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Revised Turbidity Criterion to Protect Florida Coral and Hardbottom Communities

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1.0 Introduction

1.1 Purpose of the Report

The purpose of this document is to summarize the current scientific understanding of coral species sensitives and responses to turbidity and describe efforts to revise the generally applicable turbidity criterion to better protect coral reef and hardbottom communities that occur in South Florida. The document also provides recommendations for additional studies to further refine the numeric turbidity criterion in the future.

1.2 Proposed Criterion Revision

The Department recommends adoption of a two-part turbidity criterion. The first part of the criterion, which applies to all Florida waters, would add a narrative provision to the existing numeric turbidity criterion of 29 NTU above natural background. The second part of the criterion is intended to provide added protection for sensitive coral and hardbottom species in South Florida and would specify that there shall be no increase in turbidity levels outside of the range of natural variability. The second part of the criterion would only apply to coastal waters in areas specifically described and listed in the rule.

We recommend that the existing turbidity criterion in subsection 62-302.530(70), Florida Administrative Code (F.A.C.), be revised to include two paragraphs:

a. Turbidity shall not be increased more than 29 NTU above natural background, nor shall turbidity levels be increased to levels that negatively affect designated uses or result in increased sedimentation or reduced light transmission to the point that the normal growth, function, reproduction, or recruitment of aquatic life is impaired.
b. Turbidity shall not be increased above background conditions within the Southeast Florida Coral Reef Ecosystem Conservation Area, Biscayne National Park, Biscayne Bay Aquatic Preserve, Florida Keys National Marine Sanctuary excluding canals, and Dry Tortugas National Park, as shown on the map titled “Florida Reef Tract”, July 2019,

which is incorporated by reference herein, or other areas of the state where coral reef or hardbottom communities, are currently found. For the purposes of evaluating this criterion, background conditions shall take into account the natural variability of turbidity levels and shall be established following the methods described in the document Implementation of the Turbidity Criterion for the Protection of Coral Reef and Hardbottom Communities, dated September 2019, which is incorporated by reference.

The Florida Reef Tract (FRT, **Figure 1**) is specifically listed and identified in the criterion because it contains waters, including marine sanctuary, state parks, and national parks, known to currently or historically support extensive coral reefs. Consideration of the historical presence of coral is of critical importance because the FRT has experienced significant declines in coral since 2014 due to Stony Coral Tissue Loss Disease (SCTLD). Coral and hardbottom organisms have a potential to colonize and grow throughout the FRT; the turbidity criterion is intended to ensure that turbidity is not a limiting factor to their survival, recruitment, growth, or recovery from SCTLD, regardless of whether these species currently occur within an area. Additionally, most of the FRT has been designated as critical habitat for Acropora, a genus of coral designated as endangered by the National Oceanographic and Atmospheric Administration (NOAA) National Marine Fisheries Service (NMFS), and such critical habitat warrants additional proactive protection.

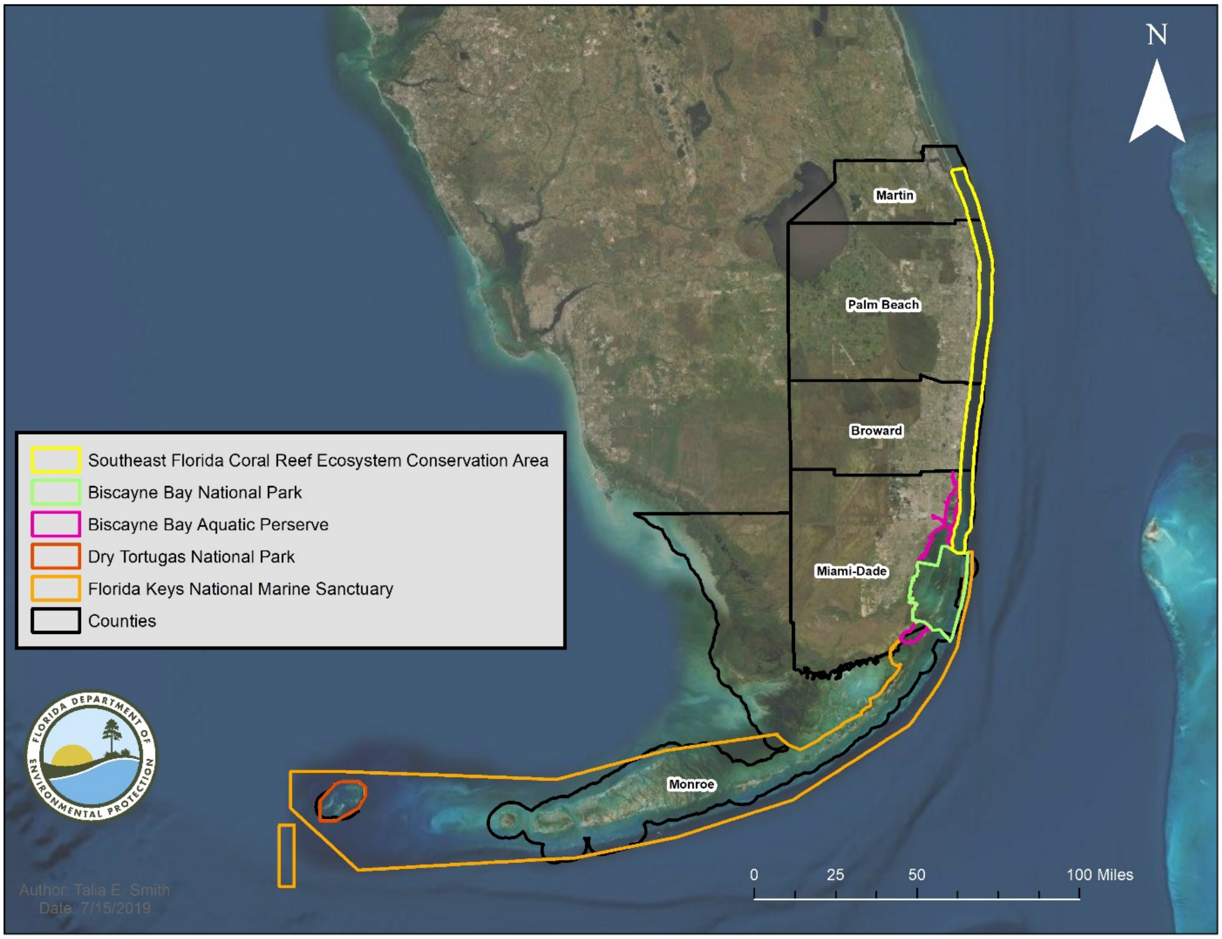

Figure 1. The Florida Reef Tract (FRT).

The spatial distribution of coral reefs, hardbottom, and worm rock (Serpulidae reefs) outside of the FRT is patchy, limited by other factors (e.g., lack of a hard rock substrate), and not well delineated (**Figure 2**). Therefore, paragraph 62-302.530(70)(b), F.A.C., only applies in areas outside of the FRT to waters where coral, reef, hardbottom, or worm rook communities are found. For purposes of interpreting the turbidity criterion in Paragraph 62-302.530(70)(b), F.A.C., “coral reef” shall mean a marine benthic community that includes hard coral species (Scleractinia), and “hardbottom” shall be defined as a marine habitat that includes benthic epifaunal organisms that are attached to a hard rock substrate. To be considered hardbottom, the epifaunal community of organisms must include either hard coral, octocorals, anemones, bryozoans, and/or sponge species.

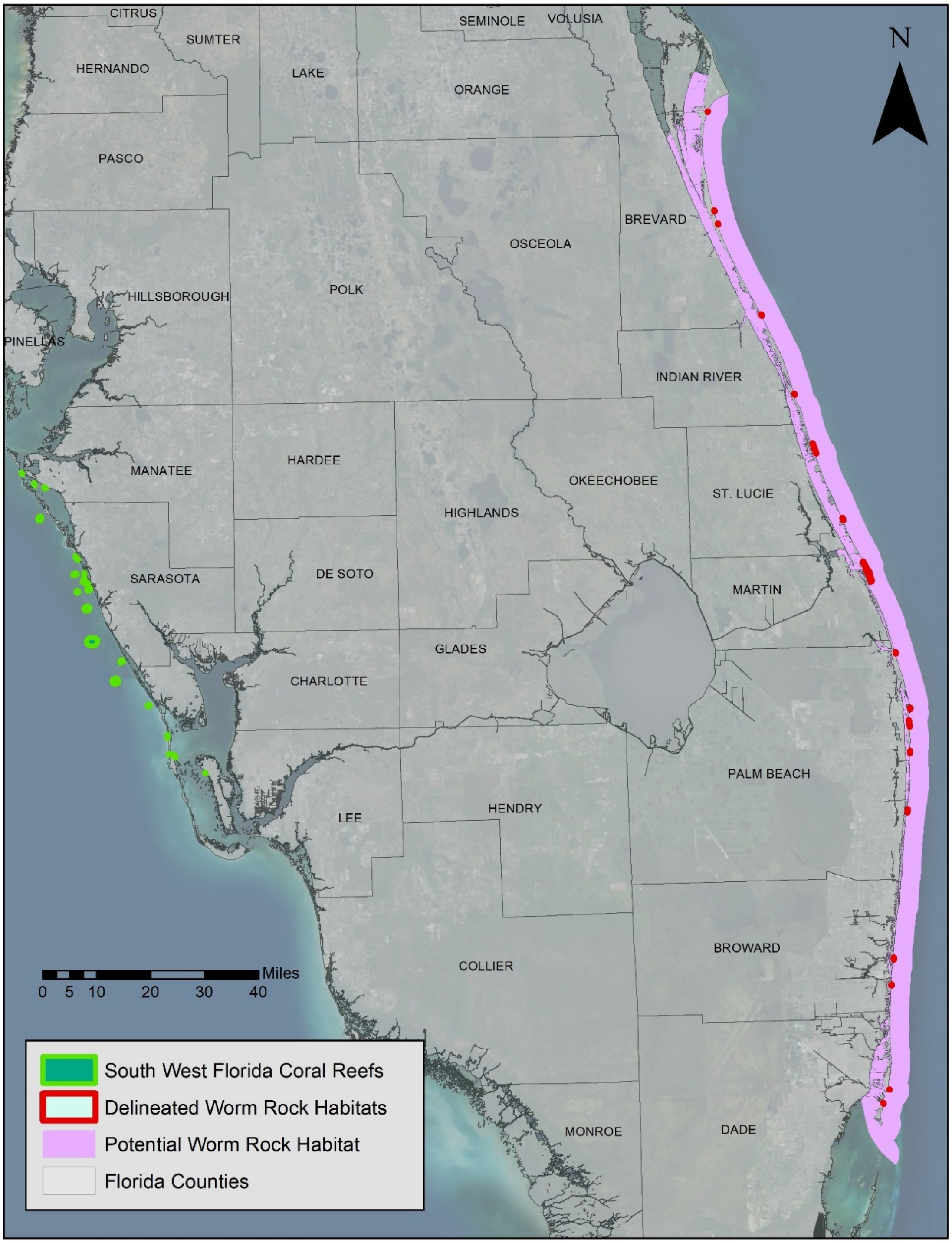

Figure 2. Spatial distribution of coral reefs and worm rock habitats on the southwest and southeast, respectively, coasts of Florida. Potential worm reef habitat is based on Kirtley and Tanner (1968) and shows where Serpulidae may potentially occur. Delineated worm rock reef habitats are from the Florida Fish and Wildlife Commission (FWC) (http://geodata.myfwc.com/datasets/dff9b71b85c04e47b8e54d0eed167205_2) and show the location of surveyed worm reefs.

