you have observed?
- What measures do you think might help improve the health of the littoral zone?

This compilation serves as a record of the input received by the team across all three lines of outreach activity. It serves as a companion document to the *Summary of Stakeholder Input* (S*ummary)* which is incorporated as an appendix in the main body of the study report.

The opinions and ideas outlined here are those of the stakeholders who offered them. They do not necessarily reflect the opinions or conclusions of the team. They are also not the product of a statistically valid sampling of stakeholder groups. The individuals interviewed were chosen either because they represented user or community groups, or because they had particularly deep or broad experience in the issues facing the lake. Those who participated in the workshops or who provided input online were self-selected. Taken together, however, the perspectives outlined in this summary do suggest the range and focus of public stakeholder thinking about the challenges facing the lake and how they might be addressed.

Summary of Interview Themes

As part of the outreach effort, the Consensus Center interviewed thirty-six individuals (*interviewees*) representing fishing, recreational, environmental, agricultural, and business groups, communities around the lake, scientific organizations and state and federal agencies, using the three questions described above as starting points.

This portion of the compilation presents the themes and some individual suggestions from the interviews. Interviewees had very different backgrounds, and often focused on the topics they knew best. The resulting array of themes is therefore a composite of their responses. The themes are grouped here by the questions posed by the team to elicit input.

Changes Observed in the Lake

Natural Systems

Direct experience with or knowledge of the lake varied among interviewees. Those with more direct experience and knowledge, whether as regular users or in a professional capacity, answered this question with more detail and often with more of a focus on specific areas within the lake than is reflected here.

Decline in Submersed Aquatic Vegetation (SAV) Virtually all interviewees highlighted this as one of the defining changes in their experience of the lake. Many pointed to the decline of hydrilla in addition to the decline of native vegetation as significant.

Change in location, extent, composition and structure of shoreline marshes All interviewees offered some comment on these changes, although the degree of detail varied depending on the extent of the respondent's direct experience on the lake. The following were common observations relating to this theme among interviewees:

- Migration and/or compression of marshes closer to the to the outer perimeter of the lake along the dike, with concomitant decline in marsh area
- Changes to the structure of the littoral zone – The deeper water has resulted in shrinkage of especially middle and short hydroperiod marshes, and formerly vegetated areas becoming open water.
- Where there used to be lots of edges in the form of pockets and ponds, there is now often solid vegetation, frequently cattail.

Dark water A large majority of interviewees highlighted the increased opacity of lake water. This theme was especially pronounced among those with longer experience on the lake. Many talked about the role of sediments and turbidity in increasing the opacity of the water.

Decline in fisheries A significant majority of interviewees with direct experience of recreational fisheries emphasized the decline in the abundance of sports fish over time. Several emphasized that the lake has recently been removed from the list of top ten lakes nationally for bass. Comments on the decline were nevertheless offered with several qualifications. Bass fishing in particular remains strong for now at a few locations on the lake. This has resulted in visible concentrations of boats during tournaments and other times of heavy use. There is strong concern that with the decline in SAV available for nursery habitat even these locations will decline further in the near future.

Many of the interviewees with less direct experience on the lake but experience in the communities surrounding it also emphasized this as a perception and topic of conversation in the communities with which they were familiar.

Declines in numbers of waterfowl Most of the interviewees with direct experience on the lake pointed to declines in the number of waterfowl, including ducks and wading birds, on the lake. They attributed the decline in ducks to the decline of food sources in the SAV, especially hydrilla. The decline of wading birds they attributed to the decline in food sources resulting from shrinking littoral marshes. Several noted that ducks in particular are now abundant in the stormwater treatment areas south of the lake, where SAV is also abundant.

Decline in marsh wildlife Many interviewees also noted a concomitant decline in other marsh wildlife, especially frogs, and including other amphibians, reptiles and birds.

Increasing algal blooms Many interviewees included increased algal blooms in the lake in their description of changes and attributed them primarily to increased nutrient inflows, and also to decreased competition for those nutrients resulting from the decline in other vegetation. A few discussed the interactions between nutrient outflows from the lake to the St. Lucie and Caloosahatchee estuaries, and downstream nutrient contributions from local sources such as septic tanks, in promoting algal blooms in the estuaries.

Economic Impacts of Observed Changes

Current Impacts Interviewee perceptions of current economic impacts varied by region, and with the personal circumstances of the individual. Almost all of the interviewees involved in the recreational fishing industry said they were already experiencing a drop-off in business.

Interviewees in communities around the lake but not involved in the recreational fishery (about 20% of the total number of interviewees) offered similar but distinguishable responses. Those in communities north of the lake reported that they were already experiencing significant impacts, especially in businesses dependent on seasonal visitors who come to the area to fish. Those in communities south and west of the lake stated that they expected economic impacts from current conditions but were not yet seeing them at a significant level.

Potential Impacts All interviewees from communities around the lake expected significant economic impacts if current conditions continue. Some worried that those impacts would not be easily reversible, since they would entail loss of the businesses that serve the fisheries. It would be difficult for communities to quickly return to accommodating very large numbers of visitors without this infrastructure.

Other

Awareness of lake issues Interviewees in the recreational fisheries industry all indicated a high degree of awareness of lake issues among customers and others with whom they interact regularly. Most of the interviewees in communities around the lake but not involved in the recreational fishery noted that awareness in their communities varied, often with distance from the lake or the frequency with which they visit the lake. These interviewees indicated that the people with whom they interact are likely to be aware that there are issues with the health of the lake, but to be less aware of detail.

Perception of a limited window for restoration Several of the interviewees indicated that they and those with whom they interact believe there is a small and rapidly closing window to improve the health of the ecosystem. Some of these spoke of approaching a possible "tipping point". They feared that past a certain point it would be much harder to reverse the declines they were seeing.

Factors Contributing to Changes

Stakeholder responses to this question are articulated below as separate themes for ease of understanding: Almost all respondents, however, pointed to the interrelationships among factors. Some stakeholders answered this question with a focus on dynamics within the lake, while others answered primarily from an ecosystem-wide or historical perspective.

High water While addressing water levels in the lake is outside the scope of the study, essentially all interviewees cited high water in the lake as a major factor. A large majority cited it as the single biggest factor driving recent changes. Most cited it in conjunction with other factors such as excess nutrients and turbidity. Some interviewees stated that earlier periods of extended high water, especially in the 1970s, had not been as damaging to SAV and the lake's ecology, and attributed the difference to current higher levels of turbidity.

Lake-bottom sediment/mud and legacy nutrients/contaminants Almost all interviewees cited this as the most important factor after water level, emphasizing the relationship not just to excess nutrients but to turbidity as well.

Turbidity Most interviewees also cited turbidity (often referring to it as dark water) as a major factor. Several pointed to the correlation between wave action in the center of the lake and reduced water clarity in the littoral zone. Several also noted that although stages of 16-18 feet were the norm for much of the 1970s, turbidity was not as bad during that time and therefore the impacts of high water were not as severe.

Vegetation management, including herbicide spraying Very few interviewees cited spraying as one of the most important drivers of changes in the lake. Many, however, cited it as a contributing factor among several. Many of these interviewees believed agencies rely too heavily on herbicides. Some believed this reliance contributed to plant and therefore nutrient build-up in lake-bottom sediments, while others expressed concern about temporary, localized, but significant dissolved oxygen depletion because of plant matter decomposition after major spraying. Some also expressed concern about excessive spraying in shorter hydroperiod marshes that by their nature have less time for native species to recover after major spraying, or in stressed marshes.

Many also suggested that hydrilla and other nonnative species can play a constructive role in removing nutrients from the lake in the absence of robust populations of native plants. They suggested that agencies with management responsibility should reevaluate the desirability of trying to eradicate all non-native plant species.

Inflows of nutrient-laden water Many interviewees acknowledged that nutrient inflows from the Kissimmee River and creeks were largely beyond the scope of the study but highlighted them nevertheless as drivers of change. They also noted that reducing or stopping the inflow of nutrients would be essential to maximizing the benefits of nutrient removal.

Changes in climatological and meteorological conditions and increasing urbanization increase the volume of inflows Some interviewees highlighted that inflows to the lake have been increasing because of a number of factors: increasing urbanization in the watershed, increased or more intense rainfall caused by normal weather variability and climate change, and an extended wet period without a subsequent dry period or drought.

Man-made changes to the greater Everglades ecosystem over long periods of time Several interviewees focused on the role of human changes to the South Florida environment, from the draining of a large portion of the Everglades, to construction of the Herbert Hoover dike, to channelization of the Kissimmee River, to agriculture and ongoing urbanization of the watershed.

Stakeholder suggestions of Potential Action

Responses to this question differed in several ways from responses to the first two questions. Many interviewees were more tentative in their answers and framed their suggestions in terms of possibilities that should be tried or explored. There was also less in common among the answers: most of the themes below are drawn from the responses of a smaller percentage of interviewees than was the case for themes under the first two questions. A significant number of interviewees stated that they did not believe any measures would provide meaningful relief if current water levels continued for extended periods.

Because an important part of the outreach effort was compilation of stakeholder suggestions for possible actions, this list contains not just themes, but some items suggested by a single respondent.

Mud removal or reuse – A large majority of interviewees indicated they thought that after lowering the lake stage, removal of lake-bottom mud would be one of the more impactful measures that could be undertaken to improve the health of the lake. Removal of lake-bottom mud would reduce excess nutrients and reduce the potential for turbidity.

Interviewees acknowledged the challenges to doing this, including the size of the lake, the possibility of aggravating turbidity during removal, and the need to dispose of the resulting material. They suggested several approaches to addressing them:

- Hydraulic dredging: Respondents generally understood the difficulty of doing this throughout the lake. Many suggested identifying areas that could benefit from mud removal and conducting smaller-scale or pilot projects there.
- Excavating or burning the mud, if sufficiently low water occurs naturally.
- Use of nutrient reduction techniques to remove mud and transport it as a slurry.
- Using mud to build spoil-islands surrounded by muck sumps to facilitate further mud settling and removal.
- Building free-standing mud sumps in the lake to facilitate mud removal.

Other Measures to Reduce Excess Nutrients Some interviewees also suggested other measures to reduce excess nutrients in the lake. These included:

- Encouraging circulation of incoming water through the littoral zone to promote natural removal of incoming nutrients. These respondents noted the relative clarity of water in the remaining littoral zone, and the nutrient loads in water inflows. They suggested that cutting trails parallel to the shore through dense areas of vegetation near the inflows would help channel incoming water through vegetation that would remove some of the excess nutrients.
- Encouraging circulation between the center of the lake and the littoral zone to promote natural removal of legacy nutrients. The same observations led some respondents to suggest developing mechanisms to promote the exchange of water between the center of the lake and the remaining littoral zone, again with the objective of channeling water with large loads of nitrogen and phosphorous through potentially cleansing vegetation.
- Harvesting vegetation to remove nutrients from the lake. These respondents suggested several approaches, use of the techniques developed for FWC's Nutrient Reduction Project, removal of cut cattail, and regular harvesting of all vegetation from designated areas.

Changing the approach to management of nonnative and nuisance vegetation, including reduction of spraying and toleration of some nonnatives

- A few interviewees suggested reducing or discontinuing spraying as a potential action to improve the health of the lake. Most interviewees did not believe discontinuing spraying would significantly improve ecosystem health and might adversely affect it.
- Many interviewees suggested that some nonnatives, especially hydrilla, might play a role in removing excess nutrients and supporting some ecosystem functions.

Turbidity mitigation Most interviewees suggested or supported testing the impact of wave attenuation devices to reduce turbidity. Many were also aware of suggestions to cap or chemically bind mud to reduce turbidity but were unsure of the potential effectiveness of these approaches.

SAV planting Most interviewees suggested planting SAV as part of restoration efforts. Most of these respondents were aware that high, dark water would make it more difficult for planted SAV to survive but believed there were a number of locations around the lake where such efforts might still be successful. These respondents usually suggested the SAV planting take place as part of a coordinated site-specific effort that could include other components such as localized mud removal and wave attenuation measures.

Increase dispersed storage of water north of the lake – Several interviewees suggested expansion of dispersed water storage or detention north of the lake to reduce inflows. These respondents understood that reduction of inflows was outside the bounds of this study but believed that this measure had the potential to provide some short-term relief from high and increasing volumes of inflows and therefore contribute to lower lake stages and lower levels of incoming nutrients.

Other engineered solutions Several interviewees noted but did not necessarily support earlier proposals to build structures to segment the lake into "treatment" and "natural" areas, or circular structures surrounded by trenches to facilitate the collection of mud and its subsequent containment within the circular structure.

Use the LOSOM recovery mode Several interviewees suggested implementing the recovery provisions of the Lake Okeechobee Operating Manual (LOSOM) to lower lake stage for 90 days to a point that would allow natural germination of SAV.

Try lots of approaches Many interviewees strongly supported the exploration of multiple possibilities to improve the health of the lake. These included:

- Pilot projects to test many of the specific technology or approaches outlined in this report
- Site specific efforts to restore SAV or other habitat, using a combination of the possible actions outlined here

Contingency fund Several interviewees suggested the establishment of a standing contingency fund, ideally with a dedicated source of funding for replenishment. This fund would hold sufficient monies to quickly implement large-scale measures to improve the health of the lake, as opportunities arise. The example most often cited was the opportunity for burning or excavating lake-bottom mud afforded by natural low water or drought. Taking advantage of such an opportunity would require the ability to implement measures faster than normal funding allocation processes might allow.

Establish an interagency coordinating body focused on Lake Okeechobee One interviewee recommended establishment of an interagency task force to develop and implement coordinated, multi-agency efforts to improve the health of the lake.

Aquifer Storage and Recovery (ASR) wells One interviewee recommended revisiting the possibility of using ASR technology to store excess water underground that would otherwise flow into the lake.

Additional Research Many interviewees suggested conducting additional research on a number of topics related to the possibilities described here. Among the topics for additional research were:

- The viability of natural seed beds in the lake
- Uses for removed mud
- Turbidity reduction measures
- Approaches to improving the survival of planted SAV

List of Interview Participants

Barnett	Ernie	Executive Director Florida Land Council
Bates	Terrie	Consultant, SFWMD retired
Cook	Newton	United Waterfowlers
Daniels	Keitha	Director Hendry County EDC
Eastwick	Andrew	USFWS
Eisken	Katrina	Reporter Lake Okeechobee News
Elfenbein	Mike	Isaac Walton League
Elliot	Rebecca	FDACS
Fojtik	Jake	Florida Farm Bureau
Fllori	Rosemary	Executive Director Glades County EDC
Gelber	Adam	DOI Office of Restoration Initiatives
Gibson	Brad Gibson	Guide/Outfitter
Gray	Paul	Audubon
Gray	Susan	SFWMD retired/consultant
Hooven	Jayson	B.A.S.S.
Jeffrey	Brian	USFWS
Lacey	Savannah	USACE
Martin	Scott	Scott Martin Productions/Roland Martin Marina
Owens	Kelly	Commissioner, Okeechobee County
Owens	Bob	Fisherman
Iglesias	Ramon	Commissioner, Hendry County
MacVicar	Tom MacVicar	President MacVicar Consulting
Osceola	Betty Osceola	Miccosukee Tribe of Florida

Reynolds	Jennifer	SFWMD
Ritter	Gary	City Administrator, City of Okeechobee
Stanely	Tim	Chair Glades County Commission
Swain	Hilary	Archbold Biological Station
Thompson	Travis	Cast & Blast
Watford	Dowling	Mayor, City of Okeechobee
Welch	Zach	SFWMD
Whalen	Benita	Florida Cattlemen's Association
Williams	Wes	Chair Economic Council of Okeechobee County
Wittman	Chris	Captains for Clean Water
Wright Jr.	Bishop	Lake Okeechobee Airboat Association

STAKEHOLDER WORKSHOPS ROUND 1

The first round of input workshops was held on November 6 & 7, 2024. The objectives of the workshops were to present an overview of the study of Lake Okeechobee ecosystem health, and solicit stakeholder input on the three key outreach questions:

- What changes have you observed in the ecosystem of the littoral zone in recent years?
- What factors do you think may be contributing to any changes you have observed?
- What measures do you think might help improve the health of the littoral zone?

Approximately 80 stakeholders attended one or both workshops. The agenda for both workshops was the same, and appears below:

6:00 pm Welcome and introductions
Overview of study objectives and recent trends
Discussion and collection of input:
- What changes have you observed in the ecosystem of the littoral zone in recent years?
- What factors do you think may be contributing to any changes you have observed?
- What measures do you think might help improve the health of the littoral zone?

7:50 pm Next steps and opportunities for additional input
8:00 pm Adjourn

Key points of participant input are presented below, grouped by agenda question. Subsections under each question further group input by workshop date.

Stakeholder suggestion of Potential Actions

November 6, 2024

- I would say a major solution for the lake health is, if you can minimize the spraying from September to May, you will reduce the turbidity and have better growth. And you will not cook the spry.
- Maintain lower water levels.
- Artificial purifiers for the water – Aquaphor.
- Muck in the middle historically didn't used to be there. Until we get that out, we won't be able to have the water clean. When the water could overflow during hurricanes, that cleaned it so less muck accumulated on the bottom.
- Does it go back to the straightening of the Kissimmee? After WWII, there was more industrial agriculture.
- Open up our marshes to the point where this lake breathes like it used to. You should be able to go back into Moonshine Bay and other areas. The exchange of water between those areas and the center of the lake constantly, cleaned and filtered the water. And it created a zone along the edge of the littoral zone that was clear at least half the time. Allowed eel grass to flourish. High water and hurricanes have uprooted the vegetation and piled it up along the shoreline, and there has been zero remediation of that shoreline to get the exchange of water back. Used to be once you opened a trail, duck hunters and others would keep it open, and it facilitated the exchange of water. Open those areas up – instant habitat and better water quality.
- We agree, and we need to identify a few areas – Coot Bay? – to look at wave attenuation devices. Coot Bay was an area where you could show clear water no matter how much the wind was blowing. You could show clear water, even if dark. Now, due to bottom that does not hold the grass, and spraying, we have lost the outer barrier. We will put in wave attenuation devices and test plots behind – some where we didn't touch and some where we scraped.
- Remove the muck from the lake ASAP, every day until it is all gone. We have the ability to do that. We understand the muck is the problem. Not only would that clean the water but would free up volume for additional storage.
- Lower the water.
- Redefine which grasses you might want to kill. Any vegetation is better than no vegetation. Keep the hydrilla and sawgrasses that are there.
- When the lake went down to 8.05 feet – that is what we need. Another drought. Buckhead Ridge, Tin House. The water out there now is like chocolate milk. There is no grass there.
- Basically, create a containment corral, and use vegetation that is already growing to remove nutrients and cleanse the water column.
- Replanting native vegetation.

- Number 1, we need a budget, a fund that is ready to be used for projects when the lake does get low. In the past when the water dropped, there was no money to be had. Pull from the Northern Lake Okeechobee fund or from other source. We need 25 million, recurring, sitting in that fund at all times.
- Have spent a lot of time walking around the lake in the last six months. Muck is a major issue. That is a real factor hurting this lake. Have walked most of Blue Hole, Monkey Box, Fisheating Creek where it enters the lake. There is not much in those areas. Natural lake bottom. We have lost it because we have lost the vegetation that was holding it in. If we could get the lake low in recovery mode, we have an opportunity to see vegetation rebound in those areas. Identify areas that have muck and remove. Identify areas that do not and take advantage of that opportunity to bring back vegetation.
- Mechanical removal. We need some people looking into that. You could have small harvesters at every waterway. Big ones could handle the larger open areas.
- It seems so simple. TDC dollars for Hendry are .5 million. Identify the source of funds to acquire 4-6 mechanical harvesters. Maybe one agency has to hire an additional human. A small improvement, but easier than just spraying or not doing anything.
- If the high water is here to stay, canals start to get plugged. If we had those harvesters positioned strategically, it could help eliminate some of the spraying. In the past, after some of the events, the first thing was spraying.

- Remember that the mechanical harvesters will take everything in front of them. And at the distance from shore at which they will be working, it will be hard for them to get to areas to dump the vegetation.
- We have a small mechanical harvester at the marina. When we have a large mat come in, they can go in and take it out. Agree that you can't just go in and indiscriminately harvest.
- Then you have to deal with EPA, because the material is contaminated.

November 7, 2024

- As a fisherman, I know it is very important to not change the environment during spawning. Leave the levels alone during spawning season.
- Lower the lake level. Also, more northern storage, and perhaps ASR wells.
- Clean up the bottom of the lake. Nutrient reduction project – that needs to be addressed. Clean
  up the bottom of the lake.
- What is the long-term effect of the all the chemicals you are dumping in? What will be the effects 10-20 years from now?
- Help grow some of the positive vegetation we need.
- Make LOSOM enact its recovery provisions immediately, bringing the lake down to 13 feet for 90 days.
- Septic to sewer conversion. Fewer septic tanks. Control runoff.

- Funding from the legislature for the septic to sewer conversion. We ask every year and never get anything like the amounts we need.
- Most of the homes on Lake Okeechobee are on the other side of the rim canal. The sewage from the few homes that are on the lake goes to the canal.
- Projects to replant *Hydrilla* and eelgrass along the lake.
- Create some kind of funding mechanism specific to Lake Okeechobee so we don't have to wait for legislative action on an annual basis. So we have a source that is readily available when opportunities arise (for burning, etc.). From a dedicated funding source for Lake Okeechobee.
- Back 20 years ago when the lake was in real trouble like it is now, the agencies set up a task force that meets 3-4 times a year. It had one challenge: to restore the health of the lake. All the agencies were involved. And it worked. Do that again.
- Limit development.
- The process that is in place to secure funding for water projects needs considerably more transparency than it currently has.
- I think we need to follow Louisianna in aquatic plant management. They spend $1.5 million a year on treatments. Their approach is to drawdown and clean the lake. Also they use bio-insect control. We have turtles, manatees – airlift them into lakes where they could eat the vegetation. And millions of aquatic snails are sprayed daily. They eat enormous amounts of vegetation. They could become a problem but we would not need diquat to do it.

- Manage the lake as a lake, not a reservoir.
- If we have to live with the lake at this level, why don't we find vegetation that will live in the water that deep. Bring in the hydrilla from lake Toho – it doesn't seem to die, although they have been trying hard to kill it.
- There used to be a ton of hydrilla at Hardee Pond canal. Do you know why not now? Carp? (No)

STAKEHOLDER WORKSHOPS ROUND 2

The second round of input workshops was held on December 16 & 17, 2024. The objectives of the workshops were to:

- Present an overview of the Lake Okeechobee Ecosystem Health Study
- Present considerations and possibilities identified by the study
- Discuss and solicit stakeholder input on potential considerations and possibilities identified in the study
- Suggest and discuss possible strategies for addressing issues facing the lake, reflecting the considerations and possibilities identified by the study

The agenda for the workshops appears below:

6:00 pm Welcome and introductions
Overview of study and workshop objectives
Presentation of possibilities/considerations for addressing the ecosystem health of Lake Okeechobee

- Mud removal, habitat enhancement
  - Presentation of considerations and possibilities
  - Questions for clarification
- Turbidity abatement
  - Presentation of considerations and possibilities
  - Questions for clarification
- Vegetation management
  - Presentation of considerations and possibilities
  - Questions for clarification

7:15 What is the way forward?

- Table discussions followed by full group discussions to explore strategies that take into account the considerations described in the study.
  - What pilot projects or other activities would you undertake?
  - What would you do first?
  - What do you think will have most impact?

7:55 pm Next steps – 5 min
8:00 pm Adjourn

The first four sections present input for each agenda discussion in turn. The last three sections present comments from input worksheets completed by participants.

Mud and Habitat Enhancement (Planting)

Participant questions and comments
Presenter responses are in italics. Presenter slides are available separately.

- What is the cause of the light not getting through?
- *Depth is important, even if the water is perfectly clear. Turbidity includes fine sediments that have been redistributed and reactivated and cause more turbidity than in the past. Algae collect the light as well and keep it from reaching the bottom*
- The root cause of the light not getting through is the level of the lake. I know you can't address that, but that is the critical conversation that you need to have. Are the effects of LOSOM being monitored and is that information available to the public, and is there a process to amend the LOSOM schedule? If this goes on for 10 years, there won't be anything left at all.

- Since you already have a seed bank, why do you need to plant? As soon as the water goes over 15 feet, the plants are going to die. There are better places to put the money. There are other places where the agencies are planting eelgrass on a lake and wasting the money because the vegetation dies.
- As we try to prioritize ideas for how to move forward, what is the life expectancy of the vegetation that is still in the lake?
- *The bits that are left, unless conditions deteriorate, should stay. Conditions have been suitable for them to survive this far. Making the water clearer and shallower is your best shot.*
- Didn't hear you take into account the natural tannins?
- *Anything that adds to that will make it more of a challenge. Will never be the open ocean blue.*
- The legislation talked about improving conditions for fish and wildlife. You focused on bass. How will we know how birds and other wildlife are doing? Will there be more chapters that look at other things that are ailing in the lake?

Turbidity Abatement

Presenter comments

No slides were used for this presentation.

- Part of this project is understanding the turbidity, the particles. Some of it is colloidal (very, very fine – microscopic) particles. That part doesn't come out of the water. In a large tube, it was still coming out of the water a week later. A lot of it is resuspended. That will not be changed by barriers.
- There is plenty of blue-green algae, but not enough to consistently block the light. They float up and down in daily cycle. Something goes wrong and it gets stuck at the top.
- We studied the settling rate and size of the particles, before and after Milton.
- We want to take advantage of the lake stage coming down. Will want to look at the effects and the seed back at regular intervals as the lake goes lower.
- Light penetration now is only about 1 foot into the water. Light has to penetrate further for germination to occur.
- We need to identify plausible actions. We can't just say that CERP will fix the problems. It will help some, but the short-term solutions will also be important.
- For example, try planting and growing within a large column to protect from wind and waves as the SAV gets started.
- Start small.

Participant questions and comments

Presenter responses are in italics

- Can you talk about the logistics of algicides to combat the blue-green algae?
- *It's not a swimming pool. In open water you have a limited kill zone, and everything that dies will give its nutrients to everything around it. Maybe in a marina or canal. I don't think they work more generally.*

- Strong wind tides pull the water back and forth. When the wind tide starts moving around, it draws chemicals, including herbicides (ProcellaCOR). That has a six-day life. It is a go-to for killing SAV around the state. Have you considered what happens when you plant and tides pull the chemical across that area?
- What would you consider a small-scale test area, in acres, and what depth?
- *Fairly shallow. It would not be cheap. Would like to do enough test sites to do repetition. Say 12 cylinders 6' tall. Enough to say this works here but not there. It needs to be done in the lake. The best result would be if when you take the cover off, the plants start spreading.*

Nuisance Vegetation Management
Participant questions and comments

Presenter and FWC comments are in italics. Presenter slides are available separately.

- Do the contractors buy the chemical up front and get reimbursement?
- *Yes, or FWC buys up front.*
- *It varies and depends on the extent of the project. For larger scale projects, the agency purchases. For day to day activities, the contractors purchase and we reimburse costs.*
- If they are paying up front, do they ask for reimbursement regardless of how much they have used?
- They are told how much to buy?
- *They are reimbursed only for what they actually spray. We verify that the work was done and done correctly.*
- Very familiar with this, several looking into this. Have any of you looked at the 454 schedule for Lake Okeechobee? Go look at this. Also look at accepted bid: $308 per gallon. Other contractors charge under $200/gallon.
- Has it been considered that with the lake being held higher longer, we will wind up with a massive expansion of floating vegetation? Might go from 10 to 20K acres of hyacinth.
- *As long as we stay in maintenance control as we are now, plant levels will never get to that point.*

Discussion

Participants were asked to consider the following questions, in light of the information just presented:

What pilot projects or other activities would you undertake?
What would you do first?
What do you think will have most impact?

Participants first discussed their answers with others at their tables, then shared answers with the full group.

- We want to start with something positive – we have just had two victories for the lake in 10 days. The Colonel decided to go into recovery mode. We should have the lake down to 12 feet for 90 days. And there is now a captive breeding program for the Cape Sable sparrow. That will allow us to move 18k cfs on the Tamiami Trail, which will allow the whole system to drain, including the lake.
- We agreed that some sort of pilot de-mudding program needs to be the first priority. Where the heaviest mud is, based on the maps shown in the presentation. Port Mayaca.
- Sloughing. When you didn't spray very much, we had lakes that looked like salad bowls, but with sand bottoms. Quit spraying floating plants. Allow them to clean up the water.
- FWC sprays thousands of acres statewide and on Lake Okeechobee. Cattails clean the water, and we have a fraction of what we used to have. Also, Carolina willow. We will never have recovery as long as you keep doing this.
- We have seen vegetation being cut. Just like the spraying allows more vegetation to sink and add to the issue, the vegetation being cut is allowed to lay there and sink to the bottom. If you continue to add to decaying vegetation to the bottom, efforts to de-mud or have good SAV will be problematic. Those will continue at a faster rate than the dredging can keep up with.
- I sat the Water Resources Advisory Committee. When the lake was at 8', we dredged and were going to send it to fields. EPA determined it was full of arsenic and other bad stuff and would not let us do it. Build islands with it. But you could put 5 or 6 deep-well injection wells into the bottom of the lake and put it 3000 ft. done, and in 35-40 years will get to the ocean, and will bubble up there. Cheap, requires no property. And it will work.
- The easiest, quickest and simplest thing is to manage the lake level.
- Specifically, that gets back to monitoring regularly the impacts of LOSOM and having policy in place that allows for amendment of LOSOM.
- After LOSOM, as the EAA reservoir comes online, there will be a complete relook at how the schedule works.
- Port St. Lucie, PSL utilities, they haul tons of mechanically harvested SAV. Right now they put it on fields. You could probably get what you need for replanting without going to Lake Apopka, and it has been only minimally sprayed. It's a mix of hydrilla, coontail, eelgrass, and others species. But there would be no point to doing this unless you stop spraying.
- Policy suggestion for reimbursing contractors: if I buy herbicide, and get reimbursed only for what I use, will do everything in my power to use as much as I can.
- The majority of the population lives on the coast, and we should educate them about how much the lake means to them, and maybe they would give us a hand with it.

- Enforcement of agricultural Best Management Practices.

- We need more surveys in the lake of wildlife trends and populations – document success or say this isn't working. Basically accountability. Systematic monitoring of birdlife, amphibians, turtles, everything that goes to make up the ecosystems.

Top three pilot projects (from worksheets)

- Pilot mud removal project, consider ideas from the Diatom Group
- Turbidity barrier experiments/research, with and without plantings
- Muck removal – east side of the lake
- Wave attenuation at a small area in Buckhead Ridge at Indian Prairie
- Stop spraying in the marsh, stricter monitoring of contractors
- Control water level
- Control spraying so you don't kill the plants you want to live
- STA – runoff filtrations
- STA – runoff
- What a cow field can filter before it gets here
- Projects to "de-muck" the lake and stop projects (i.e., spraying) to stop adding vegetation
- Use mechanical harvesting (or other methods) instead of spraying
- Manage lake level to enhance natural cycle
- Not true: oxygen plants
- With consideration to level of lake, plant test beds in various levels of the lake to study growth response
- Mud removal via deep well injection to boulder zone which takes muck to bottom of Atlantic ocean
- Turbidity studies, based on lake levels, to evaluate effect on SAVs
- 5 to 10 deep injection wells in lake "sinks" holding muck. Send muck 300 ft into boulder zone to Atlantic Ocean
- Build structure at south end of Lake that will drain 18,500 cfs south (now only 6,000 cfs)
- Slow flow into the lake from the north. Expand Kissimmee River restoration. Construct north reservoir.
- Managing the lake water at a lower level will help the lake health and mother nature will take place
- Remove the mud even if only to build muck islands
- Use more mechanical vegetation removal
- Pilot dredge project to remove mud as well as dead vegetation from the lake
- **Diatom Lagoon** – silt/fluid mud collected into a spoil island and water filtered back out through a littoral zone on the outer perimeter of the island
- Suction dredge of fluid mud in the deepest parts of the lake – Northeast area by Port Mayaca

- BMP enforcement

- Mechanical vegetation removal – actually remove the cuttings so the vegetation doesn't add organic material!
- Dredge from the center of the heaviest concentration of muck
- Continue dredging
- Continue exploring wave attenuation measures
- Restore at least some littoral zone on the east side of the lake

Most Impactful Actions (from worksheets)

- Wildlife surveys: we cannot assess whether we are benefiting fish and wildlife unless we know their population levels and trends. Without such information, management "flies blind." Accountability depends on this. Include harvest surveys for waterfowl, snipe and other birds.
- Adding more SAV
- Army Corp change policy
- Lower lake level and less spraying
- Enact recovery provision of LOSOM yearly to give new SAV a chance
- Flow water down to the south of the lake to managed lake levels. Lake levels being reduced will help to correct many of the current problems we face.
- Build 18,500 cfs structure at south end of lake now that action has begun to remove the CSSS blockage at the Tamiami Trail.
- LOWER LAKE LEVEL
- Managing nuisance plants will have the most impact in the short term, as these out-compete and drive loss of native vegetation
- BMP enforcement in the entire basin
- Short term, change the way contractors are paid for chemicals, so they aren't incentivized to use more to make more money
- Medium term, reconsider lake levels/water savings clause redo when EAA reservoir is done
- Consider starting with wave attenuation, then dredging

Additional Considerations (from worksheets)

- Better vegetation community monitoring for trends. They are starting to use new technology to do this and it needs more funding.
- Farming SAV – floating islands
- Lake level. Lack of vegetation. STA
- 1 foot visibility – why?
- Build structure at south end capable of moving 18k cfm at minimum
- Add flow structure on the south end of lake to allow flow south to the trail
- More water releases east and west
- Inputs to the lake should be heavily considered. Addressing nutrients from the north is vital to a proactive approach and addressing the problem at one of the major sources

- Critical considerations moving forward - discontinue any projects or management of the lake that allows freshly sprayed or cut vegetation to settle on the bottom of the lake adding to the mud and decay already there.
- Water storage north of the lake as well as cleaning water before it enters the lake. Storage south of the lake will not have an impact on the condition of Lake Okeechobee.
- As was discussed during the meeting/workshops, planting SAV is likely to be a futile effort as long as the lake levels are kept too high (based on current LOSOM schedule) because light will not be sufficient to support SAV growth and viability.
- Finally – regarding LOSOM, and accountability thereof – there is a need to have a transparent process in place to: 1) monitor the impact of LOSOM; 2) prepare and allow access to studies and the results of their studies monitoring said LOSOM impacts; and 3) have a policy/practice in place to allow for an amendment process for LOSOM based on regular, ongoing studies.
- Re: chemical spraying – change policy regarding how contractors are reimbursed for chemicals purchased. If I understand this correctly, they are buying – at this time – the product out of pocket and then reimbursed for what they used/sprayed. I feel this incentivizes the contractors to use all the chemical they have invested in whether needed or not.
- Monitoring of more indicator species
- Rethink what is being planted (SAV)
- Need definition of "monoculture." Many natives targeted should not be: we need list of nuisance plants, with justification. Protect pistia meadows except for navigation
- Monitor LOSOM to see impact on lake health. Study building islands in the lake with mud (muck) to keep inside the lake and clean bottom.
- Apply A.I./machine learning tools to spraying technology to help identify specific weedy plants to target with herbicide to avoid spraying desirable plants

Appendix 4: Turbidity- Biogeochemical characterization of suspended and underlying sediments in Lake Okeechobee

Prepared by: Florida Atlantic University-Harbor Branch Oceanographic Institute: Jonathan Terzado, Mason Thackston, Christian Walker, Hanna Bridgham, Alexis Base, Steven Soini, Vivian Merk, Wayne Slade, Aditya Nayak, and Jordon Beckler; and Florida Gulf Coast University Water School: Megan Feeney, Serge Thomas, Puspa Adhikari and Barry Rosen.

Appendix 4. Executive Summary

Submerged aquatic vegetation (SAV) plays an important role in sediment retention and nutrient reduction in lakes. For lake Okeechobee, water transparency and depth are key variables that affect SAV cover (Havens, 2003; Steinman et al., 2002). SAV biomass is negatively impacted by turbidity (suspended solids) (Havens, 2003). Turbidity (rather than color or chlorophyll) is responsible for the majority of light reduction in lake Okeechobee (Havens, 2003). Suspended solids can prevent the growth of SAV by blocking the light needed for photosynthesis. Hurricanes can resuspend large amounts of lake sediments and uproot SAV beds (T. R. James et al., 2008; Jin et al., 2011).

