Examining Ambient Turbidity and Total Suspended Solids Data in South Florida Towards Development of Coral Specific Water Quality Criteria

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Executive Summary

Anthropogenically elevated sediment loads to the coastal ocean have the potential to negatively impact the coral reefs of south Florida. Currently, in the State of Florida, there are no state sediment water quality standards that are designed to be protective of coral health. This analysis examines turbidity and total suspended solids (TSS) data from the southeast Florida reef tract, collected from 2016 to 2020, with the goal of informing the development of sediment associated water quality criteria that are protective of coral reefs. Data from 115 sites, sampled monthly, were used for this analysis. We found that neither turbidity nor TSS varied significantly by depth. Both TSS and turbidity varied geographically, with statistically significant differences between Inlet Contributing Areas (ICAs). However, these patterns are different between the two analytes, which suggests that TSS and turbidity should not be used interchangeably. This is supported by the lack of strong correlation between TSS and turbidity at a given site. While there are some significant correlations between turbidity/TSS and existing biological data, more spatial and temporal coverage in biological data would be useful to better understand these relationships.

Comparison of measured turbidity data to existing turbidity criteria for the state of Florida (29 NTU above background), suggests that the current criteria is unlikely to be protective of corals. It is also critical to explicitly define what is meant by background values, because how these are calculated can have a huge impact on the efficacy of any standards.

Using previously published threshold values (3.2 mg/L) for TSS that are protective of coral reefs, 32% of observations for bottom water reef sites exceed that threshold. Additional research is needed to better articulate functional biological thresholds, e.g. through laboratory-based experiments.

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Background

Water quality problems, including sedimentation, are a major threat to coral reefs worldwide, especially in the near shore environment. Elevated sedimentation levels have been linked to several types of reef degradation including fewer coral species, altered species composition, less live tissue cover, reduced recruitment, lower growth rates and calcification, increased prevalence of disease, and lower rates of reef accretion (Rogers 1990; Harvell et al. 1999, Smith et al. 2008). Increased sediment in the water column can also cause decreases in water clarity, which can impact the symbiotic zooxanthellae associated with corals (López-Londoño et al. 2021). In addition, sedimentation can cause tissue necrosis due to the burial and smothering of corals (Erftemeijer et al. 2012). In Florida, data from a dredge project in the Fort Thompson and Anastasia formations at the Port of Miami entrance channel showed that fine, colloidal sediments proved particularly difficult for corals to shed and resulted in extensive partial and likely complete mortality of many coral colonies (Miller et al. 2016).

Two common water quality measurements related to sediments in the water column are total suspended solids (TSS) and turbidity. Total suspended solids is a physical (mass) measurement of the amount of material suspended in the water column; this variable is quantified by filtering a known volume of water and measuring the amount of material on the filter. Turbidity is an optical measurement of the relative clarity of a liquid. It measures the amount of light that is scattered by material in the water when a light is shined through the water sample. It is important to understand that while both of these variables are related to the amount of sediment stress to corals, they are fundamentally different variables and may tell us different things.

While sediment delivery to the coastal zone is a natural process, it can be accelerated through anthropogenically enhanced erosion of the landscape, e.g. from agriculture or construction activities. Additionally, discrete coastal management actions such as dredging and beach renourishment can cause potentially damaging spikes in TSS and turbidity. Understanding the concentrations of suspended sediment at which corals undergo stress due to sediment flux are critical to effective management. The intent of management actions is to maintain suspended sediment below the threshold that causes stress to the corals. Similarly, it is important to understand the natural variability of a system so as to be able to discern anthropogenic spikes in sediment from natural processes.

There are currently no national water quality criteria that are specifically protective of corals. The state of Florida has some water quality criteria in place (FDEP 2019), but none were designed with coral health in mind. The current turbidity standard is 29 NTU above natural background (FDEP 2019). This value is being re-evaluated by the state of Florida and USEPA as of 2021 with the potential of developing criteria that will be protective of coral health, as the current standard was not designed to be protective of corals.

A recent meta-analysis of worldwide sedimentation data and coral impacts (Tuttle and Donahue 2020) proposed that 3.2 mg/L is a potential suspended sediment threshold that is protective of juvenile and adult corals. This threshold was based on a literature review of 86 studies, and because it was global, it is not species specific nor tied to any one region. Because there are no local thresholds to use, for the purposes of our analysis, we will use this proposed, globally relevant threshold for TSS comparison.