2.0 Background

Turbidity is the optical property of a suspension that causes light to be scattered and absorbed rather than transmitted through the water column; it implies muddiness and lack of clarity and transparency. The more total suspended solids in the water, the higher the effect on light transmission and the higher the turbidity value. Although turbidity and suspended sediments are highly related, the turbidity value is influenced by sediment type, grain size, and the optical properties of the sediment. Turbidity is also influenced by algae and bacteria suspended in the water column; that is, there can be a non-sediment (algae and bacteria) fraction to turbidity.

The State of Florida established a water quality criterion for turbidity in subsection 62-302.530(70), Florida Administrative Code (F.A.C.), that applies to all waterbody classifications. In accordance with subsection 62-302.530(70), F.A.C., surface waters of the State of Florida shall not exceed 29 Nephelometric Turbidity Units (NTUs) above natural background conditions. The State's original turbidity criterion was 50 Jackson Candle Units, but in 1983 it was converted to 29 NTUs. The earlier 50 Jackson Candle Unit criterion dates back to the 1962 Sanitary Code of Florida, Chapter V (Rules of the State Board of Health). The basis of the criterion is only conjecture at this time because there is no available documentation supporting the 1962 Sanitary Code.

Stress from elevated suspended sediments, turbidity and reduced water clarity have been shown to cause significant adverse effects on coral and hardbottom ecosystems globally and in Florida waters. The source of the sediment may be natural or anthropogenic activities. Natural processes that cause suspended sediments and turbidity include resuspension processes related to wave action, tidal fluctuations, run-off from land, and storms. Anthropogenic activities that increase suspended sediments include dredging, beach nourishment, agricultural activities, urban runoff, construction, and resuspension from boat activity. Additionally, anthropogenic nutrient enrichment (nitrogen and phosphorus) can increase algal densities, which can result in reduced transparency and water clarity.

A review of the available literature strongly suggests that the existing 29 NTU above natural background turbidity criterion is not protective of sensitive marine habitats, particularly the coral reef communities of Southeast Florida and the Keys. In marine environments, dredging and construction activities. The settlement of the re-suspended sediment in particular is a well-known stressor, requiring epi-benthic organisms to expend energy self-cleaning or become progressively smothered in sediments (Stark et al., 2017).

In addition, a variety of stakeholder groups, such as Our Florida Reefs (OFR), Coastal Ocean Task Force (COTF), US Coral Reef Task Force (USCRTF), and the South East Florida Coral Reef Initiative (SEFCRI), , have recognized the value of the coral reef resources in this area and the unique threats they face from maritime industry and coastal construction impacts, which will be in part ameliorated by a more protective turbidity standard as proposed. Examples of recommendations include:

1. OFR (Our Florida Reefs):
    a. S-104: Set new and appropriate water turbidity standards for marine construction to limit damage from coastal constructions to reefs and associated habitats.
    b. S-103: Create and enforce BMPs that eliminate destructive impacts to coral reefs from coastal construction projects (beach renourishment, port expansion, etc.) to eliminate burials, habitat removal, and excessive siltation and turbidity on coral reefs.
    c. N-98: Develop, fund, and implement a SEFCRI-wide beach management plan for sustainable management of beaches and to protect and minimize impacts to reefs from turbidity caused by erosion.
    d. N-127: Improve permit conditions and BMPs for coastal construction using recommendations from past monitoring (turbidity, sedimentation, and hardbottom) results to reduce negative impacts to reefs from future construction projects.
2. COTF (Coastal Ocean Task Force)
    a. Improve methods of offshore sediment dredging for beach nourishment to reduce muddy runoff turbidity and sediment stress on corals, eliminate damage from dredging "accidents," and enhance sea turtle nesting beaches.
    b. Set new and appropriate water turbidity standards for marine construction to limit damage to reefs and associated habitats from coastal construction projects.
3. USCRTF (US Coral Reef Task Force) Sedimentation and Turbidity Workshop

a. The water quality threshold of 29 NTU above background for construction projects is too high to be protective of coral reef resources and needs to be revised. Monitoring turbidity through NTU alone is an outdated method and should be complemented with diverse abiotic and biotic monitoring parameters.
b. Construction near valuable benthic resources should occur during environmental windows that respect seasonal periods of biological importance and stress for those resources (i.e., spawning, bleaching, rainy season, etc.). These are not universal and may vary by location.

3.0 Stressor of Concern – Suspended Sediments

Suspended sediments originate from resuspended marine sediments, soil erosion, terrestrial runoff, discharges, and construction activities (i.e., dredging and fill placement). Suspended sediments are made up of organic and inorganic materials, although bacteria and algae can also contribute to the total SSC. Increased suspended sediments are a significant factor in reduced water clarity, reduced light attenuation, and increased turbidity, and can cause additional problems when they settle on the bottom (sedimentation).

A review of peer-reviewed literature on the environmental impacts of dredging (sedimentation and turbidity) was done by Erftemeijer et al., 2012, and impacts to coral reefs due to dredging events have been documented world-wide. The major problems arising from turbidity and sedimentation derived from coastal construction and dredging are related to the shading caused by decreases in ambient light and sediment cover on the coral's surface, as well as problems for the feeding apparatus under a sediment blanket and energy costs associated with mucus production, sediment clearance, and impaired feeding (Erftemeijer et al., 2012). The accumulation of sediment on coral reefs or "sedimentation" associated with coastal construction/dredging can have negative impacts on coral reefs and is a widespread cause of coral reef degradation (Rogers 1990; Riegl 1995).

In many cases, dredging operations have contributed to the loss of coral habitats, either directly due to the removal or burial of reefs or indirectly as a consequence of lethal or sublethal stress to corals caused by elevated turbidity and sedimentation (Erftemeijer et al 2012). For example, a large-scale dredging project and corresponding monitoring event was conducted off Miami

Beach to observe the effects of dredging activities on a subtropical coral community beginning in 1977 (Marszalek 1981). Monitoring revealed that approximately one centimeter of sediment was deposited on the nearby reef surface in less than two hours (Marszalek 1981). Scleractinian corals suffered the most damage and were observed actively cleaning themselves of sediments; most were partly covered with a layer of mucus and sediment, and the polyps were distended and swollen (Marszalek 1981). Many of the small colonies of *Dichocoenia stokesii*, *Montastraea cavernosa*, and other hemispherical forms showed a band of dead tissue adjacent to the substrate, buried beneath the layer of silt (Marszalek 1981). In addition, there was a general increase in turbidity throughout the study area, with turbidity levels varying depending on proximity to the dredge, weather conditions, and tidal cycles. A transect survey completed during the winter of 1980 concluded that an average of 9.7% (range: 3% to 32.4%,) of coral colonies exhibited signs of coral stress, which was a large increase from the 5% measured in 1978 (Marszalek 1981).

Summaries of species sensitivities and responses to turbidity, suspended sediment, and sedimentation from dosing and *in situ* experiments are provided in **Section 5.0**. The preponderance of evidence from these studies indicate that corals are sensitive to suspended sediments and that the existing 29 NTU criterion is not adequately protective of these species. The next section, **Section 4.0**, presents a conceptual model that describes the stressor-response relationships to suspended sediments in coral species.

4.0 Conceptual Model

A conceptual model is a written description and diagram that provides a visual representation of predicted relationships between stressors and resulting ecological conditions (U.S. EPA, 1998). It can be used to describe predicted relationships between biological, physical, and chemical conditions of a waterbody; develop hypotheses regarding cause and effect relationships; determine the most sensitive end-point(s); and determine the most critical stressors.

The conceptual model shown in **Figure 3** summarizes natural and anthropogenic sources of suspended sediments, potential biological responses, and transport pathways on adult and early life-history stages of corals. The model links exposure characteristics such as low light availability, sedimentation (covering, smothering and deposition), and suspended sediment with detrimental outcomes. The stressor is the physical, chemical, or biological agent that directly causes one or more biotic responses of concern, which in this case are suspended sediment or turbidity, decreased light availability, and sedimentation.

4.1 Effects of Suspended Sediment on Corals

Corals are both autotrophs and heterotrophs. Ingestion of sediments by corals has been observed in many studies (Lewis and Price, 1975; Lewis, 1976; Logan, 1988; Marshall and Orr, 1931; Stafford-Smith and Ormond, 1992; Stafford-Smith, 1993) and appears to be part of a normal feeding mechanism. Suspended particulate matter constitutes a potentially diverse food source containing bacteria, microalgae, protozoa, detrital organic matter (Marshall, 1965), interstitial invertebrates, undissolved mucus (Wild et al., 2004), microbial exudates, and excretory products from other animals (e.g. from fish, Meyer and Schultz, 1985; Lopez and Levinton 1987; Houlbrèque and Ferrier-Pagès, 2009). Many studies have shown that corals are capable of assimilating and obtaining nutritional benefits from organic matter associated with ingested sediments (Anthony, 1999, 2000; Anthony and Fabricius, 2000; Mills and Sebens, 1997; Mills et al., 2004; Rosenfeld et al., 1999). However, Mills and Sebens (1997) suggested that high loads of clean sediments may cause polyps to stop feeding and reject sediments, reducing ingestion rates. Similarly, Anthony (2000) indicated that at concentrations >30 mg L^{-1} *Acropora millepora* and *Pocillopora damicornis* from clear water offshore environments showed a tendency to retract their polyps, which reduced the potential for energy gains from feeding.

Low SSCs may be beneficial for some corals in some circumstances and detrimental at higher concentrations, depending on organic content, water flow and coral morphology. A low dose stimulation and high dose inhibition has been reported in numerous studies (Anthony, 1999, 2000; Logan et al., 1994; Mills and Sebens, 1997; Mills et al., 2004; Mills and Sebens, 2004; Rosenfeld et al., 1999; Stafford-Smith and Ormond, 1992; Tomascik and Sander, 1985). While low SSCs can have beneficial effects, high SSC is one of the key stressors because it reduces feeding activity and increases energy expenditures to continually process and transport intercepted sediments (**Figure 3**).

4.2 Light Availability

Spectral composition and the quantity and quality of the submarine light field is fundamentally important for the physiology and ecology of coral-algal symbiosis. Light attenuation, mediated by absorption and scattering of light by suspended particles, is one of the key stressors to corals in the short- and long-term (Jones et al., 2016). In very low or zero light conditions, corals can enter a state of hypoxia and then anoxia due to reduced photosynthetic production of oxygen (Jones et al., 2016).

4.3 Sediment Covering

The initial response of corals to deposition of sediments on their surfaces is an attempt to self-clean by moving sediments to edges where they are dropped off the colony (Marshall and Orr, 1931). The principal sediment rejection mechanisms identified for a range of coral species, representing different families, are: ciliary action, hydrostatic inflation, tentacle movement, contractions, and mucus entrapment (Bak and Elgershuizen, 1976; Hubbard and Pocock, 1972; Logan, 1988; Marshall and Orr, 1931; Schuhmacher, 1977; Stafford-Smith and Ormond, 1992; Stafford-Smith, 1993; Vaughan, 1916; Yonge and Nicholls, 1931). These are usually referred to as active processes (requiring energy).

If sedimentation rates exceed the coral's sediment clearance rate, sediments will inevitability build up on a coral's surface and the coral becomes progressively buried in a sediment deposit. The fate of the underlying tissues is partial mortality (lesion formation), unless the sediment layer is removed by a storm.