Here we better characterize the suspended solids in lake Okeechobee following a hurricane event at two sites. We determine the size of suspended solids in lake Okeechobee by filtering water through filters with increasingly small pore sizes. We characterize the biological, chemical and geological makeup of suspended solids and underlying sediments. We profile light through the water column. Settling experiments were conducted to determine the rate at which turbidity settles out of the water column, both using natural waters and in simulations of deliberate sediment erosion.

At the time of sampling, light (photosynthetically active radiation, PAR) was not sufficient to either yield photosynthesis (euphotic zone) or counteract respiration (compensation depth) near bottom of the water column. The depth of the euphotic zone, the layer of water with enough light for photosynthesis to occur, was consistently shallow. On average, photosynthesis could only occur as deep as 1.7 feet (0.53 m) for algae and hydrilla (defined as 1% of subsurface PAR) and 1.1 feet (0.34 m) for vascular plants (defined as 20% of subsurface PAR) deep including all sites and all time points sampled. Issues with light penetration continue to persist for one month following hurricane Milton. The growth and distribution of submerged aquatic vegetation in lake Okeechobee is limited by light (Steinman et al., 1997). These prolonged periods of limited light penetration would prevent the growth of aquatic plants in deeper water and remain a significant challenge to SAV recovery.

Resuspended sediment responsible for light reduction in lake Okeechobee primarily consists of small particle sizes (<10 µm). Based on chemical composition, a significant fraction of this material is transported laterally from the deep, mud-rich lake areas. These smaller particle sizes will take longer to settle out of the water column. Through settling experiments, we determined that it takes 24-48 hours of no disturbance for the suspended solids to settle out of the water column. Cold fronts, generating strong winds and waves in lake Okeechobee, help prevent this material from settling out of the water column (Jin et al., 2002; Jin & Ji, 2004)

. Sediments resuspended from hurricanes can remain in the water column for years (T. R. James et al., 2008; Jin et al., 2011). Further action is needed to improve light penetration and reduce turbidity in Lake Okeechobee. Temporary lowering of the lake stage could help improve conditions for SAV recovery. The periods of drought following hurricanes have contributed to lowering turbidity in the lake and has improved SAV recovery (T. R. James et al., 2008). Lower water levels would allow the euphotic zone to reach deeper areas of the lakebed to better support SAV growth.

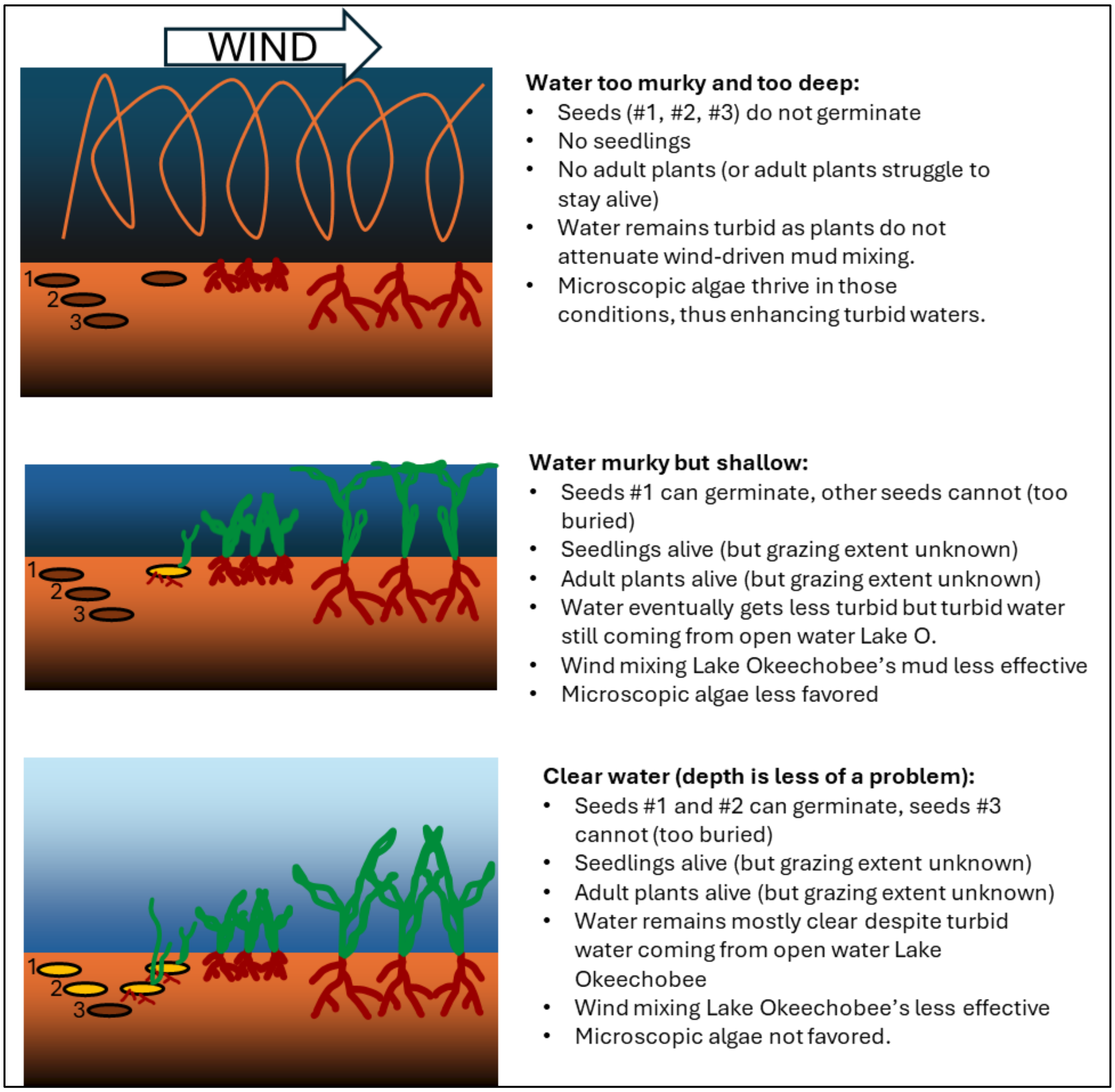


Figure illustrating the various conditions affecting both SAV and SAV seeds growth in Lake Okeechobee. The top cartoon represents the current self-feeding condition, the second carton represents a lowering of lake level to allow SAV and SAV's seed germination (triggered by light), and the third cartoon represents the ideal condition of a stable state with clear water and thriving SAV. Note that although light reaching the lakebed is the main driving factor, grazing as well as seed bank conditions need also to be assessed.

Appendix 4. Scientific Details

Submerged aquatic vegetation (SAV) plays an important role in sediment retention and nutrient reduction in freshwater lakes (Dierberg et al., 2002; Knight et al., 2003; Vermaat et al., 2000). Water transparency and depth are key environmental variables for SAV coverage in Lake Okeechobee (Havens, 2003; Steinman et al., 2002). Of all SAV species in Lake Okeechobee, *Chara* spp. was reported to have the highest biomass (Havens, 2003). *Chara* spp. biomass was strongly negatively correlated with total suspended solids (TSS) and inorganic suspended solids (Havens, 2003). This TSS is responsible for the majority of light reduction in Lake Okeechobee, compared to color (Pt Units) and Chlorophyll *a* (μg/L) (Havens, 2003). Here we characterize suspended solids from two sites in Lake Okeechobee following a hurricane event. Particle size was characterized through a series of sequential size fractionation filtration steps. Carbon content and extracellular polymeric substances (EPS) of resuspended sediments were determined. Light (photosynthetically active radiation, PAR) was profiled through the water column. Settling experiments were conducted to determine the rate at which turbidity settles out of the water column.

Resuspended sediment responsible for light reduction in Lake Okeechobee primarily consists of small particle sizes (<10 μm). The carbon content of resuspended sediment in or adjacent to the littoral zone is greater than the organic content of the respective underlying sediments in Lake Okeechobee, suggesting that mud is transported laterally from deeper, pelagic areas or that localized water column organic production could further modify the chemical composition. Indeed, EPS is an important component of the suspended particulates, which were found to be largely unstructured organic-mineral aggregates in form. The suspended sediments, however, are less dominated by detrital iron oxides relative to deep lake areas, and instead presumably phytoplankton-derived production of calcium carbonate and silica minerals is more prevalent in the littoral zone. These findings suggest that turbidity mitigation measures may present disparate efficacy depending on the lake zone.

At the time of sampling, PAR did not reach the bottom of the water column. The depth of the euphotic zone (defined at the depth where 1% of subsurface PAR reaches), the layer of water with enough light for photosynthesis to occur, was consistently shallow. Following Hurricane Milton on 10/18/2024 this was 0.315 m at the LOCB site and remained shallow for the duration of sampling (0.691 m on 10/25/2024, and 0.406 m on 11/22/2024). The euphotic zone was deepest at the LOSS site on 11/22/2024 at 0.790 m. On average photosynthesis for algae and hydrilla could only occur at 0.53 m deep including all sites and all time points sampled. For vascular plants like *Valisneria* and *Potamogeton*, this figure is even reduced to 0.34 m (using the 20% of subsurface PAR figure instead of 1%). As a rule of thumb, this is about one Secchi disk depth. Issues with light penetration continue to persist for one month following Hurricane Milton. The growth and distribution of *Chara* spp. in Lake Okeechobee is limited by light (Steinman et al., 1997). Prolonged periods of limited light penetration would prevent the growth of macrophytes in deeper water.

Through settling experiments, we determined that it takes 24-48 hours of no disturbance for this resuspended particulate to settle out of the water column. Cold fronts, generating unidirectional winds, high waves, and high shear stress at the bottom of Lake Okeechobee, further prevent this material from settling out of the water column (Jin et al., 2002; Jin & Ji, 2004). Material resuspended by hurricanes takes a long time to consolidate and settle out of the water column and can persist for more than 4 years following a hurricane event (T. R. James et al., 2008; Jin et al., 2011). Further action is needed to improve light penetration and reduce turbidity in Lake Okeechobee. Temporary lowering of the lake stage could help improve conditions for SAV recovery. The periods of drought following hurricanes have contributed to lowering turbidity in the lake and has improved SAV recovery (T. R. James et al., 2008). Lower water levels would allow the euphotic zone to reach deeper areas of the lakebed to better support SAV growth.

These findings are presented as part of three chapters:

1. A comprehensive bulk characterization of Lake Okeechobee suspended and underlying sediments to elucidate the origin, composition, reactivity, fate, and interconnectedness during erosion events. This study addresses themes such as algal vs. detrital and inorganic vs. organic of the suspended sediments, as well as elemental composition which serves as a tracer of origin.

2. A more detailed examination of the particle size classes in the lake, as well as their respective contributions to light attenuation. This chapter provides further information regarding particle composition in situ, i.e., the extent that particles aggregate and how this affects their persistence and light attenuating properties.

3. An examination of the dynamics of the above properties as a function of environmental conditions, and major implications for light availability for SAV.

Sampling Overview

The following three Chapters present a synthesis of field and laboratory work designed to understand the turbidity issue and conducted on three occasions at each of two sites (Fig. 1). Site LOCB has a depth of approximately 1 m in an open basin on the northeastern edge of a grassy marsh, just south of the navigable Intracoastal Waterway channel. The site is relatively exposed, with an approximate ~40-mile fetch during NE wind events and thus transport of more pelagic lake water is possible, while its geography may also enable influence from canal discharges. Site LOSS, while deeper (~2 m), lies directly adjacent to the marsh at the entrance to Mayaka Cut and is sheltered from wind on all sides except from the east. It was selected due to the observation of bass fishermen in the adjacent marsh. Site LOLZ is in the littoral zone wetlands of west Lake Okeechobee and has a water depth of only 0.4 m. Site LOPE is in the central pelagic zone of the lake directly adjacent to the SFWMD LZ40 monitoring tower with a water depth of ~4 m. Hurricane Milton passed through the area on 10/9/24, and the sites were sampled on 10/18/24 (LOCB and LOSS), 10/25/24 (LOCB) and 10/28/24 (LOSS), 11/22/24 (LOCB and LOSS), 2/4/2025 (LOPZ), 2/6/2025 (LOCB and LOSS), and 2/10/2025 (LOLZ).

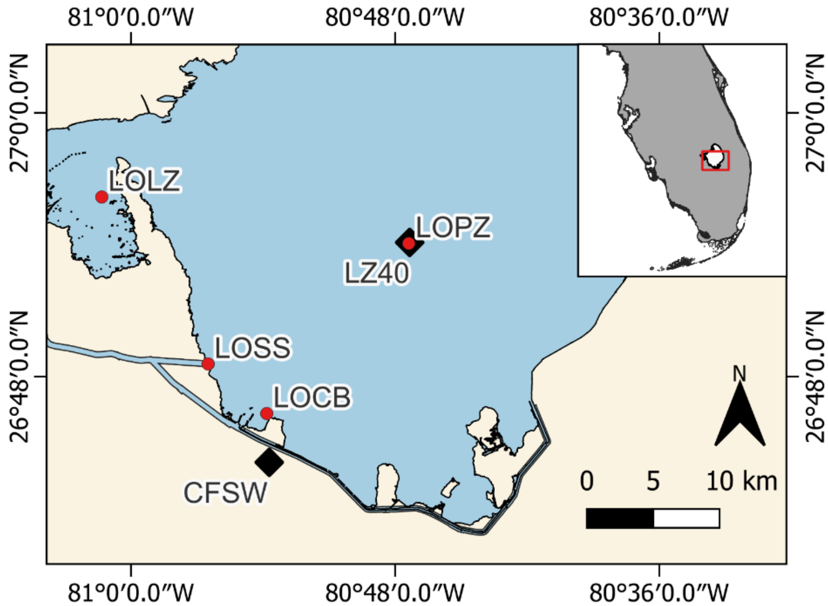


Figure 1. Site map. Samples were collected from two sites; one located in Coot Bay (LOCB) and one to the north of Coot Bay (LOSS).

REFERENCES

Dierberg, F. E., DeBusk, T. A., Jackson, S. D., Chimney, M. J., & Pietro, K. (2002). Submerged aquatic vegetation-based treatment wetlands for removing phosphorus from agricultural runoff: response to hydraulic and nutrient loading. *Water Research*, *36*(6), 1409–1422.

Havens, K. E. (2003). Submerged aquatic vegetation correlations with depth and light attenuating materials in a shallow subtropical lake. *Hydrobiologia*, *493*, 173–186.

James, T. R., Chimney, M. J., Sharfstein, B., Engstrom, D. R., Schottler, S. P., East, T., & Jin, K.-R. (2008). Hurricane effects on a shallow lake ecosystem, Lake Okeechobee, Florida (USA). *Fundamental and Applied Limnology*, *172*(4), 273.

Jin, K.-R., Chang, N.-B., Ji, Z.-G., & James, R. T. (2011). Hurricanes affect the sediment and environment in Lake Okeechobee. *Critical Reviews in Environmental Science and Technology*, *41*(S1), 382–394.

Jin, K.-R., & Ji, Z.-G. (2004). Case study: modeling of sediment transport and wind-wave impact in Lake Okeechobee. *Journal of Hydraulic Engineering*, *130*(11), 1055–1067.

Jin, K.-R., Ji, Z.-G., & Hamrick, J. H. (2002). Modeling winter circulation in Lake Okeechobee, Florida. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, *128*(3), 114–125.

Knight, R. L., Gu, B., Clarke, R. A., & Newman, J. M. (2003). Long-term phosphorus removal in Florida aquatic systems dominated by submerged aquatic vegetation. *Ecological Engineering*, *20*(1), 45–63.

Steinman, A. D., Havens, K. E., Rodusky, A. J., Sharfstein, B., James, R. T., & Harwell, M. C. (2002). The influence of environmental variables and a managed water recession on the growth of charophytes in a large, subtropical lake. *Aquatic Botany*, *72*(3–4), 297–313.

Steinman, A. D., Meeker, R. H., Rodusky, A. J., Davis, W. P., & Hwang, S.-J. (1997). Ecological properties of charophytes in a large subtropical lake. *Journal of the North American Benthological Society*, *16*(4), 781–793.

Vermaat, J. E., Santamaria, L., & Roos, P. J. (2000). Water flow across and sediment trapping in submerged macrophyte beds of contrasting growth form. *Archiv Für Hydrobiologie*, *148*(4), 549–562.

Appendix 4, Chapter 1.

Biogeochemical characterization of suspended and underlying sediments in the Lake Okeechobee littoral zone

INTRODUCTION

Submerged aquatic vegetation (SAV) includes any vegetation growing completely submerged below the waterline. SAV plays an important role in improving water clarity through sediment retention and nutrient reduction with both photosynthesis and increased sedimentation in freshwater lakes (Dierberg et al., 2002; Knight et al., 2003; Vermaat et al., 2000). The added underwater structure of SAV slows water movement and reduces bed shear stress, increasing sedimentation rates (Hestir et al., 2016). Lakes dominated by SAV are characterized as having higher than expected water transparency (Jeppesen et al., 1990). SAV are important primary producers supporting higher trophic levels (Thomaz, 2023). SAV serves as an important habitat for invertebrates and small fish which in turn affects higher trophic levels including sport fish populations (Deosti et al., 2021; Dibble & Thomaz, 2009; Gomes et al., 2012; Thomaz, 2023).

Lake Okeechobee is a large, shallow, nutrient rich, freshwater subtropical lake that is subject to frequent blooms of cyanobacteria (Dang et al., 2023). Historically, one-third of the bottom of Lake Okeechobee was covered with a stiff organic mud, the western half of the lake had a sandy bottom, and the eastern and southern parts had rock or calcareous marl with peat deposits along the southern margin (Missimer et al., 2020). High nutrient loading since roughly 1900 has increased the sedimentation rate in the lake, resulting in the accumulation of fine grain mud sediments (Brezonik & Engstrom, 1998). Sedimentation rates have increased by a factor of two between 1860 and 1980, and the spatial extent of mud sediments has expanded especially in the southern direction between 1975 and 1988 (Brezonik & Engstrom, 1998; K. E. Havens & James, 1999). Currently, an unconsolidated floc layer of a thixotrophic, fluid like organic mud that can be resuspended with little energy sits on top of consolidated mud layers (Missimer et al., 2020). Increased sedimentation rates are likely due to increased organic production due to eutrophication (Brezonik & Engstrom, 1998). The expansion and redistribution of mud sediments in Lake Okeechobee has resulted in increased turbidity in southern portions of the lake (K. E. Havens & James, 1999).

SAV biomass in Lake Okeechobee is low and dominated by *Chara* spp. (Havens, 2003). *Chara* spp. biomass was strongly negatively correlated with total suspended solids (TSS) and inorganic suspended solids (Havens, 2003). This TSS is responsible for the majority of light reduction in Lake Okeechobee, compared to color (Pt Units) and Chlorophyll *a* (chl *a)* (µg/L) (Havens, 2003). In shallow regions, frequent exposure to winds resuspends soft mud sediments into the water column, resulting in high light reduction (Havens, 2003; Steinman et al., 2002). The availability of light limits the growth of SAV in these areas. Storm events can result in additional SAV loss;

uprooting SAV and generating high concentrations of TSS (Chimney, 2005; Hanlon & Jordan, 2023) . In Lake Okeechobee, dense SAV cover is only found at locations where water depth was <2m and TSS was <20-30 mg/L (Havens, 2003).

Here we better characterize the biogeochemistry of both the resuspended and underlying sediments. This study focuses primarily on directly characterizing the organic and inorganic composition of these particulates in an effort to elucidate their origin, reactivity, and fate. We used a combination of bulk characterization, i.e., analyses of surface and deep sediments and suspended particulates concentrated on a filter, as well as more directed analysis of individual particles using spectroscopy and microscopy techniques.

One particular analyte of interest was extracellular polymeric substances (EPS) biopolymers, a matrix of various compounds secreted by microorganisms or released with cell lysis (More et al., 2014). EPS production plays an important role in sedimentation and can contribute to the adsorption and deposition of pollutants (Decho & Gutierrez, 2017; W. Li et al., 2021). Bacterial and microalgal communities are both important producers of EPS in freshwater sediments and marine surface waters (Decho & Gutierrez, 2017; Gerbersdorf et al., 2009). EPS has been tested for use in removing suspended solids, natural organic matter, and turbidity in drinking water and wastewater treatment applications (Siddharth et al., 2021). To our knowledge, EPS has not yet been quantified in lake Okeechobee. A better understanding of how much algal EPS is present in suspended solids from Lake Okeechobee is needed given its importance in particle aggregation, and thus, sedimentation.

METHODS

Sampling and processing. For bulk suspended sediment characterization, 5L of surface water was collected from all four sites (LOCB, LOSS, LOPZ, LOLZ) in 10 L LDPE carboys and transported at ambient temperatures for filtration onto 47 mm GF/F filters immediately following field collection. At the LOCB site only, 3 L of surface water was collected in HDPE bottles for EPS extraction.

Immediately after collection, surface water samples were processed on-site at a field lab. A total of 250 mL water was filtered onto individual, pre-weighted 47 mm GF/F filters which were transported on ice and frozen (-20 °C) for CHN analysis, iron (Fe) mineral phase partitioning and gravimetric total suspended solids (TSS) measurements. For EPS extraction, 100 mL of surface water was filtered onto 47 mm, 0.4 µm pore size polycarbonate (PCTE) membrane filters under low pressure (150 mm Hg) and filtrate was retained for fine-scale PAR profiles (Azetsu-Scott & Passow, 2004). An additional 100 mL of surface water was filtered onto pre-weighted 47 mm, 0.4 µm pore size polycarbonate (PCTE) membrane filters for TSS determination. For gravimetric TSS determination pre-weighted filters were dried to a constant weight at 103-105° C and re-weighed to compute TSS as mg/L.

Intact sediment cores were collected only from LOCB and LOLZ using a telescopic pole corer vacuum suction device with a 3.5" diameter core coupler assembly (Fig. 1). The overlying water of the sediment cores was aerated for transport, to prevent artificial hypoxia. Samples were stored at ambient temperatures in the light for transport to the lab. Sediment cores were extruded in a glove bag saturated with nitrogen gas and manually sectioned into 0-2 mm, 2-10 mm, and 10-50 mm sections. Recovered solids were used to determine porosity and sediment composition of total C, total N, organic C, organic N, amorphous Fe, reactive Fe, and total Fe.

Figure 1. Sediment core photograph. Cores were collected from LOCB using a 3.5” diameter telescopic pole corer.

Carbon and nitrogen determination. Total non-purgeable organic carbon (NPOC) and total nitrogen (TN) of water samples was determined using a Shimadzu TOC-L total organic carbon analyzer (Shimadzu, Kyoto, Japan). Samples were acidified with 35 µL of concentrated HCL to remove inorganic carbon and sparged for 2 minutes with high purity air to purge volatile organic carbon before measuring. CHN analysis was conducted on dried samples using a Thermo FlashSmart elemental analyzer (ThermoFisher Scientific, Waltham, Massachusetts, USA). Samples were combusted at 950 °C in the presence of oxygen and copper (II) oxide for the determination of C and N mass percent of sample. For organic C and N, separate dried sample was fumigated with 37% HCL in a desiccator for 24 hours. Acidified samples were then heated at 60 ° C using a hot plate for 24 hours.

Iron partitioning. Dithionite-extractable and total iron content of solids was determined using methods modified from Kostka and Luther III (1994). Dithionite reagent was prepared with 0.17M sodium citrate, 0.35 M ammonium acetate, and 0.287M sodium dithionite. Aqua regia reagent was prepared for total iron content as a mixture of concentrated HCl with HNO_3 in a 3:1 ratio. 20 mL of dithionite reagent or aqua regia reagent was added to GF/F filters with TSS sample and samples with dithionite reagent were incubated in a hot water bath at 60 ° C for 4 hours. The samples were manually agitated every 15 minutes. Following extraction, samples with dithionite were centrifuged for 5 minutes at 2000 RPM and supernatant was frozen for further analysis. Samples with aqua regia reagent were extracted for 24 hours at room temperature in a fume hood and were subsequently brought to a working pH range of 4-6 using 5M sodium hydroxide. Supernatant was later analyzed spectrophotometrically for total extracted Fe $(II)_d$ using the ferrozine technique on a 1 cm path length at 562 nm with an Ocean Optics Flame Spectrometer (Viollier et al., 2000). A solution of hydroxylamine hydrochloride was added to reduce Fe(III) to Fe(II) before measurement. 100 µL of hydroxylamine hydrochloride reagent (0.1 M HCL, 0.2 M hydroxylamine hydrochloride) was added to a total volume of 1.8 mL of sample and left to react in the dark over 12 hours before determination using the ferrozine technique.

EPS determination. EPS, as both loosely bound EPS (LB-EPS) and tightly bound EPS (TB-EPS) was extracted using methods modified from Ye et al. (2011). For LB-EPS, 15 mL of saline (0.05% NaCl) was added to sample filtered onto 0.4 µm pore size polycarbonate filters. These were lightly sonicated at 20 kHz and 300 W L^{-1} for 2 minutes non-pulsed using a FB120 sonic dismembrator (ThermoFisher Scientific, Waltham, Massachusetts, USA). This was followed by horizontal shaking at 150 rpm for 10 minutes at 25 °C. Samples were centrifuged at 3220 g for 10 minutes and the remaining supernatant was saved for LB-EPS determination. Supernatant was filtered through 0.2 µm pore size PES membrane filters to retain any solids. Remaining solids were resuspended with 15 mL of saline (0.05% NaCl) for TB-EPS extraction and sonicated at 20 kHz and 300 W L^{-1} for 3 minutes non-pulsed. Samples were incubated in a hot water bath at 60 °C for 30 minutes and then centrifuged at 3220 g for 20 minutes. Supernatant was retained for TB-EPS determination and filtered through 0.2 µm pore size PES membrane filters to remove any solids. LB-EPS and TB-EPS samples were stored at -20 °C for total carbohydrate, protein, and total organic carbon (TOC) content. TOC content was analyzed using a TOC analyzer (TOC-LCSH, Shimadzu scientific instruments, Tampa, FL, USA). Protein content was determined using a modified Lowery method to account for humic acid interference, using BSA (bovine serum albumin) as a standard (Frølund et al., 1995; Shen et al., 2013). Carbohydrate content was determined using the antherone-sulfuric acid method with glucose as a standard (Frølund et al., 1996). To relate EPS back to TSS, additional sample on pre-weighted 0.4 µm pore size polycarbonate filters was dried at 60 °C for 7 days before weighing.

Advanced microscopy and spectroscopic characterization. All sediments and raw water samples were freeze-dried and stored in a desiccator under nitrogen until further analysis by Scanning Electron Microscopy, Transmission Electron Microscopy with SEM-based elemental mapping (TEM/TEM-EDS), Fourier-Transform Infrared Spectroscopy (FT-IR), and x-ray diffraction (XRD). Freeze-dried samples were suspended on double-sided carbon tape (PELCO) on an aluminum stub. Prior to SEM analysis, samples were sputter-coated with a 10-15nm thin layer of platinum under an argon atmosphere at 8mA for 30s using a MicroNanoTools MNT-JS1600 plasma sputtering coater. SEM images were collected with a COXEM EM-30N tabletop SEM at acceleration voltages of 9-15kV using a secondary electron (SE) detector under high vacuum conditions.

For TEM, lake water was dropped onto B-type carbon-coated TEM grids (PELCO) and left to dry in a desiccator. A 10µg of freeze-dried sediment sample resuspended in 1mL water was dropped onto a TEM grid to ensure adequate particle dispersion. A 120kV JEOL JEM-1400 transmission electron microscope (TEM) equipped with a scanning TEM unit for bright-field and dark-field imaging, and Oxford AZtec energy-dispersive X-ray detector was utilized to image the particles and perform elemental microanalysis.

FT-IR spectra were obtained from freeze-dried powders with a Thermo Scientific Nicolet iS10 Infrared spectrometer equipped with attenuated total reflection (ATR). FT-IR spectra were acquired from 400-4000 cm^{-1} with 120 scans at 2 cm^{-1} spectral resolution using the OMNIC Series Software and the data were displayed and analyzed using the Origin 2020b software. The spectral raw data were baseline-corrected using atmospheric correction and subsequently normalized against the highest corrected absorbance. XRD patterns were collected over $2\theta = 5\text{-}80°$ using an Anton Paar XRDynamic 500 Diffractometer equipped with a copper source.

Chapter 1: RESULTS AND DISCUSSION

Bulk characterization of suspended and underlying sediments. Sediments at LOCB consisted of mostly dense peat material with some dark brown to black mud mixed throughout. This area of the lake is not considered the pelagic area where legacy muds known as thixotropic muds are known to accumulate (Missimer et al., 2021), and thus sediment types were visually consistent with previous literature observations. Site LOLZ exhibited sediments that consisted mostly of living macroalgae, SAV roots, and other detrital organic material overlying a layer of sand. On the other hand, while we attempted to collect sediments at LOPZ, we could not successfully retain any sediment using our pole coring device due to depth constraints. Therefore, there is no sediment data presented for LOPZ.

Figure 2 shows solid phase data for organic and inorganic concentrations of C obtained from sediment cores at LOCB and LOLZ. TSS measurements from the mid-water column show distinct organic and inorganic fractions, while sediments are composed of predominately organic C (C_{org}) at both LOCB and LOLZ. Concentrations of C_{org} (and total C) increase with depth in the sediment, but C_{org} in the water column is notably higher than in near-surface sediments in all cores except the cores collected on 10/25/2024 and 02/06/2025 at LOCB, while total C is always more elevated in the water column. While considerable variability exists between the replicate samples from 10/18/24 (R1 and R2, Figure 2), the suspended particles are more enriched in inorganic carbon relative to the sediments, suggesting mixing with an allochthonous source (i.e., the pelagic lake area) or in situ phytoplankton production. Greater C content is associated with lower settling velocities and increased sediment instability, making material easier to resuspend (Gowland et al., 2007). Greater C_{org} in the deeper layers of sediment could mean that dredging would only further destabilize lake sediments.

While not necessarily surprising given we expected to find high concentrations of EPS in the water column, the increase of C_{org} with depth in sediments is surprising, considering that deeper sediments should represent older, more degraded sediments (i.e., loss of C_{org} but accumulation of inorganic carbon phases). This suggests that long term (year to decade) depositional processes are variable, or that the surface sediments have selectively lost C_{org} due to frequent resuspension. The loss of SAV could be a cause of both processes, as we would expect a decrease in newly fixed organic carbon production and storage, as well as more intense sediment resuspension events due to a more exposed lake floor (analogous to the "dust bowls" of the 1930s). Considering that lakes are considered important carbon reservoirs, this finding has important implications for carbon sequestration (i.e., a decreased burial efficiency). And because of this, dredging in these areas would decrease sediment stability and likely cause more problems with low water clarity (Gowland et al., 2007).

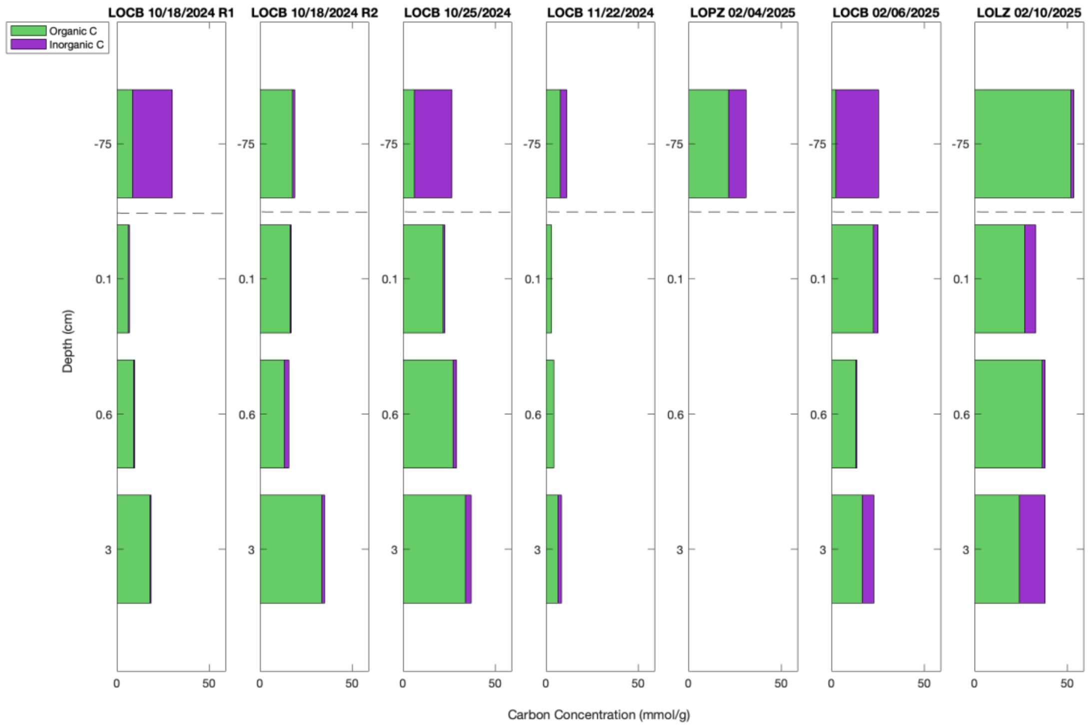


Figure 2. Solid-phase C sediment core profiles. Organic and inorganic carbon fractions were measured from site LOCB in the mid-water column (suspended sediments at 75 cm above the sediment-water interface) and at distinct depth points (.1, .6, 3.0 cm) in the sediment. The dashed line represents the sediment-water interface (SWI, 0 cm). Duplicate sediment cores were collected on 10/18/2024 indicated by R1 and R2, respectively. Sediment was not collected from LOPZ.

Figure 3 shows solid-phase N concentrations present during sampling in Coot Bay and LOLZ. TSS measurements show the relatively high concentration of N in the mid-water column compared to the sediment. Sediment N concentrations increase with depth and largely mirror patterns of carbon, consistent with organic matter accumulation and storage. This lack of storage at the surface is again potentially attributable to a decline in SAV, which is an important finding with respect to mitigation approaches such as dredging. It is thus important to capture the suspended sediment load and not to focus solely on removing underlying sediments.

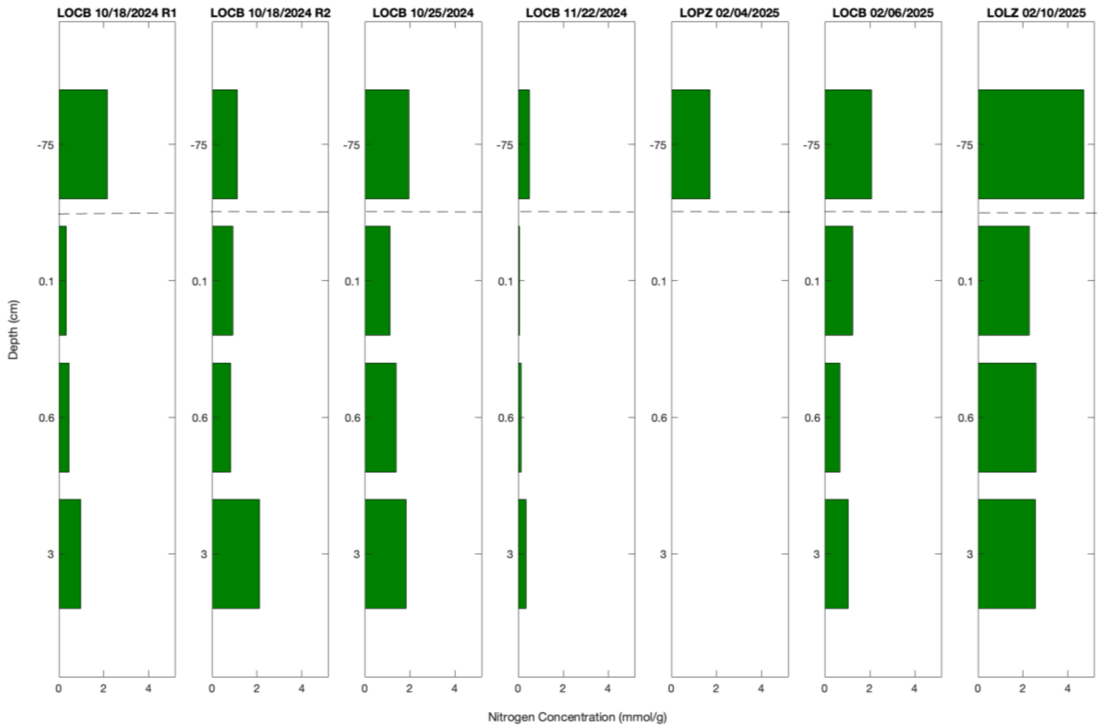


Figure 3. Solid-phase N sediment core profiles. Total nitrogen was measured from site LOCB and LOLZ in the mid-water column (suspended sediments at 75 cm above the sediment-water interface) and at distinct depth points (0.1, 0.6, 3.0 cm) in the sediment. The dashed line represents the sediment-water interface (SWI, 0 cm). Duplicate sediment cores were collected on 10/18/2024 indicated by R1 and R2, respectively. Sediment was not collected from LOPZ.