Purpose and Goals

The purpose of this analysis was to synthesize existing TSS and turbidity data from the joint NOAA-Florida Department of Environmental Protection (FDEP) water quality assessment program for the southeast Florida Reef Tract. This statistical analysis builds on the work of Whitall et al. (2019) and includes additional field data, through August 2020, collected since that report was published.

This report presents the statistical patterns in TSS and turbidity data across the region, as well as the extent to which each variable correlates with available biological data, with the overall goal of being useful in the setting of water quality criteria for the region that are protective of coral reefs. It should be noted that these data represent ambient field conditions that are either “normal” or possibly “post-storm” conditions, and are not specifically representative of the transient effects of dredging or other construction projects.

Key questions relevant to criteria development that will be answered here are:

- Are there significant differences between surface and bottom water values? In other words, when considering criteria specific to corals, bottom water values will be most relevant. If there are no differences between surface and bottom water values in this region, sites where only surface water values exist might also be valuable to consider when gathering data to characterize the region.
- Are there differences between site types (reef vs inlet vs outfall)? If so, then only reef values should be considered for reef specific criteria development.
- Is turbidity or TSS better correlated with observed biology? If the ultimate goal is coral reef ecosystem protection, it would be useful to know which sediment related variable is best correlated with variability in benthic habitat.
- Are there spatial differences within the study region for TSS and turbidity? If so, perhaps only one regional criterion won't be sufficient, or the criterion will have to be structured with that variability within the system in mind.
- How do existing criteria (or potential criteria) compare with the observed values of TSS and turbidity?

Site Description

The study region, referred to here as the southeast Florida Reef Tract, extends from St. Lucie Inlet in the north to Biscayne Bay National Park in the south. The adjacent watersheds include four counties (Miami-Dade, Broward, Palm Beach, and Martin) populated by over six million people (United States Census Bureau 2021). There are nine major inlets that contribute freshwater inflows, containing land-based sources of pollution, to coastal waters. These inlets are, from north to south (see Figure 1): St. Lucie (STL), Jupiter (JUP), Lake Worth (ILW), South Lake Worth (Boyton Inlet, BOY), Boca Raton (BOC), Hillsboro (HIL), Port Everglades (PEV), Baker's Haulover (BAK) and Government Cut (GOC). Because the hydrology of the area has been heavily altered by human activity, the areas that drain to these inlets are often called inlet contributing areas (ICAs) rather than watersheds; this terminology will be used hereafter. Land use/land cover varies among ICAs with the southern ICAs having more urban development than the northern ICAs, and the northern ICAs having a larger agricultural footprint (Pickering and Baker 2015).

The reef ecosystems in the study region provide habitat to important fisheries (Ferro et al. 2005, SAFMC 2009, Kilfoyle et al. 2015). For example, NOAA National Marine Fisheries Service reports that three of the top dockside value commercial Florida fishery species (>$70 million) and live-specimen aquaria fish ($3.5 million) are all reef-dependent. NOAA estimates that coral reefs in southeast Florida have an asset value of $8.5 billion, generating $4.4 billion in local sales, $2 billion in local income, and 70,400 full and part-time jobs (NMFS, 2018). The ecosystem consists of a mix of contiguous coral reefs, soft substrate habitats (e.g. tidal sand flats and mud flats), seagrass, oyster reefs, mangroves, offshore hardbottom and nearshore hardbottom (Walker and Klug 2014). The reefs generally occur within 3 to 4 km from shore