One of the significant issues associated with smothering is tissue hypoxia, brought about by either light attenuation or a reduction in gas (solute) transfer across diffusive boundary layers. Corals are oxygen conformers and routinely experience pronounced diel changes in tissue oxygen concentrations ranging from super-saturation (hyperoxia) during the daytime associated with algal photosynthesis, to night-time oxygen shortage (hypoxia) or even anoxia by host and algal respiration (Jones and Hoegh-Guldberg, 2001; Kuhl et al., 1995; Shashar et al., 1996). In darkness or low flow conditions, oxygen concentrations can fall to levels where aerobic respiration and adenosine triphosphate (ATP) generation is limited (Bailey-Serres and Voesenek, 2008; Fukao and Bailey-Serres, 2004).

4.4 Combined Effects of Proximal Stressors

The key pressure parameters identified above are highly interconnected, with suspended-sediments causing biological effects directly, and also causing changes in light quality and quantity (through attenuation and scattering in the water column). Similarly, high SSCs are a prerequisite for sediment deposition, mediated by the process of sedimentation in the water column. While the direct physical effects of coral smothering are generally more of an acute concern, accumulated sediments also have a longer-term effect as they reduce the amount of light reaching the coral surface and impact feeding processes (**Figure 3**).

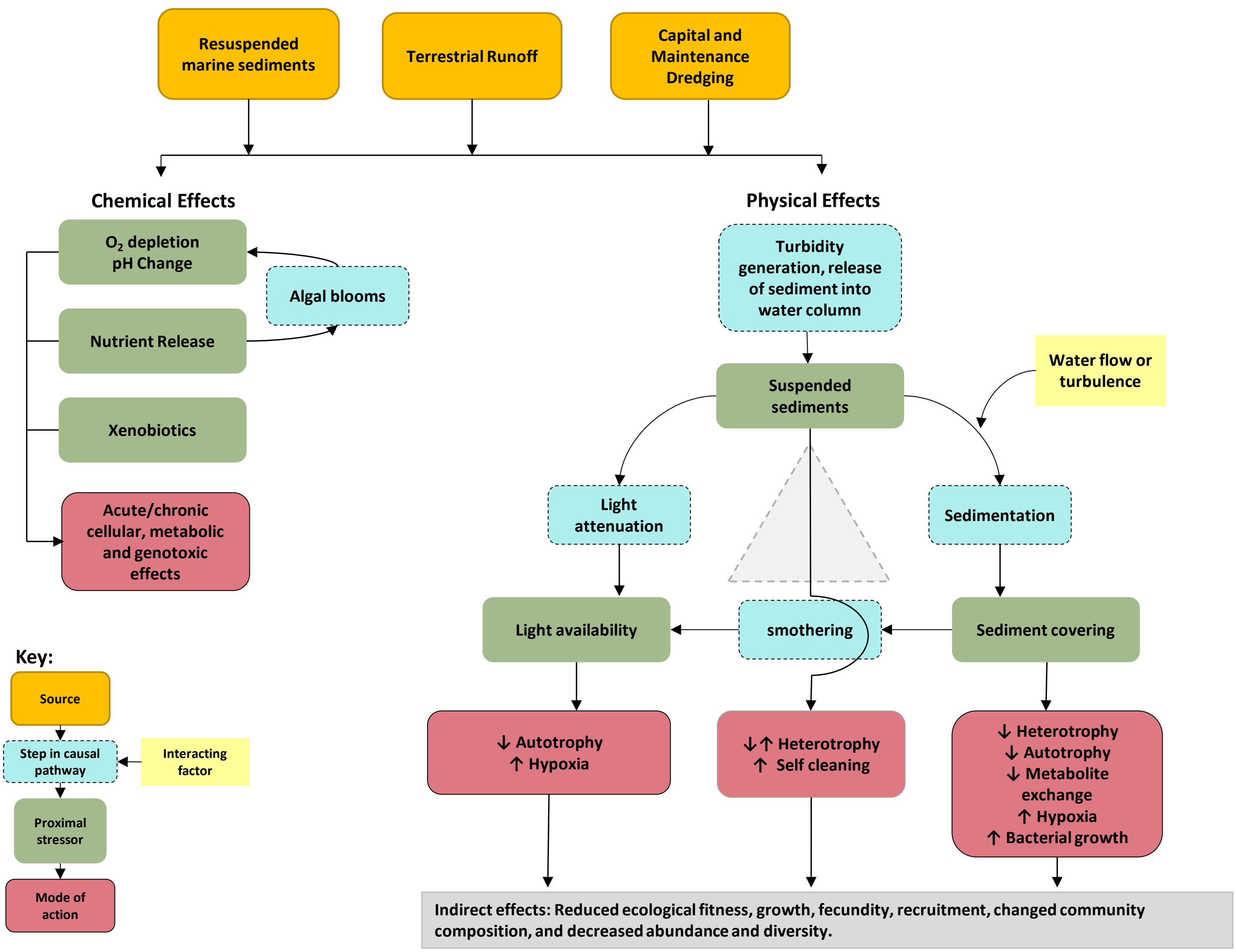

Figure 3. Conceptual model for suspended sediment effects on coral larvae and adult energy expenditure (Adapted from Jones et al., 2016).

5.0 Assessment of Effects

There is limited literature available on the effects of turbidity and sedimentation on Florida reefs; however, many studies showing significant negative effects have been conducted in the Caribbean and many of the coral species commonly found in Florida waters are also found across the Caribbean. These studies show sensitivity of different species to SSC, turbidity, light reduction, and sedimentation. This section describes the relative sensitivity of adult and early life stages of corals found in Florida to turbidity and sedimentation based on research conducted in Florida and the Caribbean. Biological responses to experimentally manipulated turbidity, SSC, light, or sedimentation are summarized in **Table 1**.

5.1 Sensitivity of Adult Florida Coral Species

Although information on the sensitivity of Florida's coral species to turbidity and associated stressors is limited, the available studies have demonstrated that several coral species, including the endangered *Acropora cervicornis* (staghorn coral), are sensitive to turbid conditions and sedimentation. Conversely, other species such as *Siderastrea spp.* and *Meandrina meandrites,* are either adapted to naturally higher turbidity ranges or have the ability to tolerate limited duration exposures to elevated turbidity or increased sedimentation. However, the overall duration of exposure is critically important to all species and even the most tolerant species exhibit stress if exposed to high levels for prolonged durations.

Acroporids are particularly sensitive to sediment as they are among the least effective of the reef building corals at trapping and removing sediment from their surface (NOAA fact sheet; https://sero.nmfs.noaa.gov/protected_resources/outreach_and_education/documents/acropora_factsheet.pdf). *Acropora spp*. found in Florida depend heavily on wave action to clear sediment, making them highly sensitive to anthropogenic turbidity and sedimentation (Bak and Elgershuizen, 1976). *Acropora palmata* (elkhorn coral) exhibited partial mortality when exposed to a single application of 200 mg/cm^2 of clean calcareous sediment (Rogers, 1983). When exposed to 600 mg of sediment[1], *A. palmata* photosynthetic rates dropped significantly (Abdel-Salam et al., 1988). *In situ* observations indicate that *Acropora spp*. are almost completely absent from reefs near influxes of terrigenous sediment (Acevedo et al., 1989).

[1] Sediment was dumped into a cup approximately the "size of a small 35 mm film canister"

Many studies have shown that *Acropora cervicornis* is sensitive to SSC. When exposed to moderate SSC (150 mg/L) for 96 hours, polyp retraction and mucus production occurred, while partial mortality occurred in colonies exposed to high SSC levels (476 mg/L) (Thompson, 1980). Physiological stress responses occurred at lower levels of SSC. Colonies exposed to 25 mg/L of drilling mud for 24 hours exhibited a 62% decrease in calcification rates, and colonies exposed to 100 mg/L showed a 50% decline in soluble tissue protein (Kendall et al., 1983). Exposure to 100 mg/L of kaolin reduced calcification rates and free amino acid content (Kendall et al., 1985). *A. cervicornis* is also sensitive to sediment applications, experiencing major bleaching from a single application of 400 mg/cm^2 of clean calcareous sediment (Rogers 1983).

Kendall et al (1983) found that drilling muds and turbidity influenced the native coral *Acropora cervicornis* in Carysfort Reef, Florida in several ways. The study examined, *in situ*, the effects of exposure to used drilling muds and turbidity on the calcification rate, ninhydrin positive substance (NPS) content, and tissue protein content of corals. The study found that total soluble protein in the coral decreased significantly in 25, 50, 100 and 500 ppm drilling mud treatment, with a dramatic loss noted in the 500 ppm treatment. Soluble protein concentration was 50% lower after 24-hour exposure to 100 ppm and 68-92% lower in corals exposed to 500 ppm. Calcification rate also declined in response to increasing drilling mud concentrations, with calcification rates declining by 62, 83, 88, and 95% at 25, 50, 100, and 500 ppm, respectively (Kendall et al., 1983). Additionally, a loss of zooxanthellae was observed in the field in corals exposed to 500 ppm.

Montastraea annularis (bounder star coral), *Acropora palmata*, and *Acropora cervicornis* are considered to be more sensitive to turbidity, sedimentation, and SSC than other species of corals found in Florida. Multiple studies have shown that, as the input of terrigenous sediment on reefs increases, *M. annularis* cover decreases (Torres and Morelock, 2002; Acevedo et al., 1989; Bégin et al., 2014). Physiological responses have been measured on colonies that inhabit highly turbid sites. *M. annularis* living in sites impacted by high turbidity and sedimentation have significantly lower skeletal extension rates than those on unimpacted reefs (Torres 2001). When exposed to 120 mg/mL of SSC, *M. annularis* exhibited significant decreases in photosynthetic rates (Abdel-Salam, 1988). When exposed to a single application of 400 mg/cm^2 of clean calcareous sediment, *M. annularis* showed mild discoloration, which is the first indication of bleaching (Rogers 1983). Chronic exposure (6 weeks) to low levels of SSC (100 mg/L) also produced minor sub-lethal effects, including reduced rates of respiration, photosynthesis, calcification and nutrient uptake (Szmant-Froelich et al., 1981). When exposed to 150 mg/L of SSC for 96 hours, *M. annularis* exhibited polyp retraction and mucous production, and when SSC was increased to 476 mg/L, all colonies showed mortality within 65 hours of exposure (Thompson, 1980).

Agaricia agaricites (lettuce coral) cover was significantly decreased at reefs near an influx of terrigenous sediment (Acevedo et al., 1989). When exposed to moderate SSC levels (150 mg/L) for 96 hours, *Agaricia agaricites* experienced polyp retraction and increased mucus production, while partial mortality occurred in colonies exposed to high SSC levels (476 mg/L) (Thompson, 1980).

Some coral species can tolerate short duration exposure to sedimentation and turbid conditions; however, these conditions are still stressful to the corals and longer-term exposure or increased concentrations of suspended sediments can adversely affect the corals. For example, *Montastrea cavernosa* (great star coral), *Siderastrea radians*, *Siderastrea siderea*, and *Meandrina meandrites* were found to dominate highly turbid reefs in Puerto Rico (Loya, 1976). *M. cavernosa* can tolerate higher turbidity and sediment environments because they effectively remove sediment through active and passive rejection. The morphology and large polyps of *M. cavernosa* allowed them to passively shed most sediment and remove the rest with little energy input under laboratory conditions using fine and coarse sediment for five days and similar results were observed using existing natural sediment *in situ* (Lasker, 1980).