All solid-phase Fe data can be found in Figure 4. Total Fe concentrations were far greater in suspended solids than in the sediment across all sampling events except at LOLZ, presumably due to lateral transport from the Fe-rich deepwater legacy mud accumulation areas. Without another explanation, this suggests that solid phase iron serves as an excellent tracer of this pelagic lake material. This also suggests that the relatively low Fe concentrations in suspended particles compared to the sediments at LOLZ could be attributed to the lack of sediment transport from the pelagic zone due to the dense grass and SAV abundance in this area of the lake. Most of the Fe was in a phase that is not redox active (i.e., other Fe) in both the suspended sediments and underlying sediments, although total Fe in TSS was not measured for the first replicate from the sampling event on 10/18/24 (and thus "other Fe" cannot be derived by difference), and reactive Fe comprised almost the entire Fe pool of suspended sediments on 11/22/24. However, reactive Fe dominated the total Fe pool in the surface most sediment layer and gradually decreased with depth, indicative of reductive dissolution via microbial Fe respiration. At the same time, the overall total Fe pool increased in concentration with depth as well as the fraction of other Fe, suggesting sequestration of Fe in non-redox active phases such as vivianite ($Fe_3(PO_4)_2$) or siderite ($FeCO_3$), which is common in Fe-rich freshwater sediments (Rothe et al. 2016). On the other hand, total Fe in the sediments at LOLZ was more than double in concentration compared to LOCB with the majority being in a form other than the redox active fraction. In general, amorphous Fe concentrations were about 5 to 10 times less concentrated than sediments in the pelagic muddy areas of the lake as previously measured by Co-PI Beckler's group (Beckler et al., 2022). This suggests that the local suspended sediments, while mixing with the pelagic lake area, still contain considerably autochthonous phytoplankton production. Interestingly, however, total Fe concentrations were approximately double recently reported values in this region of the lake (Osborne et al. 2021), which may be due to the difference in the strength of extractant used (1 M HCl extraction versus concentrated aqua regia solution). Still, the relatively low concentrations of reactive iron suggest that unlike the legacy mud pelagic areas, Fe chemistry may not play as dominant of a role in the littoral zone (although its role as a tracer of lake source area should not be discounted).

Table 1 presents a non-comprehensive literature review of the most used flocculating agents in removing suspended particles from natural waters. These coagulants flocculating agents can be categorized as inorganic, organic (synthetic), or plant-based (biopolymers), with associated advantages and limitations for each. However, synthetic polymers are generally used in the treatment of wastewater effluent as there are concerns with non-biodegradability and toxicity to aquatic life at low concentrations (Shatat et al. 2019). Iron sulfate ($Fe_2(SO_4)_3$) and aluminum sulfate ($Al_2(SO_4)_3$) are both common inorganic coagulants that are used to precipitate organic matter out of the water column as part of large-scale water treatment (Matilainen et al., 2005). Both of these compounds can also precipitate inorganic P out of the water column and have been used in treating eutrophic lakes and reservoirs (Deppe & Benndorf, 2002; Foy, 1985; Hsu, 1957; Kennedy & Cook, 1982). Aluminum compounds are insensitive to redox fluctuations at the sediment/water interface, as oxygen depletion risks the release of P from iron compounds (Cooke et al., 1993; Deppe & Benndorf, 2002; Klapper, 1992). Iron compounds are more adequate for P precipitation at pH levels ≥ 8, as pH levels below 5.5 or above 8 results in the release or formation of soluble toxic aluminum ions and compounds (Deppe & Benndorf, 2002; Jekel, 1991). Treatment with $Fe_2(SO_4)_3$ can result in the release of iron and P, which could impact sediment and water column iron chemistry (Foy, 1958). The use of $Al_2(SO_4)_3$ in drinking water poses human health risks, resulting in brain changes characteristic of Alzheimer's disease, osteomalacia with fracturing osteodystrophy, damage to the nervous system, and other concerns (Matilainen et al., 2005). Aluminum in soil results in toxic effects on the growth of some plant species (Wright, 1943). The intravenous and oral use of $Fe_2(SO_4)_3$ in humans is associated with gastrointestinal side effects (Machado et al., 2011; Tolkien et al., 2015). $Fe_2(SO_4)_3$ in aquatic environments also likely results in chronic and sublethal effects, such as the reduced viability of water flea offspring, and cortisol response of carp larvae (Van Anholt et al., 2002). There are risks associated with the use of both compounds, though the use of $Al_2(SO_4)_3$ likely poses greater human and environmental health risks. Lake Okeechobee is used as a drinking water supply among other uses (Aumen, 1995; K. E. Havens & James, 2005). Alternatively, biopolymers have shown promising results in the treatment of turbidity in natural waters, with no adverse human or environmental health impacts. However, the application of biopolymers on a large scale is rare due to the associated high dose required for successful coagulation and high cost of extracting the active compounds from plant material (Jiang et al. 2021). Treatment with coagulants such as aluminum sulfate provides a faster, less expensive solution compared to dredging, provided TMDL for TP can be met prior to treatment (James & Pollman, 2011). Chemical treatment with alum has been successfully implemented in

European lake restoration studies, only when external load reduction is achieved (James & Pollman, 2011). Chemical treatment should only be considered if external P loads are reduced, and water column TP does not decline, due to associated costs with such treatment (James & Pollman, 2011).

Table 1. Literature review and associated cost of the most common flocculating agents used to remove suspended particles from natural waters.

Flocculant Type	**Examples (cost kg^{-1})**	**Mechanism of Action (Typical dosage mg L^{-1})**	**Advantages**	**Limitations (Cost per 1,000 m³ of Water)**	**Case Studies**	**References**
Inorganic Flocculants	Alum, Ferric Sulfate, PAC, Ferric Chloride, Sodium Aluminate ($0.10 – $10.00; alibaba.com)	Neutralizes negative charges on suspended particles, allowing them to aggregate and settle. Forms insoluble precipitates with phosphorus, reducing internal loading. (8 – 150 mg L-1)	Cost-effective, widely used, effective in phosphorus removal and turbidity reduction.	Can lower pH, may require buffering, metal residues in sediments can impact benthic ecosystems. ($0.8-$1500)	**Successful alum treatment in 600-acre Minnesota lake -** https://www.solitudelakemanagement.com/case-study-restoring-water-quality-in-600-acre-lake-with-alum/ **Shallow man-made Brazilian lake -** PAC application in mesocosms reduced turbidity ~90% (Araujo et al. 2015)	Choi et al. 2010; Zand & Hoveidi 2015; Arcadia et al. 2012; Kalavathy et al. 2017
Organic (Synthetic) Flocculants	Polyacrylamides (PAMs), DADMAC, Epi-DMA ($2 – $6; alibaba.com)	Acts as a bridge between particles, forming large, easily settled flocs. Some act as charge neutralizers. (0.03-0.4 mg L-1; https://www.sinofloc.com/how-to-determine-the-dosage-of-polyacrylamide.html)	Highly efficient, works at low dosages, adaptable to different water conditions, effective for fine particulates.	Some types may be non-biodegradable, potential toxicity concerns for aquatic life. ($0.06-$2.4)	**No large-scale or environmental applications.** Mostly used to treat wastewater effluent or construction site runoff	Abujazar et al. 2022; Shatat et al. 2019

Natural (Biopolymer) Flocculants	Moringa Oleifera seed extract, Chitosan, Starch-based flocculants, Alginate (Variable cost; generally higher than inorganic and synthetic options)	Uses cationic proteins or polysaccharides to bind particles together and form large flocs. (Variable dose; generally higher than inorganic and synthetic options)	Eco-friendly, biodegradable, safe for aquatic life, does not introduce metal residues.	Less commonly used at large scales, effectiveness varies with water conditions, requires higher dosages compared to metal-based flocculants. (Variable cost; generally higher than inorganic and synthetic options)	**No large-scale applications.** Promising lab-based tests have revealed potential for biopolymers to have high floc capability, low environmental impact, low energy demand, and high economic value.	Jiang et al. 2021; Okoro et al. 2021; Bouaidi et al. 2022

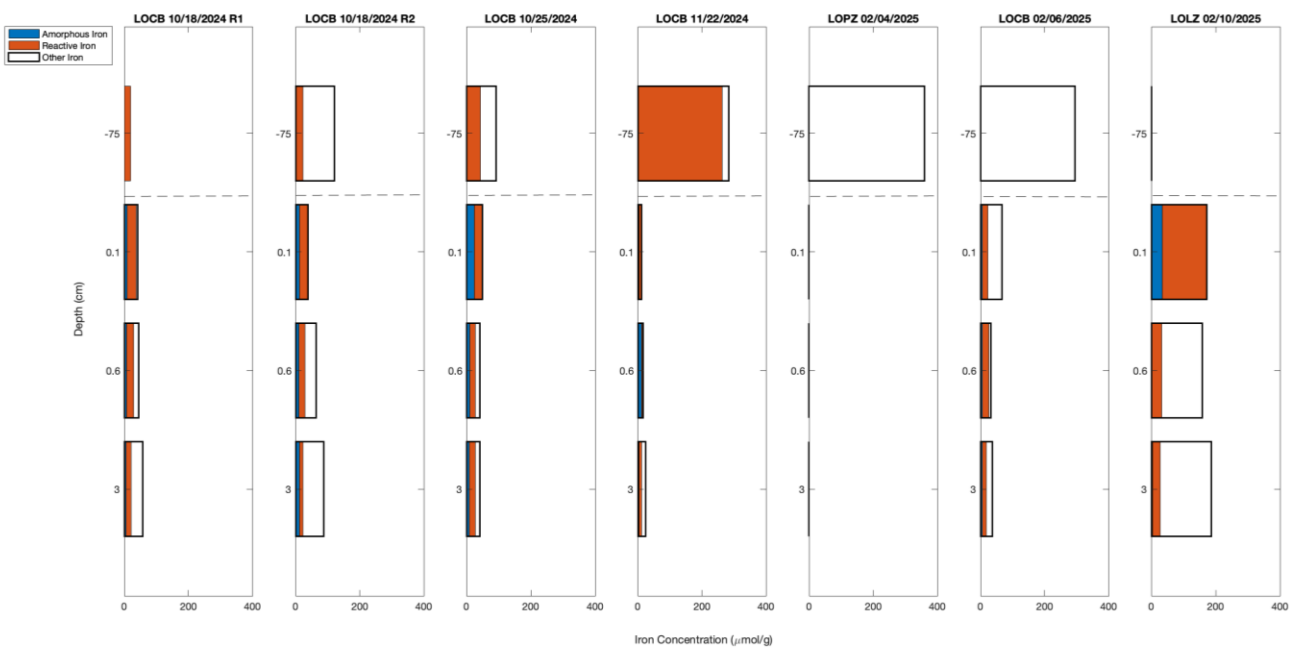


Figure 4. Solid-phase Fe sediment core profiles. Three solid-phase Fe pools (amorphous Fe, total reactive Fe, and total Fe) were measured at site LOCB and LOLZ in the mid-water column (75 cm above the sediment-water interface) and at distinct depths (.1, .6, 3.0 cm) in the sediment. The dashed line represents the sediment-water interface (SWI, 0 cm). Duplicate sediment cores were collected on 10/18/2024 indicated by R1 and R2, respectively. Sediment was not collected from LOPZ.

Examining elemental ratios of organic carbon to nitrogen (Fig. 5) and organic carbon to iron (Fig. 6) provides insights into the source, reactivity, and likelihood of precipitation and aggregation. Carbon is depleted relative to nitrogen in water column suspended sediments relative to the underlying sediments. This suggests that the water column particulates are fresher, perhaps enriched in algal material, whereas the underlying peat sediments are aged and highly degraded, with selective N utilization. Ratios in the water column particulates are still above Redfield (i.e., >106:16 C:N, and well above those expected from N-rich cyanobacteria), suggesting we have a mixture of both algal and sedimentary material. On the other hand, the relative enrichment of suspended sediments in reactive iron relative to the underlying sediments suggest that 1) despite low concentrations overall, iron may still play some role in both biological and carbon dynamics in the water column given that at low iron concentrations, the formation of organic-iron complexes and colloids can delay precipitation processes due to negative-negative charge repulsion; and/or 2) lateral transport of iron-rich legacy sediment may be entrained in littoral zone waters.

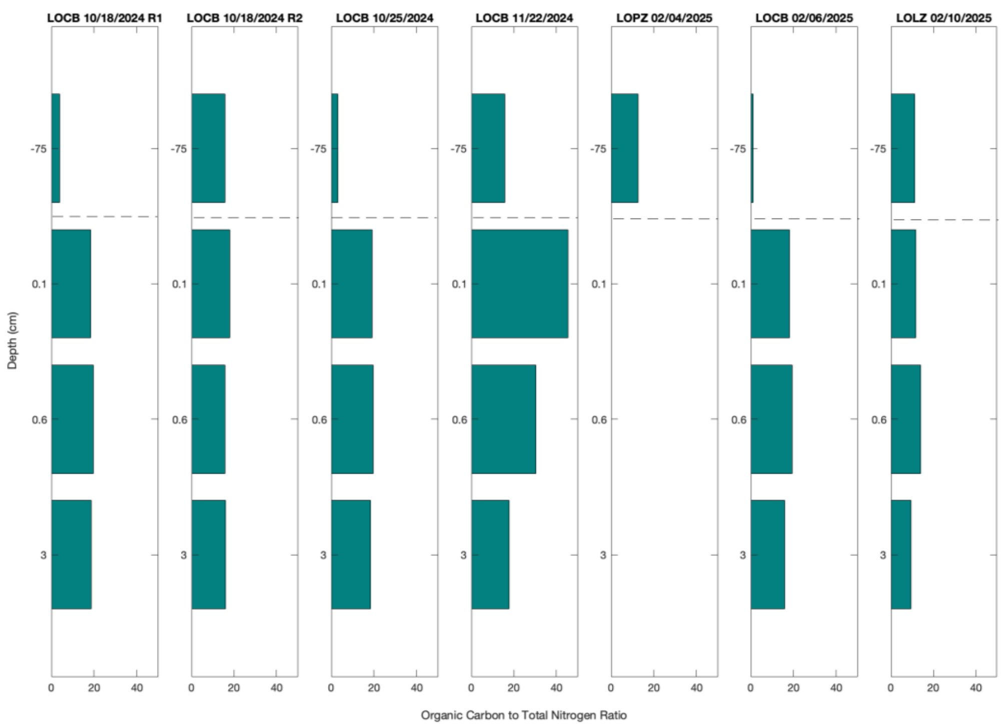


Figure 5. C to N ratios. Ratios of organic C concentrations to total N concentrations obtained from sampling events at LOCB, LOPZ, and LOLZ. The dashed line represents the sediment-water interface (SWI, 0

cm). Sediment was not collected from LOPZ.

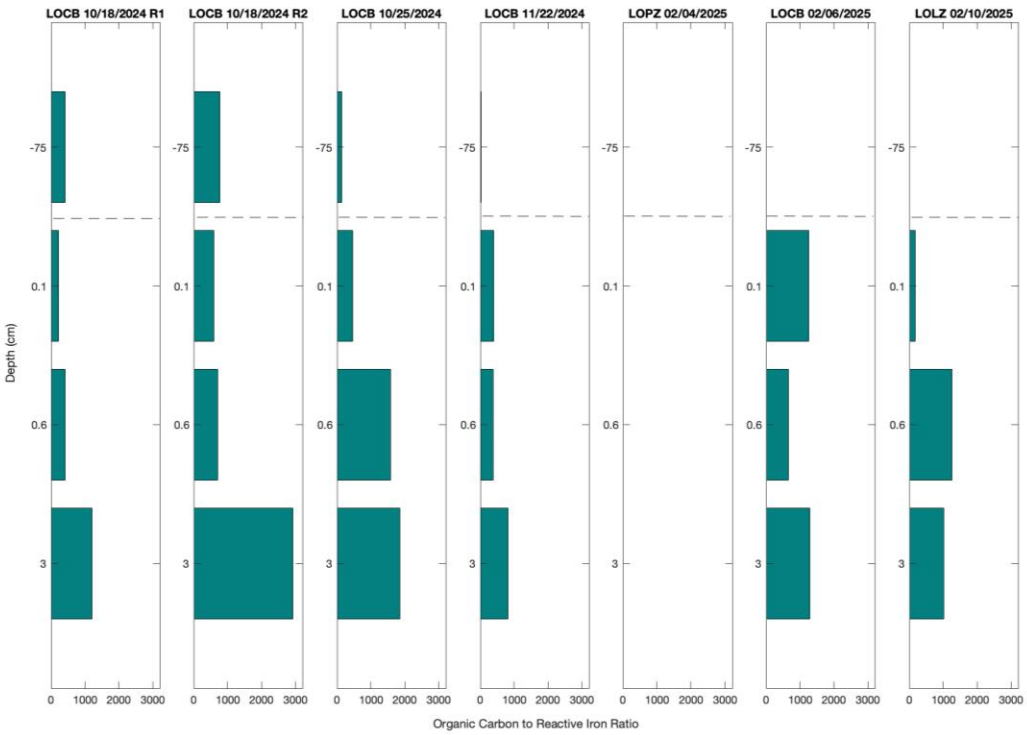


Figure 6. C to Fe ratios. Ratio of organic C concentrations to reactive Fe concentrations obtained from sampling events at LOCB, LOPZ, and LOLZ. The dashed line represents the sediment-water interface (SWI, 0 cm). Sediment was not collected from LOPZ. Reactive Fe could not be recovered from the water column during the 2025 sampling events.

These concentrations are summarized in Table 2. The total % carbon and total organic % carbon is similar to that measured previously in Lake Okeechobee sediments (20% organic content) (Jin et al., 2011). Interestingly, site LOSS suspended sediment load has greater organic carbon than site LOCB, in excess of pelagic lake sediments, and a similar amount of iron. This suggests that this site has a greater relative degree of local primary production, e.g. from the SAV or algal communities. Thus, high concentrations of organic carbon itself may not be directly indicative of an unhealthy ecosystem. More likely, it is when this organic material forms a matrix with small detrital, clastic material (i.e., formed by compaction of rock/soil fragments derived from rock weathering) to create small aggregates that cause a high degree of light scattering. If turbidity mitigation is undertaken, it is therefore important to establish appropriate monitoring analytes that can identify the degree of mixing of allochthonous (i.e., external pelagic lake sediments) vs in situ algal material (i.e., formed at the site), while also establishing what a “healthy” suspended sediment environment should look like (chemically). To our knowledge, clear and well-defined end goals with respect to biogeochemistry (i.e., suspended sediment composition) have not been established. Lake Okeechobee has been historically described as a turbid lake, and end goals will need to account for the natural turbidity of Lake Okeechobee (Canfield Jr et al., 2020; Heilprin, 1887; Joyner, 1971).

Table 2. Surface water TSS, carbon and nitrogen content. Gravimetric TSS (mg/L) and both total and organic particulate N and C (% and µmol/L). Duplicate samples were taken from LOCB during the first sampling event.

Sample		TSS (mg/L)	Total % N	Total % C	Total N (µmol/L)	total C (µmol/L)	Org % N	Org % C	Org N (µmol/L)	Org C (µmol/L)
10/18/24	LOCB	64.5	2.31	29.3	74.9	1180.7	1.37	15.81	71.0	958.6
	LOSS	68.4	3.05	37.9	140.5	2035.3	2.55	27.58	132.0	1663.0
10/25/24	LOCB	54.2	2.73	31.9	40.3	549.5	0.73	7.39	45.7	540.4
10/28/24	LOSS	24.3	3.47	36.9	70.6	875.5	6.15	34.56	87.8	576.0
11/22/24	LOCB	60.2	0.71	15.6	29.4	327.2	0.55	11.08	24.4	193.0
	LOSS	22.8	0.75	28.2	12.0	242.0	0.26	22.31	4.3	68.6

EPS content of suspended sediments. Here we present the first reports of EPS for Lake Okeechobee suspended sediments. Alcian blue stain is specific to acid mucopolysaccharides and can help visualize EPS (Bar-Zeev et al., 2009). Stained particulate shows the importance of EPS in the composition of suspended sediment in Lake Okeechobee (Fig. 7). EPS appears to be the primary "glue" that is holding particulate together (Fig. 7). While EPS is prevalent throughout the particle, EPS makes up a small portion of the total C associated with suspended solids (Fig. 8). Together, LB-EPS and TB-EPS made up 7.8% of organic C on 10/18/2024, 1.9% on 10/25/2024, and 14.1% on 11/22/2024 for LOCB. On 10/18/2024, a greater proportion of EPS (mg TOC/g SS) was as TB-EPS, where on 10/25/2024 and 11/22/2024 a greater proportion of EPS was as LB-EPS (Table 3). On both 10/18/2024 and 10/25/2024, TB-EPS was primarily composed of protein, compared to LB-EPS which had both proteins and carbohydrates (Table 3). This is an important finding, because methods to deliberately mitigate turbidity (i.e., force it to settle out) must take into account the nature of these particles. For example, the true solid phase (inorganic) fraction of the particles may be small clays merely a few microns in size, but they are essentially "glued" together with the EPS. The EPS might serve to cause aggregation such that the larger particles eventually settle out, but more likely, the organic matrix instead causes higher buoyancy and limits sedimentation. EPS production plays a crucial role in settling particulate out of the water column through aggregation, however the low density of EPS can result in smaller settling velocities than that of pure clay particles of the same size (Liu et al., 2003; Tan et al., 2012). Therefore, it is important that mitigation methods take this latter possibility into account – the role of the EPS would need to be overcome.

Total EPS content (mg TOC/g SS) was comparable to that of activated sludges (Ye et al., 2011). Protein and carbohydrate content was low for suspended solids on 10/18/2024 compared to activated sludges in other studies (Li & Yang, 2007; Yang & Li, 2009; Ye et al., 2011). Where protein and carbohydrates could be detected, samples from 10/25/2024 had protein or carbohydrate content more comparable to that of activated sludges (Li & Yang, 2007; Yang & Li, 2009).

Simulating the production of algal EPS has been tested in wastewater settings to remove sediments and pollutants from the water (Siddharth et al., 2021). Microbial EPS synthesized by different microbial strains, isolated, and added to water to successfully remove suspended solids and bacteria (More et al., 2014). The combination of both EPS and $Fe_2(SO_4)_3$ is promising for wastewater treatment, as there was no residual Ferric or Aluminum ion accumulation (More et al., 2014; Ma et al., 2008). EPS can improve turbidity removal when used in combination with a coagulant ($Fe_2(SO_4)_3$ or $Al_2(SO_4)_3$) increased turbidity removal and reduced the concentration of residual metallic elements in solution (Ma et al., 2008).

Table 3. EPS content of suspended solids. Average (n=2) TSS (mg/L) concentrations from 0.4 µm pore size filters as part of EPS extraction and determination, TOC of EPS as mg TOC as EPS per g suspended solids (SS) extracted, protein content as mg protein per g SS extracted, carbohydrate content as mg carbohydrates per g SS extracted, the percentage of TOC as EPS attributed to proteins (assuming 53% of protein is carbon by weight), and the percentage of TOC as EPS attributed to carbohydrates (assuming 40% of carbohydrates is carbon by weight). For both LB-EPS and TB-EPS.

		TSS (mg/L)	mg TOC as EPS /g SS	protein (mg/g SS)	carbohydrates (mg/g SS)	% TOC protein	% TOC carbohydrates
LOCB 10/18/2024	LB-EPS	102.15	2.39	0.54	0.67	12	11
LOCB 10/18/2024	TB-EPS	102.15	5.32	3.95	0.33	39	2
LOCB 10/25/2024	LB-EPS	21.4	5.26	0.00	10.12	0	77
LOCB 10/25/2024	TB-EPS	21.4	0.57	44.06	0.00	4077	0
LOCB 11/22/2024	LB-EPS	64.6	8.71	5.03	0.00	58	0
LOCB 11/22/2024	TB-EPS	64.6	6.33	3.35	0.00	53	0

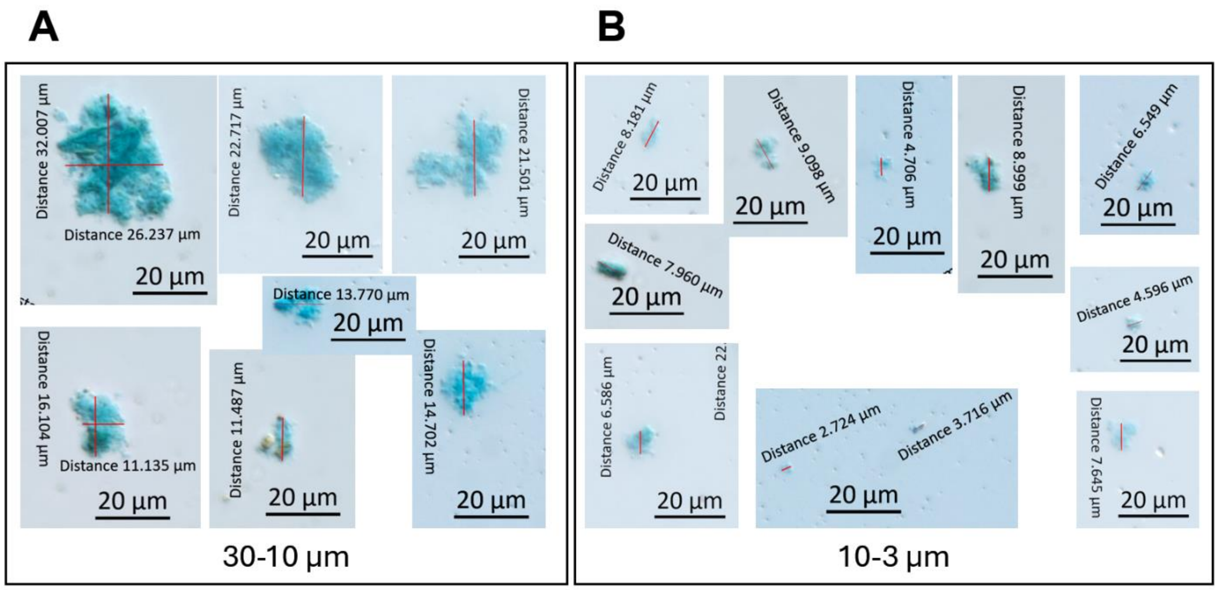


Figure 7. EPS in suspended sediment. Alcian blue stained particulate from unfiltered site water collected on 11/22/2024. Alcian blue stains acidic polysaccharides. Showing diameter of each particle. Organized by size fraction, 30-10 µm (A) and 10-3 µm (B).

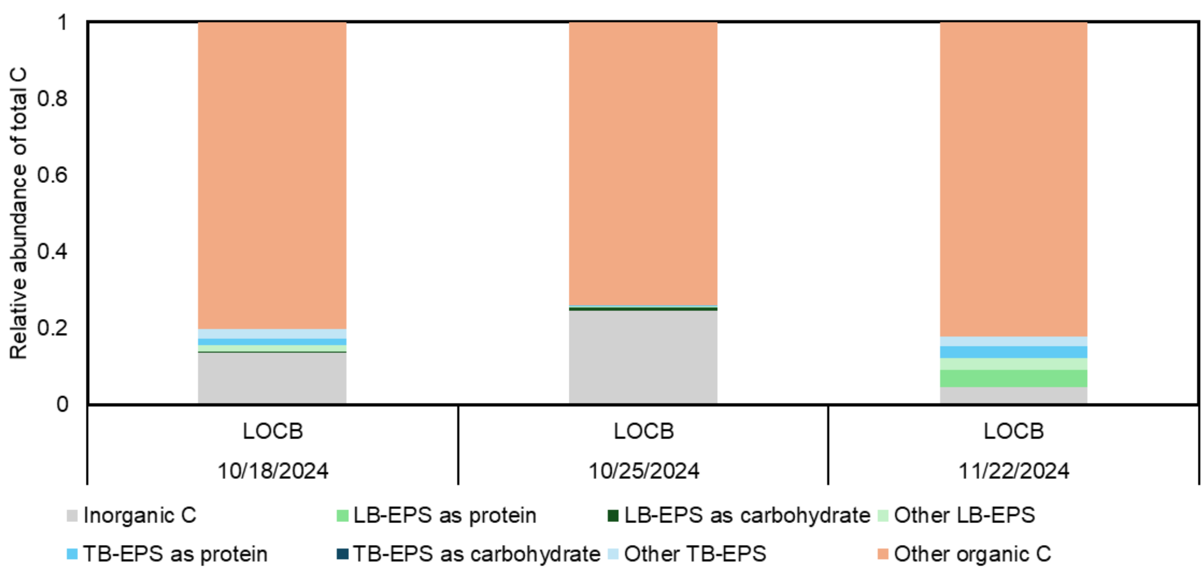


Figure 8 EPS content of total C. Relative contribution of different forms of C to the total C of suspended solids. Showing relative contribution of EPS and EPS components to total organic C.

FT-IR of suspended and underlying sediments. As of now, little is known about the chemical composition and minerology of suspended particles and nearby sediments from Lake Okeechobee, FL. The project investigated how surface sediments differ from deep sediments, how suspended sediments are different from true sediments, and how surface sediments are different before and after a resuspension event (e.g., hurricanes or tropical storms). The composition of lyophilized sediments and solid matter from the water column was determined using Fourier-transform Infrared spectroscopy (FT-IR), in which molecular vibrations from polar bonds are excited by infrared radiation. Based on FT-IR data (Table 4), solid matter isolated from the water column seems to be more organic in nature than sediments from the same sampling site based on the relative peak intensity, as shown in Figure 9. For instance, solids extracted from turbid water exhibit prominent absorption bands between 2,850-2,950 cm^{-1} originating from C–H vibrations in $–CH_3$, $–CH_2$ and –CH groups. Absorptions at around 1125 cm^{-1} are due to C-O-C stretching vibrations of complex carbohydrates, and absorptions between 1070 and 1040 cm^{-1} are ascribed to C-O vibrations of carbohydrates (Meyer-Jacob et al. 2014). C=O stretching at 1740 cm^{-1}, amide I (C=O stretching) at 1640 cm^{-1}, lignin or cellulose from vascular plants and algae (absorbed O–H or conjugated C–O) in the band 1650–1600 cm^{-1}, amide II (C–N stretching and N–H deformation) at 1550 cm^{-1}, and polysaccharides in the 1180–950 cm^{-1} region (Maxson et al. 2021). IR bands at 1,500–1,700 cm^{-1} have been assigned to amide I and amide II vibrations in proteins. Alternatively, IR peaks at 1,650 cm^{-1} may stem from C=O stretching vibrations in carboxyl groups common in humic substances (Rosén et al. 2010). A broad peak around 3,300 cm^{-1} is attributed to hydroxyl vibrations, which occur in clay minerals, opal (amorphous silica) and organic substances present in lake sediments (Vogal et al. 2008).

FT-IR peaks around 1,000-1150 cm^{-1} and 800 cm^{-1} are attributed to Si-O bonds from silica (Rosén et al. 2010). The sediments consist of calcite (crystalline $CaCO_3$) and layered silicate minerals (phyllosilicates), such as chlorite, smectite, illite, kaolinite, quartz (crystalline SiO_2), K-feldspar ($KAlSi_3O_8$) or opal (amorphous SiO_2) (Rosén et al. 2010). Crystalline SiO_2 (quartz), which was primarily found in Lake Okeechobee sediments, is characterized by the Si-O-Si bending transition around 698 cm^{-1}, the SiO_4 symmetric stretching at 778 and 798 cm^{-1} as well as the antisymmetric stretching vibrations of the SiO4 tetrahedron at 1084 cm^{-1} (Hahn et al. 2018; Farmer, 1974). Silicate minerals are a dominant mineral class in Lake Okeechobee sediments, quartz sand grains compromise the bulk of most soils in the Lake Okeechobee basin with coatings of quartz, hydroxyl-interlayered vermiculite, kaolinite, and organic carbon, organometal complexes (Harris, 2011). Dispersed matter from the water column contains biogenic amorphous calcium carbonate (ACC), as indicated by the carbonate peak at ~960 cm^{-1}, presumably originating from bloom-forming cyanobacteria (Blondeau et al., 2018; Mehta et al., 2022). FT-IR peaks centered around 1795, 1460, 875, and 715 cm^{-1} indicate the presence of calcite ($CaCO_3$) in the sediments, which could stem from marine calcifying organisms, e.g., shells (Hahn et al., 2018). Overall, these FT-IR results suggest that a considerable degree of local algal production is mixing with a suspended sediment load derived from the deeper, pelagic lake area. The chemical nature of the suspended sediment load is important to characterize, because turbidity mitigation approaches may be specific with respect to, for example, the chemical mechanism of its binding.

Table 4. FT-IR peaks. Fourier-transform infrared spectroscopy from lyophilized lake water and sediments. FT-IR peaks from inorganic (blue) and organic compounds (green).

Water	Si-O	Si-O-Si			CO_3^{2-} (ACC)	C-O	C-O	C-O	C-O	O-H	C-H	C-N	C=C	C=O NH	C=O	C-H	C-H	C=C	N-H	O-H	N-H
Lake water 10/18/24	616	685	785		861	1032	1093	1217	1266	1366	1419			1638-1648	1739	2941	2970	3016	3224	3376	3464
Lake water (LOCB)	603				861	1037	1092	1217		1377	1418			1620	1740	2945	2970	3027	3220	3364	
Lake water (Erosion)	599				859	995	1109	1217		1365	1418			1628-1646	1738	2943	2970	3015		3355	3456

Sediment	Si-O	Si-O-Si	Si-O-Si	$[SiO_4]_{sym}$	CO_3^{2-} (calcite)	C-O	C-O $[SiO_4]$ asy			O-H	C-H			C=O NH	C=O	C-H	C-H	C=C	N-H	O-H	N-H
LOCB Sediment 0-2 mm		693	779	798	880	1036	1165	1208	1267	1401		1507	1567			2842	2925			3304	
LOCB Sediment 10-50 mm		643	776	797	878	1028	1125	1213	1268	1387		1507	1572			2851	2922			3302	
Sediment 242421	627	694		797		1028	1123	1219	1258	1388	1456	1508	1565			2847	2913			3339	
Sediment 242423		671		805		1033	1158	1227	1263	1395	1451	1507	1559			2828	2918			3338	

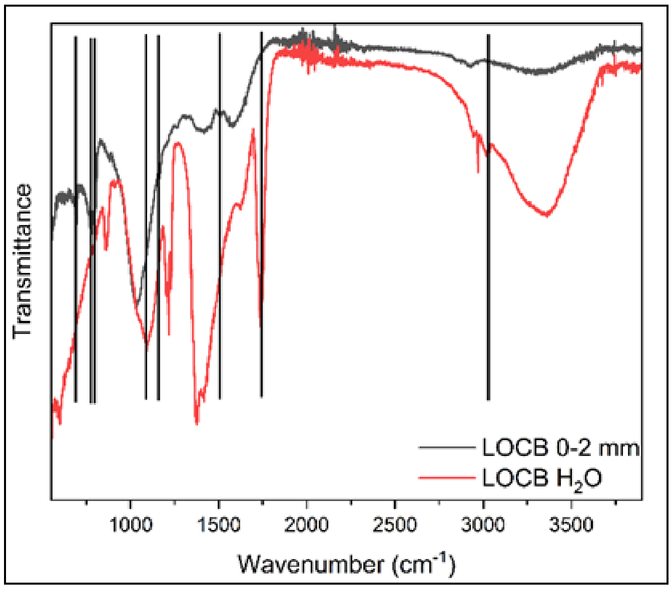


Figure 9. FT-IR spectra. Fourier-transform infrared spectroscopy from lyophilized lake water and sediments from LOCB.