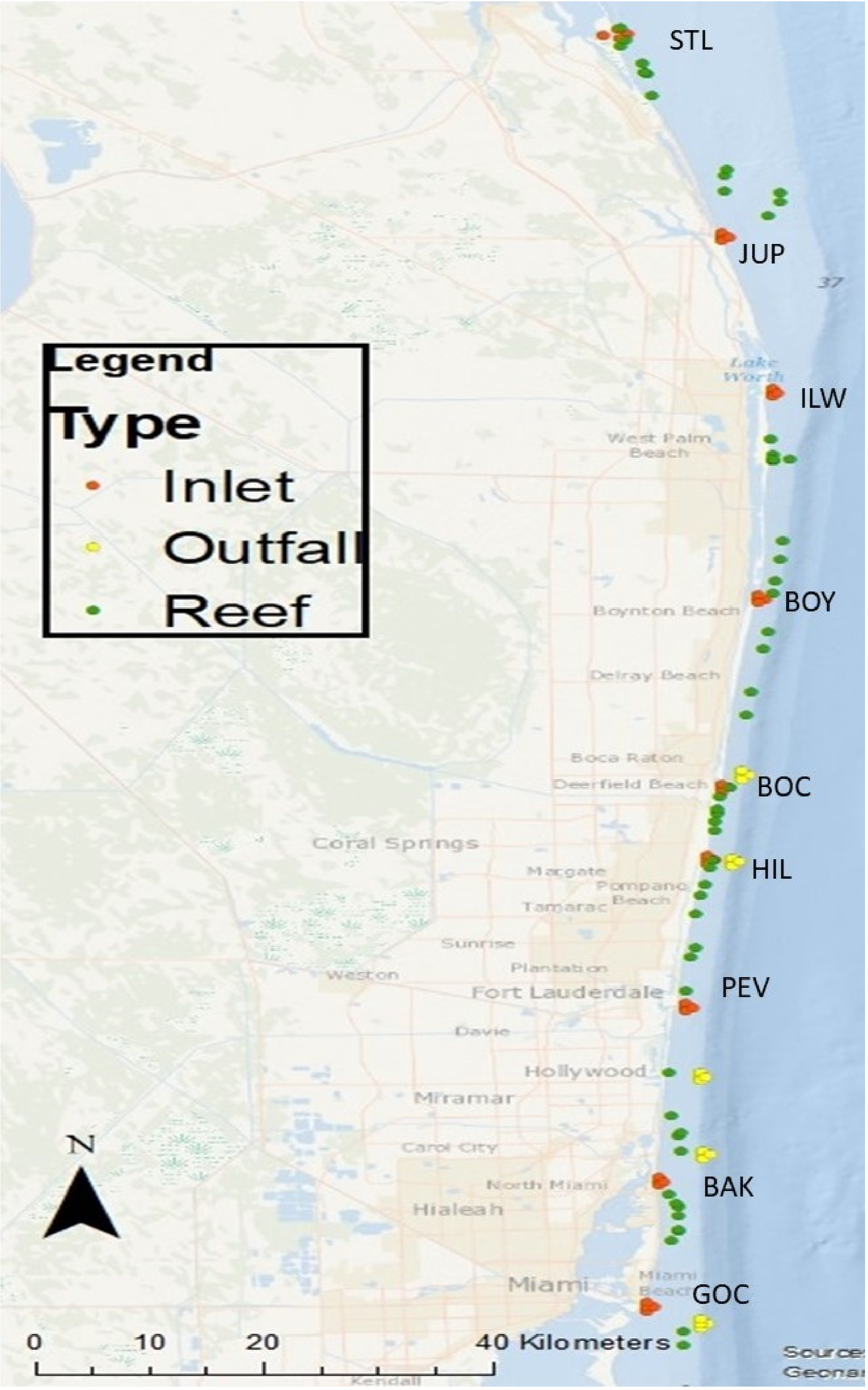

Figure 1: Water quality sampling sites.

and include limestone ridges colonized by reef organisms such as sponges, octocorals, macroalgae and stony corals (Banks et al. 2007, Gilliam 2010). Nearshore hardbottom habitats range from flat expanses of exposed rock with little relief to patch reef-like vertical mounds in water depths from 0 to 4 m. The benthic assemblages of nearshore hardbottom habitat include octocoral, macroalgae, sponge and stony corals (Gilliam 2010).

Methods

A more robust discussion of the methodology used to collect data is available in Whitall et al. (2019). Briefly, a total of 115 sites were selected for recurring water quality sampling (Figure 1). Three different types of sites were sampled during this effort: reef, inlet and outfall. Reef sampling sites are limited to relatively shallow reefs (10m depths or less) due to limitations of sampling equipment (water samples were collected from both surface and bottom). Outfall sites were located at the offshore wastewater outfalls which discharge partially treated sewage into the coastal system. These sites were sampled “at the boil” (i.e. where the outfall water is bubbling to the surface), when visible, but we acknowledge that the exact location of the outfall was not sampled each time because the location of the boil is not static. Inlet sites were located at each of the nine ICAs. All sites were visited once per month for water sampling.