Siderastrea spp. are adapted to nearshore, stressful environments and can tolerate periodic high turbidities (Lirman and Manzello, 2009). Torres and Morelock (2002) found that *S. siderea* (massive starlet coral) populations in Puerto Rico at five different sites were unaffected by high inputs of terrigenous sediments onto reefs. The *in situ* study was conducted under different natural sedimentary regimes, with sites ranging from no exposure to high exposure to terrigenous sediment. There were upward growth responses for a five-year period as well as changes in coral cover as a result of increased sediment influx (Torres and Morelock, 2002). *S. radians* showed only slight reductions in photosynthesis when subject to short-term burials (2-24 hours) and recovered quickly under laboratory conditions.

Only under extended chronic sediment burial (≥48 hours) and extreme salinity (15 or 45 psu) did colonies experience tissue mortality (Lirman and Manzello, 2009). Small colonies (2-3 cm) of *S. radians* in Biscayne Bay were able to survive 4 days of complete burial of natural sediment with only slight reductions in photosynthetic rates. After 7-10 days of burial at low salinity (15 ppt), colonies were thought to have experienced complete mortality, with no evident photosynthesis or respiration occurring; however, in 2-3 weeks, tissue began to regrow and in 6 weeks, colonies appeared healthy (Lirman et al., 2002).

Meandrina meandrites (maze coral) and *Dichocoenia stokesii* (pineapple coral) were shown to tolerate turbidity in short-term laboratory experiments, but adverse effects on these species were noted after only a few days of exposure to turbid conditions. When exposed to 28-30 NTU for three days, colonies experienced mucous production, reduced photosynthesis to respiration (P:R) ratios, and lesions; however, no bleaching or mortality was seen (Telesnicki and Goldberg, 1995). Colonies of *Meandrina meandrites* showed significant increases in respiration after day two, and *Dichocoenia stokesii* exhibited significant increases in respiration after three days. P:R ratios were significantly different from controls in both species when exposed to 14-16 NTU for seven days.

Porites astreoides (mustard hill coral) and *Diploria strigose* (brain coral) have also shown some tolerance to SSC in laboratory experiments. *Porites astreoides* exposed to moderate SSC levels (150 mg/L) for 96 hours in the laboratory had no physiological effects on colonies. Only under extended exposure to 476 mg/L did colonies show major sub-lethal stress responses, but there was no colony mortality (Thompson, 1980). Even when exposed to 1,000 mg/L for 65 hours, no mortality was seen (Thompson and Bright, 1980). *Diploria strigosa* exhibited no discoloration even when exposed to sediment applications of 800 mg/cm^2(Rogers, 1983). *Diploria strigosa* was able to clear sediment quickly, and photosynthetic rates were unaffected by 120 mg/ml of suspended sediment (Abdel-Salem, et al., 1988).

High turbidity levels produced by sediment resuspension was investigated to test the effects on the survival and growth rates of hard corals collected from the Gulf of Mexico patch reefs off west central Florida. This experiment was done under controlled laboratory conditions that were intended to simulate the levels of suspended sediment that might be expected to occur on the periphery of an ocean dredged material disposal site (Rice and Hunter 1992). Four different levels of suspended sediment (49, 101, 165, and 199 mg/L) were tested in 10-day survival and growth experiments. Eight species of hard corals were used for suspended sediment experiments. Loss of color associated with expulsion of zooxanthellae was a common response in *Manicina*, *Scolymia*, *Isophyllia*, and *Solenastrea* (Rice and Hunter 1992). Partial polyp death and/or polyp bleaching, shrinkage of soft tissue, and exposure of underlying skeletal features were observed in *Manicina*, *Scolymia*, and *Isophyllia* (Rice and Hunter 1992). The average coral growth rates for seven species exposed to 165 mg/L suspended sediment load for 10 days were significantly different in control and experimental treatments (Rice and Hunter 1992).

5.2 Early Life Stages

Suspended sediment and sedimentation have several effects on early life stages of coral, and these effects may be substantially more detrimental to coral recruits than adult corals. Coral settlement rates are significantly depressed by elevated turbidity and sedimentation because sediment covers the hard substrates that coral recruits require for settlement. Sediment deposition can also interfere with sexual reproduction and recruitment by sediments binding directly to egg-sperm bundles and causing them to sink. Several studies have reported that suspended sediments can reduce fertilization success at concentrations as low as 50 mg/L (Ricardo et al., 2015).

Because early life-history stages of corals are susceptible to elevated suspended sediments, high turbidity during spawning periods could lead to loss of the entire reproductive output for the year (Jones et al., 2015; Harrison et al., 1984; Hughes and Tanner, 2000; Hughes et al., 2000). Several studies have suggested that increased levels of sedimentation and/or suspended sediments can affect reproductive success (Erftemeijer et al., 2012; Perez III et al., 2014; Ricardo et al., 2015; Fourney and Figueiredo, 2017; Humanes et al., 2017; Moeller et al., 2017). However, the majority of these studies were conducted using non-Florida or Caribbean species.

Fourney and Figueiredo (2017) conducted the only published Florida study on the effects of suspended sediments on early coral life stages. *Porites astreoides* recruits were exposed to four levels of sedimentation (30, 60, 90, and 120 mg cm^{-2} of deposited sediment) and two temperature levels (26˚C and 30˚C). The experiment was conducted twice: first with large grained “natural” sediment, and a second time with small grained “anthropogenic” sediment typical of dredging conditions. The first experiment used 1,503 newly settled recruits and ran for three months, while the second experiment used eighty 5-month old recruits and ran for one month (Fourney and Figueiredo 2017). Between the two experiments, temperature and anthropogenic sedimentation additively affected the survival of *Porites astreoides* recruits; higher temperatures and anthropogenic sedimentation (30˚C and 60 mg cm^{-2}) displayed significantly higher mortality (Fourney and Figueiredo 2017). After 4 weeks of exposure to low turbidity (<7 NTU) levels, 80% of *Porites astreoides* recruits remained alive, but after 4 weeks at 29 NTU, survival dropped to 10%. Fourney and Figueiredo (2017) recommended that the Florida turbidity criterion be revised to < 7 NTU based on this result.

Table 3. Sensitivity (dose-response thresholds) of Florida coral species to turbidity, suspended sediments, light limitation, or sedimentation. Growth forms: B = branching, L = laminar, E = encrusting, M = massive, S = solitary. Modified from Erftemeijer et al, 2012.

Coral species	Experimental SSC, turbidity, or light level	Response	Growth Form	References
Acropora cervicornis	Severe light reduction (shading) for 5 wks	Mass bleaching (3 wks), mortality/algal cover (7 wks), no recovery (8 months)	B	Rogers (1979)
	50 mg/l (96 h)	No effect		Thompson (1980)
	150 mg/l (96 h)	Polyp retraction, mucus production but no mortality		
	476 mg/l (96 h)	Partial mortality after 96 h.		
	25 mg/l (drilling mud) (24 h)	62% Decrease in calcification rate		Kendall et al. (1983)
	100 mg/l (drilling mud) (24h)	50% Decline in soluble tissue protein		
	50 and 100 mg/l (kaolin, 24h)	Reduced calcification rate and free amino acids at 100 mg/l (recovery in 48 h)		Kendall et al. (1985)
	1000 mg/l (for 65 h)	Mortality of colonies		Thompson and Bright (1980)
Acropora spp.	170 mg/l (hours) of marine snow/SPM	Mucus production in response to flocculation		Fabricius and Wolanski (2000)
Agaricia agaricites	Severe light reduction (shading) for 5 wks	Partial bleaching after 5 wks, recovery within wks	L	Rogers (1979)
	50 mg/l (96 h)	No effect		Thompson (1980)
	150 mg/l (96 h)	Polyp retraction, mucus production but no mortality		
	476 mg/l (96 h)	Mortality after 65 h		
	<1% SI (several days)	33% Decrease in calcification rate (for >1 month), but survival		Bak (1978)
	1000 mg/l (for 65 h)	Mortality of colonies		Thompson and Bright (1980)
Cladocora arbuscula	49, 101, 165 and 199 mg/l (10–20 days)	No effect on growth rate or survival (10 d), minor bleaching (20 d)	B	Rice and Hunter (1992)
Colpophyllia natans	Severe light reduction (shading) for 5 wks	Partial bleaching (5 wks), limited recovery & some algal growth (15 wks)	M	Rogers (1979)

Coral species	Experimental SSC, turbidity, or light level	Response	Growth Form	References
Dichocoenia stokesii	0–2 NTU and 7–9 NTU (wks)	No effect on P:R ratio	M	Telesnicki and Goldberg (1995)
	14–16 NTU (wks)	Mucus production, P:R ratio <1 after 6 days exposure		
	28–30 NTU (wks)	Mucus production, P:R ratio <1 after 3 days exposure		
	50–150–476 mg/l (96 h)	No effect at 50 and 150 mg/l; extreme sub-lethal stress but survival at 476 mg/l		Thompson (1980)
	1000 mg/l (for 65 h)	No mortality		Thompson and Bright (1980)
Diploria labyrinth-iformis	Severe light reduction (shading) for 5 wks	Substantial bleaching (5 wks), no recovery & some algal growth (15 wks)	M	Rogers (1979)
Eusmilia fastigiata	Severe light reduction (shading) for 5 wks	No visible effects	M	Rogers (1979)
Isophyllia suniosa	49,101, 165, and 199 mg/l	No effect on growth rate or survival after 10 d, minor bleaching after 20 days	M	Rice and Hunter (1992)
Madracis auretenra	<1% SI (several days)	33% drop in calcification rate (for >1 month) but survived	B	Bak (1978)
Manicina areolata	49, 101, 165 and 199 mg/l	No effect on growth rate or survival after 10 d, minor bleaching after 20 days	M	Rice and Hunter (1992)
Millepora alcicornis	Severe light reduction (shading) for 5 wks	Partial bleaching (5 wks), algal growth (6 wks), no recovery of damaged tissue	B	Rogers (1979)
Meandrina meandrites	0-2 NTU and 7-9 NTU (wks)	No effect on P:R ratio	M/E	Telesnicki and Goldberg (1995)
	14–16 NTU (wks)	Mucus production, P:R ratio <1 after 6 days exposure		
	28–30 NTU (wks)	Mucus production, P:R ratio <1 after 3 days exposure		
Montastraea annularis	severe light reduction (shading) for 5 wks	substantial bleaching (5 wks), partial recovery (6-8 wks), some algae/mucus	M/E	Rogers (1979)
	50 mg/l (96 h)	No effect		Thompson (1980)
	150 mg/l (96 h)	Polyp retraction, mucus production but no mortality		
	476 mg/l (96 h)	Mortality after 65 h		
	100 mg/l (6 wks)	Major sub-lethal effects (photosynthesis, respiration, calcification, and nutrient uptake)		Szmant-Froelich et al. 1981
	1-10 mg/l (6 wks)	only (some) effect on feeding response		
	525 mg/l	Decreased net production and tissue chlorophyll content, increased respiration and mucus		Dallmeyer et al. (1982)
	1000 mg/l (for 65 h)	Mortality of colonies		Thompson and Bright (1980)
Montastraea cavernosa	severe light reduction (shading) for 5 wks	No visible effects	M	Rogers (1979)
Mussa angulosa	Severe light reduction (shading) for 5 wks	No visible effects (1 colony showing minor bleaching after 8 wks)	M	Rogers (1979)
Phyllangia Americana	49, 101, 165, 199 mg/l	No effect on growth rate or survival (10 d), minor bleaching (20 d)	E	Rice and Hunter (1992)
Porites astreoides	50-150-476 mg/l (96 h)	No effect at 50 and 150 mg/l; extreme sub-lethal stress but survival at 476 mg/l	M/E	Thompson (1980)
	<1% SI (several days)	Bleaching and mortality		Bak (1978)
	1000 mg/l (for 65 h)	No mortality		Thompson and Bright (1980)
Porites astreoides	30–120 mg cm^{-2} d^{-1} (0.07–42 NTU)[1]	After four weeks of exposure to low turbidity (<7 NTU), 80% of *P. astreoides* recruits remained alive;	L	Fourney and Figueiredo (2017)