XRD. X-ray powder diffraction (Figure 10) was used to identify crystalline minerals in the suspended matter and the sediments. The XRD pattern from the sediment was consistent with crystalline SiO_2 (quartz) as major constituent and $CaCO_3$ (aragonite) in deeper layers. This is expected, as quartz sands make up the bulk of most soil in the Lake Okeechobee Basin (Harris, 2011). The X-ray scattering signal from the water-suspended matter was weaker overall, suggesting a higher proportion of amorphous matter. The mineral NaCl (halide) was identified as a major crystalline compound in water-suspended matter, but this is likely an artifact of the sample drying technique. Notably, we did not observe any obvious chemical changes in FT-IR or XRD after an erosion event in the lake; in other words, the erosion event resuspended surface sediments from site LOCB, which resembled the suspended sediments already there. Therefore, resuspension is important in both a local and a distal sense – it can result in both the transport of particles from the pelagic lake, but also, the resuspension of local particles in the littoral zone as well. The mud sediment in Lake Okeechobee contains a significant fraction of Mg silicate minerals (palygorskite and sepiolite), however this was not detected with XRD analysis (Harris, 2011). This

Mg silicate particulate is small, fibrous and low-density making it easy to resuspend, contributing to turbidity in the water column (Harris, 2011).

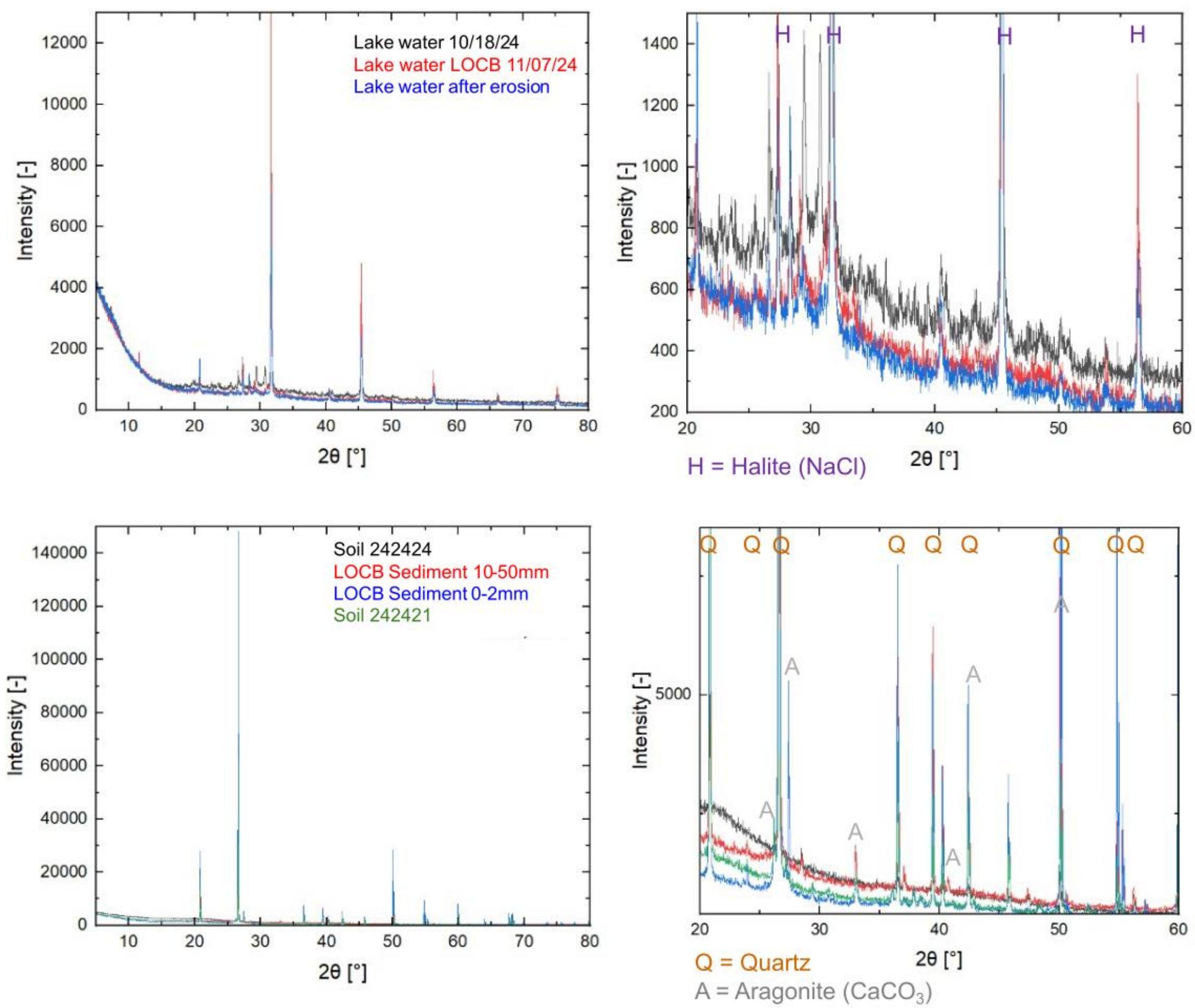


Figure 10. X-ray powder diffraction from solid matter extracted from raw water and sediments.

TEM-EDS. Transmission Electron Microscopy (TEM) revealed the morphology, aggregation state and size distribution of solid particles down to the nanometer scale. The elemental composition was subsequently determined using energy-dispersive X-ray spectroscopy (EDS) point analysis, as previously shown by Seaman et al. (1997). EDS results are displayed in Table 5. As shown in Figure 11 A,B, sediments collected from sampling site LOCB (0-2mm depth) contain particles of diverse sizes, ranging from ≥ 2µm to ≤ 100 nm. Larger particles in Fig. 11A resemble rhombohedral calcite ($CaCO_3$) minerals. At higher magnification, 200 nm long needle-shaped particles can be discerned. These fibrous particles resemble the Mg silicates Harris et al. observed in Okeechobee mud sediment under TEM (2007). In contrast, raw water samples collected from LOCB include monodisperse spherical nanoparticles ≤ 10 nm (Figure 11 C,D).

The elemental composition of sediments and water-suspended matter was quantified by energy-dispersive X-ray spectroscopy (EDS) microanalysis inside the TEM (Figure 12; Table 5). The elements C and Cu were excluded from the analysis since the samples were imaged on carbon-coated copper grids. Based on EDS microanalysis, water-suspended matter is primarily composed of K, Ca, S and minor amounts of Si, Fe, Mg, Al, K, Cl, while sediments contain considerable amounts of Si, Ca, Fe, and minor amounts of S, Mg, Al, and K. The elemental makeup of the sediments is consistent with the presence of layered silicate minerals containing Al, Fe, Mg and K ions. Our previous research demonstrated that bloom-forming hydrogels are rich in P, K, Ca and S (Duersch et al. 2023, 2023 & 2024). Given the high proportion of organic matter and variations in morphology, the results suggest that the suspended particles are of algal instead of sedimentary origin. Infrared spectroscopy and X-ray diffraction results are consistent with siliceous and carbonate minerals in sediments, in particular quartz and calcium carbonate (specifically aragonite). Transmission Electron Microscopy revealed a fraction of microscale particles that have been identified as minerals rich in Si, Mg and Ca, in particular rhombohedral calcite ($CaCO_3$) or fibrous Mg silicates. There is no indication for resuspension of particles into the water column. Water turbidity samples contain colloidal, nanoscale particulates of organic nature.

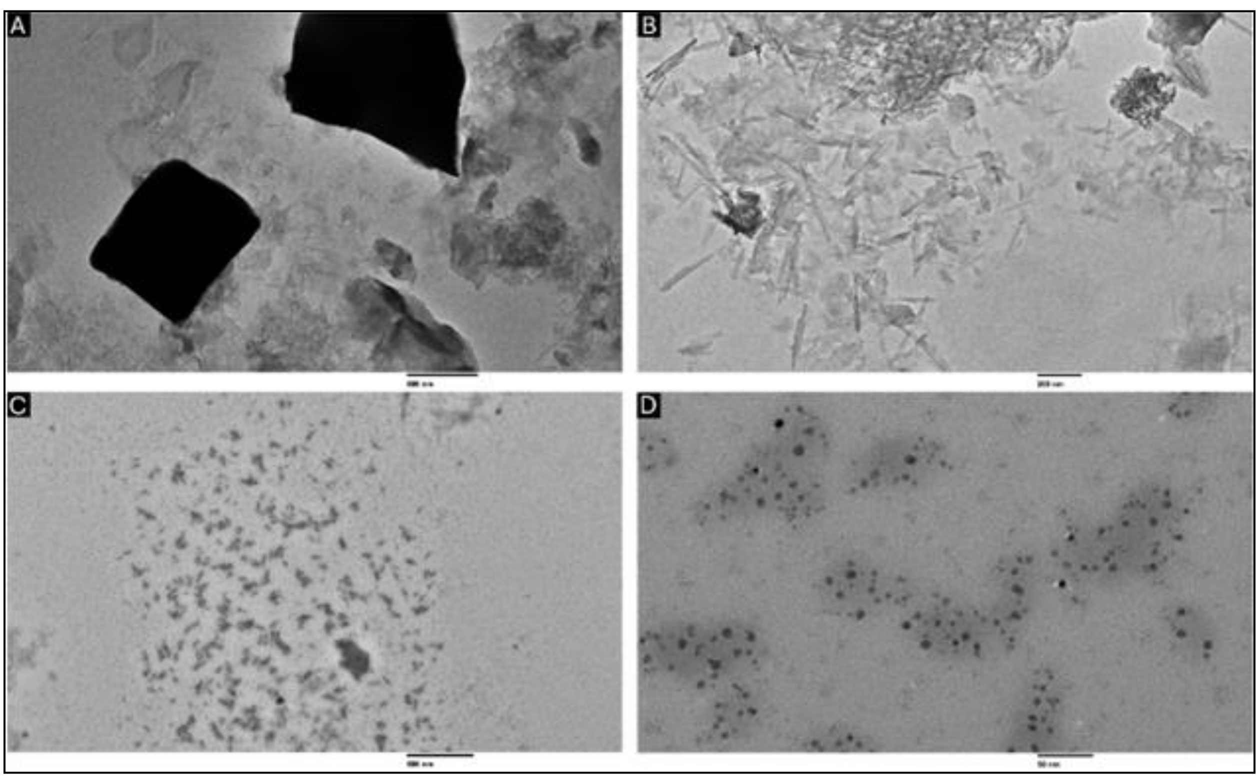


Figure 11. Transmission Electron Microscopy. A-B) Sediments collected from sampling site LOCB (0-2mm depth) contain particles of various sizes, ranging from ≥ 2 µm to ≤ 100 nm. B) 200 nm long needle-shaped particles. C-D) Raw water samples collected from LOCB reveal round particles ≤ 10 nm.

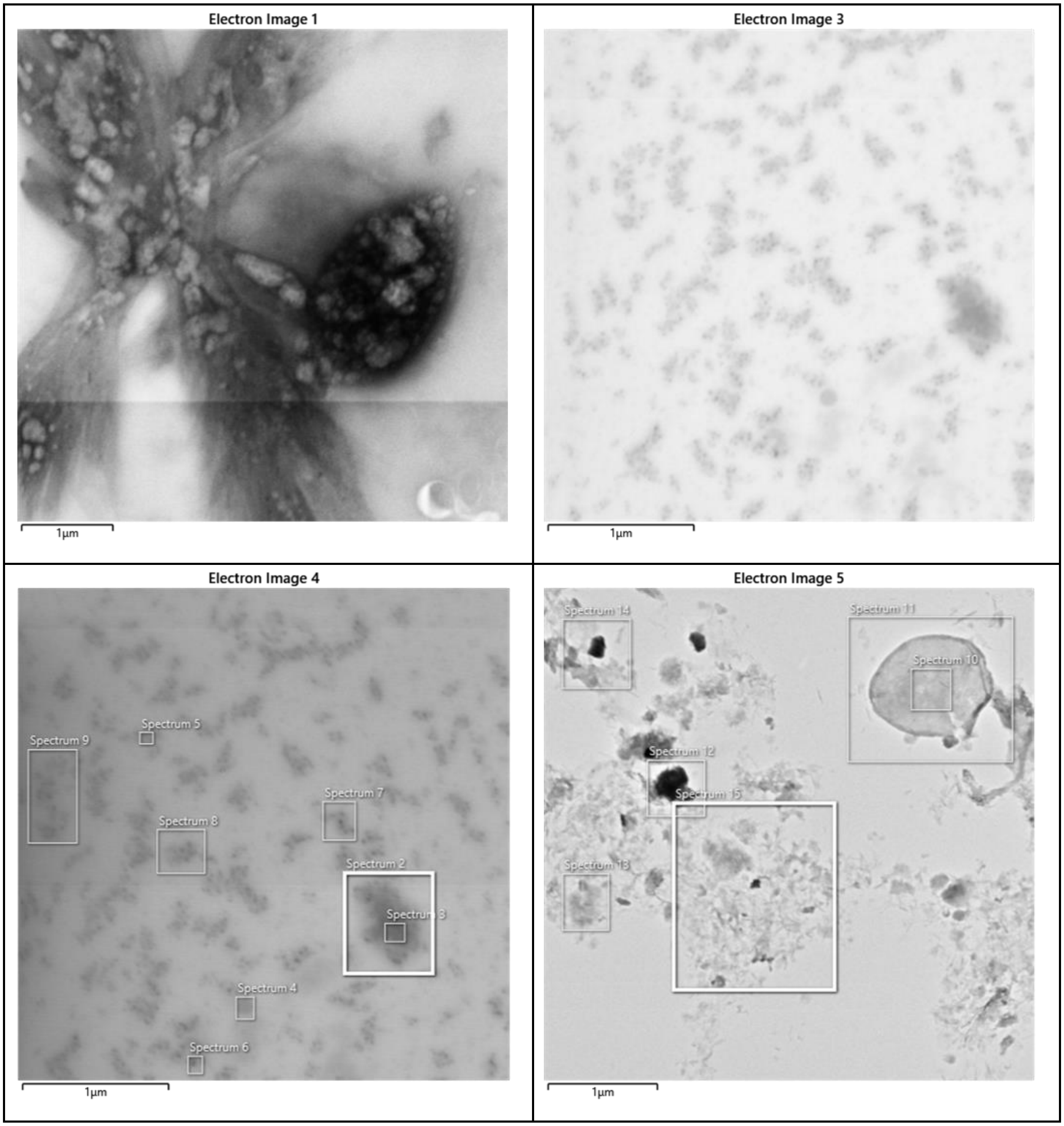


Figure 12. Transmission Electron Microscopy Elemental Mapping. Boxed image regions correspond to elemental composition results provided in Table 3.

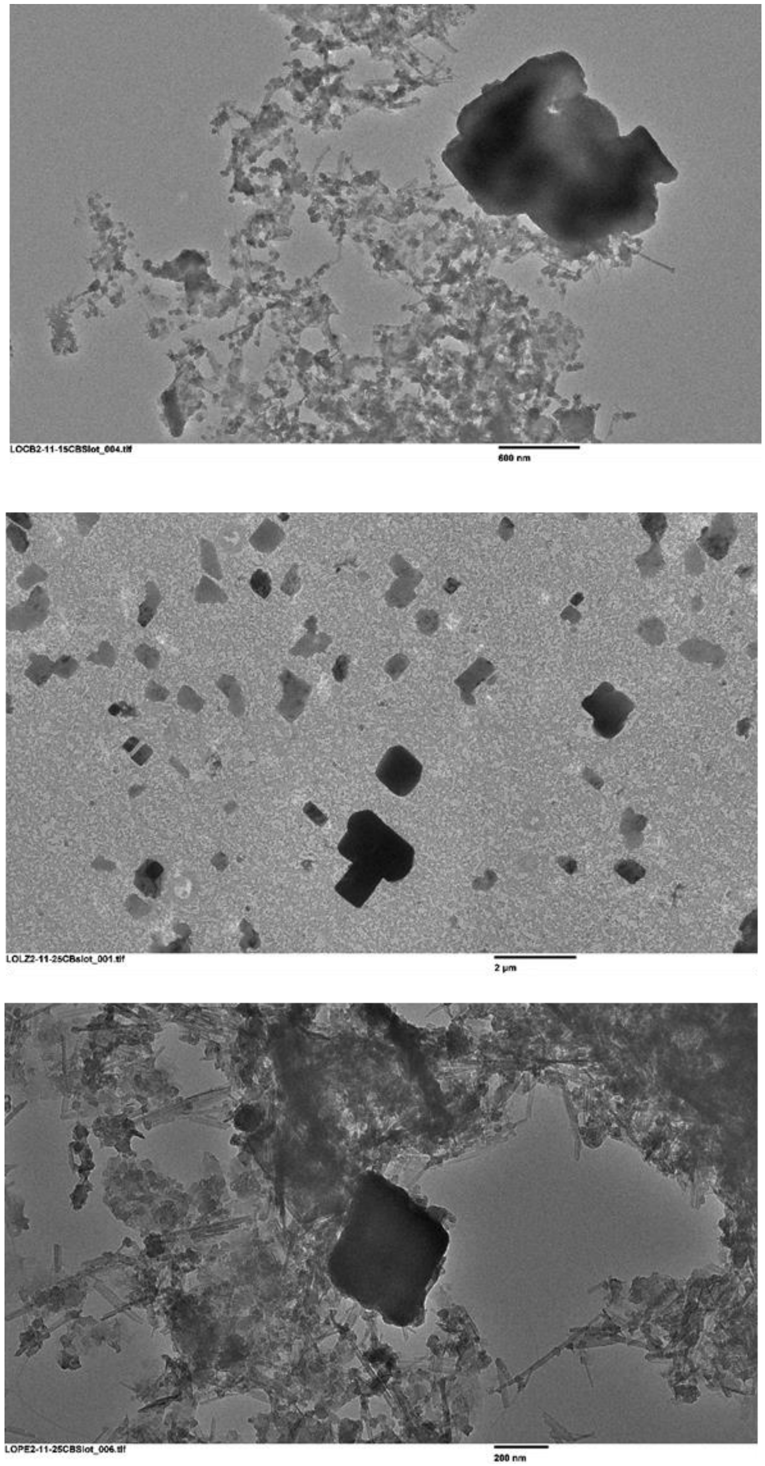


Figure 13. Transmission Electron Microscopy. Transmission Electron Microscopy from suspended particles from most recent sampling event in February 2025.

Table 5. Energy-dispersive X-ray (EDS) microanalysis. Analyses of water-suspended particles and sediments collected from the same sampling site (LOCB) on December 12, 2024. Elemental composition given in weight percentage with standard deviation σ = ±0.0-0.7wt%. The elements C and Cu were excluded from the analysis.

Weight percentage [wt%]	O	Si	Fe	Ca	S	Mg	Al	P	K	Os	Na	Ti	Cl	Sr	Cr	Mn
Water	40.4	0.9	0.9	14.3	9.3	0.7	0.3	1.8	22.7	0.0	6.2	0.0	0.9	1.5	0.0	0.0
Water	54.7	4.9	1.5	7.1	5.3	1.7	0.3	3.0	18.8	0.0	1.2	0.0	1.2	0.0	0.2	0.1
Water	55.6	6.5	1.6	7.0	4.9	1.8	0.5	3.0	17.2	0.0	0.6	0.0	1.4	0.0	0.0	0.0
Water	54.4	4.3	1.4	7.0	6.2	1.9	0.3	3.5	19.3	0.0	0.2	0.0	1.4	0.0	0.0	0.0
Water	51.9	4.1	1.4	6.8	8.3	2.1	0.3	3.0	20.7	0.0	0.0	0.0	1.3	0.0	0.0	0.0
Water	52.0	4.8	1.7	6.5	7.8	1.6	0.5	2.8	19.6	0.0	1.3	0.0	1.4	0.0	0.0	0.0
Water	54.3	7.6	1.4	7.1	5.3	1.8	0.3	2.8	18.5	0.0	0.0	0.0	1.0	0.0	0.0	0.0
Sediment	51.7	13.6	9.1	8.2	6.5	6.5	3.7	0.3	0.3	0.2	0.0	0.0	0.0	0.0	0.0	0.0
Sediment	53.7	8.8	7.1	14.8	7.6	4.4	2.9	0.0	0.3	0.1	0.0	0.0	0.4	0.0	0.0	0.0
Sediment	51.6	10.6	9.1	12.4	8.1	5.1	2.9	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sediment	56.3	11.4	5.5	12.4	4.6	3.7	4.5	0.0	0.5	0.0	0.0	0.7	0.4	0.0	0.0	0.0
Sediment	54.7	18.7	6.8	5.0	3.8	3.9	6.4	0.0	0.3	0.4	0.0	0.0	0.0	0.0	0.0	0.0
Sediment	56.0	21.9	5.2	6.2	3.7	3.2	3.1	0.0	0.1	0.5	0.0	0.0	0.0	0.0	0.0	0.0
Sediment	53.2	15.2	9.1	7.0	6.0	4.7	4.5	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Chapter 1: CONCLUSIONS

Suspended solids are organic in nature, having a greater proportion of organic compounds than underlying sediments. N and C increase with depth in lake sediments, which could be due to changes in the deposition rate of material and increased resuspension, both of which could be attributed to SAV loss. The high concentrations of inorganic C and total Fe in suspended material compared to underlying sediments could indicate mixing with suspended solids from the pelagic zone of the lake. Suspended sediments contain a greater proportion of organic compounds compared to underlying sediments, suggesting water column primary production. The elemental makeup of suspended sediments, and the presence of biogenic amorphous calcium carbonate suggests the considerable contribution of local algal production to suspended sediments. There is no indication for resuspension of local sediments into the water column. These aggregates of biogenic and clastic materials are responsible for high light scattering in Lake Okeechobee. If turbidity mitigation is undertaken, it is therefore important to establish appropriate monitoring analytes that can identify the degree of mixing of allochthonous (i.e., external pelagic lake sediments) vs in situ algal material (i.e., formed at the site), while also establishing what a "healthy" suspended sediment environment should look like (chemically). To our knowledge, clear and well-defined end goals with respect to biogeochemistry (i.e., suspended sediment composition) have not been established. Treatment with chemical coagulants, such as inorganic, synthetic organic, and natural organic coagulants could help bind to suspended solids and precipitate it out of the water column.

Chapter 1 References

Abujazar, M. S. S., Karaağaç, S. U., Amr, S. S. A., Alazaiza, M. Y., & Bashir, M. J. (2022). Recent advancement in the application of hybrid coagulants in coagulation-flocculation of wastewater: A review. *Journal of Cleaner Production*, *345*, 131133.

Araújo, F., Becker, V., & Attayde, J. L. (2016). Shallow lake restoration and water quality management by the combined effects of polyaluminium chloride addition and benthivorous fish removal: a field mesocosm experiment. *Hydrobiologia*, *778*, 243-252.

Arcadia, C. A., Noblet, J. A., Campbell, E., & Cervantes, G. (2012). A JAR TEST STUDY ON THE USE OF ALUM FOR TURBIDITY AND NUTRIENT REMOVAL IN CANYON LAKE, CA.

Aumen, N. G. (1995). The history of human impacts, lake management, and limnological research on Lake Okeechobee, Florida(USA). *Advances in Limnology[ERGEB. LIMNOL./ADV. LIMNOL.]. 1995.*

Azetsu-Scott, K., & Passow, U. (2004). Ascending marine particles: Significance of transparent exopolymer particles (TEP) in the upper ocean. *Limnology and Oceanography*, *49*(3), 741–748.

Beckler, J.S., Ruiz-Xomchuk, V., Jiang, M., Tang, Y., McFarland, M., Nayak, A., Moore, T., Hanisak, D. (2022). Harmful Algal Bloom Innovative Technology: The Harmful Algal Bloom Assessment of Lake Okeechobee (HALO). Final report, FDEP Innovative Technology project MN016.

Bar-Zeev, E., Berman-Frank, I., Liberman, B., Rahav, E., Passow, U., & Berman, T. (2009). Transparent exopolymer particles: Potential agents for organic fouling and biofilm formation in desalination and water treatment plants. *Desalination and Water Treatment*, *3*(1–3), 136–142.

Blondeau, M., Sachse, M., Boulogne, C., Gillet, C., Guigner, J.-M., Skouri-Panet, F., Poinsot, M., Ferard, C., Miot, J., & Benzerara, K. (2018). Amorphous calcium carbonate granules form within an intracellular compartment in calcifying cyanobacteria. *Frontiers in Microbiology*, *9*, 1768.

El Bouaidi, W., Libralato, G., Douma, M., Ounas, A., Yaacoubi, A., Lofrano, G., ... & Loudiki, M. (2022). A review of plant-based coagulants for turbidity and cyanobacteria blooms removal. *Environmental Science and Pollution Research*, *29*(28), 42601-42615.

Brezonik, P. L., & Engstrom, D. R. (1998). Modern and historic accumulation rates of phosphorus in Lake Okeechobee, Florida. *Journal of Paleolimnology*, *20*, 31–46.

Canfield Jr, D. E., Bachmann, R. W., & Hoyer, M. V. (2020). Restoration of Lake Okeechobee, Florida: mission impossible? *Lake and Reservoir Management*, *37*(1), 95–111.

Chimney, M. J. (2005). Surface seiche and wind set-up on Lake Okeechobee (Florida, USA) during hurricanes Frances and Jeanne. *Lake and Reservoir Management*, *21*(4), 465–473.

Choi, Y. I., Jung, B. G., Son, H. J., & Jung, Y. J. (2010). Determination of optimum coagulants (ferric chloride and alum) for arsenic and turbidity removal by coagulation. *Journal of Environmental Science International*, *19*(8), 931-940.

Cooke, G. D., Welch, E. B., Peterson, S., & Nichols, S. A. (2016). *Restoration and management of lakes and reservoirs*. CRC press.

Dang, T. D., Arias, M. E., Tarabih, O., Phlips, E. J., Ergas, S. J., Rains, M. C., & Zhang, Q. (2023). Modeling temporal and spatial variations of biogeochemical processes in a large subtropical lake: Assessing alternative solutions to algal blooms in Lake Okeechobee, Florida. *Journal of Hydrology: Regional Studies*, *47*, 101441.

Decho, A. W., & Gutierrez, T. (2017). Microbial extracellular polymeric substances (EPSs) in ocean systems. *Frontiers in Microbiology*, *8*, 922.

Deosti, S., de Fátima Bomfim, F., Lansac-Tôha, F. M., Quirino, B. A., Bonecker, C. C., & Lansac-Tôha, F. A. (2021). Zooplankton taxonomic and functional structure is determined by macrophytes and fish predation in a Neotropical river. *Hydrobiologia*, *848*, 1475–1490.

Deppe, T., & Benndorf, J. (2002). Phosphorus reduction in a shallow hypereutrophic reservoir by in-lake dosage of ferrous iron. *Water Research*, *36*(18), 4525–4534.

Dibble, E. D., & Thomaz, S. M. (2009). Use of fractal dimension to assess habitat complexity and its influence on dominant invertebrates inhabiting tropical and temperate macrophytes. *Journal of Freshwater Ecology*, *24*(1), 93–102.

Dierberg, F. E., DeBusk, T. A., Jackson, S. D., Chimney, M. J., & Pietro, K. (2002). Submerged aquatic vegetation-based treatment wetlands for removing phosphorus from agricultural runoff: response to hydraulic and nutrient loading. *Water Research*, *36*(6), 1409–1422.

Duersch, B. G., Luo, Y., Chen, S., Soini, S. A., Somu, D. M. R., & Merk, V. M. (2022). Visualizing the Macro- and Micronutrient Distribution of Toxic Cyanobacteria in Two and Three Dimensions. *Microscopy and Microanalysis*, *28*(S1), 1128-1131.

Duersch, B. G., Luo, Y., Chen, S., Soini, S. A., Somu, D. M. R., & Merk, V. M. (2023). Synchrotron-based X-ray fluorescence microscopy mapping the ionome of a toxic freshwater cyanobacterium. *Environmental Pollution*, *334*, 121781.

Duersch, B. G., Soini, S. A., Luo, Y., Liu, X., Chen, S., & Merk, V. M. (2024). Nanoscale elemental and morphological imaging of nitrogen-fixing cyanobacteria. *Metallomics*, *16*(10), mfae040.

Farmer, V.C. 1974. "Vibrational Spectroscopy in Mineral Chemistry", The Infrared Spectra of Minerals, V. C. Farmer

Frølund, B., Griebe, T., & Nielsen, P. H. (1995). Enzymatic activity in the activated-sludge floc matrix. *Applied Microbiology and Biotechnology*, *43*, 755–761.

Foy, R. H. (1985). Phosphorus inactivation in a eutrophic lake by the direct addition of ferric aluminum sulphate: impact on iron and phosphorus. *Freshwater Biology*, *15*(5), 613–629.

Gerbersdorf, S. U., Westrich, B., & Paterson, D. M. (2009). Microbial extracellular polymeric substances (EPS) in fresh water sediments. *Microbial Ecology*, *58*, 334–349.

Gomes, L. C., Bulla, C. K., Agostinho, A. A., Vasconcelos, L. P., & Miranda, L. E. (2012). Fish assemblage dynamics in a Neotropical floodplain relative to aquatic macrophytes and the homogenizing effect of a flood pulse. *Hydrobiologia*, *685*, 97–107.

Gowland, J. E., Mehta, A. J., Stuck, J. D., John, C. V, & Parchure, T. M. (2007). Organic-rich fine sediments in Florida, Part II: Resuspension in a lake. In *Proceedings in Marine Science* (Vol. 8, pp. 167–188). Elsevier.

Hahn, A., Vogel, H., Andó, S., Garzanti, E., Kuhn, G., Lantzsch, H., ... & Zabel, M. (2018). Using Fourier transform infrared spectroscopy to determine mineral phases in sediments. *Sedimentary geology*, *375*, 27-35.

Hanlon, C. G., & Jordan, A. (2023). Influence of habitat and other factors on Largemouth Bass abundance in Lake Okeechobee, Florida. *Transactions of the American Fisheries Society*, *152*(4), 429–442.

Harris, W. (2011). Mineral distribution and weathering in the Greater Everglades: implications for restoration. *Critical Reviews in Environmental Science and Technology*, *41*(S1), 4–27.

Harris, W. G., Fisher, M. M., Cao, X., Osborne, T., & Ellis, L. (2007). Magnesium-rich minerals in sediment and suspended particulates of South Florida water bodies: implications for turbidity. *Journal of Environmental Quality*, *36*(6), 1670–1677.

Havens, K. E., & James, R. T. (1999). Localized changes in transparency linked to mud sediment expansion in Lake Okeechobee, Florida: ecological and management implications. *Lake and Reservoir Management*, *15*(1), 54–69.

Havens, K. E., & James, R. T. (2005). The phosphorus mass balance of Lake Okeechobee, Florida: implications for eutrophication management. *Lake and Reservoir Management*, *21*(2), 139–148.

Havens, K. E. (2003). Submerged aquatic vegetation correlations with depth and light attenuating materials in a shallow subtropical lake. *Hydrobiologia*, *493*, 173–186.

Heilprin, A. (1887). *Explorations on the west coast of Florida and in the Okeechobee wilderness: with special reference to the geology and zoology of the Floridian peninsula* (Vol. 1). Wagner Free Institute of Science.

Hestir, E. L., Schoellhamer, D. H., Greenberg, J., Morgan-King, T., & Ustin, S. L. (2016). The effect of submerged aquatic vegetation expansion on a declining turbidity trend in the Sacramento-San Joaquin River Delta. *Estuaries and Coasts*, *39*, 1100–1112.

Hsu, P. H. (1975). Precipitation of phosphate from solution using aluminum salt. *Water Research*, *9*(12), 1155–1161.

Jin, K.-R., Chang, N.-B., Ji, Z.-G., & James, R. T. (2011). Hurricanes affect the sediment and environment in Lake Okeechobee. *Critical Reviews in Environmental Science and Technology*, *41*(S1), 382–394.

Jekel, M. (1991). Aluminum salts as flocculants (Aluminiumsalze als Flockungsmittel). *Arbeitsgemeinschaft Trinkwassertalsperren EV, Vortragsveranstaltung "Trinkwasser Aus Talsperren*, 163–175.

Jeppesen, E., Jensen, J. P., Kristensen, P., Søndergaard, M., Mortensen, E., Sortkjaer, O., & Olrik, K. (1990). Fish manipulation as a lake restoration tool in shallow, eutrophic, temperate lakes 2: threshold levels, long-term stability and conclusions. *Biomanipulation Tool for Water Management: Proceedings of an International Conference Held in Amsterdam, The Netherlands, 8–11 August, 1989*, 219–227.

Jiang, X., Li, Y., Tang, X., Jiang, J., He, Q., Xiong, Z., & Zheng, H. (2021). Biopolymer-based flocculants: a review of recent technologies. *Environmental Science and Pollution Research*, *28*, 46934-46963.

Joyner, B. F. (1971). Chemical and biological conditions of Lake Okeechobee, Florida, 1969-70. *US Geological Survey. Open*.

Kalavathy, S., Giridhar, M. V. S. S., & Viswanadh, G. K. (2017). A jar test study on the use of alum and ferric chloride for turbidity removal. In *Proceedings of 4th National Conference on Water, Environment & Society (NCWES-2017), March* (pp. 339-344).

Kennedy, R. H., & Cook, G. D. (1982). Control of Lake Phosphorus with aluminum sulfate: dose determination and application techniques 1. *JAWRA Journal of the American Water Resources Association*, *18*(3), 389–395.

Klapper, H. (1992). Eutrophication, water pollution control (Eutrophierung und Gew. asserschutz). *Jena, Stuttgart: Gustav Fischer*.

Knight, R. L., Gu, B., Clarke, R. A., & Newman, J. M. (2003). Long-term phosphorus removal in Florida aquatic systems dominated by submerged aquatic vegetation. *Ecological Engineering*, *20*(1), 45–63.

Kostka, J. E., & Luther III, G. W. (1994). Partitioning and speciation of solid phase iron in saltmarsh sediments. *Geochimica et Cosmochimica Acta*, *58*(7), 1701–1710.

Li, W., Liu, M., Siddique, M. S., Graham, N., & Yu, W. (2021). Contribution of bacterial extracellular polymeric substances (EPS) in surface water purification. *Environmental Pollution*, *280*, 116998.

Li, X. Y., & Yang, S. F. (2007). Influence of loosely bound extracellular polymeric substances (EPS) on the flocculation, sedimentation and dewaterability of activated sludge. *Water Research*, *41*(5), 1022–1030.

Liu, Y., & Fang, H. H. P. (2003). *Influences of extracellular polymeric substances (EPS) on flocculation, settling, and dewatering of activated sludge*.

Ma, F., Zheng, L., & Chi, Y. (2008). Applications of biological flocculants (BFs) for coagulation treatment in water purification: turbidity elimination. *Chemical and Biochemical Engineering Quarterly*, *22*(3), 321–326.

Machado, K. M. de M., Ferreira, L. O. C., Souza, A. I. de, & Diniz, A. da S. (2011). The side-effects of different doses of iron sulfate on women of reproductive age: a randomized double-blind, placebo-controlled study. *Revista Brasileira de Saúde Materno Infantil*, *11*, 275–281.

Matilainen, A., Lindqvist, N., & Tuhkanen, T. (2005). Comparison of the effiency of aluminium and ferric sulphate in the removal of natural organic matter during drinking water treatment process. *Environmental Technology*, *26*(8), 867–876.