All nine ICAs were sampled monthly starting in late 2017. There are additional data for TSS from 2016 for GOC and STL, which were part of a pilot project. Although these data were analyzed by a different laboratory (TDI Brooks, College Station, TX) they have been included in this analysis because TSS is a relatively straightforward physical (rather than chemical) measurement that is easy to produce comparable data between labs.

Grab samples were collected from both surface (collected approximately 0.5 m below surface) and bottom (via Niskin bottle, approximately 1 m above bottom) at all sites, with the exception of the outfall sites, at which only surface water was collected because the depth of these sites exceeded the sampling ability of the equipment. Sampling equipment was rinsed with deionized water three times between sites and then three times with site water once on site. Field clean equipment blanks were collected (at least one per day and at least one per 20 samples collected). The above SOPs adhere to the following FDEP SOPs for sampling of surface waters: FC 1000 (Cleaning & Decontamination Procedures); FS 2000 (General Aqueous Sampling); and FS 2100 (Surface Water Sampling).

Total suspended solids (TSS) was measured by Standard Method 2540D (comparable to USEPA Method 160.1), which utilizes pre-weighed filters, a known volume of filtered material and then final weighing of dried filters, with the sample mass being determined by difference and adjusted for volume to arrive at a TSS concentration (USEPA 1983). Turbidity was determined via USEPA Method 180.1, in which a nephelometer is used to measure the refraction of light caused by suspended material in a sample as compared to known values (USEPA 1993e). Reported units are Nephelometric Turbidity Units (NTU).

Previously collected biological data from NOAA's National Coral Reef Monitoring Program (NCRMP) (www.coris.noaa.gov/monitoring/) were also compiled. NCRMP sites from the 2016 sampling year that were within an operationally defined 500m buffer from water quality sites were selected for comparison. Percent benthic cover (by categorical type) was compared with both mean (chronic) and maximum (acute) water quality concentrations.

This report focuses on turbidity and TSS, but it may be useful for the reader to know that other water quality parameters (nitrate, nitrite, ammonium, urea, total nitrogen, total phosphorus, orthophosphate, silica) have been quantified as part of this study (Whitall et al. 2019).

Statistical Methods

Because these data were not normally distributed, non-parametric statistics were used. To examine potential correlations between analytes, and between analytes and biological metrics, Spearman Rank Order Correlation was used. A Wilcoxon test, with post hoc Dunn's test, was used to examine differences between ICAs, depths and site types. Basic summary statistics (mean, quantiles, standard deviation) are also included (Tables 1 through 3). JMP software was used for all statistical analysis.

Data Storage/Access

All data from this monitoring program are publicly available and are housed in the FDEP Watershed Information Network (WIN) database and NOAA's National Centers for Environmental Information (NCEI; https://doi.org/10.25921/x6hb-3e37). Data are also linked through NOAA's Coral Reef Information System (CoRIS; https://www.coris.noaa.gov/).

Results and Discussion

Across all site types and depths, turbidity had a mean value of 0.75 NTU, a median value of 0.35, a maximum value of 52, and a standard deviation of 1.78. TSS had a mean value of 9.7 mg/L, a median value of 1.88, a maximum value of 840, and a standard deviation of 39.9. As indicated by the standard deviations, there is a lot of variability in these datasets, both over time and between sites (Table 1).

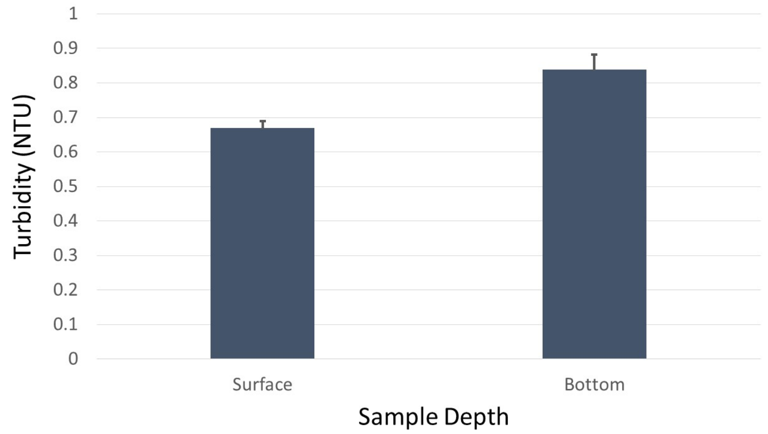

Figure 2: Turbidity by depth (surface vs bottom). Error bars are standard error.