Coral species	Experimental SSC, turbidity, or light level	Response	Growth Form	References
		exposure to turbidity levels above 29 NTU led survival to drop to 10%.		
Porites divaricata	50-150-476 mg/l (96 h)	No effect at 50 and 150 mg/l; extreme sub-lethal stress but survival at 476 mg/l	B	Thompson (1980)
	1000 mg/l (for 65 h)	No mortality		Thompson and Bright (1980)
Porites Furcata	50-150-476 mg/l (96 h)	No effect at 50 and 150 mg/l; extreme sub-lethal stress but survival at 476 mg/l	B	Thompson (1980)
	1000 mg/l (for 65 h)	No mortality		Thompson and Bright (1980)
Porites porites	Significant light reduction due to eutrophication	Reduced reproductive success (ova maturation, larval development)	M	Tomascik and Sander (1987)
Scolymia cubensis	49, 101, 165, 199 mg/l	No effect on growth rate or survival after 10 d, minor bleaching after 20 days	S	Rice and Hunter (1992)
	49-199 mg/l (10 days)	Partial polyp death and partial bleaching (in some individuals)		Rice (1984)
Siderastrea radians	49-199 mg/l (10 days)	Partial polyp death and partial bleaching (in some individuals)	M/E	Rice (1984)
Siderastrea siderea	Severe light reduction (shading) for 5 wks	Partial bleaching after 5 weeks, partial recovery in 6–8 weeks	M	Rogers (1979)
Solenastrea hyades	49, 101, 165, 199 mg/l	No effect on growth rate or survival after 10 d, minor bleaching after 20 d	M	Rice and Hunter (1992)
	49-199 mg/l (10 days)	Partial polyp death and partial bleaching (in some individuals)		Rice (1984)
Stephano-coeania intersepta	49, 101, 165, 199 mg/l	No effect on growth rate or survival after 10 d, minor bleaching after 20 d	M	Rice and Hunter (1992)
	49-199 mg/l (10 days)	Partial polyp death and partial bleaching (in some individuals)		Rice (1984)

1. Study was conducted as a sedimentation study. Turbidity was measured in the first 24 hours of the study.

6.0 Options for Criterion Revision

The primary challenge to revising the turbidity criterion to protect sensitive coral reef and hardbottom communities is the limited dose-response data (laboratory or *in situ*) on Florida species. The data on how turbidity effects the full life cycle of Florida corals are extremely limited, thus it is difficult to quantify the larval and recruitment sensitivities, which are critical to establishing a protective numeric criterion. Many of the available studies evaluated high turbidity levels over short durations that are not reflective of human-induced turbidity (*i.e.*, long duration exposures). Corals are likely adapted to short-term turbidity perturbations because they evolved within ecosystems that experience periodic natural turbidity spikes associated with storms and hurricanes; however, longer term increases, even at much lower levels, are unnatural and potentially exert deleterious effects on coral health and recruitment.

Another challenge is that the majority of the available dose-response data are provided as SSC in mg/L rather than turbidity (NTU). Although SSC is a more direct measure of the proximal stressor, it is not the ideal water quality measure for permitted projects because it requires a relatively lengthy laboratory analysis. In contrast, turbidity provides an instantaneous measure of the potential stressor that can be used to quickly address problems if an environmentally relevant threshold has been exceeded.

There are several options for addressing the turbidity criterion given the existing challenges: a) develop additional narrative components to supplement and strengthen the existing turbidity criterion; b) propose a numeric criterion based on the limited Florida and Caribbean data; c) seek partnerships with Florida universities to design and implement dose-response studies on Florida resident species, or d) do nothing. The "do nothing" option is least protective and does not fulfill the Department's obligation to adopt criteria for sufficient parameters or constituents to protect all designated uses. There is currently sufficient information to demonstrate that the existing turbidity criterion does not adequately protect sensitive aquatic life uses associated with Florida's coral reef tract; therefore, option "d" will not be discussed further.

6.1 Develop Additional Narrative Components

Water quality criteria must be based on a sufficiently sound scientific rationale. There are currently insufficient data and information to support specific numeric thresholds that are protective of sensitive coral community species including all life stages. However, as previously stated, there is clear evidence to demonstrate that the existing 29 NTU above natural background is not sufficiently protective of sensitive aquatic life uses. U.S. EPA encourages states and authorized tribes to establish narrative criteria where numeric criteria cannot be established or to supplement numerical criteria. Therefore, the currently best and most defensible alternative would be for the State to adopt additional narrative components to supplement and strengthen the existing turbidity criterion.

A number of states currently include narrative criteria for turbidity or related parameters in their state water quality standards, examples include:

- Connecticut Class AA Waters: Shall not exceed 5 NTU over ambient levels and none exceeding levels necessary to protect and maintain all designated uses. All reasonable controls or Best Management Practices are to be used to control turbidity.
- Connecticut Class SA Waters: (Turbidity) none other than of natural origin except as may result from normal agricultural, road maintenance, or construction activity, dredging activity or discharge of dredged or fill material provided all reasonable controls and Best Management Practices are used to control turbidity and none exceeding levels necessary to protect and maintain all designated uses.
- Louisiana: Turbidity other than that of natural origin shall not cause substantial visual contrast with the natural appearance of the waters of the state or impair any designated water use. Turbidity shall not significantly exceed background; background is defined as the natural condition of the water. Determination of background will be on a case-by-case basis.
- New Mexico: Turbidity attributable to other than natural causes shall not reduce light transmission to the point that the normal growth, function or reproduction of aquatic life is impaired or that will cause substantial visible contrast with the natural appearance of the water. Activities or discharges shall not cause turbidity to increase more than 10 NTU over background turbidity when the background turbidity, measured at a point immediately upstream of the activity, is 50 NTU or less, nor to increase more than twenty percent when the background turbidity is more than 50 NTU. However, limited-duration turbidity increases caused by dredging, construction or other similar activities may be allowed provided all practicable turbidity control techniques have been applied and all appropriate permits, certifications and approvals have been obtained.
- Tennessee: There shall be no turbidity, total suspended solids, or color in such amounts or of such character that will materially affect fish and aquatic life. In wadable streams, suspended solid levels over time should not be substantially different than conditions found in reference streams.

The recommended revisions to Florida's turbidity criteria would include two components to address different issues associated with turbidity or suspended solids. The first component, which would apply to all Florida waters, would maintain the existing 29 NTU above natural background and add a narrative statement modelled after the narrative turbidity criteria from other states that addresses fully protection of aquatic life. The proposed language for paragraph 62-302.530(70)(a), F.A.C., is as follows:

> Turbidity shall not be increased more than 29 NTU above natural background, nor shall turbidity levels be increased to levels that negatively affect designated uses or result in increased sedimentation or reduced light transmission to the point that the normal growth, function, reproduction, or recruitment of aquatic life is impaired.

The second component would be designed to provide additional protection to sensitive coral species and reef habitat including endangered species in Southeast Florida. The provision would state that turbidity shall not be increased above background for coastal waters within the South Florida Coral Reef Ecosystem Conservation Area, Biscayne Bay National Park, Biscayne Bay Aquatic Preserve, Florida Keys National Marine Sanctuary excluding canals, and Dry Tortugas National Park (**Figure 4**) or within other areas of the state where coral reefs, hardbottom communities, or Serpulidae reefs (worm rock) are currently found. The proposed language for paragraph 62-302.530(70)(b), F.A.C., is as follows:

> Turbidity shall not be increased above background conditions within the Southeast Florida Coral Reef Ecosystem Conservation Area, Biscayne National Park, Biscayne Bay Aquatic Preserve, Florida Keys National Marine Sanctuary excluding canals, and Dry Tortugas National Park, as shown on the map titled "Florida Reef Tract", July 2019, which is incorporated by reference herein, or other areas of the state where coral reef or hardbottom communities, are currently found. For the purposes of evaluating this criterion, background conditions shall take into account the natural variability of turbidity levels and shall be established following the methods described in the document Implementation of the Turbidity Criterion for the Protection of Coral Reef and Hardbottom Communities, dated September 2019, which is incorporated by reference.

The determination of background, under paragraph 62-302.530(70)(b), F.A.C., will include consideration of natural variability and allow for limited duration activities such as dredging or construction provided turbidity levels do not exceed an upper percentile of background levels (e.g., 90th percentile). The logic behind the allowance of natural variability is that any corals present will be adapted to both the average turbidity levels as well as the range of natural variability around that average. However, longer duration (beyond natural variability) perturbations from the background condition may have deleterious effects on the resident coral. Thus, implementation of the criterion is intended to maintain the background turbidity magnitude, frequency, and duration.

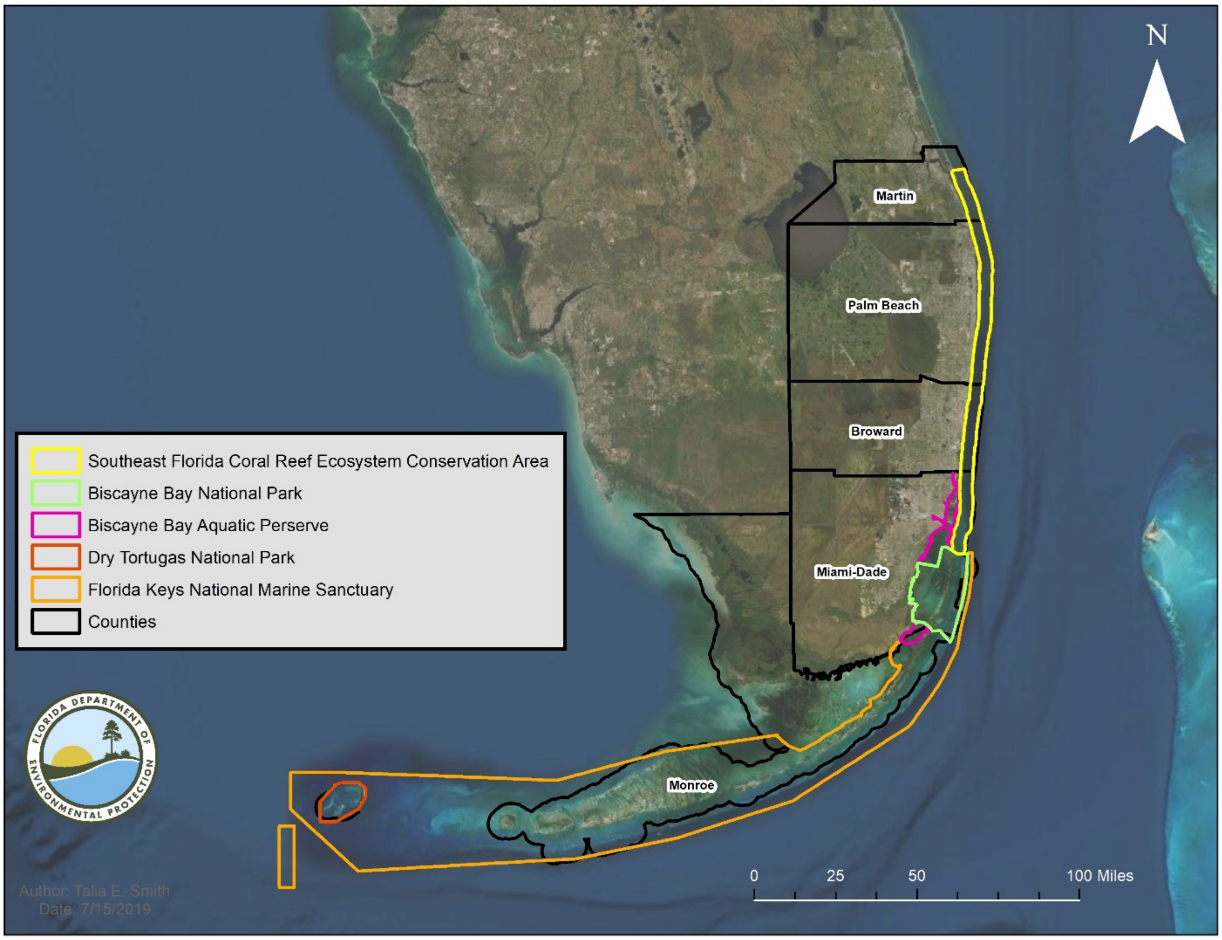

Figure 4. Florida Reef Tract.