Maxson, C., Tribby, J., Marshall, J., Kent, M., Tyler, J., Barr, C., McGregor, G., Cadd, H., Schulz, C., & Lomax, B.H. (2021). Fourier transform infrared spectroscopy as a tracer of organic matter sources in lake sediments. *Palaeogeography, Palaeoclimatology, Palaeoecology 581*, 110622

Mehta, N., Gaëtan, J., Giura, P., Azaïs, T., & Benzerara, K. (2022). Detection of biogenic amorphous calcium carbonate (ACC) formed by bacteria using FTIR spectroscopy. *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy*, *278*, 121262.

Meyer-Jacob, C., Vogel, H., Gebhardt, A. C., Wennrich, V., Melles, M., and Rosén, P. (2014). Biogeochemical variability during the past 3.6 million years recorded by FTIR spectroscopy in the sediment record of Lake El'gygytgyn, Far East Russian Arctic, Clim. Past, 10, 209–220.

Missimer, T. M., Thomas, S., & Rosen, B. H. (2020). Legacy phosphorus in Lake Okeechobee (Florida, USA) sediments: A review and new perspective. *Water*, *13*(1), 39.

More, T. T., Yadav, J. S. S., Yan, S., Tyagi, R. D., & Surampalli, R. Y. (2014). Extracellular polymeric substances of bacteria and their potential environmental applications. *Journal of Environmental Management*, *144*, 1–25.

Okoro, B. U., Sharifi, S., Jesson, M. A., & Bridgeman, J. (2021). Natural organic matter (NOM) and turbidity removal by plant-based coagulants: A review. Journal of Environmental Chemical Engineering, 9(6), 106588.

Osborne, T., Schafer, T.B., Julian, P., Inglett, P.W. (2021). Lake Okeechobee Sediment Quality Mapping Project 2020. Final report, South Florida Water Management District project 4600004016 WO03.

Rosén, P., Vogel, H., Cunningham, L., Reuss, N., Conley, D. J., & Persson, P. (2010). Fourier transform infrared spectroscopy, a new method for rapid determination of total organic and inorganic carbon and biogenic silica concentration in lake sediments. *Journal of Paleolimnology*, *43*, 247-259.

Seaman, J. C., Bertsch, P. M., & Strom, R. N. (1997). Characterization of colloids mobilized from southeastern coastal plain sediments. *Environmental science & technology*, *31*(10), 2782-2790.Shen, Y., Xiao, K., Liang, P., Ma, Y., & Huang, X. (2013). Improvement on the modified Lowry method against interference of divalent cations in soluble protein measurement. *Applied Microbiology and Biotechnology*, *97*, 4167–4178.

Shatat, R. S., Niazi, S. K., & Batati, F. S. A. (2019). Synthetic Polyelectrolytes based on polyacrylamide: non-ionic, anionic and cationic Polyacrylamides and their applications in water and wastewater treatment: literature review. *Chem. Sci. Int. J*, *25*, 1-8.

Shen, Y., Xiao, K., Liang, P., Ma, Y., & Huang, X. (2013). Improvement on the modified Lowry method against interference of divalent cations in soluble protein measurement. *Applied Microbiology and Biotechnology*, *97*, 4167–4178.

Siddharth, T., Sridhar, P., Vinila, V., & Tyagi, R. D. (2021). Environmental applications of microbial extracellular polymeric substance (EPS): a review. *Journal of Environmental Management*, *287*, 112307.

Steinman, A. D., Havens, K. E., Rodusky, A. J., Sharfstein, B., James, R. T., & Harwell, M. C. (2002). The influence of environmental variables and a managed water recession on the growth of charophytes in a large, subtropical lake. *Aquatic Botany*, *72*(3–4), 297–313.

Tan, X.-L., Zhang, G.-P., Hang, Y. I. N., & Furukawa, Y. (2012). Characterization of particle size and settling velocity of cohesive sediments affected by a neutral exopolymer. *International Journal of Sediment Research*, *27*(4), 473–485.

Tolkien, Z., Stecher, L., Mander, A. P., Pereira, D. I. A., & Powell, J. J. (2015). Ferrous sulfate supplementation causes significant gastrointestinal side-effects in adults: a systematic review and meta-analysis. *PloS One*, *10*(2), e0117383.

Thomaz, S. M. (2023). Ecosystem services provided by freshwater macrophytes. *Hydrobiologia*, *850*(12), 2757–2777.

Van Anholt, R. D., Spanings, F. A. T., Knol, A. H., Van der Velden, J. A., & Wendelaar Bonga, S. E. (2002). Effects of iron sulfate dosage on the water flea (Daphnia magna Straus) and early development of carp (Cyprinus carpio L.). *Archives of Environmental Contamination and Toxicology*, *42*, 182–192.

Vermaat, J. E., Santamaria, L., & Roos, P. J. (2000). Water flow across and sediment trapping in submerged macrophyte beds of contrasting growth form. *Archiv Für Hydrobiologie*, *148*(4), 549–562.

Viollier, E., Inglett, P. W., Hunter, K., Roychoudhury, A. N., & Van Cappellen, P. (2000). The ferrozine method revisited: Fe (II)/Fe (III) determination in natural waters. *Applied Geochemistry*, *15*(6), 785–790.

Wright, K. E. (1943). Internal precipitation of phosphorus in relation to aluminum toxicity. *Plant Physiology*, *18*(4), 708.

Yang, S., & Li, X. (2009). Influences of extracellular polymeric substances (EPS) on the characteristics of activated sludge under non-steady-state conditions. *Process Biochemistry*, *44*(1), 91–96.

Ye, F., Peng, G., & Li, Y. (2011). Influences of influent carbon source on extracellular polymeric substances (EPS) and physicochemical properties of activated sludge. *Chemosphere*, *84*(9), 1250–1255.

Zand, A., & Hoveidi, H. (2015). Comparing aluminium sulfate and poly-aluminium chloride (PAC) performance in turbidity removal from synthetic water. *Journal of Applied Biotechnology Reports*, *2*(3), 287-292.

Appendix 4, Chapter 2.

Contribution of suspended sediments to the optical environment of the Lake Okeechobee littoral zone

INTRODUCTION

Submerged aquatic vegetation (SAV) plays an important role in sediment retention and nutrient reduction in freshwater lakes (Dierberg et al., 2002; Knight et al., 2003; Vermaat et al., 2000). In freshwater treatment wetlands, SAV supports greater phosphorus (P) removal rates compared to rooted, emergent aquatic vegetation (Dierberg et al., 2002; Knight et al., 2003). SAV serves as important habitat for zooplankton, invertebrates, and other communities; affecting higher tropic levels including fish populations (Deosti et al., 2021; Dibble & Thomaz, 2009; Gomes et al., 2012; Thomaz, 2023). SAV coverage can be influenced by a variety of factors including sediment type, water depth, transparency, wave disturbance (Havens, 2003; Hudon et al., 2000; Schwarz et al., 2002; Wallsten & Forsgren, 1989). Water transparency is measured as $K_{d\ PAR}$, the diffuse attenuation coefficient of photosynthetically active radiation (PAR), light utilized for photosynthesis between the wavelengths 400 and 700 nm (Falkowski & Raven, 2013; Kirk, 1994; Myers et al., 2024). Light attenuation is depth dependent and influenced by chlorophyll *a,* colored dissolved organic matter (CDOM), and suspended solids (Sathyendranath, 2000; Saulquin et al., 2013).

Lake Okeechobee is the largest freshwater subtropical lake in surface area in the United States (Dang et al., 2023). It is shallow, nutrient rich and subject to frequent blooms of cyanobacteria (Dang et al., 2023). Nutrient loading and resulting increases in organic production have increased the sedimentation rate in the lake, resulting in the accumulation of fine grain mud sediments (Brezonik & Engstrom, 1998). Sedimentation rates have increased by a factor of two between 1860 and 1980, and the spatial extent of mud sediments has expanded especially in the southern direction between 1975 and 1988 (Brezonik & Engstrom, 1998; K. E. Havens & James, 1999). The expansion and redistribution of mud sediments in Lake Okeechobee has resulted in increased turbidity in southern portions of the lake (K. E. Havens & James, 1999). This turbidity reduces water transparency and limits the depth at which SAV can grow.

SAV biomass in Lake Okeechobee is relatively low; of all SAV species present (including *Hydrilla verticillata, Vallisneria americana,* and *Potamogeton illinoinensis*), *Chara* spp. was reported to have the highest biomass (Havens, 2003). Water transparency and depth are key environmental variables for SAV coverage in Lake Okeechobee (Havens, 2003; Steinman et al., 2002). *Chara* spp. biomass was strongly negatively correlated with total suspended solids (TSS) and inorganic suspended solids (Havens, 2003). This TSS is responsible for the majority of light reduction in Lake Okeechobee, compared to color (Pt Units) and chlorophyll *a* (chl *a*) µg/L) (Havens, 2003). In shallow regions, frequent exposure to winds resuspends soft mud sediments into the water column, resulting in high light reduction (Havens, 2003; Steinman et al., 2002). The high wind and wave energy generated during storm events, such as hurricanes, can also result in the additional loss of SAV cover; uprooting SAV and generating high concentrations of resuspended sediment

(Chimney, 2005; Hanlon & Jordan, 2023). This resuspended sediment has negative impacts for economically important fish species. The abundance of Largemouth Bass (*Micropterus salmoides*), an economically important freshwater game fish, in Lake Okeechobee is related to vascular SAV cover which is influenced by TSS (Hanlon & Jordan, 2023; Havens et al., 2005). In Lake Okeechobee, dense SAV cover is only found at locations where water depth was <2m and TSS was <20-30 mg/L (Havens, 2003).

Resuspended solids contribute most to light attenuation in Lake Okeechobee and remain poorly characterized for the lake. Here we better characterize the resuspended particulate matter that contributes to light attenuation in Lake Okeechobee by determining particle size classes both in-situ and lab-based methods. We are mainly interested in the relative light-absorbing contribution of the individual size classes. In other words, are larger or smaller particles responsible for attenuating the most light? This has important implications for any turbidity mitigation methods, which may be designed to act on a specific size class.

METHODS

Fieldwork. Two sites on the southern end of Lake Okeechobee were sampled roughly 1 week following Hurricane Milton's landfall on 10/18/2024, on 10/25/2024, and on 11/22/2024. Samples were collected at one site in Coot Bay (LOCB) and a secondary site (LOSS). In addition, LOCB and LOSS, additional sampling was performed 4 months after Hurricane Milton's landfall at two new sites in the pelagic and littoral zone of the lake, LOPZ and LOLZ, respectively. At all sites surface water was sampled for filtration and water column profiles were taken. At all sites 35 mL of surface water was collected in 35 mL glass amber vials and transported on ice for CDOM (ppb), total chlorophyll *a* (μg/L), and turbidity determination (NTUs). 5L of surface water was collected in 10 L LDPE carboys and transported at ambient temperatures for filtration onto 47 mm GF/F filters immediately following field collection. At every site except LOSS, 10 L of additional surface water was collected in an HDPE carboy and transported at ambient temperatures for size fractionation filtration.

In situ measurements. Aquatic particles and plankton were imaged in situ using an AUTOHOLO submersible holographic imaging system. The recording medium is a high resolution, 4920 x 3280 (16 MP) Imperx camera, acquiring data at a frame rate of 1 Hz. Processing of the holograms enable characterization of particles within ~ 20 μm – 2 cm using the system, providing a baseline of the local particle composition, which can help supplement direct sampling efforts. An added advantage of the system design is the variable sampling length between the two windows (1-20 cm), which corresponds to a sampling volume of 4.86-97.2 mL per hologram in the lenless optical configuration used in the current deployment. The large sample volume also allows for studying particles, bubbles and droplets in their natural environment, while minimizing breakage/dispersal. Due to the highly turbid nature of Lake Okeechobee, the sampling length of 1 cm with sampling volume of 4.86 mL per hologram was used. Data are stored on-board using 4 TB solid state hard drives and retrieved and processed after each deployment. Data were recorded in two separate deployments from 10/1/24 to 10/2/24 and from 10/28/24 to 10/29/24. A total of 6 and 9 files were recorded, respectively, consisting of 1000 holograms each, totaling

15,000 holograms across the entire set of experiments. Each file took ~20 minutes to record and the time between each successive data acquisition time point was approximately 165 min.

Lab processing. Immediately after collection, surface water samples were processed on-site at a field lab. Unfiltered surface water was measured for CDOM (ppb) and total chlorophyll *a* (µg/L) readings using trilogy fluorometers (Turner designs, San Jose, California, USA) and turbidity readings (NTUs) using an Oakton T100WL turbidity meter kit (Oakton instruments, Vernon Hills, Illinois, USA). 250 mL water was filtered onto individual, pre-weighted 47 mm GF/F filters which were transported on ice and frozen (-20 °C) for gravimetric total suspended solids (TSS) measurements.

A total of 5L of surface water was sequentially filtered through pre-weighted, 47 mm decreasing pore size filters to determine the size of suspended particulate in surface waters. The volume of water filtered for each pore size was measured and recorded. Water was filtered through 215, 120, and 62 µm nominal pore size 47 mm diameter nylon mesh disks (CMND-215-047, CMND-120-47, CMND-62-047, Component supply, Sparta, Tennessee, USA) followed by 30, 10, 3, 0.4 and 0.2 µm pore size, 47 mm polycarbonate (PCTE) membrane filters (PCT30047100, PCT10047100, PCT3047100, PCT0447100, PCT0247100, Sterlitech, Auburn, Washington, USA). Solids retained on filters were used in gravimetric TSS determination. Filtrate from each step was retained. 30 mL of filtrate was collected in LDPE bottles for CDOM and EPA 180.1 turbidity measurement. Separately, 35 mL was collected in glass amber vials for CDOM and total chlorophyll *a* determination using trilogy fluorometers and turbidity determination using a turbidity meter kit as described previously. Turbidity (EPA 180.1) was also measured as NTUs using a Hach 2100Q meter (Hach, Loveland, Colorado, USA).

A fine-scale PAR profiling system was developed to measure PAR through the water column in a known volume of water. A US-SQS/L submersible spherical micro quantum sensor (Walz,) and LI-1500 light sensor logger (LI-COR) was lowered through a black painted PVC cylinder using a caliper. The bottom of the cylinder was illuminated using a 2” diameter 10000 lumens LED light source on low power setting (XM-L T6, Semlos). A 400 ml water sample was poured inside the cylinder and, after removing all bubbles stuck onto the black painted PVC wall, PAR was recorded every 10 mm from subsurface to 15mm, but only the first 8 measurements (i.e., 0-80mm were retained to avoid getting too close to the LEDs of the light source). Blank profiles in deionized (DI) water were also taken to account for the light source proximity. Unfiltered site water (LOCB and LOSS) as well as filtered LOCB site water (10 µm, 0.7 µm, and 0.4 µm filtered water) were profiled so that $K_{d\ PAR}$ could be determined.

$K_{d\ PAR}$ (units m^{-1}) of the resulting profiles was equal to:

$K_{d\ PAR} = K_{d\ PAR}(H20) + K_{d\ PAR}(\text{Light source}) + K_{d\ PAR}(>10\mu m) + K_{d\ PAR}(10\text{-}0.7\mu m) + K_{d\ PAR}(0.7\text{-}0.4\mu m) + K_{d\ PAR}(<0.4\mu m)$, where:

- $K_{d\ PAR}$ is the overall light extinction coefficient of the water profiled with the artifact linked to the near proximity of the source of light.

- $K_{d\,PAR}$(Light source) is the light extinction coefficient linked to the proximity of the light used (normally negligible when doing profiles outside since the sun is at 149 million km from Earth)
- $K_{d\,PAR}$(H2O) is the published light extinction coefficient of distilled water (0.027 m^{-1}, Smith and Baker, 1978)
- $K_{d\,PAR}$(>10µm), $K_{d\,PAR}$(10-0.7µm), $K_{d\,PAR}$(0.7-0.4µm) and $K_{d\,PAR}$(<0.4µm), are the light extinction coefficients for the particles above 10µm, 10-0.7µm, 0.7-0.4µm and less than 4µm respectively.

All $K_{d\,PAR}$ were determined directly or indirectly by plotting the $Ln(I_0/I_z)$ as a function of depth "z", where I_0 is the deepest PAR measurement in the cylinder and I_z is the light measured at depth z expressed in reversed order since the light profile starts from the deepest to the shallowest (i.e., an 80mm depth becomes a 0mm depth). The slope was determined in Excel using the LINEST function with 0 intercept.

For gravimetric TSS determination pre-weighted filters were dried to a constant weight at 103-105 °C and re-weighed to compute TSS as mg/L.

Beam attenuation of each aqueous filter fraction was obtained within 24 hours of filtration (samples stored at 20 °C) using a custom 3D printed beam transmissometer with a halogen source (Avantes Avalight-HAL) and CMOS spectrometer (Avantes AvaSpec-ULS2048-CL-EVO-RS), collimation optics and ~0.6° half-angle FOV receive optics (https://doi.org/10.5281/zenodo.14566972). The system was adjusted for different cuvette pathlengths as necessary, and data were logged with Avantes AvaSoft with MATLAB used to process data to yield beam attenuation.

Meteorological data. Wind speed data was downloaded from the South Florida Water Management District's DBHYDRO corporate environmental database (available at apps.sfwmd.gov; accessed January 2025) for the CFSW meteorological station (26° 44' 6.2334" N, -80° 53' 43.2204" W).

Analysis Turbidity (NTU and mg/L), CDOM (ppb), and total Chlorophyll a (µg/L) values were compared using ANOVA with TukeyHSD post-hoc testing. Where data could not meet normality assumptions with a Shapiro-Wilk test, these values were compared using Kruskal-Wallis with Dunn post-hoc tests. Analysis was conducted in R v 4.3.2 and p-values <0.05 were considered significant (R Core Team 2017).

Chapter 2: RESULTS AND DISCUSSION

Bulk optical properties. Across all sampling events, turbidity (NTU) and CDOM (ppb) did not differ between either site, while total Chl. *a* (µg/L) was higher at LOSS (Kruskal-Wallis, turbidity, p=0.17; CDOM, p=0.23; ANOVA, Chl. *a*, p<0.001; Table 1). Turbidity (NTU) was significantly higher for 10/18/2024 compared to 10/25/2024, but there were no differences between 11/22/2024 and the 10/18/2024 or the 10/25/2024 sampling events (Dunn, 10/18-10/25, p=0.015; 10/18-

11/22, p=0.18; 10/25-11/22, p=0.21). CDOM concentrations (ppb) were significantly higher on 10/25/2024 compared to 10/18/2024, but CDOM concentrations on 11/22/2024 did not differ from the first and second sampling events (Dunn, 10/18-10/25, p<0.001; 10/18-11/22, p=0.052; 10/25-11/22, p=0.077). There were no differences in total Chl. *a* concentration (µg/L) between any of the three sampling events (ANOVA, p=0.42). Across all three sampling events gravimetric TSS (mg/L) was higher at LOCB compared to LOSS (ANOVA, p=0.003; Table 1). TSS, as measured gravimetrically, was on average 81.2 mg/L for the LOCB site, and 95 mg/L for the LOSS site. Gravimetric TSS (mg/L) was highest on 10/18 compared to the second and third sampling events and did not differ between 10/25 and 11/22 (TukeyHSD, 10/18-10/25, p=0.005; 10/18-11/22, p=0.014; 10/25-11/22, p=0.85). Greater wind speeds during the 10/18 sampling event likely resulted in elevated TSS concentrations (Fig. 2). The LOSS site is more sheltered by vegetation, likely resulting in less disturbance from wind and lower TSS values. Gravimetric TSS (mg/L) values are within the range of TSS values previously recorded for Lake Okeechobee and are similar to values observed in 2005 and 2006 following hurricane disturbances (Jin et al., 2011; T. R. James et al., 2008). Prior to hurricane disturbances, TSS averaged around 10 mg/L for the nearshore zone (T. R. James et al., 2008).

Particle size classes – Fractionation study. The majority of suspended particulates are very fine (<10 um in diameter) (Fig. 1). On 11/22/2024, the most abundant particle size fraction was between 0.4 and 0.2 µm, unlike previous months. This fine particulate (<10 um in diameter) is also responsible for the majority of the turbidity (NTU) and total Chl. *a* detected (Fig. 3).

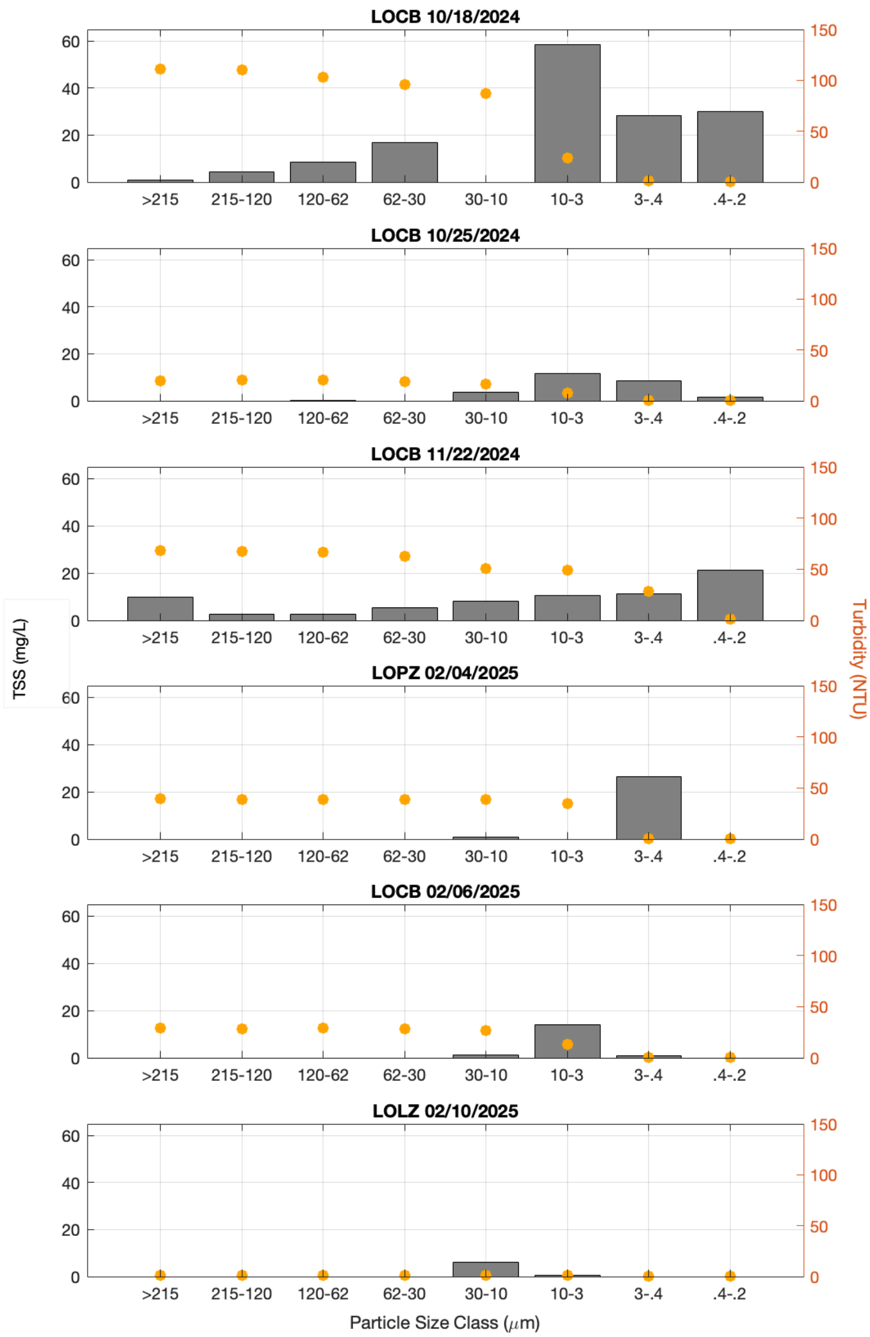


Figure 1. Turbidity (NTU) and TSS (mg/L) obtained from fractionation study. TSS measurements were highest at LOCB following the landfall of Hurricane Milton. The 30-10 and 10-3 µm particle size classes were a consistent source of suspended particles across each sampling event and location. Fine grained particles dominated TSS measurements at LOPZ. Corresponding turbidity

measurements of each size fraction display the contrast between particle size and turbidity levels. Larger particle sizes, while less in amount, can contribute significantly to turbidity.

Particles >3 µm accounted for 57% of the total surface water turbidity (NTU) on 10/18/2024, 41% of the total surface water turbidity on 10/25/2024, and 6% of total turbidity on 11/22/2024. This is followed by particles >0.4 µm, which accounted for 99% of total surface water turbidity on 10/18/2024, 74% on 10/25/2024, and 31% on 11/22/2024. Particles >0.2 µm accounted for 99% of total surface water turbidity on 10/18/2024, 76% on 10/25/2024 and 89% on 11/22/2024. Similarly, the majority of total Chl. *a* was attributed to particles <10 µm (Fig. 3). Particles >3 µm accounted for 55% of the total Chl. *a* on 10/18/2024, 50% on 10/25/2024, and 32% on 11/22/2024. This is followed by particles >0.4 µm, which accounted for 68% of total Chl. *a* on 10/18/2024, 56% on 10/25/2024, and 47% on 11/22/2024. Particles >0.2 µm accounted for 68% of total Chl. *a* on 10/18/2024, 58% on 10/25/2024, and 68% on 11/22/2024. Particle sizes < 10 µm in diameter contributed most turbidity. The decline in total Chl. *a* values with decreasing pore size could be due to algal cells attached to suspended solids being filtered out of solution.

The larger particle sizes observed on 10/18/2024 and 10/25/2024, compared to 11/22/2024, could be due to hurricane disturbance resuspending larger particle sizes. In 2024, Florida was impacted by hurricanes Debby (August 2024), Helene (September 2024) and Milton (October 2024), with hurricane Milton making landfall on October 9th, roughly one week prior to field sampling. The hurricane could have resuspended larger particle sizes that remained entrained through October. This could also be due to increased wind activity at the time of sampling from cold front disturbance. Daily average wind speeds at station CFSW peaked at 16.33 MPH on 10/10/2024, and again at 13.3 MPH on 10/17/2024 (Fig. 2). Wind speeds were lower for the other sampling events, averaging 7.21 MPH on 10/24/2024 and 9.68 MPH on 11/21/2024 (Fig. 2). Particle sizes were smallest on 11/22/2024. Following 10/18/2024, average wind speeds remained lower than in early October, which may have allowed some larger particles to settle out of the water column (Fig. 3).

Table 1. Surface water. Average Secchi transparency (cm), turbidity (NTU), CDOM (ppb) and total Chl. *a* (µg/L) concentrations for each site and each sampling event. Secchi transparency (cm) could not be measured for LOSS on 10/28/2024.

Sample		Secchi visibility	Turbidity (NTU)	CDOM (ppb)	total Chl. *a* (µg/L)
10/18/2024	LOCB	16	67.2	77.75	18.53
	LOSS	24	38.2	84.6	35.3
10/25/2024	LOCB	30	31.12	138.34	27.61
10/28/2024	LOSS	N/D	36.31	153.99	37.63
11/22/2024	LOCB	18.67	60.7	96.82	20.06
	LOSS	32.67	32.3	109.31	26.65

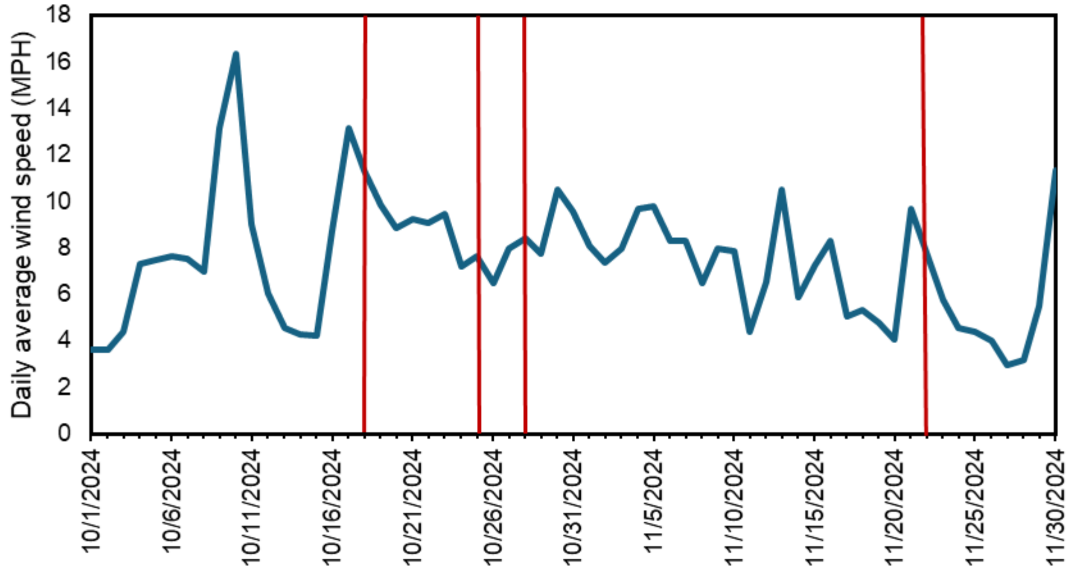


Figure 2. Daily average wind speeds at station CFSW. Daily average wind speeds (MPH) for station CFSW (26° 44' 6.2334" N, -80° 53' 43.2204" W) from 10/1/2024 to 11/30/202, with sampling events (10/18/2024, 10/25/2024, 10/28/2024 and 11/22/2024) shown in red. Data downloaded from the South Florida Water Management District's DBHYDRO corporate environmental database provided by SFWMD.

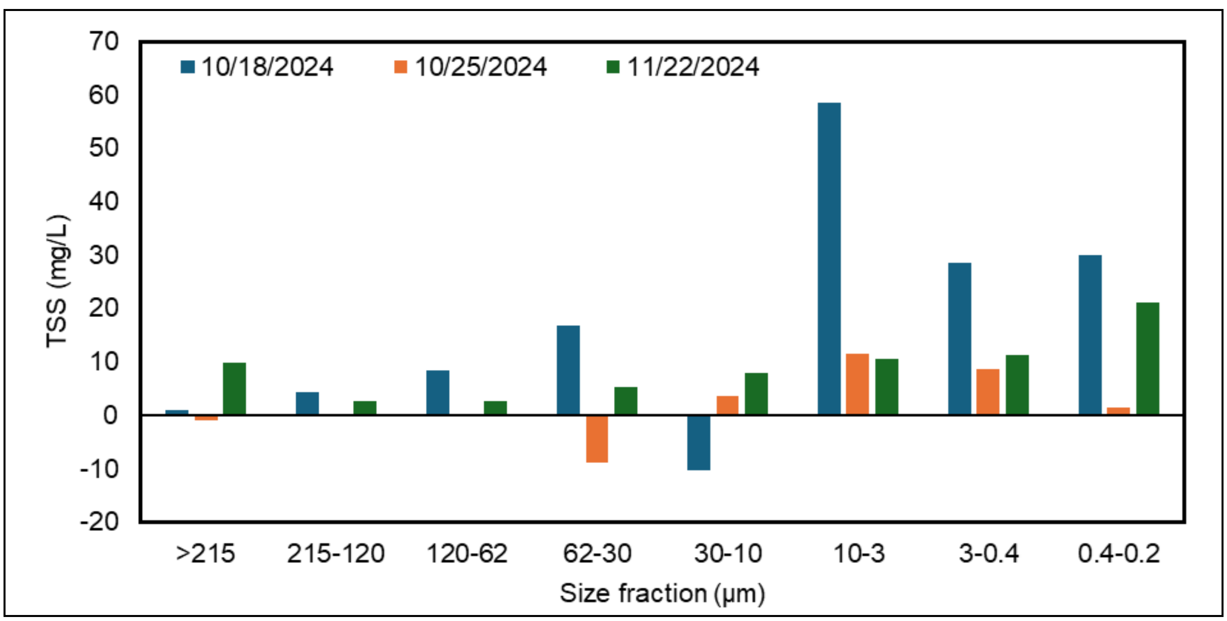


Figure 3. TSS of different size fractions. Gravimetric TSS (mg/L) for each pore size fraction of surface water collected from LOCB on 10/18/2024, 10/25/2024, and 11/22/2024.

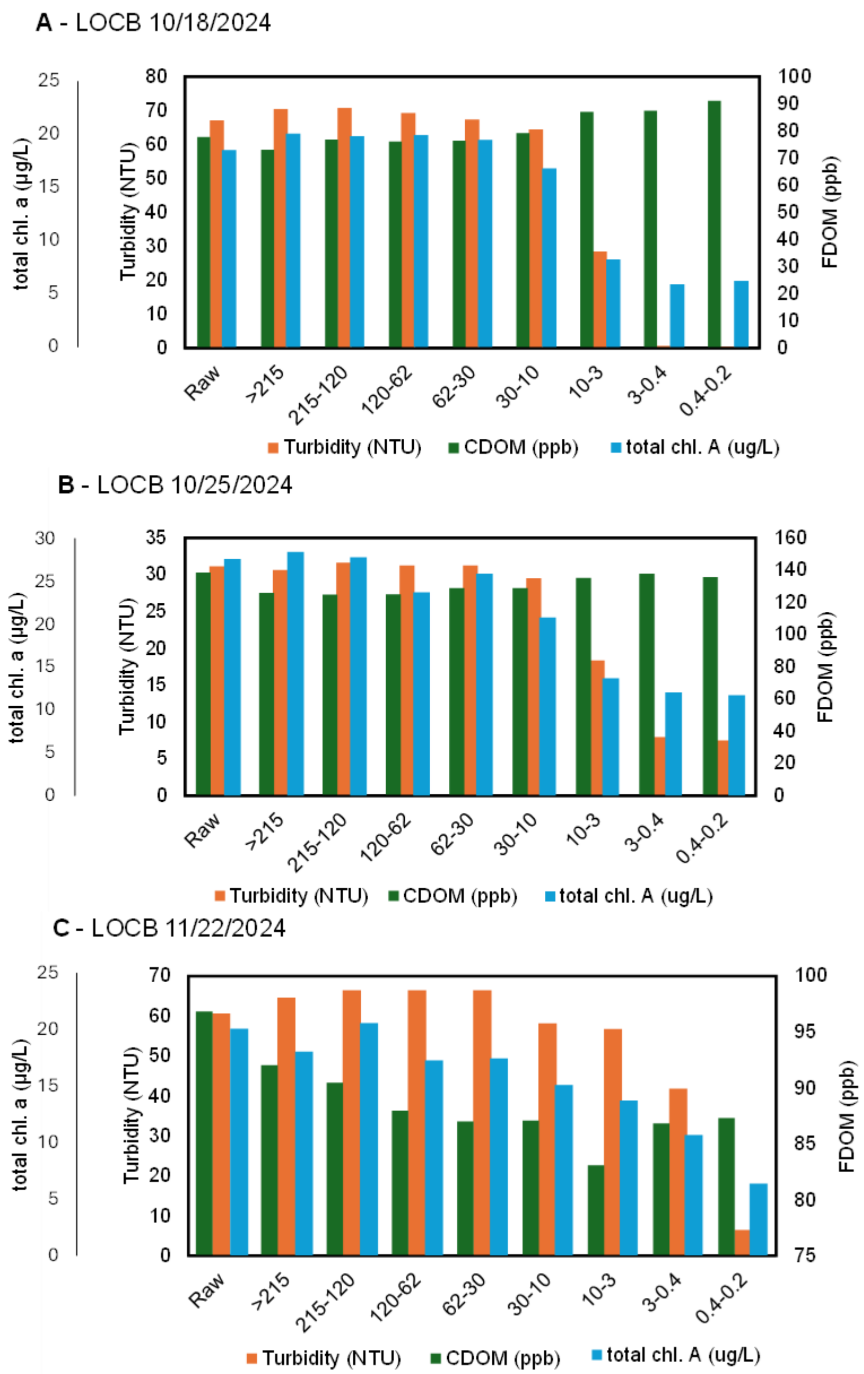


Figure 4. Turbidity, CDOM, and total Chl. *a* associated with size fractions. Turbidity (NTUs), CDOM (ppb), and total Chl. *a* (µg/L) measured from filtrate of each size fraction. Using surface water collected from LOCB on 10/18/2024 (top), on 10/25/2024 (middle), and on 11/22/2024 (bottom).