There are no statistically significant differences for either turbidity (Figure 2) or TSS (Figure 3) between surface and bottom, but bottom water values are qualitatively higher for both analytes. This suggests that the system is relatively well mixed, and the qualitatively higher bottom water values may indicate the role of resuspension of sediments in the dynamics of the system.

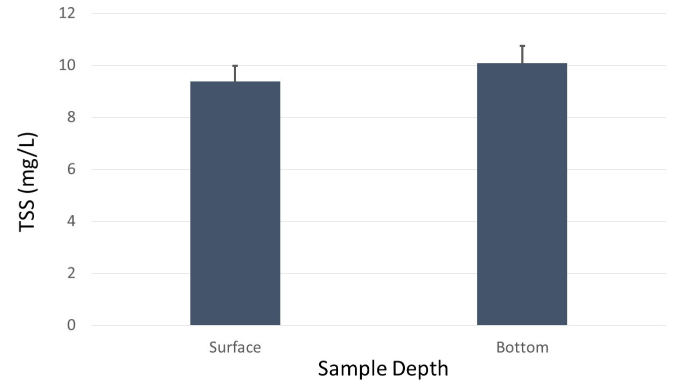

Figure 3: Total Suspended Solids (TSS) by depth (surface vs bottom). Error bars are standard error.

There are statistically significant differences between ICAs (Figures 4 and 5, and Table 2). Therefore, one water quality criterion might not be appropriate for the entire region (or the selected value must be low enough to be protective of the most sensitive areas). While we acknowledge that ICA boundaries in the marine ecosystem are operationally defined and the ecosystem does not behave based on these boundaries (i.e. it is a connected unit), it is still useful to demonstrate these spatial differences within the study region.

There are statistical differences between site types (Figures 6 and 7). Reef sites are different than inlet or outfall sites. If the goal is to develop criteria protective of reefs, itwill be important to make sure data used to generate said criteria were collected on reefs. However, data from reefs is relatively harder to come by than data from other near shore coastal areas.

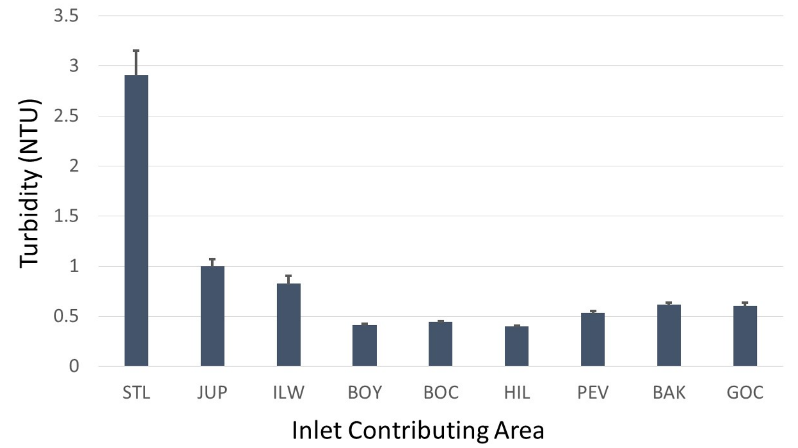

Figure 4: Turbidity by Inlet Contributing Area (ICA), from north (left) to south (right). Error bars are standard error.

While TSS and turbidity are significantly correlated (Spearman rho, p<0.0001), the relationship is relatively weak (rho=0.42). This pattern holds true even if you examine only bottom water reef sites (which would be most applicable to coral reef health; rho=0.40). This demonstrates that TSS and turbidity are not interchangeable and care should be used when selecting between the analytes for monitoring activities or for criteria development. This is also very evident when comparing ICAs. For example, for St. Lucie (STL) the TSS and turbidity values tell very different stories (Figures 4 and 5).

TSS and turbidity each have statistically significant correlations with benthic habitat characteristics, but these vary among analytes (Table 3). Correlation does not equal causation, and many biotic and abiotic factors influence benthic habitat, but these relationships are potentially useful. The fact that correlations vary between TSS and turbidity suggests that, from a biological response perspective, TSS and turbidity cannot be used interchangeably and one may be more appropriate as a criterion than the other.