6.1.1 Inclusion of Sabellariid Worm Reef Communities

The Department received public comments during the first round of Triennial Review workshops in May 2019 requesting that worm reef (Sabellariidae) communities along the Florida's southeast coast be considered in the revised turbidity criterion. Specifically, the commenters stated that worm rock communities were sensitive to turbidity increases and were threatened by activities that may smother these organisms. The main species of worm rock or tube worm found in

Florida waters is *Phragmaopoma lapidosa*. These worm reefs thrive in high energy conditions and are distributed along a 320 km segment of the Southeastern coast of Florida from Key Biscayne to Cape Canaveral. Most sabellariid reefs are near landward edges in the intertidal and shallow surf zones (1-4 meters); however, some have been scarcely found up to depths of 100 meters and have also been found along channels of inlets with high tidal currents.

The biological processes of tube building by sabellariid worms serve important functions such as reef-building, accumulation of hardbottom and beach rock, and coastal protection (resiliency). The tube-worms help sort and lithify (petrify, change to stone) particles and are directly related to the accumulation of hardbottom beachrock. The tube-building activity of sabellariid worms promotes the formation of hardbottom substrate along Florida's southeast coastline, which supports the eventual formation of hardbottom epifaunal communities. Additionally, many species live among the worm reef structures, and the presence of these structures increases species diversity in the low diversity surf zone (Nelson and Main 1985).

The beachrock that is created by sabellariid worms has high material strength and can stand high energy waves, making this beachrock an important factor in the stability and development of a resilient coastline. Kirtley and Tanner (1968) recommend that sabellariid worm reefs should be protected and considered in future erosion control programs for beaches. Other studies that focused on the engineering aspects of worm reefs have found that they decrease wave action and trap sand on the landward side, reducing coastal erosion (Mehta 1973, Kirtley and Tanner 1968).

These worm rock communities are formed in high energy coastal environments that have naturally high turbidities; however, the sabellariid worms are sensitive to sediment burial and smothering over extended periods of time. Nelson and Main (1985) studied worm reefs under multiple burial conditions to assist with permitting decisions for beach nourishment projects. The study tested the effects of sediment burial on reef-building tubeworms under 5 different sediment types over durations ranging from 24 to 72 hours. The tested grain sizes ranged from coarse to fine sediments and included muddy sand with higher organic matter content. The percent survival was analyzed using two-way ANOVA tables with replication. The results of the burial experiment indicate that *P. lapidosa* can tolerate burial by any of the tested sediment types for up to 24 hours without suffering significantly increased mortality. Furthermore, at relatively cooler temperatures (17 - 23° C), burial by any of the sediment types resulted in no significant increase in mortality relative to controls. However, higher water temperatures (28 - 31°C), significantly increased mortality, which occurred after 48 hours for all sediment types. At higher temperatures, mortality due to burial by fine sediments greatly increased (Nelson and Main 1985).

P. lapidosa showed no adverse effects in high silt loads and high turbidity (e.g., up to 50 NTU) conditions (within a four-day period) if the silt did not bury the worms (Nelson and Main 1985). Silt is rapidly removed during beach nourishment in high energy conditions and dispersed via long-shore drift. However, if conditions do not allow for dispersal of silt, any type of burial of the worm reefs will likely result in the morality rates found in these experiments. The tolerance levels of the reef-building tubeworm larvae and other organisms that live alongside the worms have not been determined and may have higher sensitivities to silt and burial.

In conclusion, *P. lapidosa* can tolerate high silt load levels for at least four days, can only tolerate burial by sediment for 24 hours at high temperature, and may tolerate burial for at least 72 hours at cooler temperatures (17 - 23 °C). The available literate suggests that sabellariid worms are not particularly sensitive to turbidity or suspended sediments; however, they can be sensitive to sediment burial or smothering. There is an inherent relationship between turbidity and sedimentation, although it is highly dependent on water turbulence, flushing, and the characteristics of the suspended sediments. However, when all these factors are equal, there will be a greater likelihood of excess sedimentation and burial at higher turbidity levels. Therefore, the Department recommends applying the proposed narrative turbidity criterion for corals to worm rock to ensure the protection of this ecologically significant habitat. The Department expects that the background levels near the worm reefs will be higher than those typically found in coral communities, which will allow for beach nourishment projects, while still protecting the worm rock. Protection of the worm reefs will provide protection to the sabellariid worms; biological communities dependent on the habitat created by the worms; and promote coastal resiliency. Additionally, including worm rock habitats under the narrative turbidity criterion provides protection to the more turbidity sensitive hardbottom species, including hard and soft coral, that can colonize the hard substrate created by the sabellariid worms.

6.2 Propose a Numeric Criterion Based on Available Florida Data

The second alternative for revising the turbidity criterion is to adopt a criterion using the limited available data conducted in Florida and Caribbean (on species that exist in Florida). Although the data are currently limited and do not meet the data sufficiency requirements typically associated with derivation of aquatic life criteria, it can be argued that the existing criterion is not adequately protective and is allowing harm to critically important coral reef species and habitats in Florida. Therefore, the revision would represent a significant improvement in the level of protection afforded. One major technical limitation of this approach is the fact that a majority of the studies have been conducted using SSCs (mg/L), rather than turbidity (see **Tables 1** and **2**).

6.2.1 TSS, NTU, and Light Attenuation Translator Study

The Standards Development Section (SDS), the Coral Reef Conservation Program (CRCP) in the Office of Resilience and Coastal Protection (RCP), and BIPP have designed and are currently implementing a study to collect concurrent samples of total suspended solids (SSC, mg/L), turbidity (NTU) and light attenuation (PAR) in the vicinity of beach nourishment projects located in Southeast Florida. The primary objective of the study is to develop relationships between the three water quality parameters that, if determined to be sufficiently robust, would be used to either translate the literature-based thresholds from SSC (mg/L) to an equivalent NTU-based criterion; or, as translators that dredge and fill permittees could use to convert an SSC-based criterion to a protective NTU threshold for use during project implementation. If the latter options is used, the Department would include an option for a permittee to develop a site-specific translator based on the specific sediment characteristics of the site.

6.2.2 Potential Turbidity Threshold

As previously stated, the literature to support a specific turbidity or SSC threshold in Florida waters is limited; however, there are several specific studies that are currently or soon to be available that could be used as the basis for a best available science approach (**Table 2**). Telesnicki and Goldberg (1995) demonstrated significant differences in P:R in relatively tolerant *Meandrina meandrites* and *Dichocoenia stokesii* species at 14-16 NTU. Additionally, several articles state that SSC above 10 mg/L have the potential to cause significant sub-lethal and lethal effects to coral reef systems (Rogers 1990; Lirman et al., 2003; Flores et al., 2012; Erftemeijer et al., 2012). However, the SSC based thresholds from these papers would need to be translated to an NTU equivalent to be directly useful for criteria derivation.

The results of Fourney and Figueiredo (2017) suggest that turbidity levels less than 7 NTU near coral reefs will facilitate coral recruit survival. Additionally, a current graduate student at NOVA Southeastern University recently completed a study similar to Fourney and Figueiredo (2017) using a more sensitive *Acropora sp*. (Joana Figueiredo, personal communication). The data from this more recent study are still being analyzed and have not been published; however, a preliminary review of the data suggests a criterion in the range of 4 to 5 NTU would be protective of recruitment in the more sensitive *Acropora* (Joana Figueiredo, personal communication).

The best available science supports a revised turbidity criterion for areas with coral reef habitat at approximately <7 NTU, based primarily on the work by Fourney and Figueiredo (2017) and Telesnicki and Goldberg (1995). The value may be reconsidered based on pending study results from NOVA Southeastern University, which currently suggest a criterion of approximately 4 NTU. The recommended duration of the criterion is either an instantaneous value (single sample maximum) or daily average value. However, any criterion would need to account for natural variability. The recommendation is based on the duration of exposure used in the principle studies, particularly Fourney and Figueiredo (2017). Although Fourney and Figueiredo (2017) conducted their study over 5 to 12 weeks, turbidity was only measured in the first 24 hours of the study, and thus represents an initial disturbance that was later linked to longer-term (5-12 week) sedimentation effects on settled larval polyps.

Table 4. Studies done with Florida and/or Caribbean species summarizing the sensitivity of coral and the response of corals and coral comminutes to different concentrations of sedimentation, suspended sediments, and turbidity.

Citation	Location	Species	Experimental turbidity levels	Summary
Fourney and Figueiredo, 2017	Florida	*P. Astreoides*	7 and 29 NTU for four weeks	Sedimentation reduced coral survival in increased temperatures. Dredged (fine) sediment reduced survivability. Natural sediment did not. Suggest to lower FL standard to <7 NTU.