Total beam attenuation of individual size fractions, which is a measurement of the total light throughput, similarly indicated that the majority of particles responsible for attenuating light are between 3 and 30 µm in diameter (Figure 5). We intend to normalize this data to TSS for each size fraction to determine mass-specific attenuation, which will allow us to identify that specific particle size class with a biogeochemical composition and physical conformation most responsible for absorbing light (independent of the quantity of those particles). Additionally, this is critical data for conducting planned light modeling studies. Light attenuation is affected by particle concentration, size, shape and index of refraction (Baker & Lavelle, 1984). Particle size is the most influential variable that affects the optical characteristics of a suspension (Baker & Lavelle, 1984; Gordon et al., 1980). Smaller particles attenuate light more efficiently than larger particles, greater mass-specific attenuation would be expected for smaller size classes (Baker & Lavelle, 1984; Boss et al., 2001). Mass specific attenuation is strongly driven by particle density, the composition of particles for different size fractions and during different sampling events could also affect the attenuation of light (Neukermans et al., 2012). Interestingly, the 10/18/24 sampling event, which was closer in time to the passage of Hurricane Milton, had a greater degree of larger suspended particles. We would not expect these larger particles to be transported from the central lake, given they should be likely to settle out. Instead, these are likely particles generated from local resuspension or algal production. It is interesting to find that these particles could comprise a substantial fraction of the suspended sediment and light-attenuating load. However, relative to their concentration (i.e., the TSS), they contribute a lesser degree of light attenuation than the smaller particles. Thus, the smaller particles, which are at least partially transported from the central lake, are the more aggreious particles with respect to causing light issues for SAV. Following Stoke's law smaller particles have lower settling velocities and will take longer to settle out of the water column (Agrawal & Pottsmith, 2000). Efforts to remediate turbidity therefore should include small particle sizes to effectively increase light penetration for SAV growth. Differences in particle size can affect how suspensions respond to chemical coagulation treatments, with smaller particle sizes settling out faster and requiring lower coagulant doses (Black & Vilaret, 1969). Barriers to prevent local wave resuspension of sediments would also help to reduce turbidity and promote SAV recovery. Living shorelines, narrow marsh fringes with or without adjacent structures, can increase resilience by reducing wave energy and facilitating sedimentation (Vona et al., 2021). The presence of both non-erodible structures as well as living shorelines could help maximize the deposition of sediments (Vona et al., 2021). Low lake stages associated with drought are also associated with turbidity declines in the offshore regions of Lake Okeechobee following hurricane disturbance (T. R. James et al., 2008). When the lake stage is less than 15 ft msl, an underwater ridge helps prevent the transport of sediment and nutrient-rich water into the near-shore zone (Havens, 2002; Johnson et al., 2007).

Dredging to address the issue of resuspended sediments is a slow and costly solution to reducing turbidity that is likely to only show modest improvements to lake TP concentrations (James & Pollman, 2011). Treatment with coagulants such as alum provides a faster, less expensive solution provided TMDL for TP can be met prior to treatment (James & Pollman, 2011). Reducing the load of TP to the lake is a preferred alternative, as there is no additional cost and no additional environmental issues that would need to be addressed (James & Pollman, 2011). Chemical treatment with alum has been successfully implemented in European lake restoration studies, only when external load reduction is achieved (James & Pollman, 2011). Chemical treatment should only be considered if external P loads are reduced, and water column TP does not decline (James & Pollman, 2011).

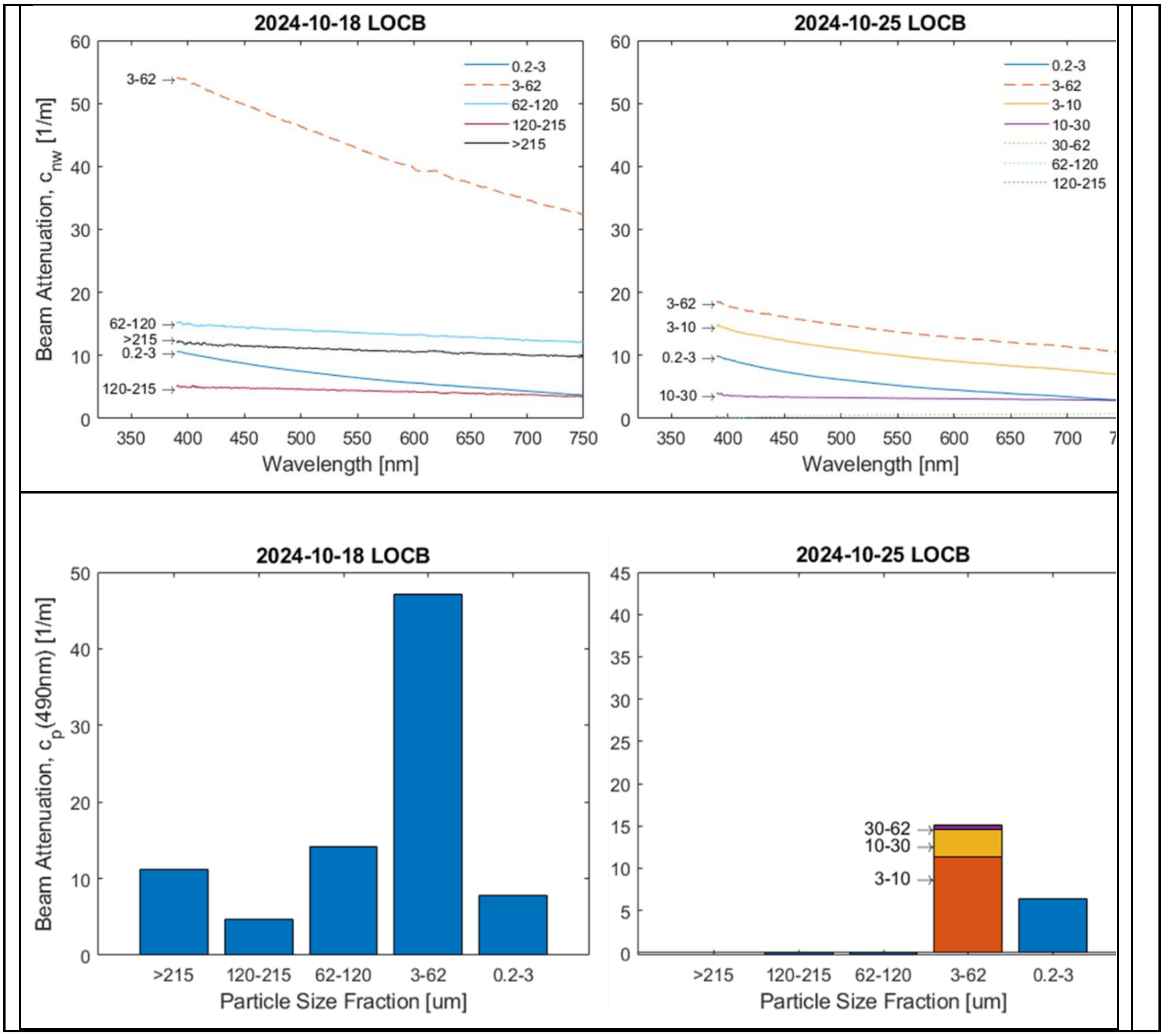


Figure 5. Beam attenuation of size fractions. (Top panels) Difference spectra (top panels) show the beam attenuation spectra associated with the size fractions of suspended particulate matter. The 2024-10-25 LOCB measurements included both 30µm and 10µm filtered measurements allowing for better characterization of the small particle pools from 3µm–10µm, 10µm–30µm, and 30µm–62µm. (Bottom panels) Beam attenuation at 490nm light wavelength for each of the measured fractions. 2024-10-25 LOCB includes the 3µm–62µm fraction further broken down into 3µm–10µm, 10µm–30µm, and 30µm–62µm. For 2024-10-25 LOCB, total (unfiltered) water was not measured, so the fraction >215µm is not included (expected to be insignificant due to the near-zero values for 62µm–120µm and 120µm–215µm).

Particle size classes – Holographic microscope. We chose to use two spatially co-located sample datasets across the two different deployments (A2 and B1) to highlight the difference in particle abundances and size distributions, including slope (Fig. 7). Particle size is characterized by the equivalent size diameter (ESD) which is defined as:

$$ESD = \sqrt{4A/\pi},$$

where A is area of the particle. Particles >20 um in equivalent size diameter are resolved in the data. Higher particle abundances in B1 (Oct 28) are expected due to a wind event prior to deployment. There was minimal temporal variability in the PSD data during the first deployment, as evidenced by Figure 7-left. However, there are some differences observed in deployment B (Fig. 6-right). Figure 7 shows that the last dataset (B9) depicts lower particle counts in the 30-400 µm size range, compared to the other four datasets (B1, B3, B5 and B7). These data demonstrate the capability of in situ holography for looking at spatial and temporal variabilities in particle loads, which can then be integrated with other data streams (velocity, wind, etc.) to obtain a holistic picture of the physical dynamics in Lake Okeechobee.

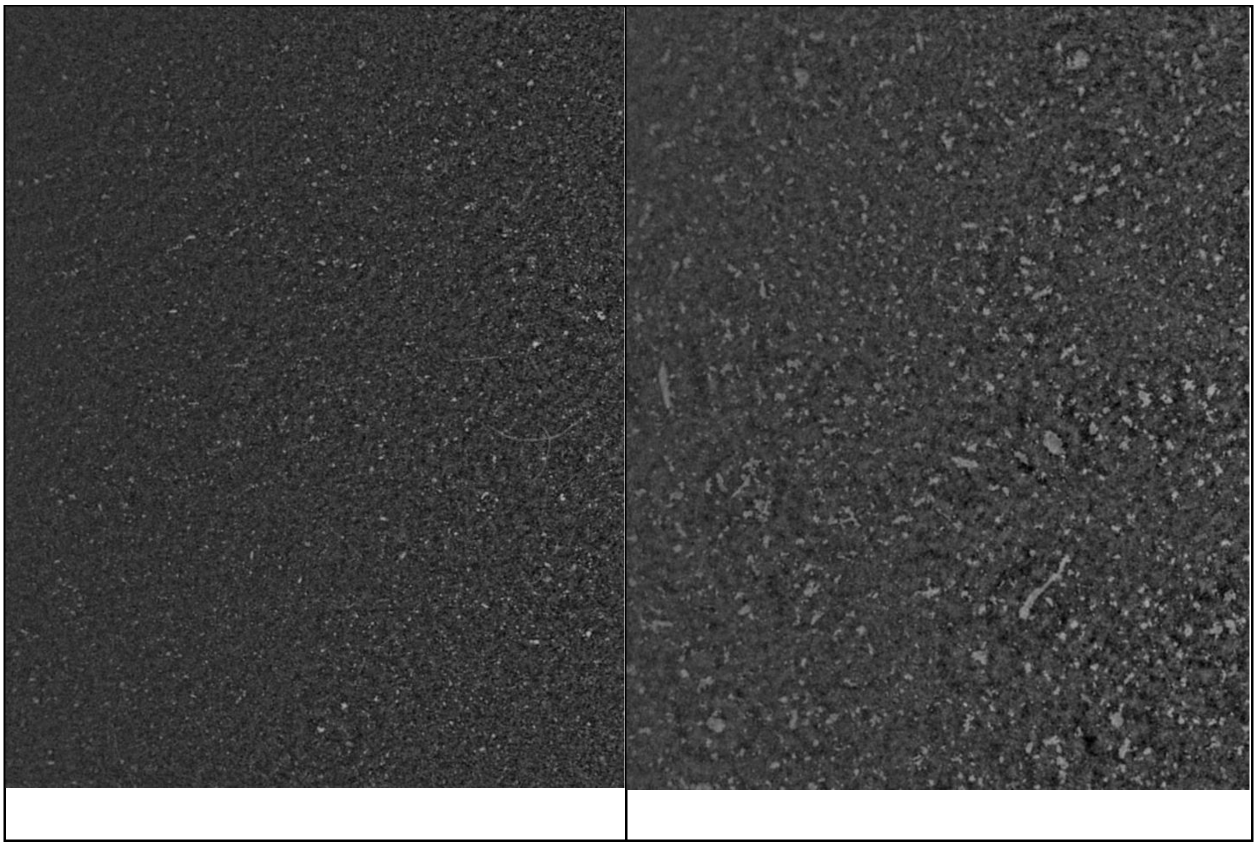


Figure 6. AUTOHOLO raw imagery. The AUTOHOLO collects thousands of images over the course of deployment, with each image corresponding to the entire sensor field of view. Light colored pixels correspond to particulates, and thus the total sum of all particles and their respective size can be used to derive a particle size distribution. Images are from 10/1/24 (left) and 10/28/24 (right) and roughly correspond in time to the particle size distributions presented below (Fig. 7).

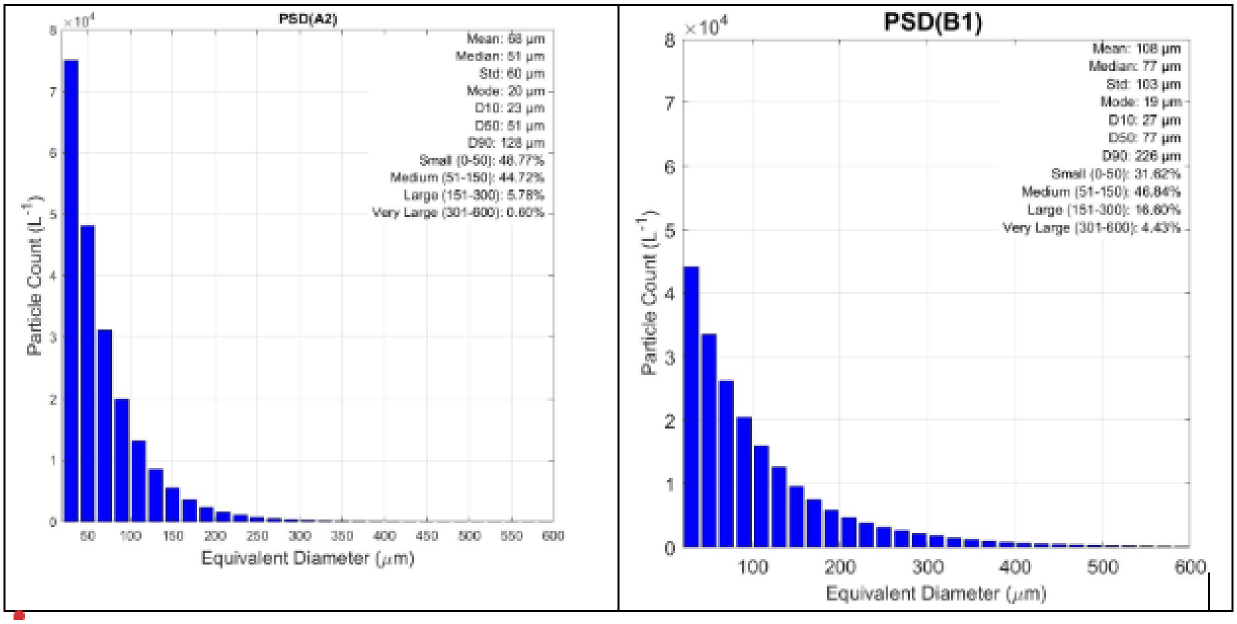


Figure 7. AUTOHOLO results. Resulting particle size distributions from the in situ holographic microscope deployed at site LOCB from 10/1/24 at 3:18 pm (left, “A2”) and 10/28/24 at 12:51 pm (right, “B1”).

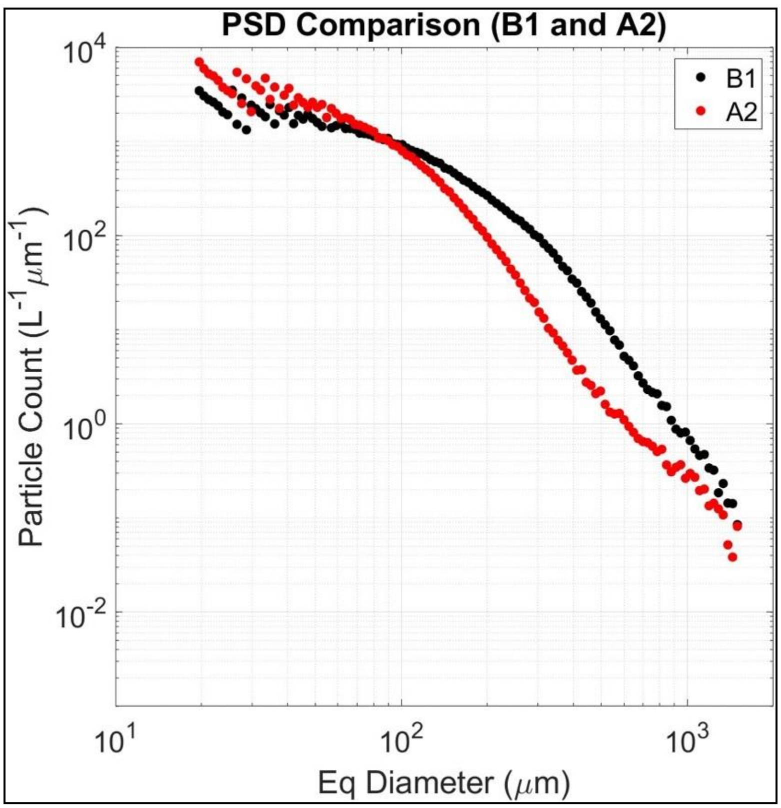


Figure 8. AUTOHOLO PSD Comparison. Particle size distributions corresponding to the two deployments dates in Fig. 7.

$K_{d\,PAR}$ determined in the laboratory was about 1.5-1.8 times higher than $K_{d\,PAR}$ determined in the field. It is not known why such a discrepancy exists, but this could be linked to the light source used. One way to alleviate the issue would be to use a steady 490nm light source and use algorithms found in the literature (or develop our own) to convert Kd490 into $K_{d\,PAR}$. The changes of $K_{d\,PAR}$ over time and across locations were, however, consistent with those changes measured in the field. The relative contribution of the various size fractions in the water column to the overall $K_{d\,PAR}$ shows that after the hurricane, most of the light attenuation was linked to the 0.7µm-0.4µm size fraction (58%) followed by the fraction of particles sized 10µm or higher (37%) (Table 2). This pattern however changed as the particles in suspension sedimented for event 2 (Table 2). For event 2, the overall $K_{d\,PAR}$ light attenuation dropped by 1.8 and the particles in the 10µm-0.7µm and less than 0.4µm attenuated the light most (45% and 40% respectively) (Table 2). For the last event, which had a $K_{d\,PAR}$ similar to event 1, light attenuation was largely attributed to the 10-0.7µm fraction (61%) and above (21%) (Table 2). The light attenuation per size fraction does need additional investigations (and also require a refinement of the apparatus used to measure PAR profiles in the laboratory), but overall, the results show that gravitoidal (net settling) and non-gravitoidal (suspended) particles as well as solutes (particles less than 0.45µm are normally no longer particulate) are responsible for light attenuation and shift from one another or can be attributed to both depending on the trophic and hydrodynamic conditions.

Table 2. $K_{d\,PAR}$ results. Summary of $K_{d\,PAR}$ and percentage of light attenuation attributed to different particle sizes. Values for LOLZ from 2/10/2025 not shown.

		$K_{d\,PAR}$ (m^{-1}) for particle size (µm)					% of light attenuation per particle size (µm)				
Event	Location	all	>10µm	10-0.7µm	0.7-0.4µm	<0.4µm	all	>10µm	10-0.7µm	0.7-0.4µm	<0.4µm
1	LOCB	22.49	8.33	-1.37	12.95	2.58	100%	37%	-6%	58%	11%
	LOSS	16.06	NA	NA	NA	NA	100%	NA	NA	NA	NA
2	LOCB	12.38	1.28	5.57	0.53	5.01	100%	10%	45%	4%	40%
	LOSS	9.07	NA	NA	NA	NA	100%	NA	NA	NA	NA
3	LOCB	20.49	4.23	12.60	0.86	2.80	100%	21%	61%	4%	14%
	LOSS	9.27	NA	NA	NA	NA	100%	NA	NA	NA	NA
4	LOCB	11.14	3.29	5.25	0.75	1.85	100%	30%	47%	7%	17%
	LOSS	11.50	NA	NA	NA	NA	100%	NA	NA	NA	NA
	LOPZ	12.71	-0.45	10.86	0.68	1.63	100%	-4%	85%	5%	13%

Chapter 2: CONCLUSIONS

Turbidity was highest and particle sizes were largest during the 10/18/2024 sampling event, likely due to greater wind activity during this sampling and due to increased resuspension during hurricane Milton. Particle sizes were smallest on 11/22/2024, which can also be attributed to reduced wind activity allowing some larger particles to settle out of the water column. Most resuspended particles observed in Lake Okeechobee were small, <10 µm in diameter. These smaller particles are responsible for the majority of turbidity measured in the water column. The majority of particles responsible for attenuating light are also between 3 and 30 µm in diameter. Relative to concentration, smaller particles contribute most to light attenuating properties. Gravitoidal, non-gravitoidal, and solutes all contribute to the attenuation of PAR in Lake Okeechobee. These smaller particles will take longer to settle out of the water column. Efforts to remediate turbidity in Lake Okeechobee should help prevent the resuspension of sediments in shallow areas and act on smaller particle sizes (< 10 µm) for the greatest impact on water clarity. Wave barriers and chemical coagulants could help improve water clarity. Lowering lake stages would also help improve water clarity and help separate the littoral zone from the turbid water at the center of the lake.

Chapter 2 References

Agrawal, Y. C., & Pottsmith, H. C. (2000). Instruments for particle size and settling velocity observations in sediment transport. *Marine Geology*, *168*(1–4), 89–114.

Baker, E. T., & Lavelle, J. W. (1984). The effect of particle size on the light attenuation coefficient of natural suspensions. *Journal of Geophysical Research: Oceans*, *89*(C5), 8197–8203.

Black, A. P., & Vilaret, M. R. (1969). Effect of particle size on turbidity removal. *Journal-American Water Works Association*, *61*(4), 209–214.

Boss, E., Pegau, W. S., Gardner, W. D., Zaneveld, J. R. V, Barnard, A. H., Twardowski, M. S., Chang, G. C., & Dickey, T. D. (2001). Spectral particulate attenuation and particle size distribution in the bottom boundary layer of a continental shelf. *Journal of Geophysical Research: Oceans*, *106*(C5), 9509–9516.

Brezonik, P. L., & Engstrom, D. R. (1998). Modern and historic accumulation rates of phosphorus in Lake Okeechobee, Florida. *Journal of Paleolimnology*, *20*, 31–46.

Chimney, M. J. (2005). Surface seiche and wind set-up on Lake Okeechobee (Florida, USA) during hurricanes Frances and Jeanne. *Lake and Reservoir Management*, *21*(4), 465–473.

Dang, T. D., Arias, M. E., Tarabih, O., Phlips, E. J., Ergas, S. J., Rains, M. C., & Zhang, Q. (2023). Modeling temporal and spatial variations of biogeochemical processes in a large subtropical lake: Assessing alternative solutions to algal blooms in Lake Okeechobee, Florida. *Journal of Hydrology: Regional Studies*, *47*, 101441.

Deosti, S., de Fátima Bomfim, F., Lansac-Tôha, F. M., Quirino, B. A., Bonecker, C. C., & Lansac-Tôha, F. A. (2021). Zooplankton taxonomic and functional structure is determined by macrophytes and fish predation in a Neotropical river. *Hydrobiologia*, *848*, 1475–1490.

Dibble, E. D., & Thomaz, S. M. (2009). Use of fractal dimension to assess habitat complexity and its influence on dominant invertebrates inhabiting tropical and temperate macrophytes. *Journal of Freshwater Ecology*, *24*(1), 93–102.

Dierberg, F. E., DeBusk, T. A., Jackson, S. D., Chimney, M. J., & Pietro, K. (2002). Submerged aquatic vegetation-based treatment wetlands for removing phosphorus from agricultural runoff: response to hydraulic and nutrient loading. *Water Research*, *36*(6), 1409–1422.

Falkowski, P. G., & Raven, J. A. (2013). *Aquatic photosynthesis*. Princeton University Press.

Gomes, L. C., Bulla, C. K., Agostinho, A. A., Vasconcelos, L. P., & Miranda, L. E. (2012). Fish assemblage dynamics in a Neotropical floodplain relative to aquatic macrophytes and the homogenizing effect of a flood pulse. *Hydrobiologia*, *685*, 97–107.

Gordon, H. R., Smith, R. C., Ronald, J., & Zaneveld, V. (1980). Introduction to ocean optics. *Ocean Optics VI*, *208*, 14–55.

Hanlon, C. G., & Jordan, A. (2023). Influence of habitat and other factors on Largemouth Bass abundance in Lake Okeechobee, Florida. *Transactions of the American Fisheries Society*, *152*(4), 429–442.

Havens, K. E. (2002). Development and application of hydrologic restoration goals for a large subtropical lake. *Lake and Reservoir Management*, *18*(4), 285–292.

Havens, K. E. (2003). Submerged aquatic vegetation correlations with depth and light attenuating materials in a shallow subtropical lake. *Hydrobiologia*, *493*, 173–186.

Havens, K. E., Fox, D., Gornak, S., & Hanlon, C. (2005). Aquatic vegetation and largemouth bass population responses to water-level variations in Lake Okeechobee, Florida (USA). *Hydrobiologia*, *539*, 225–237.

Havens, K. E., & James, R. T. (1999). Localized changes in transparency linked to mud sediment expansion in Lake Okeechobee, Florida: ecological and management implications. *Lake and Reservoir Management*, *15*(1), 54–69.

Hudon, C., Lalonde, S., & Gagnon, P. (2000). Ranking the effects of site exposure, plant growth form, water depth, and transparency on aquatic plant biomass. *Canadian Journal of Fisheries and Aquatic Sciences*, *57*(S1), 31–42.

James, T. R., Chimney, M. J., Sharfstein, B., Engstrom, D. R., Schottler, S. P., East, T., & Jin, K.-R. (2008). Hurricane effects on a shallow lake ecosystem, Lake Okeechobee, Florida (USA). *Fundamental and Applied Limnology*, *172*(4), 273.

James, R. T., & Pollman, C. D. (2011). Sediment and nutrient management solutions to improve the water quality of Lake Okeechobee. *Lake and Reservoir Management*, *27*(1), 28–40.

Jin, K.-R., Chang, N.-B., Ji, Z.-G., & James, R. T. (2011). Hurricanes affect the sediment and environment in Lake Okeechobee. *Critical Reviews in Environmental Science and Technology*, *41*(S1), 382–394.

Johnson, K. G., Allen, M. S., & Havens, K. E. (2007). A review of littoral vegetation, fisheries, and wildlife responses to hydrologic variation at Lake Okeechobee. *Wetlands*, *27*(1), 110–126.

Kirk, J. T. O. (1994). *Light and photosynthesis in aquatic ecosystems*. Cambridge university press.

Knight, R. L., Gu, B., Clarke, R. A., & Newman, J. M. (2003). Long-term phosphorus removal in Florida aquatic systems dominated by submerged aquatic vegetation. *Ecological Engineering*, *20*(1), 45–63.

Myers, E. M., Juhl, A. R., & Subramaniam, A. (2024). Spatial and temporal variability of water transparency, its primary drivers, and other optical properties in the Hudson River Estuary. *Estuarine, Coastal and Shelf Science*, *305*, 108855.

Neukermans, G., Loisel, H., Mériaux, X., Astoreca, R., & McKee, D. (2012). In situ variability of mass-specific beam attenuation and backscattering of marine particles with respect to particle size, density, and composition. *Limnology and Oceanography*, *57*(1), 124–144.

Sathyendranath, S. (2000). *Remote sensing of ocean colour in coastal, and other optically-complex, waters.*

Saulquin, B., Hamdi, A., Gohin, F., Populus, J., Mangin, A., & d'Andon, O. F. (2013). Estimation of the diffuse attenuation coefficient KdPAR using MERIS and application to seabed habitat mapping. *Remote Sensing of Environment*, *128*, 224–233.

Schwarz, A.-M., de Winton, M., & Hawes, I. (2002). Species-specific depth zonation in New Zealand charophytes as a function of light availability. *Aquatic Botany*, *72*(3–4), 209–217.

Smith, R. C., & Baker, K. S. (1977). *The bio-optical state of ocean waters and remote sensing*.

Steinman, A. D., Havens, K. E., Rodusky, A. J., Sharfstein, B., James, R. T., & Harwell, M. C. (2002). The influence of environmental variables and a managed water recession on the growth of charophytes in a large, subtropical lake. *Aquatic Botany*, *72*(3–4), 297–313.

Thomaz, S. M. (2023). Ecosystem services provided by freshwater macrophytes. *Hydrobiologia*, *850*(12), 2757–2777.

Vermaat, J. E., Santamaria, L., & Roos, P. J. (2000). Water flow across and sediment trapping in submerged macrophyte beds of contrasting growth form. *Archiv Für Hydrobiologie*, *148*(4), 549–562.

Vona, I., Palinkas, C. M., & Nardin, W. (2021). Sediment exchange between the created saltmarshes of living shorelines and adjacent submersed aquatic vegetation in the Chesapeake Bay. *Frontiers in Marine Science*, *8*, 727080.

Wallsten, M., & Forsgren, P. O. (1989). *The effects of increased water level on aquatic macrophytes.*

Appendix 4, Chapter 3.

Dynamics and regulation of light attenuating components in Lake Okeechobee

INTRODUCTION

Submerged aquatic vegetation (SAV) is important for nutrient reduction and sediment retention in freshwater environments (Dierberg et al., 2002; Knight et al., 2003; Vermaat et al., 2000). SAV is an important habitat for invertebrates which affects higher tropic levels including fish populations (Deosti et al., 2021; Dibble & Thomaz, 2009; Gomes et al., 2012; Thomaz, 2023). Photosynthetically active radiation (PAR) is light utilized by phytoplankton for photosynthesis, between the wavelengths 400 and 700 nm (Falkowski & Raven, 2013; Kirk, 1994). Light attenuation is depth dependent and influenced by chlorophyll *a,* colored dissolved organic matter (CDOM), and suspended solids (Sathyendranath, 2000; Saulquin et al., 2013). Light attenuation is an important determinant of the depth at which SAV can colonize (Chambers & Kaiff, 1985; Sand-Jensen & Madsen, 1991). Compared to phytoplankton, macrophytes have higher light requirements for growth, and the maximum depth of colonization can vary depending on macrophyte species (Middelboe & Markager, 1997; Sand-Jensen & Madsen, 1991).

Here, we investigate light attenuation in Lake Okeechobee as a function of environmental drivers. Lake Okeechobee is a large, shallow, nutrient rich, freshwater subtropical lake that is subject to frequent blooms of cyanobacteria (Dang et al., 2023). SAV biomass in Lake Okeechobee is low and dominated by *Chara* spp. (Havens, 2003). Charophyte growth in Lake Okeechobee is strongly influenced by light availability (Steinman et al., 1997). In Lake Okeechobee, dense SAV cover is only found at locations where water depth was <2m and TSS was <20-30 mg/L (Havens, 2003). *Chara* spp. biomass was strongly negatively correlated with total suspended solids (TSS) and inorganic suspended solids which are responsible for attenuating light (Havens, 2003). Light availability can impact both the growth of charophytes and their germination. The germination of oospores from different charophyte species is influenced by soil anoxia, light availability, temperature, and burial depth (Bonis & Grillas, 2002).

TSS is responsible for the majority of light reduction in Lake Okeechobee, however, colored dissolved material also significantly attenuates light even when suspended sediment loading is low (Havens, 2003). In shallow regions, frequent exposure to winds resuspends soft mud sediments into the water column, resulting in high light reduction (Havens, 2003; Steinman et al., 2002). Storm events can result in additional SAV loss; uprooting SAV and generating high concentrations of TSS (Chimney, 2005; Hanlon & Jordan, 2023).

This sediment is easily resuspended and kept in suspension by wind action from cold fronts, generating unidirectional winds, high waves, and high shear stress at the bottom of lake Okeechobee (Jin et al., 2002; Jin & Ji, 2004). Hurricanes resuspend consolidated sediment from the mud zone in Lake Okeechobee, resulting in a greater amount of fine, easily resuspended material that affects light penetration in the lake (Jin et al., 2011). Material resuspended by hurricanes takes a long time to consolidate and settle out of the water column and can persist for more than 4 years following a hurricane event (T. R. James et al., 2008; Jin et al., 2011). Only drought conditions in the years following hurricane disturbances indicated a reduction in TSS in the lake (T. R. James et al., 2008). These fine sediments are generally microaggregates composed of primary silt particles and biological particles such as phytoplankton and bacteria, tightly bound with polymeric organic matter and fibrils (Droppo 2001).

Here, we evaluate field observations of light availability and particle dynamics in the context of environmental conditions. We further simulate in laboratory settling tube experiments and in sediment erosion experiments how rapidly the water clarifies after a turbidity-creating event. Observational and experimental data should provide insights into the causes and timing of light-attenuating particulates in the water column, while informing the potential efficacy of future mitigation measures – everything from natural attenuation and SAV planting, to active wave-attenuating devices.

METHODS

Discrete field measurements and sample collection. Two sites on the southern end of Lake Okeechobee were sampled roughly 1 week following Hurricane Milton's landfall: on 10/18/2024, and again on 10/25/2024 and 11/22/2024. Samples were collected at one site in Coot Bay (LOCB) and a secondary site (LOSS) sample. At both sites surface water was sampled for filtration and water column profiles were taken. Additional sampling was performed 4 months after Hurricane Milton's landfall at two new sites in addition to LOCB and LOSS. LOPZ and LOLZ represent sampling locations in the pelagic zone and littoral zone of the lake, respectively.

For each site, photosynthetic active radiation (PAR) light profiles were taken using a LICOR LI-250A light meter and a LI-193 spherical underwater quantum sensor (LI-COR, Lincoln, Nebraska, USA). PAR measurements were recorded every 25 cm below the surface of the water until PAR reached 0 µmol s^{-1} m^{-2} or if the bottom was reached. Suspended particle size profiles were taken using a LISST 200x submersible particle size analyzer (Sequoia Scientific Inc., Bellevue, Washington, USA). Turbidity (TSS, mg/L), dissolved oxygen (% and mg/L), conductivity (µS/cm), salinity, pH, temperature (℃), total chlorophyll (µg/L) and phycocyanin (µg/L) profiles were taken using a YSI EXO II multiparameter probe (YSI, Yellow Springs, Ohio, USA).

At both sites 35 mL of surface water was collected in 35 mL glass amber vials and transported on ice for CDOM (ppb), total chlorophyll *a* (µg/L), and turbidity determination (NTUs). For both sites, 5L of surface water was collected in 10 L LDPE carboys and transported at ambient temperatures for filtration onto 47 mm GF/F filters immediately following field collection. 2L of surface water was collected in 1L HDPE bottles and transported at ambient temperatures for fine-scale PAR profiles with a profiling device developed as part of this study. Approximately 21 L of unfiltered surface water was collected in 19L HDPE carboys for settling experiments. An additional 21 L of water was collected and filtered using a submersible pump (SPX-12-12, Alfa Marine (Shanghai) Co., Ltd., Shanghai China) and 10-inch canister filter housing with 10 µm pore size polypropylene filter cartridges to examine settling of particles only below this size threshold.

Intact sediment cores were collected from LOCB on 10/18/2024, 10/25/2024, and 02/06/2025 and LOLZ on 02/10/2025 using a telescopic pole corer vacuum suction device with a 3.5" diameter core coupler assembly. At least 5 cm of sediment was sampled. The overlying water of the sediment cores was aerated for transport to prevent artificial hypoxia. Samples were stored at ambient temperatures in the light for transport to the lab.

In situ time series measurements. A benthic lander platform (Fig. 1) was deployed at site LOCB on two occasions on 10/01/24 and 10/28/24, in a water depth of approximately 1 m. The lander platform was equipped with a holographic microscope (AUTOHOLO, described above), a LISST 200x particle size analyzer, and a water quality sonde. The sensors were all positioned such that the sensing heads were ~30 cm from the lakebed.