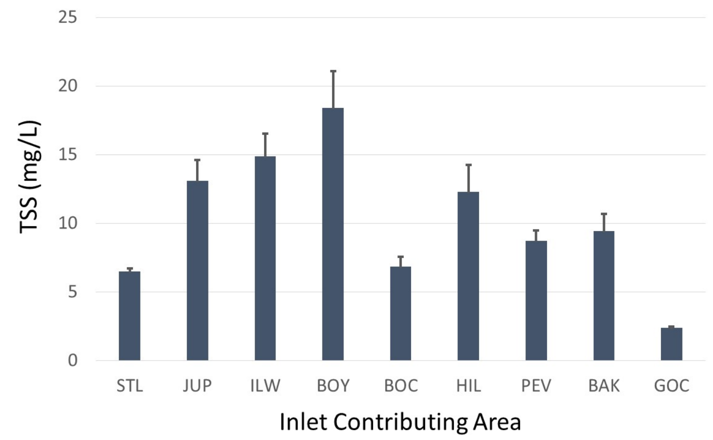

Figure 5: Total Suspended Solids (TSS) by Inlet Contributing Area from north (left) to south (right). Error bars are standard error.

Implications for Water Quality Criteria Development

Because there are statistically significant differences between ICAs across the region, one criterion value for the entire Florida coast may not be ideal. At a minimum, care would be needed to ensure that the selected criterion value was sufficient to protect the most sensitive reefs in the region. This is especially true if the standard is written as a deviation from the natural background, as that natural background may also vary across the region. Furthermore, Port Everglades (PEV) has relatively low TSS and turbidity. An ongoing dredging project around the port has the potential to greatly alter sediment dynamics in that area on an acute timescale. Considering acute events, like dredging, will make selected criteria more protective.

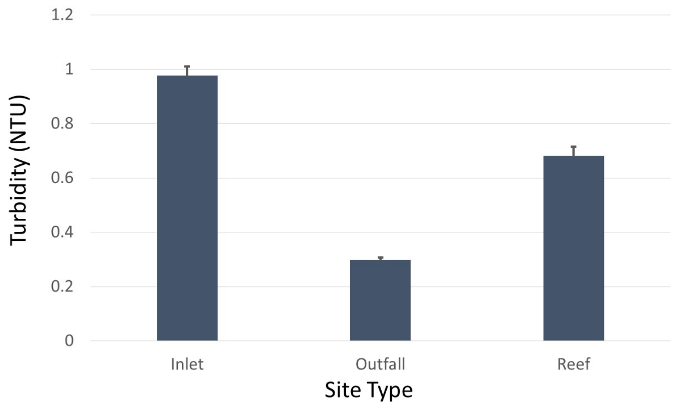

Figure 6: Turbidity by site type (inlet vs reef vs outfall). Error bars are standard error.

TSS is a better predictor of benthic habitat than turbidity (i.e. it correlates with more biological variables), suggesting that it may be a more useful criterion to consider. On the other hand, turbidity has a strong negative correlation with rugosity. Rugosity, or benthic roughness, measures the topography of a reef (Beck 1998) which is important because a more complex habitat can support a wider variety of species (Gratwicke and Speight 2005). Because rugosity can be considered an ecosystem level metric of reef structure, this may be a useful relationship, although rugosity and reef health are not the same thing.

Previous work (Whitall et al. 2019) suggests that other water quality parameters (nitrogen and phosphorus species) may be better predictors of benthic habitat than turbidity or TSS. While regulatory progress towards protective water quality criteria may be incremental (e.g. one analyte added at a time), it is likely that there is no one water quality criterion that will be completely protective of coral reef resources; using multiple analytes as criteria seems to be more likely to be successful.

The current turbidity standard for the state of Florida is written as 29 NTU above background (FDEP 2019). While it is difficult to know what a true background value might be, multiple statistical break points (quantiles) from this dataset can be operationally considered as background values, which would allow evaluation of what percentage of observed values would be in exceedance of that threshold. Logical breakpoints are the 25, 2.5 and 0.5 percent quantiles. Interestingly, when applied to bottom water values from reef sites, these yield very similar results of 0.2, 0.1 and 0.1 NTU respectively. Therefore, 29 NTU above the background would be 29.2 or 29.1 NTU. This level was only observed five times: four times in St. Lucie and once in Jupiter. This suggests that the current standard may be much too high. If the criteria were to be hypothetically changed to be 100 times more stringent (i.e. 0.29 NTU above background) and the background is defined as the 10% quantile, observations exceed this criterion 33% of the time.