Citation	Location	Species	Experimental turbidity levels	Summary
Telesnicki and Goldberg, 1995	Hollywood, FL	*D. Stokesii, M. meandrites*	7-9 (7 days), 14-16 (7 days) and 28-30 NTU (28 days)	Exposure to 14-16 NTU (1 wk) reduced P:R ratios and increased mucous production. 28-30 NTU caused lesions on *M. meandrites*.
Rice and Hunter, 1992	Florida, in lab	7 species	49, 101, and 165 mg/l for 10 days. Corals at 165 mg/l were exposed to 199 mg/l for 10 additional days	Colony survival was not impacted. Growth rates decreased at 165 mg/l for fastest growing species. Colonies died in 7-16 days under complete burial.
Kendall et al, 1983	Carysfort Reef, FL	*A. cervicornis*	25, 50, 100, 150 and 500 mg/l drilling mud for 24 hrs	Coral exposed to used drilling mud for 24 hrs showed decreased calcification rates (starting at 25 ppm), tissue protein (at 25 ppm), ninhydrin positive substance (at 100 ppm), zooxanthellae density (at 500 ppm).
Kendall et al, 1985	Carysfort Reef, FL	*A. cervicornis*	50, 100 mg/l kaolin for 24 hrs follower by 48 hr recovery	Coral exposed to 100 ppm showed reduced calcification rates and free amino acids (FAA). Calcification rates returned to normal after recovery period but FAA for 50 and 100ppm kaolin coral dropped after recovery
Rice, 1984	Florida	community study	49, 101, and 165 mg/l and 199 mg/l for 10 days.	Sub-lethal responses (bleaching, shrinkage of soft tissue, polyp death, decreased growth rates) to suspended sediments (165 mg/l) occurred in 10 days of exposure.
Vargas-Angel et al, 2007	Broward County, FL	*M. cavernosa*	Observations. control sites (24.7 and 29.2 $mg/cm^2/day$), dredging sites (58.4 and 40.9 $mg/cm^2/day$)	All coral showed mild to moderate stress and polyp retraction. High exposure led to tissue swelling, focal bleaching, mucous, reduced zooxanthella

Citation	Location	Species	Experimental turbidity levels	Summary
Lirman and Fong, 2007	Florida Reef Tract	community study	*In situ* observations	reefs closer to shore have greater coral cover despite more stressors
Walker et al, 2012	Ports of Miami, Everglades and Palm Beach	community study	*In situ* observations	Dredging at 3 FL ports effected 176 hectares of reef through burial
Jordan et al, 2010	Florida	community study	*In situ* observations	Sedimentation rates are higher and sediment is courser near shore. Resuspension is driven by waves. "Sand borrowing areas" had significantly higher sedimentation rates.
Miller et al, 2016	Port of Miami	several species	*In situ* observations	Dredging increased sedimentation on coral up to 200m away, increased coral mortality up to 700m away and increased sediment halos up to 300m away. Disease and bleaching occurred at impacted sites before controls
Malaio et al, 2008	Florida	25 species	*In situ* observations	Turbidity is one component driving keys wide variation in water quality. Macroalgae cover is increasing in coral communities
Fabricius, 2005	Literature review	several species	Various	Sedimentation: can severely degrade coastal reefs, exposure time, exposure amount and grain size/type affect impacts. Temperature organic content and bacterial activity confound. Affects settlement, recruitment and juvenile survival.
Dustan and Halas, 1987	Carysfort Reef, FL	community study	observations of benthic communities along transects	Coral living between 10 and 21 m showed decreases in abundance due to

Citation	Location	Species	Experimental turbidity levels	Summary
				sediment. Some species shifted towards shallower waters due to light availability.
CSA, 2007	Key West, FL	community study	observations during dredging events	No significant change in coral cover occurred. Bleaching and paling occurred.
Fisher et al, 2008	Broward County, FL	*M. cavernosa*, *S. bournoni*, and *S. siderea*	observations during dredging events	No significant change in coral cover occurred. Mild to moderate stress was seen on colonies, but recovery occurred post-dredging.
PBS&J, 2008	Florida	community study	observed outcomes of 26 dredging/filling projects in FL	Found 217 acres of reef were affected in total.
Lindeman and Snyder, 1999	SE Florida	community study	observed during beach widening events	Burial and loss of 5 hectares of near-shore hardbottom habitat. A 30x drop in fish density and 10x drop in fish diversity were observed.
Marszalek, 1981	Miami Beach	community study	observations during dredging event	1 cm of sediment covered nearby reef in less than 2 hours. Partial mortality and paling occurred. up to 32% of corals exhibited stress (near dredging).
Lirman and Manzello, 2009	South Florida	*S. radians*	burial of coral for 2, 4, 6, 24, 48 hr, 7 days and 21 days	Coral recovered quickly from 2-24 hrs of sediment burial at normal salinity levels. However, burial for >24 hours or burial under salinity stress led to slower recoveries, reduced growth rates, and, in some instances, mortality.
Lirman and Manzello, 2002	South Florida	*S. radians* (2-3cm diameter)	burial for 4, 7 and 10 days, under salinity of 20 psu and 15 psu	*S. radians* are highly tolerant and recover rapidly. At 20 psu and 4 days of burial coral showed slight reduction in

Citation	Location	Species	Experimental turbidity levels	Summary
				photosynthesis. At 15 psu and 7-10 days of burial coral appeared dead but regrew tissue in 6 weeks.
Erftemeijer et al, 2012	Literature review	several species	effects of turbidity and sediment on corals	Dredging can have significant impacts on corals; however, the severity of the effects depends on coral species and form; frequency, intensity and duration of turbidity, sediment type, and the presence of other stressors.
Lasker, 1980	Republic of Panama	*M. cavernosa*	*In situ* (5 days, 25 cm^{-2} per day) and laboratory (30, 60,120, 240, 360, 480 min, 74.4 mg dry weight cm^{-2} coarse and 18.5 mg cm^{-2} fine sediment) experiments	Field observations only small amounts of sediment accumulated on living tissue. Their morphology and large polyps allow them to passively shed most sediment and remove the rest with little energy input under fine and coarse sediment for laboratory experiment and existing natural sediment.
Rogers, 1983	Puerto Rico	*A. palmata*, *A. cervicornis*, *O. annularis*, *D. Strigosa*, *D. clivosa*	200, 400, and 800 mg/cm^2 of calcareous sediment applied 1 time. 200 mg/cm^2 applied daily, 3x a week, or 3x a month, for a month.	Single sediment application: at 200mg/cm^2 *A palmata* had algal growth, at 400mg/cm^2 *O. annularis* and *A cervicornis* had mild bleaching, *D. strigosa* was tolerant. *D clivosa* was damaged by repeated exposure other species were not
Abdel-Salam and Porter, 1988	USVI	*A. palmata*, *D. strigosa*, *M. annularis*	600 mg of sediment	All three species showed significant increases in respiration rates and photosynthetic rates for *M. annularis* and *A. palmata*. *Annularis* and *Strigosa* were better at clearing sediment than *A. palmata*.

Citation	Location	Species	Experimental turbidity levels	Summary
Torres, 2001	SW Puerto Rico	*O. annularis*	Field sampling	Corals at high sedimentation sites had lower skeletal extension rates.
Torres and Morelock, 2002	Puerto Rico	*O. annularis, S. siderea, P. astreoides*	*In situ* observations	*M. annularis* cover decreased in reefs with high terrigenous sediments. Linear extension was unaffected. *S. siderea* and *P. astreoides* have higher resilience to terrigenous sediments.
Acevedo et al, 1989	Ponce, PR	community study	*In situ* observations based on distance from terrigenous sediment influx	Species diversity and coral cover decreased with increased proximity to sediment influx. *M. cavernosa* dominated sites near influx and *A. palmata* were largely absent. *O. annularis* and *A. agaricities* were less common near influx.
Begin et al, 2016	Saint Lucia	community study	*In situ* observations, % terrigenous sediment of top 5 cm of sand	Percent terrigenous content in sediment loading was a significant indicator of coral cover, algal cover and % change in coral abundance.
Hernandez-Delgado et al, 2011	Vega Baja, PR	*Acropora palmata*	*In situ* observations	Turbidity from beach nourishment (10-50-fold higher than 10 NTU) along with sewage overflow led to average coral mortality of 52% in 2009. Mortality was highest near pollution sources, then nearshore, and lowest offshore.
Begin et al, 2013	Eastern Caribbean Islands	community study	observed benthic composition and %terrigenous sediment at 22 reefs on 11 islands	Increased % terrigenous content in sediment was linked with decreased coral and algae cover and increased sponge cover. Species assemblages were affected as well. *O. annualaris* decreased

Citation	Location	Species	Experimental turbidity levels	Summary
				with increased terrigenous content.
Begin et al, 2014	Saint Lucia	community study	measured sediment accumulation and modeled sources	Over the 3-4 decades, input of terrigenous and calcareous sediment has increased 2-3x. Expansion of unpaved roads and road degradation plays a large role in increased terrigenous input.
Carilli et al, 2009	Caribbean Reefs	*Faveolata*	measured skeletal growth rates at sites with varying effects from local stressors. Sedimentation was one of the local stressors included.	Corals exposed to high levels of local stressors maintained suppressed growth rates for 8 years post bleaching compared to 2-3 years for reefs with low stressors.
Dallmeyer et al, 1982	Jamaica	*O. annularis*	exposed to 525mg/L of suspended peat sediment for 2 hours. Received treatments during the day and at night	During the day exposure, reduced oxygen production but did not alter behavior. At night, respiration increased and clearing behavior occurred. Net production the following morning was significantly lower than pre-exposure levels.
Loya, 1976	Puerto Rico	*M. cavernosa, O. annularis, S. radians, S. siderea, M. meandrites*	Compared coral reefs at low (1.5 FTU or 3 mg/cm^2/day) and high (5.5 FTU or 14mg/cm^2/day) turbidity sites	Coral diversity and % cover was lower at the high turbidity site. *M. cavernosa* dominated the high turbidity site. S. *radians, S. sidere*a and *M. meandrites* were abundant, but *O. annularis* prevalence was low and colony sizes were smaller.
Nemeth and Nowlis, 2001	St. Thomas, USVI	community study	High sedimentation rates were 10-14mg/cm2/day. Low rates were 4-8mg/cm2/day.	During a bleaching event, 38% more coral bleached at high sedimentation sites compared to nearby low sedimentation sites.
Otero, 2009	SW Puerto Rico	N/A	sampled water quality indicators	Found sedimentation was rarely higher than

Citation	Location	Species	Experimental turbidity levels	Summary
				10mg/cm^2/day (only during storm events). Co-variation between sedimentation and turbidity was high.
Rogers, 1990	Review	N/A	Literature review	Mean sedimentation rates and suspended sediment concentrations for healthy reefs are <1-10mg/cm^2/day and <10 mg/l, respectively. Chronic exposure to higher rates reduce coral cover, diversity, growth rates, calcification rates, and recruitment and increased branching morphology.

6.3 Coordinate with Universities to Collect Dose-Response Data

Given that the Department lacks the expertise and facilities necessary to carry out the necessary studies to produce dose-response data for the effect of turbidity on corals, DEP is investigating universities that have the needed capabilities. Potential university partners in Florida include NOVA Southeastern University, Florida International University, Florida State University, and University of Miami Rosenstiel School of Marine and Atmospheric Science (RSMAS). DEP staff have reviewed a substantial body of literature on studies that have been conducted throughout the world. Many of these studies could be replicated using Florida resident species. The additional studies would need to address effects on adult coral, larvae, and larval recruitment. Experiments involving larvae and larval recruitment must address both brooding and broadcast spawning species because the effects of elevated turbidity are likely different between the two reproductive strategies.

Dose-response studies can be modelled after similar studies previously conducted in Australia and NOVA Southeastern University. Bessell-Browne et al., (2017) described a well-controlled experimental design that could be used to evaluate the effects of turbidity and/or light reductions on coral species over varying durations (**Figure 5**). The experimental design used by Fourney and Figueiredo (2017) should also be considered for evaluating effects to settled larval polyps;

however, the experimental design should be altered to include a control and the frequency of turbidity measurements should be increased (*i.e.*, daily measurements at a minimum).