Figure 1. Benthic lander platform. Photo of the system illustrating the position of the sonde, AUTOHOLO, and LISST-200X.

Laboratory processing. Immediately after collection, surface water samples were processed on-site at a field lab. Unfiltered surface water was measured for CDOM (ppb) and total chlorophyll *a* (µg/L) readings using trilogy fluorometers (Turner designs, San Jose, California, USA) and turbidity readings (NTUs) using an Oakton T100WL turbidity meter kit (Oakton instruments, Vernon Hills, Illinois, USA). A 250 mL sample of water was filtered onto individual, pre-weighted 47 mm GF/F filters which were transported on ice and frozen (-20 ℃) for gravimetric total suspended solids (TSS) measurements. The remaining filtrate was retained for fine-scale PAR profiles. For gravimetric TSS determination pre-weighted filters were dried to a constant weight at 103-105 ℃ and re-weighed to compute TSS as mg/L.

Natural and filtered water settling experiments. Settling experiments were conducted in acrylic cylinders (9.525 cm diameter x 91.44 cm long) constructed with ports at three different levels to dispense water. The ports were located 2 cm from the base of the tube, 38.405 cm from bottom, and 74.81 cm from the bottom (15 cm below the water surface). Settling tubes were filled with 26 L of water (either unfiltered water or 10 µm filtered water) and conducted in triplicate. Water was sampled at regular time intervals and measured for turbidity (NTU) using an Oakton T100WL turbidity meter kit (Oakton instruments, Vernon Hills, Illinois, USA). A 20 mL subsample was withdrawn from each port with a syringe at roughly 4, 8, 15, 30, 60, 120, 240, 480, 1440, 2880, 4320, 5760, 7200, 10080, and 17280 minutes following the initial setup of the tubes. The time each sample was collected was recorded.

Sediment erosion settling experiments. Approximately 24 hours after sample collection, the sediment cores were resuspended with a propeller mimicking the effects of an erosion event. The propeller was mounted at a fixed distance (3 cm) above the sediment-water interface to replicate natural sheer stress. The speed of the propeller was rapidly increased to induce a moderate shear, maintained at this speed for two minutes, and then fully stopped. Erosional depths cannot be visually monitored with high accuracy but were on the order of ~ 1 cm. Turbidity in the core overlying water was recorded immediately after resuspension and at discrete intervals for several days following the resuspension event by collecting samples from the surface-most layer of overlying water and analyzing using a Hach 2100Q portable turbidimeter (EPA 180.1 compatible). A single water sample was collected following each turbidity measurement and filtered through a pre-weighed GFF filter to determine TSS at each time step. The filtrate was placed back in the core overlying water after each sample collection to maintain a constant volume.

Meteorological data. Wind speed data was downloaded from the South Florida Water Management District's DBHYDRO corporate environmental database (available at apps.sfwmd.gov; accessed January 2025) for the CFSW meteorological station.

Calculations and Statistical Analysis. $K_{d\ PAR}$ was calculated from PAR profiles as:

$$K_{d(PAR)} = \frac{\ln(I_o) - \ln(I_z)}{Z}$$

Where I_o is PAR just below the surface, I_z is PAR at depth Z, and Z is depth. The depth of the euphotic zone (Z_{eu}) was calculated from $K_{d\ PAR}$ as:

$$Z_{eu} = \frac{\ln(100)}{K_{d(PAR)}}$$

Multiple regression analysis was used to compare the change in turbidity over time from settling experiments for the unfiltered and 10 µm filtered water. Turbidity measurements were natural log transformed to meet linearity assumptions. $K_{d\ PAR}$ values were correlated to turbidity (NTU), CDOM (ppb), total Chlorophyll a (µg/L) and Sechii depth (m) values based on Pearson correlation analysis. Turbidity (NTU and mg/L), CDOM (ppb), and total Chlorophyll a (µg/L) values were compared using ANOVA with TukeyHSD post-hoc testing. Where data could not meet normality assumptions with a Shapiro-Wilk test, these values were compared using Kruskal-Wallis with Dunn post-hoc tests. Analysis was conducted in R v 4.3.2 and p-values <0.05 were considered significant (R Core Team 2017).

Chapter 3: RESULTS AND DISCUSSION

Field observations. There was little variation in turbidity throughout the water column, with FNU values slightly higher closer to the bottom of the water column (Fig. 2). Chl. *a* followed a similar pattern, with values increasing closer to the bottom (Fig. 2). Across all three sampling events, turbidity (NTU) and CDOM (ppb) did not differ between either site, while total Chl. *a* (µg/L) was higher at LOSS (Kruskal-Wallis, turbidity, p= 0.17; CDOM, p=0.23; ANOVA, Chl. *a*, p<0.001). Turbidity (NTU) was significantly higher for 10/18/2024 compared to 10/25/2024, but there were no differences between 11/22/2024 and the 10/18/2024 or the 10/25/2024 sampling events (Dunn, 10/18-10/25, p=0.015; 10/18-11/22, p=0.18; 10/25-11/22, p=0.21). CDOM concentrations (ppb) were significantly higher on 10/25/2024 compared to 10/18/2024, but CDOM concentrations on 11/22/2024 did not differ from the first and second sampling events (Dunn, 10/18-10/25, p<0.001; 10/18-11/22, p=0.052; 10/25-11/22, p=0.077). There were no differences in total Chl. *a* concentration (µg/L) between any of the three sampling events (ANOVA, p=0.42). Across all three sampling events gravimetric TSS (mg/L) was higher at LOCB compared to LOSS (ANOVA, p=0.003). Gravimetric TSS (mg/L) was highest on 10/18 compared to the second and third sampling events and did not differ between 10/25 and 11/22 (TukeyHSD, 10/18-10/25, p=0.005; 10/18-11/22, p=0.014; 10/25-11/22, p=0.85). Gravimetric TSS was higher on 10/18/2024, following the wind impacts of Hurricane Milton on 10/10/2024 and frontal activity on 10/17/2024 (Table 1; Figure 3). TSS was high, but within the range of TSS observed previously at Lake Okeechobee (T. R. James et al., 2008; Jin et al., 2011). Without hurricane disturbance, nearshore areas in Lake Okeechobee were previously recorded to have TSS around 10 mg/L (T. R. James et al., 2008). Greater wind speeds during the 10/18 sampling event likely resulted in elevated TSS concentrations (Fig. 3). The LOSS site is more sheltered by vegetation, likely resulting in less disturbance from wind and lower TSS values.

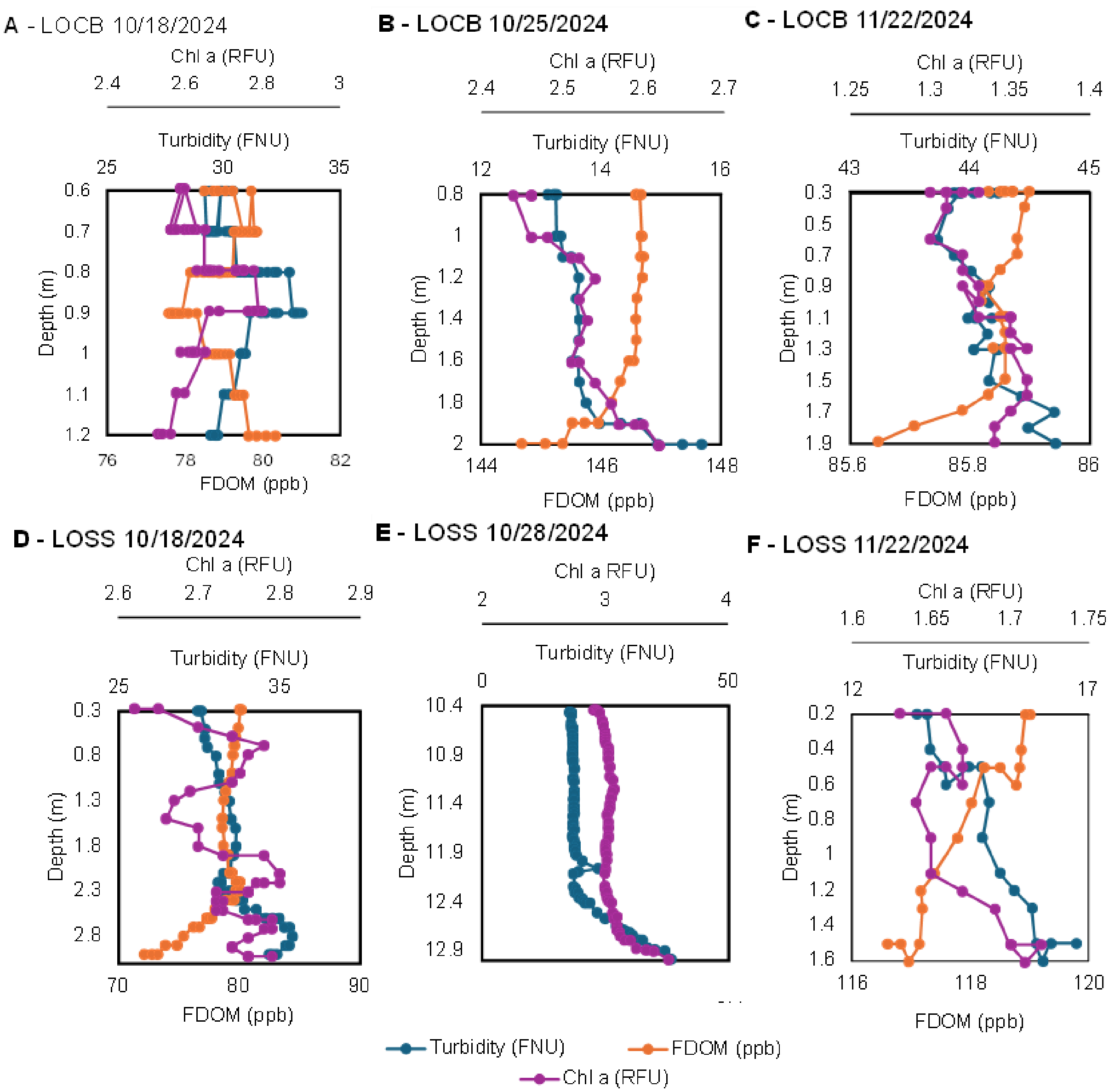


Figure 2. Turbidity, FDOM, and Chlorophyll *a* profiles for LOCB. Turbidity (FNU), FDOM (ppb) and Chl. *a* (RFU) profiles to the bottom of the water column from the site LOCB on 10/18/2024 (A), 10/25/2024 (B), and 11/22/2024 (C); and from site LOSS on 10/18/2024 (D), 10/28/2024 (E) and 11/22/2024 (F). FDOM values for 10/28/2024 are missing.

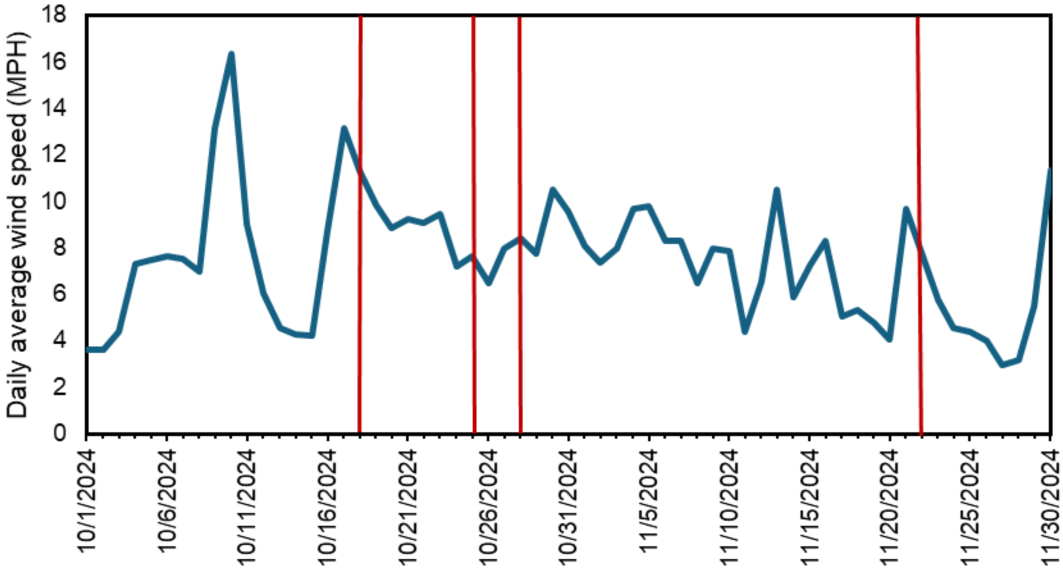


Figure 3. Daily average wind speeds at station CFSW. Daily average wind speeds (MPH)for station CFSW (26° 44' 6.2334" N, -80° 53' 43.2204" W) from 10/1/2024 to 11/30/202, with sampling events (10/18/2024, 10/25/2024, 10/28/2024 and 11/22/2024) shown in red. Data downloaded from the South Florida Water Management District's DBHYDRO corporate environmental database.

Table 1. Surface water. Average Secchi transparency (cm), turbidity (NTU), CDOM (ppb) and total Chl. *a* (µg/L) concentrations for each site and each sampling event. Secchi transparency (cm) could not be measured for LOSS on 10/28/2024.

Sample		Secchi disk depth (m)	Turbidity (NTU)	CDOM (ppb)	total Chl. *a* (µg/L)	Turbidity (mg/L)
10/18/2024	LOCB	0.16	67.2	77.75	18.53	81.6
	LOSS	0.24	38.2	84.6	35.3	56.5
10/25/2024	LOCB	0.30	31.12	138.34	27.61	41.6
10/28/2024	LOSS	N/D	36.31	153.99	37.63	24.6
11/22/2024	LOCB	0.19	60.7	96.82	20.06	57.2
	LOSS	0.33	32.3	109.31	26.65	20.5

On both sampling trips, PAR did not reach the bottom of the water column (Fig. 4). On 10/18/2024 at both sites PAR did not reach deeper than 50 cm below the surface (Fig. 4). High winds prior to sampling, on 10/10/2024 with the passing of hurricane Milton, and again on 10/17/2024 with a cold front, would have resuspended more sediments resulting in less light penetration (Fig. 3). Daily average wind speeds at station CFSW peaked at 16.33 MPH on 10/10/2024, and again at 13.3 MPH on 10/17/2024 (Fig. 3). Wind speeds were lower for the other sampling events, averaging 7.21 MPH on 10/24/2024 and 9.68 MPH on 11/21/2024 (Fig. 3). Water clarity improved somewhat by 10/25/2024, where PAR was detectible 75 cm below the surface of the water at the LOCB site (Fig. 4). By 11/22/2024, water clarity had improved at the LOSS.

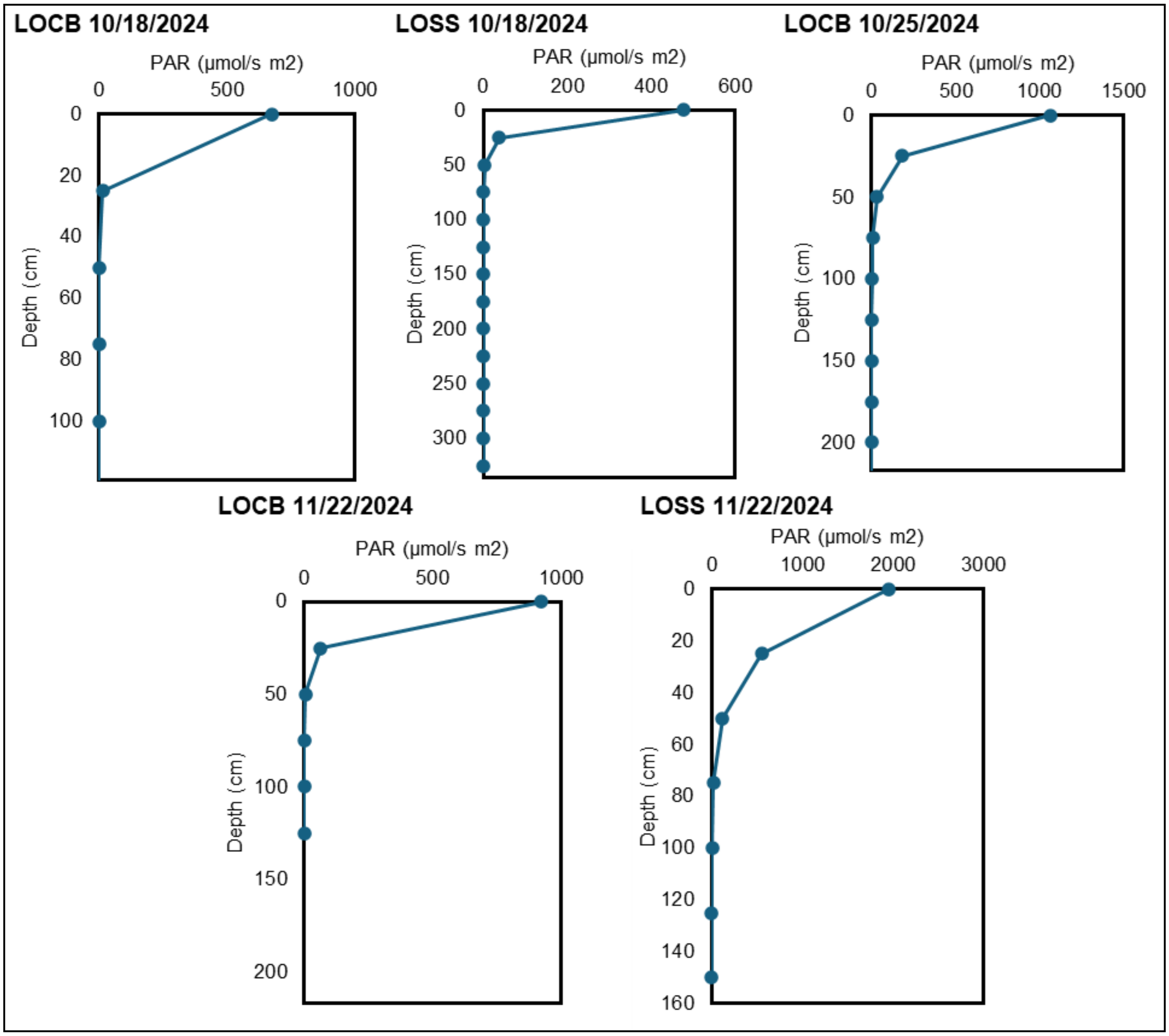


Figure 4. PAR profiles. PAR (µmol s^{-1} m^{-2}) profiles to the bottom of the water column. No PAR profile was taken for LOSS site on 10/25/2024.

site with PAR reaching 125 cm into the water column but only reaching 50 cm into the water column at the LOCB site (Fig. 4). Greater wind speeds on 11/22/2024, compared to 10/25/2024, could have contributed to the reduced PAR penetration at LOCB on 11/22/2024 (Fig. 3). The mean diffuse attenuation coefficient ($K_{d\ PAR}$) and depth of the euphotic zone were calculated based on averaged PAR profiles (Table 2). The depth of the euphotic zone was consistently shallow (Table 2). Following Hurricane Milton on 10/18/2024 this was 0.315 m at the LOCB site and remained shallow for the duration of sampling (0.691 m on 10/25/2024, and 0.406 m on 11/22/2024) (Table 2). The euphotic zone was deepest at the LOSS site on 11/22/2024 at 0.790 m (Table 2). On average photosynthesis for algae and hydrilla could only occur down to 0.53 m deep including all sites and all time points sampled. When expressed for the euphotic zone of vascular SAV, this average figure equates to 0.34 m. $K_{d\ PAR}$ was significantly, positively correlated with turbidity ($r= 0.898$, $p<0.001$); and significantly, negatively correlated with CDOM concentrations ($r=-0.808$, $p<0.001$) and Secchi visibility ($r= -0.956$, $p<0.001$). Overall, while the LOSS site, which is more sheltered and had greater abundances of SAV and fishing activity, had improved water quality relative to the LOCB site, neither site could theoretically support SAV growth at the time of sampling.

Table 2. Diffuse attenuation coefficient and euphotic zone depth. Average mean light attenuation coefficient $K_{d\ PAR}$ (m^{-1}) and depth of euphotic zone (Z_{eu}) in meters for algae and hydrilla as well as Z_{eu_sav} for vascular SAV, calculated from field PAR profiles at both sites. PAR profiles could not be taken for LOSS on 10/25/2024.

Site	Date	$K_{d\ (PAR)}$ (m^{-1})	Z_{eu} (m)	Z_{eu_sav} (m)
LOCB	10/18/2024	14.601	0.315	0.21
LOSS	10/18/2024	10.639	0.433	0.28
LOCB	10/25/2024	6.664	0.691	0.45
LOSS	10/25/2024	N/D	N/D	N/D
LOCB	11/22/2024	11.352	0.406	0.26
LOSS	11/22/2024	5.830	0.790	0.51

Turbidity and PAR profiles following a hurricane event. Following Hurricane Milton (Table 2), light penetration was overall very low with PAR not reaching more than 75 cm in the water column. Secchi disk transparency was limited to 30 cm at most, much lower than an average of 1.8 m for Florida lakes (Caffrey et al., 2007). This would limit the colonization and growth of macrophytes, as the maximum depth which macrophytes can colonize in Florida lakes is dependent on Secchi disk transparency (Caffrey et al., 2007; Canfield Jr et al., 1985). Light limitation in Lake Okeechobee is maximal during the winter, higher windspeeds resuspend greater amounts of sediment and subsequently nutrients, exacerbating problems with SAV growth (Havens, 1995; R. T. James et al., 2009; Xu et al., 2022).

In order to increase the area for potential vascular SAV coverage, additional measures should be taken. Both local algal production and resuspended sediments are important components of the light attenuating suspended solids in the lake (see Chapter 1). Remediation should therefore both reduce nutrient loading to limit algal production and limit the resuspension of sediments. For additional efforts to be effective, nutrient loading to the lake must first be reduced (James & Pollman, 2011). Non-erodible structures combined with living shorelines maximize sediment deposition, by reducing wave action and increasing sedimentation (Vona et al., 2021). Wave barriers, both concrete columns and nylon curtains, have been implemented in lake Taihu, a large, shallow lake (Huang & Liu, 2009). Wave barriers successfully reduced sediment resuspension, however high nutrient concentrations, high phytoplankton biomass, and poor transparency still persisted and additional measures such as macrophyte restoration were needed to restore water quality (Huang & Liu, 2009). Breakwaters have also facilitated SAV growth in Lake Markermeer in the Netherlands, a large shallow lake also impacted by wind driven waves (van Zuidam et al., 2022). Sediments and P can be precipitated out of the water column using chemical precipitants such as aluminum and iron-based coagulants and using modified clay mixtures (lanthanum-modified bentonite, LMB) (Pereira & Mulligan, 2023). Resuspension of precipitated solids could be an issue in Lake Okeechobee, a shallow lake with a long fetch where wind events frequently resuspend sediments (Canfield Jr et al., 2020; Jin et al., 2011). LBM stabilizes lake sediments; treated sediments resuspend less SRP and solids compared to untreated sediments during wind driven resuspension events (Yin et al., 2024). Treatment with aluminum sulfate reduces sediment stability and needs 2-4 months of ageing to achieve the same stability of untreated sediment (Egemose et al., 2009). Treatment with chemical precipitants is a more cost-effective solution compared to dredging to further reduce internal nutrient loading from resuspended sediments in Lake Okeechobee (James & Pollman, 2011). Treating Lake Okeechobee with chemical precipitants is also an added cost, treating with alum would cost approximately $500 million in 2002 USD, reducing the P loading on the lake is still recommended due to no additional in-lake cost and no additional environmental issues (James & Pollman, 2011). The long-term effectiveness of chemical precipitation of P depends on reducing nutrient loading (Jeppesen et al., 2007; Kibuye et al., 2021; Moore & Christensen, 2009; Sas, 1990).

Time series monitoring of particle properties and size distributions. The AUTOHOLO allows *in situ* characterization of the particle size distribution as at high frequency over extended durations, although 24-hour deployments were conducted here for logistical cautionary reasons (Fig. 5). While we considered the AUTOHOLO data in the context of understanding the overall size distribution and composition of the particles above (in Chapter 2), we here instead consider if trends are evident over a diel cycle or in response to weather or other environmental conditions. Between the two deployment events at site LOCB (10/1/24 and 10/28/24). We are working on interpreting these data with respect to local weather conditions too, and why the suspended particles were larger on 10/28 than on 10/1, with wind and currents the likely source of variation. Winds do tend to fluctuate over a daily cycle in the lake, and we see evidence of slightly larger particles in the water column during the night during both deployments (Table 3). Interestingly, wind conditions tend to relax at night, and this is especially evident around the 10/28/24 deployment. The fact that the mean particle size, and the overall number of particles ~80-500 μm in size were greater demonstrates that wind direction is not the sole control of resuspension, or that alternative processes such as particle aggregation, shearing, or biological production could be the dominant control. Indeed, it is possible that low winds allow particles to aggregate (i.e., less shearing), or that in situ biological production could dominate. This is consistent with the AUTOHOLO images as well as generic microscopy and TEM imagery (see Chapter 1), which show a high degree of particle aggregation. For Lake Okeechobee, there is a time lag between surface wind forcing, currents near the lake bottom, and sediment resuspension, with the time lag depending on water depth and the depositional velocity of suspended particulate which would depend on particle size and density (Jin & Sun, 2007). In deeper areas of the lake, bottom currents flow opposite that of wind driven surface currents (Jin & Sun, 2007). Differences between surface and bottom currents could also influence the resuspension patterns observed for Lake Okeechobee.

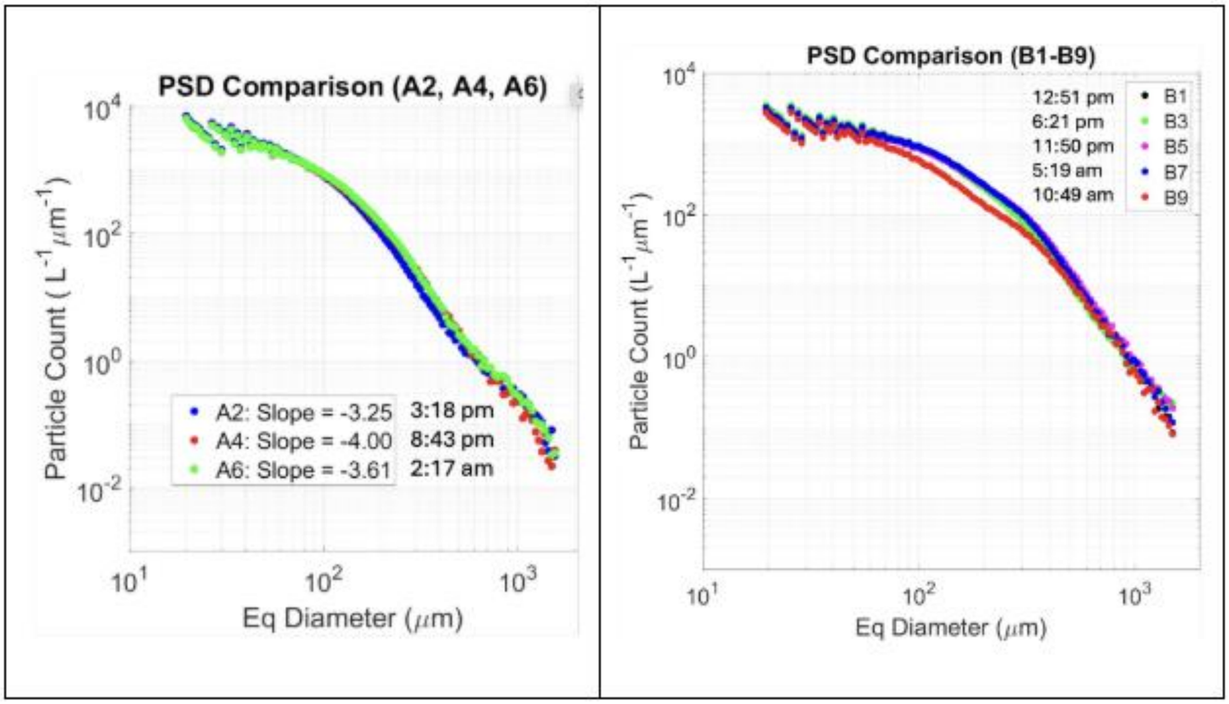
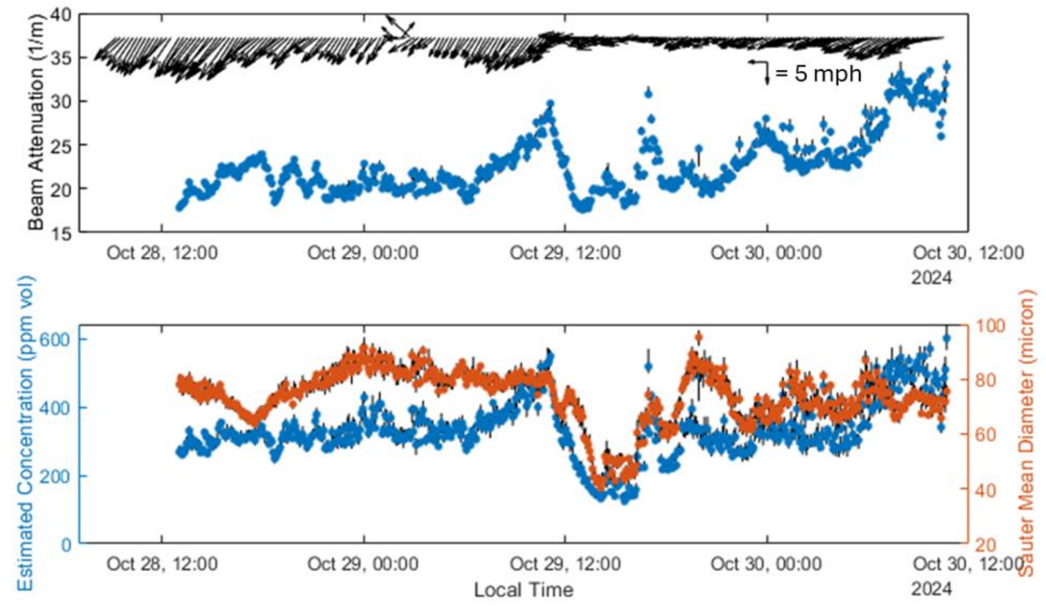


Figure 5. AUTOHOLO 24-hour time series. The *in situ* holographic microscope was deployed for two ~24 hr periods beginning on 10/1/24 (left) and 10/28/24 (right).

Table 3. AUTOHOLO summary. Table of select particle summary statistics over two 24-hour cycles.

Date	File ID	Time	Mean particle size	PSD slope
10/1/2024	A2	3:18 PM	68 µm	-3.25
10/1/2024	A4	8:43 PM	74 µm	-4
10/2/2024	A6	2:17 AM	74 µm	-3.61
10/28/2024	B1	12:51 PM	108 µm	-4.19
10/28/2024	B3	6:21 PM	104 µm	-3.9
10/28/2024	B5	11:50 PM	117 µm	-4.04
10/29/2024	B7	5:19 AM	113 µm	-4.21
10/29/2024	B9	10:49 AM	108 µm	-4.09

The LISST-200x time series (Fig. 6) deployments for the same date ranges yield a slightly smaller size distribution than the AUTOHOLO due to the measured size ranges of each instrument (LISST and AUTOHOLO particle size ranges are approximately 1µm to 500µm and 20 µm to 2cm, respectively); the LISST is able to resolve smaller particles, while the AUTOHOLO can resolve much larger particles. Photos of particles suggest that suspended sediments are predominantly packaged into aggregates, thus the significant variability in the LISST estimated concentration, mean diameter, and beam attenuation during the two deployments is a result of (likely) processes resuspending, aggregating, and breaking these particles. Additional work will connect the changes in particle size and the resulting optical properties to physical forcing such as winds and near-bottom turbulence.



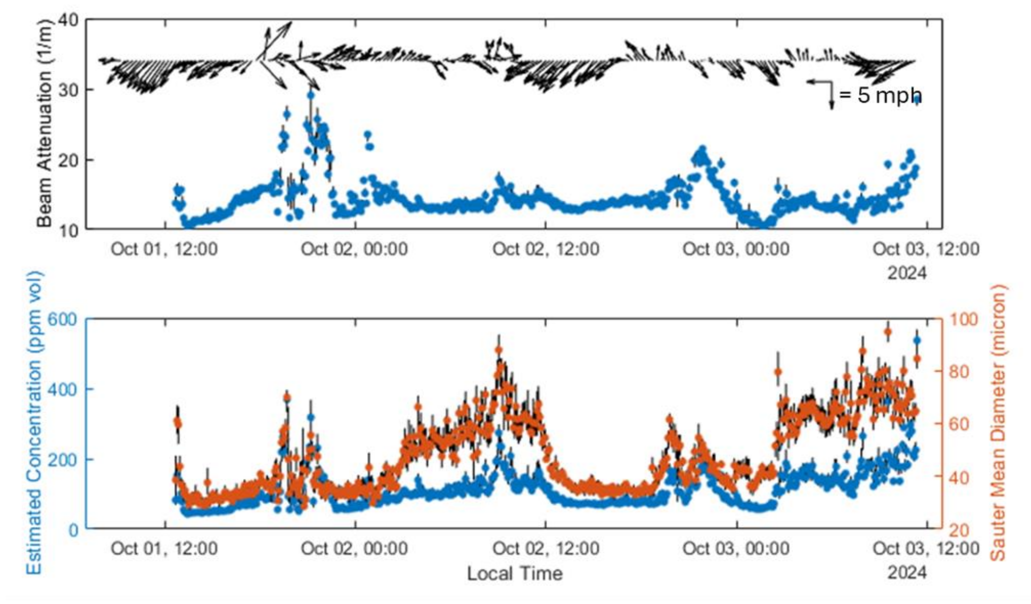


Figure 6. Timeseries of LISST-200X data for the October 1-3 and October 28-30 deployments. Beam attenuation (particulate plus dissolved) at 670nm is shown in the top panels, along with wind vectors (direction of wind flow); 5 mph northerly and easterly winds are shown for scale. Bottom panels show the estimated concentration (µL/L or ppm) and Sauter mean diameter (diameter of sphere having the same volume to surface area ratio as the entire particle suspension).

Raw and filtered (10 µm) water settling experiment. We constructed 1-meter-tall settling tubes with 3 ports for sampling: near the surface, mid-point and near the bottom. Water retrieved from the LOCB site was brought back to the laboratory and placed into the settling tubes. For all experiments, the majority of turbidity (NTU) settled out of the water column within 24-48 hours before reaching a stable background level of turbidity. For 10 µm filtered water, the majority of turbidity settled out of the water column within 48 hours. For the experiment run with water collected on 10/18/2024, initial turbidity measurements in 10 µm filtered water were on average lower compared to unfiltered site water (Fig. 7).