A similar exercise can be conducted using the TSS threshold values proposed in a recent NOAA study (Tuttle and Donahue 2020) of 3.2 mg/L. Using this standard, 32% (706 of 2232) of the observed bottom water reef values exceed this threshold. These exceedances are relatively evenly distributed among ICAs (Table 4), with the exception of St. Lucie which has nearly three times the number of exceedances as the next highest ICA. This may reflect the role that the St. Lucie River/Estuary plays in the transport of sediment to the region. Additionally, at the 3.2 mg/L threshold, all sites in the study area exceed this value on at least one occasion. It is also interesting to note that this exceedance rate (32%) is remarkably similar to the hypothetical revised threshold for turbidity (33%) suggested above, although which sites have exceedances will be different depending on whether TSS or turbidity is considered.

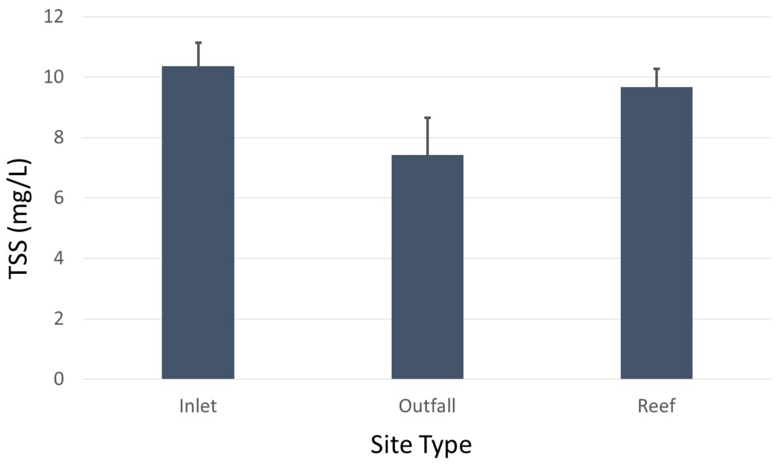

Figure 7: Total Suspended Solids (TSS) by site type (inlet vs reef vs outfall). Error bars are standard error.

Conclusions and Summary

This report statistically summarizes and interprets four years of turbidity and TSS data from the south Florida Reef Tract with the goal of being useful for water quality criteria development that is protective of coral reef ecosystems. These data show that there are important differences within the region, both between site types and latitudinally, that need to be considered when developing criteria. Also, these data show that TSS and turbidity are not interchangeable, and care should be taken in selecting one over the other. More data demonstrating the biological thresholds at which corals experience water quality stress would be useful, but data sets such as this water quality dataset are foundational for any criteria development work. We suggest that the results of this analysis for TSS and turbidity be used as a starting point for development of comprehensive thresholds for protection of coral reefs.

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Tables

Table 1: Summary statistics for turbidity and TSS. Note: there are fewer data points for turbidity because it was not measured at GOC and STL in the original pilot study in 2016.

	Mean	**SD**	**2SD**	**3SD**	**4SD**	**N**
Turbidity	0.75	1.78	3.55	5.33	7.11	6645
TSS	9.70	39.90	79.80	119.69	159.59	7936

Table 2: Statistical differences (Wilcoxon with post-hoc Dunn's test, α=0.05) for TSS and turbidity between ICAs. Only statistically significant relationships are shown.