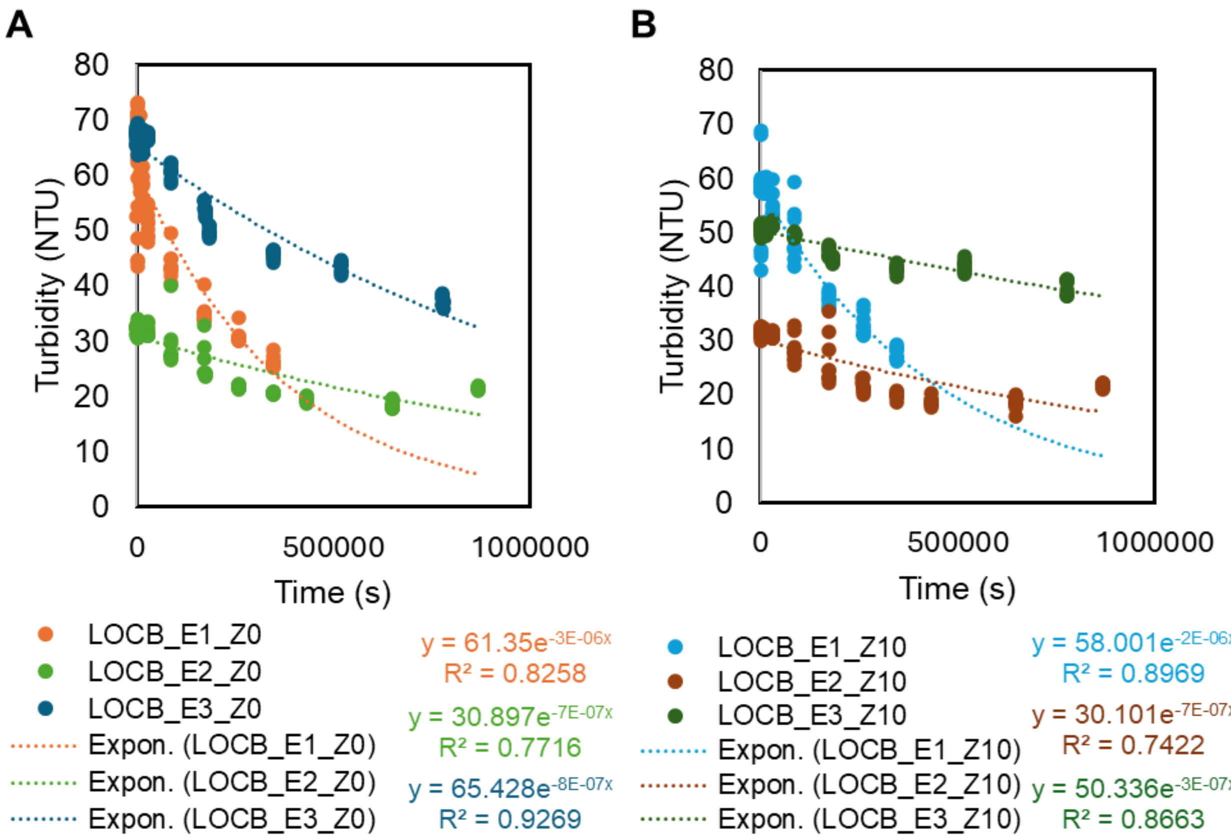


Figure 7. Turbidity settling rate over time. Turbidity (NTUs) over time (s) from settling tube experiment using water collected from LOCB on 10/18/2024 (LOCB_E1), 10/25/2024 (LOCB_E2), and on 11/22/2024 (LOCB_E3). (A) Settling rate of unfiltered site water (Z0), (B) settling rate of 10 µm filtered site water (Z10). Exponential regression line and r^2 values shown.

Across all ports, settling columns with unfiltered water sampled on 10/18/2024 started with turbidity readings of 64.4 NTU on average, which was reduced to an average of 43.8 NTU within 24 hours, and 35.2 NTU within 48 hours of settling. Turbidity on average reduced by 32% within 24 hours and reduced by 45% within 48 hours of settling in columns with unfiltered water. The reduction of turbidity in unfiltered water collected on 10/18/2024 can be described with the following equation: $61.35e^{-3x10^{\wedge}-6x}$ (Fig. 7). Across all ports, settling columns with unfiltered water sampled on 10/25/2024 started with lower turbidity readings of 32.1 NTU on average, which was reduced to an average of 29.2 NTU within 24 hours, and 25.9 NTU within 48 hours of settling. Turbidity was reduced on average by 9% within 24 hours, and by 19% within 48 hours.

The reduction of turbidity in unfiltered water collected on 10/25/2024 can be described with the following equation: $31.841e^{-1*10^{\wedge}-6x}$ (Fig. 7). Across depths, settling columns with unfiltered water sampled on 11/22/2024 started with turbidity readings of 67.1 NTU on average, which was reduced to an average of 60.6 NTU within 24 hours, and 53.8 NTU within 48 hours of settling. Turbidity was reduced on average by 10% within 24 hours, and by 20% within 48 hours. The reduction of turbidity in unfiltered water collected on 11/22/2024 can be described with the following equation: $65.248e^{-8*10^{\wedge}-07x}$ (Fig. 7). Turbidity decreased more rapidly during the 10/18/2024 experiment compared to the 10/25/2024 and the 11/22/2024 experiments (Fig. 8). Particle sizes were larger on 10/18/2024 with the most abundant size fraction was 10-3 µm in diameter, compared to 11/22/2024 where the most abundant size fraction was 0.4-0.2 µm in diameter (see Chapter 2). These larger particle sizes settled out of the water column faster on 10/18/2024, despite both 10/18/2024 and 11/22/2024 settling experiments starting at similar turbidity values (Fig. 8). Multiple regression analysis was used to test if the change in turbidity over time depended on whether the water was 10 µm filtered or not. Both seconds elapsed and filtration (either unfiltered or 10 µm filtered water) significantly predicted turbidity, with interaction for both E1 (R^2=0.8929, seconds $p<0.001$, filtration $p=0.001$, seconds x filtration $p<0.001$) and E3 (R^2= 0.9394, seconds $p<0.001$, filtration $p<0.001$, seconds x filtration $p<0.001$), but not for E2 (R^2= 0.8795, seconds $p<0.001$, filtration $p=0.03$, seconds x filtration $p=0.70$). Turbidity decreased more rapidly in unfiltered water than in 10 µm filtered water for experiments ran with water collected on 10/18/2024 and 11/22/2024 (Fig. 8). Larger particle sizes can settle out of the water column faster than smaller sized particles. Following Stoke's law larger particles have higher settling velocities (Agrawal & Pottsmith, 2000).

Lake Okeechobee has a long fetch, wind events cause frequent sediment resuspension in shallow regions of the lake (Havens, 2003; Jin et al., 2002; Jin & Ji, 2004; Steinman et al., 2002). With it taking between 24-48 hours of still water for turbidity to decline, additional measures should be taken to reduce the effects of wind driven mixing to allow particulate to settle out of the water column and water clarity to improve. Wave barrier structures combined with living shorelines could reduce suspended sediments and facilitate SAV growth (Huang & Liu, 2009; van Zuidam et al., 2022; Vona et al., 2021). Treatment with modified clay mixtures (lanthanum-modified bentonite, LMB) can also help stabilize sediments and reduce resuspension (Yin et al., 2024). Lowering lake stages could help reduce turbidity following hurricane disturbances (T. R. James et al., 2008). When the lake stage is less than 15 ft msl, an underwater ridge helps prevent the transport of sediment into the near-shore zone (Havens, 2002; Johnson et al., 2007). The establishment of SAV would further stabilize lake sediments, both preventing resuspension and increasing sedimentation rates, further contributing to improved water clarity (Dierberg et al., 2002; Knight et al., 2003; Thomaz, 2023; Vermaat et al., 2000). Once SAV coverage reaches a threshold value of >30% coverage, the lake would reach a new macrophyte-dominated state characterized by increased water transparency (Jeppesen et al., 1990; Kosten et al., 2009). Planting or transplanting diverse macrophyte communities could help improve the coverage of SAV as well as water quality, but its success would depend on other environmental factors such as water clarity, depth, herbivory, and other factors (Bakker et al., 2013; Knopik & Newman, 2018; Qiu et al., 2001; Slagle & Allen, 2018).

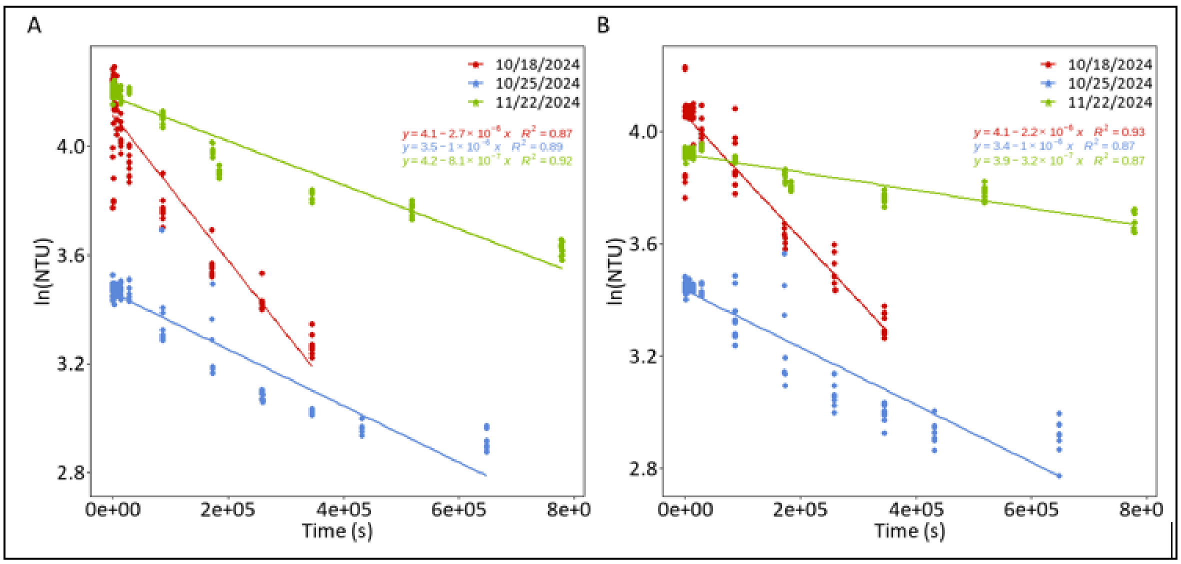


Figure 8. Turbidity settling rate comparing each experiment. Natural log transformed turbidity (NTUs) over time (s) from settling tube experiment using water collected from LOCB on 10/18/2024, 10/25/2024, and 11/22/2024. (A) Settling rate of unfiltered site water, (B) settling rate of 10 µm filtered site water. Linear regression line and r^2 values shown.

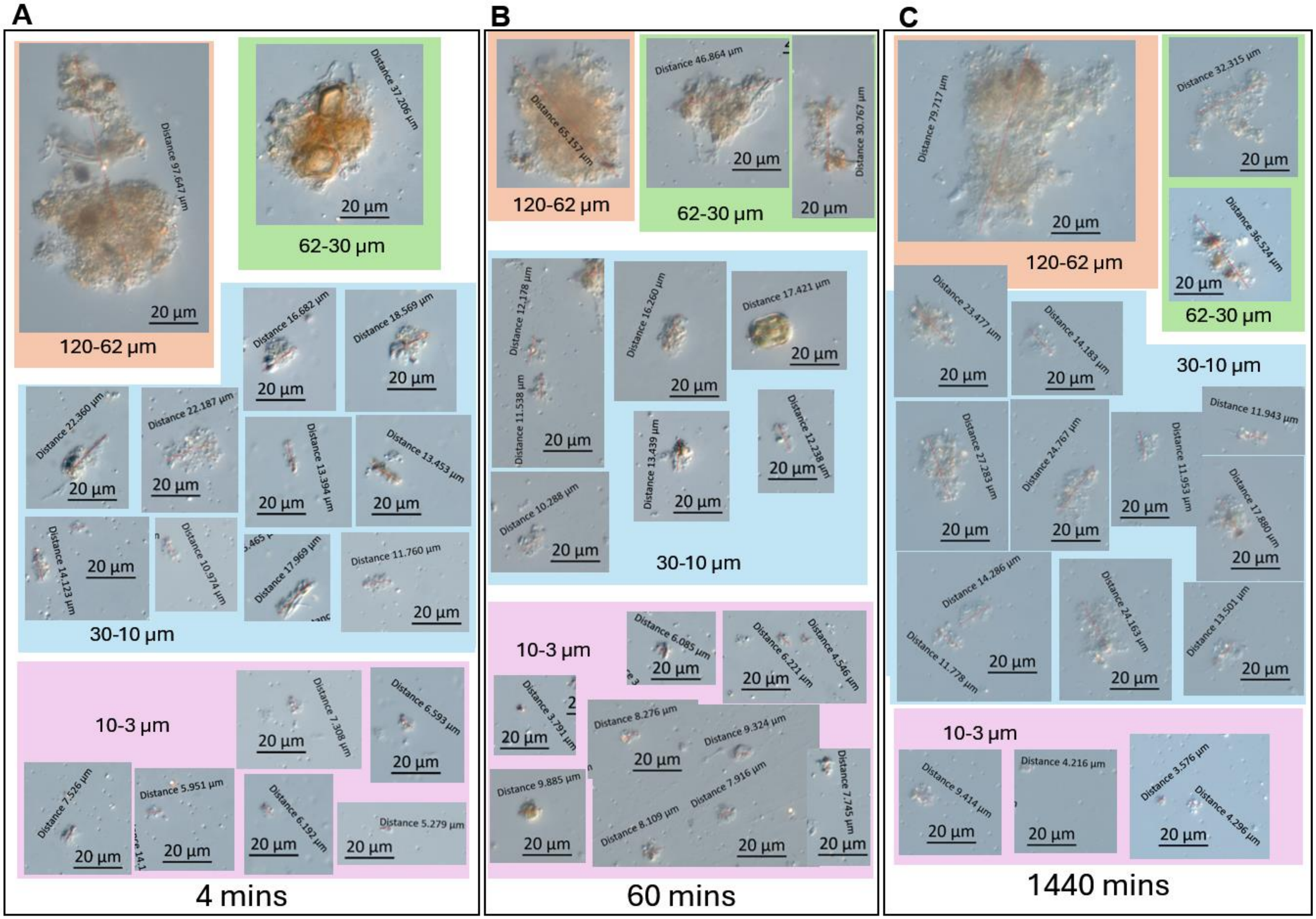


Figure 9. Imagery of suspended sediments from settling tubes. Microscopy images of representative particles from the settling tubes using water collected on 11/22/2024. Water samples collected from the bottom port of unfiltered site water at (A) 4 minutes of settling (B) 60 minutes of settling and (C) 1440 minutes of settling. Organized by size class (120-62 µm, 62-30 µm, 30-10 µm, and 10-3 µm).

Resuspended sediment settling experiments. The sediment erosion process dramatically increases turbidity, although the degree that this occurs depends on the sampling date and core heterogeneities (i.e., > 700 NTU vs. <100 NTU for the two sampling events on 10/18/2024 and 10/25/2024, respectively-Fig. 10 & 11). >80% of this induced turbidity load is removed after only 15 minutes of static conditions, suggesting that the largest particles are settling out extremely rapidly. The rate of decrease slows beyond this but was again variable depending on the sampling date. For example, on 10/18/24, turbidities reached below ~5 NTU, which represented a drastic change relative to the starting turbidity. However, on 10/25/24, despite turbidities not being initially as high due to induced erosion, the ending turbidity was ~ 9 NTU. At LOLZ, starting turbidity was lower than any of the previous sampling events, but ending turbidity was the lowest of all the experiments (~ 2 NTU). This suggests that settling rates depend on the sediment mineralogy and/or the receiving water column conditions. More excitingly, when compared to the water-only settling tubes, both a larger relative and absolute magnitude of turbidity is removed in the erosion experiments. This suggests that the entrainment of fresh sedimentary particles act as nucleation centers or adsorbents for other constituents contributing to turbidity. In a separate study, we observed similar effects for dissolved organic matter and phosphate – both of which are known to be particle reactive – effectively resulting in negative fluxes (removal) of these components, even though the sediments act initially as a source. There are major implications for the behavior of turbidity, for example, stronger turbidity events resuspending more chemically reducing sediments (i.e., iron-rich), can undergo oxidation in the water column, creating fresh surface area for colloidal aggregation. The resuspension of larger particle sizes during erosion experiments could have led to increased settling rates. Larger particle sizes have higher settling velocities, and smaller particles can quickly settle out of solution when bound to these larger particles. Heteroaggregation, the aggregation of different sized particles, results in increased rates of settling for engineered nanoparticles in water with suspended sediments compared to systems without suspended sediment (Velzeboer et al., 2015). The presence of large, suspended sediment (100-500 µm in diameter) significantly increased the settling ratio of polystyrene nanoplastics which are otherwise positively buoyant (Li et al., 2019). On the other hand, over the long term, the expected turbidities resulting from physical erosive events could depend on the strength of the event, where weaker, but more persistent winds could result in a perpetual state of elevated turbidity.

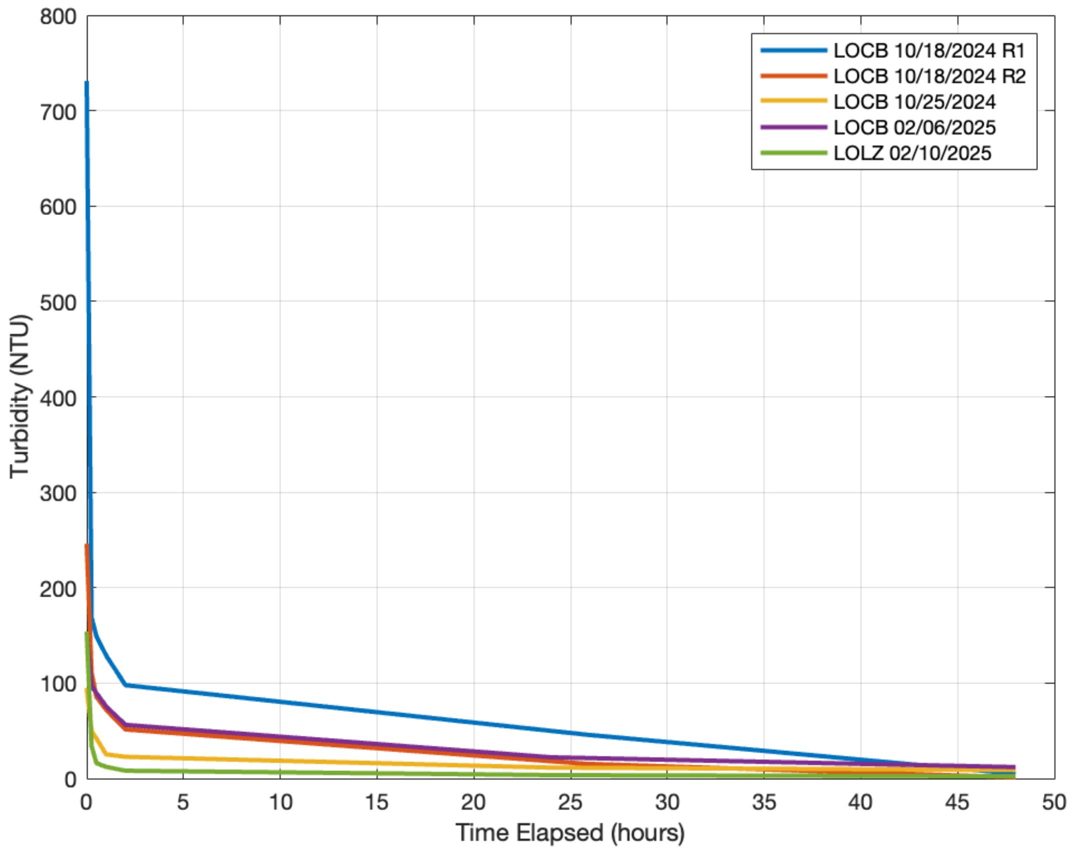


Figure 10. Resuspended sediment settling experiments. Results from the resuspension experiments in which sediment cores were subjected to a strong shear to cause erosion, and the turbidity in the overlying water monitored over time to observe settling rates. Sediment cores were obtained from each sampling event at LOCB (except 11/22/2024) and LOLZ. The sediment core from LOLZ displayed the lowest raw turbidity values, while the first replicate of the LOCB core from 10/18/2024 displayed the greatest decrease in raw turbidity.

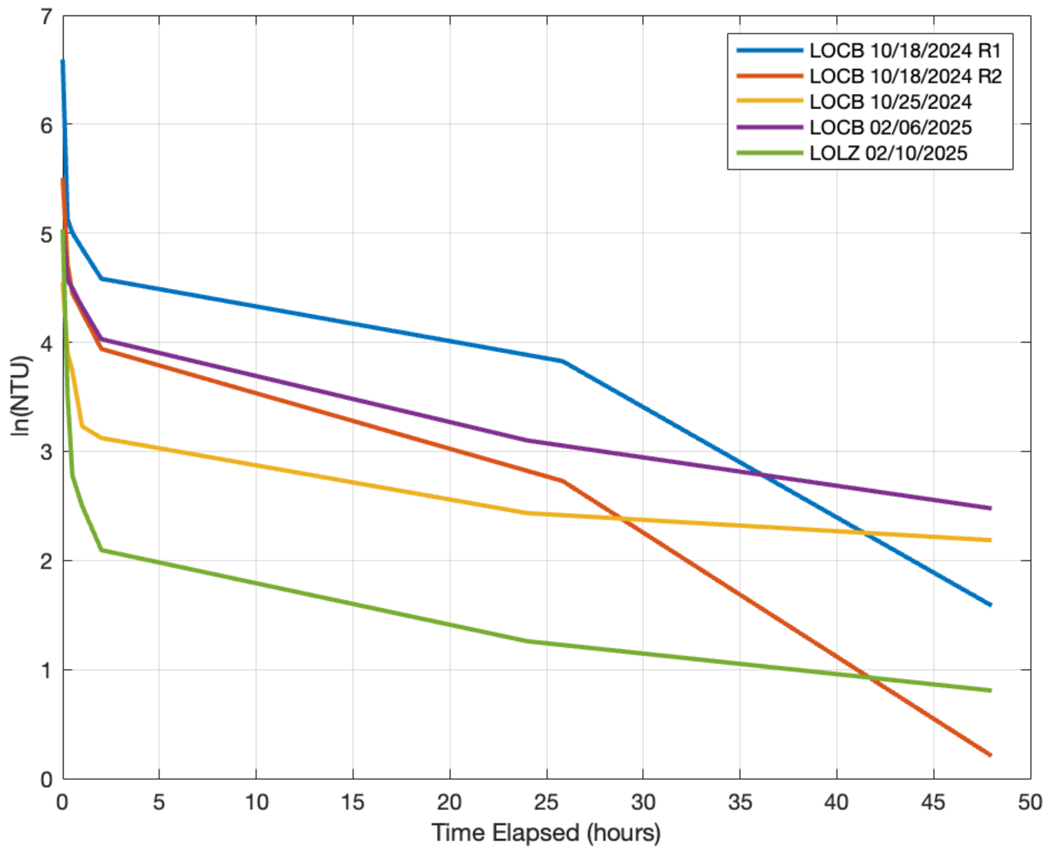


Figure 11. Resuspended sediment settling experiments. Results presented from Figure 11 as natural log of turbidity (NTU) over time. Sediment cores from the early sampling events at LOCB, where turbidity and wind speeds were at their highest, displayed the greatest change in turbidity during the resuspension experiment.

Chapter 3: CONCLUSIONS

During all three sampling events, PAR did not reach the bottom of the water column, on average photosynthesis for algae and hydrilla could only occur as deep as 0.53 m, including all sites and all time points sampled, and 0.34 m for vascular SAV. The use of wind barriers with living shorelines and the use of chemical precipitation could help improve water clarity, but the long-term effectiveness of these methods in reducing P and improving water clarity would also depend on reducing nutrient inputs to the lake. Water clarity and turbidity are all likely influenced by wind speeds, with storm events resuspending greater quantities of sediments and winter frontal systems contributing to this resuspension. The size distribution and number of particles suspended shows diel changes and is likely influenced by currents, local wind patterns, aggregation, shearing, and biological activity. Turbidity took 24-48 hours of no disturbance to settle out of the water column before reaching a stable background level of turbidity. Turbidity took longer to settle out of suspension when particle sizes were smaller. The entrainment of fresh sedimentary material can act as nucleation centers for other constituents contributing to turbidity, resulting in rapid decreases in turbidity compared to the settling of surface water. The strength of erosion events would affect resulting turbidity, with persistent winds resulting in a perpetual elevated level of turbidity. Preventing wind-driven currents through the use of wave barriers, utilizing sediment stabilizing chemical precipitants, and reestablishing SAV beds would all help settle out more material from the water column.

Chapter 3 References

Agrawal, Y. C., & Pottsmith, H. C. (2000). Instruments for particle size and settling velocity observations in sediment transport. *Marine Geology*, *168*(1–4), 89–114.

Bakker, E. S., Sarneel, J. M., Gulati, R. D., Liu, Z., & van Donk, E. (2013). Restoring macrophyte diversity in shallow temperate lakes: biotic versus abiotic constraints. *Hydrobiologia*, *710*, 23–37.

Bonis, A., & Grillas, P. (2002). Deposition, germination and spatio-temporal patterns of charophyte propagule banks: a review. *Aquatic Botany*, *72*(3–4), 235–248.

Caffrey, A. J., Hoyer, M. V, & Canfield Jr, D. E. (2007). Factors affecting the maximum depth of colonization by submersed macrophytes in Florida lakes. *Lake and Reservoir Management*, *23*(3), 287–297.

Canfield Jr, D. E., Bachmann, R. W., & Hoyer, M. V. (2020). Restoration of Lake Okeechobee, Florida: mission impossible? *Lake and Reservoir Management*, *37*(1), 95–111.

Canfield Jr, D. E., Langeland, K. A., Linda, S. B., & Haller, W. T. (1985). *Relations between water transparency and maximum depth of macrophyte colonization in lakes.*

Chambers, P. A., & Kaiff, J. (1985). Depth distribution and biomass of submersed aquatic macrophyte communities in relation to Secchi depth. *Canadian Journal of Fisheries and Aquatic Sciences*, *42*(4), 701–709.

Chimney, M. J. (2005). Surface seiche and wind set-up on Lake Okeechobee (Florida, USA) during hurricanes Frances and Jeanne. *Lake and Reservoir Management*, *21*(4), 465–473.

Dang, T. D., Arias, M. E., Tarabih, O., Phlips, E. J., Ergas, S. J., Rains, M. C., & Zhang, Q. (2023). Modeling temporal and spatial variations of biogeochemical processes in a large subtropical lake: Assessing alternative solutions to algal blooms in Lake Okeechobee, Florida. *Journal of Hydrology: Regional Studies*, *47*, 101441.

Deosti, S., de Fátima Bomfim, F., Lansac-Tôha, F. M., Quirino, B. A., Bonecker, C. C., & Lansac-Tôha, F. A. (2021). Zooplankton taxonomic and functional structure is determined by macrophytes and fish predation in a Neotropical river. *Hydrobiologia*, *848*, 1475–1490.

Dibble, E. D., & Thomaz, S. M. (2009). Use of fractal dimension to assess habitat complexity and its influence on dominant invertebrates inhabiting tropical and temperate macrophytes. *Journal of Freshwater Ecology*, *24*(1), 93–102.

Dierberg, F. E., DeBusk, T. A., Jackson, S. D., Chimney, M. J., & Pietro, K. (2002). Submerged aquatic vegetation-based treatment wetlands for removing phosphorus from agricultural runoff: response to hydraulic and nutrient loading. *Water Research*, *36*(6), 1409–1422.

Droppo, Ian G. "Rethinking What Constitutes Suspended Sediment." *Hydrological Processes* 15, no. 9 (June 30, 2001): 1551–64. https://doi.org/10.1002/hyp.228.

Egemose, S., Wauer, G., & Kleeberg, A. (2009). Resuspension behaviour of aluminium treated lake sediments: effects of ageing and pH. *Hydrobiologia*, *636*, 203–217.Falkowski, P. G., & Raven, J. A. (2013). *Aquatic photosynthesis*. Princeton University Press.

Gomes, L. C., Bulla, C. K., Agostinho, A. A., Vasconcelos, L. P., & Miranda, L. E. (2012). Fish assemblage dynamics in a Neotropical floodplain relative to aquatic macrophytes and the homogenizing effect of a flood pulse. *Hydrobiologia*, *685*, 97–107.

Hanlon, C. G., & Jordan, A. (2023). Influence of habitat and other factors on Largemouth Bass abundance in Lake Okeechobee, Florida. *Transactions of the American Fisheries Society*, *152*(4), 429–442.

Havens, K. E. (1995). Particulate light attenuation in a large subtropical lake. *Canadian Journal of Fisheries and Aquatic Sciences*, *52*(8), 1803–1811.

Havens, K. E. (2002). Development and application of hydrologic restoration goals for a large subtropical lake. *Lake and Reservoir Management*, *18*(4), 285–292.

Havens, K. E. (2003). Submerged aquatic vegetation correlations with depth and light attenuating materials in a shallow subtropical lake. *Hydrobiologia*, *493*, 173–186.

Huang, P., & Liu, Z. (2009). The effect of wave-reduction engineering on sediment resuspension in a large, shallow, eutrophic lake (Lake Taihu). *Ecological Engineering*, *35*(11), 1619–1623.

James, R. T., Havens, K., Zhu, G., & Qin, B. (2009). Comparative analysis of nutrients, chlorophyll and transparency in two large shallow lakes (Lake Taihu, PR China and Lake Okeechobee, USA). *Hydrobiologia*, *627*, 211–231.

James, T. R., Chimney, M. J., Sharfstein, B., Engstrom, D. R., Schottler, S. P., East, T., & Jin, K.-R. (2008). Hurricane effects on a shallow lake ecosystem, Lake Okeechobee, Florida (USA). *Fundamental and Applied Limnology*, *172*(4), 273.

James, R. T., & Pollman, C. D. (2011). Sediment and nutrient management solutions to improve the water quality of Lake Okeechobee. *Lake and Reservoir Management*, *27*(1), 28–40.

Jeppesen, E., Jensen, J. P., Kristensen, P., Søndergaard, M., Mortensen, E., Sortkjaer, O., & Olrik, K. (1990). Fish manipulation as a lake restoration tool in shallow, eutrophic, temperate lakes 2: threshold levels, long-term stability and conclusions. *Biomanipulation Tool for Water Management: Proceedings of an International Conference Held in Amsterdam, The Netherlands, 8–11 August, 1989*, 219–227.

Jeppesen, E., Meerhoff, M., Jacobsen, B. A., Hansen, R. S., Søndergaard, M., Jensen, J. P., Lauridsen, T. L., Mazzeo, N., & Branco, C. W. C. (2007). Restoration of shallow lakes by nutrient control and biomanipulation—the successful strategy varies with lake size and climate. *Hydrobiologia*, *581*, 269–285.

Jin, K.-R., Chang, N.-B., Ji, Z.-G., & James, R. T. (2011). Hurricanes affect the sediment and environment in Lake Okeechobee. *Critical Reviews in Environmental Science and Technology*, *41*(S1), 382–394.

Jin, K.-R., & Ji, Z.-G. (2004). Case study: modeling of sediment transport and wind-wave impact in Lake Okeechobee. *Journal of Hydraulic Engineering*, *130*(11), 1055–1067.

Jin, K.-R., Ji, Z.-G., & Hamrick, J. H. (2002). Modeling winter circulation in Lake Okeechobee, Florida. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, *128*(3), 114–125.

Jin, K.-R., & Sun, D. (2007). Sediment resuspension and hydrodynamics in Lake Okeechobee during the late summer. *Journal of Engineering Mechanics*, *133*(8), 899–910.

Johnson, K. G., Allen, M. S., & Havens, K. E. (2007). A review of littoral vegetation, fisheries, and wildlife responses to hydrologic variation at Lake Okeechobee. *Wetlands*, *27*(1), 110–126.

Kibuye, F. A., Zamyadi, A., & Wert, E. C. (2021). A critical review on operation and performance of source water control strategies for cyanobacterial blooms: Part I-chemical control methods. *Harmful Algae*, *109*, 102099.

Kirk, J. T. O. (1994). *Light and photosynthesis in aquatic ecosystems*. Cambridge university press.

Knight, R. L., Gu, B., Clarke, R. A., & Newman, J. M. (2003). Long-term phosphorus removal in Florida aquatic systems dominated by submerged aquatic vegetation. *Ecological Engineering*, *20*(1), 45–63.

Knopik, J. M., & Newman, R. M. (2018). Transplanting aquatic macrophytes to restore the littoral community of a eutrophic lake after the removal of common carp. *Lake and Reservoir Management*, *34*(4), 365–375.

Kosten, S., Kamarainen, A. M. Y., Jeppesen, E., van Nes, E. H., Peeters, E. T. H. M., Mazzeo, N., Sass, L., Hauxwell, J., HANSEL-WELCH, N., & Lauridsen, T. L. (2009). Climate-related differences in the dominance of submerged macrophytes in shallow lakes. *Global Change Biology*, *15*(10), 2503–2517.

Li, Y., Wang, X., Fu, W., Xia, X., Liu, C., Min, J., Zhang, W., & Crittenden, J. C. (2019). Interactions between nano/micro plastics and suspended sediment in water: Implications on aggregation and settling. *Water Research*, *161*, 486–495.

Middelboe, A. L., & Markager, S. (1997). Depth limits and minimum light requirements of freshwater macrophytes. *Freshwater Biology*, *37*(3), 553–568.

Moore, B. C., & Christensen, D. (2009). Newman Lake restoration: A case study. Part I. Chemical and biological responses to phosphorus control. *Lake and Reservoir Management*, *25*(4), 337–350.

Pereira, A. C., & Mulligan, C. N. (2023). Practices for eutrophic shallow lake water remediation and restoration: A critical literature review. *Water*, *15*(12), 2270.

Qiu, D., Wu, Z., Liu, B., Deng, J., Fu, G., & He, F. (2001). The restoration of aquatic macrophytes for improving water quality in a hypertrophic shallow lake in Hubei Province, China. *Ecological Engineering*, *18*(2), 147–156.

Sand-Jensen, K., & Madsen, T. V. (1991). Minimum light requirements of submerged freshwater macrophytes in laboratory growth experiments. *The Journal of Ecology*, 749–764.

Sas, H. (1990). Lake restoration by reduction of nutrient loading: expectations, experiences, extrapolations. *Internationale Vereinigung Für Theoretische Und Angewandte Limnologie: Verhandlungen*, *24*(1), 247–251.

Sathyendranath, S. (2000). *Remote sensing of ocean colour in coastal, and other optically-complex, waters.*

Saulquin, B., Hamdi, A., Gohin, F., Populus, J., Mangin, A., & d'Andon, O. F. (2013). Estimation of the diffuse attenuation coefficient KdPAR using MERIS and application to seabed habitat mapping. *Remote Sensing of Environment*, *128*, 224–233.

Slagle, Z. J., & Allen, M. S. (2018). Should we plant macrophytes? Restored habitat use by the fish community of Lake Apopka, Florida. *Lake and Reservoir Management*, *34*(3), 296–305.

Steinman, A. D., Havens, K. E., Rodusky, A. J., Sharfstein, B., James, R. T., & Harwell, M. C. (2002). The influence of environmental variables and a managed water recession on the growth of charophytes in a large, subtropical lake. *Aquatic Botany*, *72*(3–4), 297–313.

Steinman, A. D., Meeker, R. H., Rodusky, A. J., Davis, W. P., & Hwang, S.-J. (1997). Ecological properties of charophytes in a large subtropical lake. *Journal of the North American Benthological Society*, *16*(4), 781–793.

Thomaz, S. M. (2023). Ecosystem services provided by freshwater macrophytes. *Hydrobiologia*, *850*(12), 2757–2777.

van Zuidam, B. G., Bakker, E. S., van Geest, G. J., & Peeters, E. T. H. M. (2022). Submerged vegetation colonizes behind artificial wave shelter after a 10-year time-lag and persists under high grazing pressure by waterbirds. *Aquatic Botany*, *181*, 103541.

Velzeboer, I., Quik, J. T. K., van De Meent, D., & Koelmans, A. A. (2014). Rapid settling of nanoparticles due to heteroaggregation with suspended sediment. *Environmental Toxicology and Chemistry*, *33*(8), 1766–1773.

Vermaat, J. E., Santamaria, L., & Roos, P. J. (2000). Water flow across and sediment trapping in submerged macrophyte beds of contrasting growth form. *Archiv Für Hydrobiologie*, *148*(4), 549–562.

Vona, I., Palinkas, C. M., & Nardin, W. (2021). Sediment exchange between the created saltmarshes of living shorelines and adjacent submersed aquatic vegetation in the Chesapeake Bay. *Frontiers in Marine Science*, *8*, 727080.

Xu, T., Yang, T., Zheng, X., Li, Z., & Qin, Y. (2022). Growth limitation status and its role in interpreting chlorophyll a response in large and shallow lakes: A case study in Lake Okeechobee. *Journal of Environmental Management*, *302*, 114071.

Yin, Z., Yuan, Y., Zhang, R., Gan, J., Yu, L., Qiu, X., Chen, R., & Wang, Q. (2024). Understanding Bacillus response to salt stress: Growth inhibition, enhanced EPS secretion, and molecular adaptation mechanisms. *Process Biochemistry*, *146*, 412–422.