Analyte	ICA	ICA	Mean Diff	SE Diff	Z	p-Value
Turbidity	STL	BOY	2846.1	111.3	25.6	0.0000
Turbidity	STL	HIL	2440.8	110.2	22.1	0.0000
Turbidity	STL	BOC	2248.5	110.2	20.4	0.0000
Turbidity	STL	ILW	2257.5	115.1	19.6	0.0000
Turbidity	STL	PEV	1947.5	111.3	17.5	0.0000
Turbidity	STL	GOC	1985.4	124.2	16.0	0.0000
Turbidity	STL	JUP	1637.0	115.2	14.2	0.0000
Turbidity	BOY	BAK	-1310.8	93.4	-14.0	0.0000
Turbidity	STL	BAK	1535.3	111.3	13.8	0.0000
Turbidity	JUP	BOY	1209.0	97.9	12.3	0.0000
Turbidity	HIL	BAK	-905.5	92.1	-9.8	0.0000
Turbidity	PEV	BOY	898.5	93.4	9.6	0.0000
Turbidity	JUP	HIL	803.8	96.7	8.3	0.0000
Turbidity	GOC	BOY	860.6	108.5	7.9	0.0000
Turbidity	BOC	BAK	-713.3	92.1	-7.7	0.0000
Turbidity	ILW	BAK	-722.2	97.9	-7.4	0.0000
Turbidity	BOY	BOC	-597.5	92.1	-6.5	0.0000
Turbidity	JUP	BOC	611.5	96.7	6.3	0.0000
Turbidity	JUP	ILW	620.5	102.3	6.1	0.0000
Turbidity	ILW	BOY	588.6	97.9	6.0	0.0000
Turbidity	PEV	HIL	493.3	92.1	5.4	0.0000
Turbidity	PEV	BAK	-412.3	93.4	-4.4	0.0004
Turbidity	HIL	BOY	405.3	92.1	4.4	0.0004
Turbidity	HIL	GOC	-455.4	107.4	-4.2	0.0008
Turbidity	GOC	BAK	-450.2	108.5	-4.1	0.0012
Turbidity	PEV	BOC	301.0	92.1	3.3	0.0389
TSS	STL	BOY	2453.6	106.2	23.1	0.0000
TSS	STL	BAK	2324.3	106.2	21.9	0.0000
TSS	STL	BOC	2151.5	104.6	20.6	0.0000
TSS	STL	GOC	1904.9	97.0	19.6	0.0000
TSS	STL	ILW	2094.6	111.9	18.7	0.0000
TSS	STL	PEV	1934.9	106.2	18.2	0.0000
TSS	STL	HIL	1703.5	104.6	16.3	0.0000
TSS	STL	JUP	1361.1	111.9	12.2	0.0000
TSS	JUP	BOY	1092.4	117.2	9.3	0.0000
TSS	JUP	BAK	963.2	117.2	8.2	0.0000
TSS	JUP	BOC	790.3	115.7	6.8	0.0000
TSS	HIL	BOY	750.1	110.2	6.8	0.0000

TSS	JUP	ILW	733.4	122.4	6.0	0.0000
TSS	HIL	BAK	620.8	110.2	5.6	0.0000
TSS	GOC	BOY	548.7	103.0	5.3	0.0000
TSS	JUP	GOC	543.8	108.9	5.0	0.0000
TSS	PEV	JUP	-573.7	117.2	-4.9	0.0000
TSS	PEV	BOY	518.7	111.8	4.6	0.0001
TSS	HIL	BOC	448.0	108.7	4.1	0.0014
TSS	GOC	BAK	419.4	103.0	4.1	0.0017
TSS	PEV	BAK	389.4	111.8	3.5	0.0177
TSS	ILW	HIL	-391.1	115.7	-3.4	0.0262

Table 3: Correlations between TSS/Turbidity and NCRMP biological data. Only statistically significant relationships are shown (Spearman rank sum correlation, α=0.05). "Other" encompasses all cover types that do not fall under one of the following: Cliona, Dictyota, Gorgonians, Halimeda. *Montastraea cavernosa*, Palythoa, Porifera, *Stephanocoenia intersepta*, Turf Algae, Macroalgae (other fleshy), Millepora, *Siderastrea siderea*, Encrusting gorgonian, *Porites astreoides*, Rhodophyta, Bare substrate, *Diploria labyrinthiformis*, Peysonnellia

Chemistry	**Biology**	**Spearman ρ**	**Prob>|ρ|**
Max Turbidity	Rugosity	-0.845	0.008
Mean Turbidity	Rugosity	-0.845	0.008
Max TSS	Turf Algae	-0.833	0.010
Mean TSS	Turf Algae	-0.833	0.010
Max TSS	Encrusting gorgonians	0.791	0.019
Mean TSS	Encrusting gorgonians	0.791	0.019
Max TSS	Other	-0.764	0.027
Mean TSS	Other	-0.764	0.027

Table 4: Number of exceedances of TSS threshold by ICA

ICA	# of occurrences
STL	215
JUP	70
ILW	60
BOY	53
BOC	65
HIL	63
PEV	69
BAK	42
GOC	60

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