Finally, the study design and associated analyses used by Ricardo et al, 2015 to assess the effects of suspended sediments on sperm availability for two Australian coral species (*Acropora millepora* and *Acropora tenuis*) should be evaluated for potential replication on Florida species. Their study design allowed the calculation of fitted fertilization success curves (**Figure 6**) that were used to determine EC_{50} (Effective Concentration; Concentration of a substance that causes a 50% response) thresholds for fertilization success. Thresholds like an EC_{50} are typically used to develop acute and chronic water quality criteria. Most typically, a lower level of effect (e.g., EC_{20}) is used to develop protective criteria. The type of data provided by Ricardo et al. (2015) would be ideal for supporting the Department's efforts to revise the turbidity criterion.

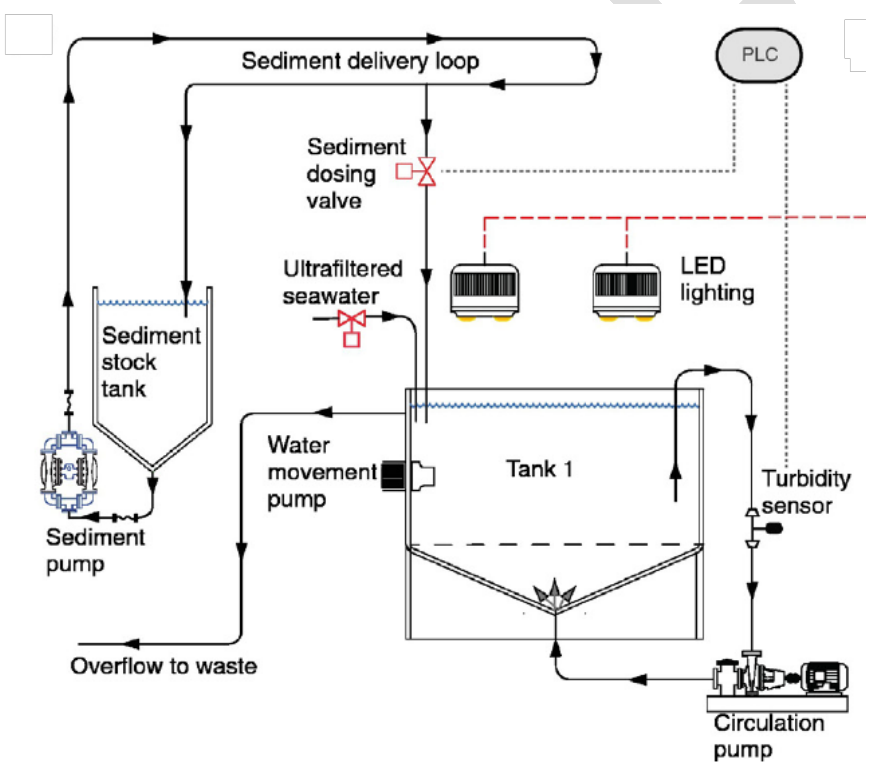

Figure 5. Schematic of the experimental dosing system used by Bessell-Browne et al. (2017) showing the sediment delivery (stock) tanks, and the position of the recirculation pump, water movement pump and in-line turbidity sensor. Delivery of sediment from the stock tanks was controlled by the programmable logic controller (PLC) system from input from the turbidity sensor. Figure taken from Bessell-Browne et al. (2017).

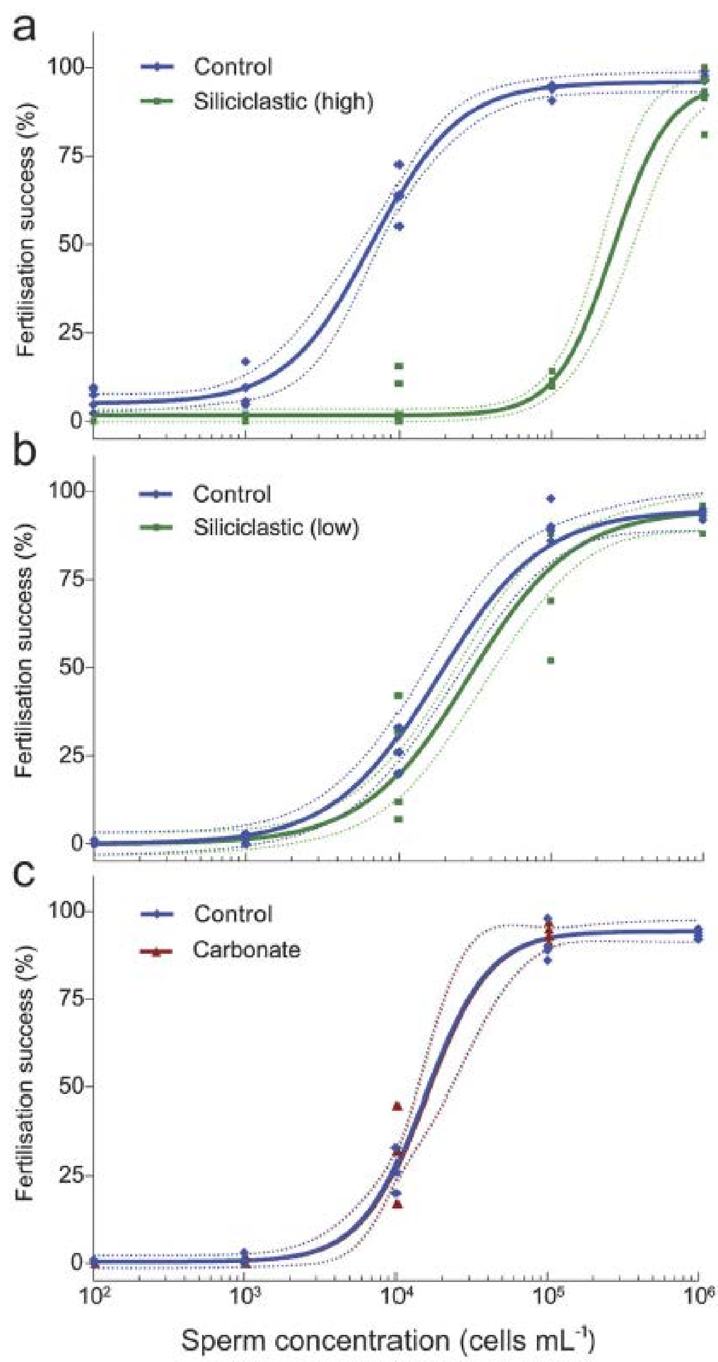

Figure 6. *Acropora tenuis* fertilization success (%) curves fitted to four-parameter logistic models plotted over a range of sperm concentrations (102–106 sperm m^{-1}). (a) Siliciclastic (high): 700 mg L^{-1}, green; control: 0 mg L−1, blue and (b) siliciclastic (low): 230 mg L^{-1}, green; control: 0 mg L^{-1}, blue) and (c) carbonate:230 mg L^{-1}, red; control: 0 mg L^{-1}, blue) suspended solid sediment concentrations. Dashed lines represent 95% confidence bands. Figure taken from Ricardo et al. (2015).

6.4 Recommend Option(s)

Three options were presented for moving forward with a revised turbidity criterion to protect coral reefs and hardbottom communities in Florida: 1) add narrative components to supplement and strengthen the existing turbidity criterion; 2) adopt a criterion based on the currently limited Florida and Caribbean data; or, 3) work with Florida researchers to design the appropriate studies to collect Florida specific data and move forward with a revised criterion once sufficient supporting research has been completed.

The Department recommends a combined approach that incorporates both near-term and longer-term revisions to the standard. First, we recommend moving forward with a revised narrative criterion (option 1) during the upcoming Triennial Review. Second, we recommend that the Department reach out, perhaps through the Coastal Office, to researchers in Florida universities in an attempt to encourage interest among the researchers in conducting the needed research and to adopt a numeric threshold, as described in **Sections 6.2 and 6.3**.

Pursuing option 1 acknowledges the fact that the existing turbidity criterion does not adequately protect sensitive aquatic species like corals. Although adoption of a numeric criteria would provide more regulatory certainty, more straightforward implementation, and be easier to assess in ambient waters under the Impaired Waters Rule, there is currently a lack of sufficient scientific studies to demonstrate a scientifically defensible threshold. There are currently only two Florida studies that can be used to develop a criterion. There is significant uncertainty regarding whether these studies, which only represent two species, provide representative information for all Florida species. It should be stressed that none of the three species are included among the list of NMFS endangered species, meaning that NMFS would most likely have concerns that the criterion is not sufficiently protective. Pursuit of a narrative criterion is currently the best option in the short-term.

Over the longer-term, SDS recommends pursuing partnerships with Florida universities to collect the dose-response data necessary to develop a numeric turbidity or SSC criterion to protect sensitive coral and hardbottom communities (Option 3). If successful, the Department could, in the future, revise the criterion to include more specific numeric thresholds linked to sensitive coral responses. Doing so will overcome the limitations of the narrative criterion listed above. It could also potentially allow for more complex expressions of duration and frequency than can be currently developed. The duration of exposure to elevated suspended solids or turbidity is critical to coral responses. Corals may be able to withstand very high concentrations of suspended solids for short periods of time, but conversely show sensitives to much lower concentrations over longer periods of exposure. The combination of concentration and duration are critical to the resultant response, as is the nature of sediment. Pursuing option 3 would afford an opportunity to fully investigate the critical durational component of the dose-response relationships.

7.0 Economic Benefits of Coral Reefs

Water quality criteria are established to protect the designated uses of a state's waterbodies, including aquatic life (flora and fauna). Economic costs are not a consideration when establishing criteria, although economic costs may be considered when establishing designated uses, antidegradation evaluations, and when applying moderating provisions such as variances and mixing zones. Even though economics is not considered in the establishment of criteria, it is important to understand the significant economic benefits Florida receives from a healthy reef ecosystem.

The economic value of an ecosystem is defined as the total value of the goods and ecological services that it provides. Coral reefs provide a number of economic and ecological benefits. In general, coral reefs serve as natural barriers and wave breakers against strong ocean waves and storms (*i.e.*, increase coastal resiliency), support ecotourism, and create a natural fishing resource.

When coral reefs frame a coastline, they provide protection from naturally occurring erosion, large waves, and intense storms. Reefs serve as natural breakwaters that absorb incoming wave energy, thereby protecting the infrastructure and habitat on the shore. For example, a study performed in Guam concluded that the average yearly damage to the island from typhoons is $4.3 million USD (Beukering et al., 2007). The same study estimated that the total cost would increase to an annual damage cost of $12.7 million USD without the services provided by coral reefs. Cesar et al. (2003) estimated that reefs annually provide $172 million and $9 billion in protective services in Florida and worldwide, respectively. Storlazzi et al., (2019) conducted an analysis of the value provided by U.S. coral reefs in coastal hazard reduction caused by flooding and erosion form extreme weather events. They estimated that coral reefs provide over $420 million in protective services to Florida on an annual basis (**Table 5**).

Table 5. Annual value of protection provided by coral reefs by Florida region (From Storlazzi et al., 2019).

Measure	Florida Peninsula	Florida Keys
Number of People Protected	4,947	716
Impacts to Buildings (2010 U.S. dollars)	323,835,761	32,125,237
Impacts to Economic activity (2010 U.S. dollars)	42,970,125	26,686,848

Ecotourism is an important source of revenue for many countries, including the U.S. Healthy coral reefs support a wide variety of animals that attract ecotourist visitors and other recreational users of the area. Millions of people flock to coastlines around the world every year to experience and participate in recreational activities. This large number of tourists creates a demand for services and amenities employing an entire tourism industry. Many visitors choose the location of their visit based on the appearance of beaches, proximity to coral reefs, and accessibility of various water sports. A healthy coral reef is essential to maintaining these qualities. For example, in Colombia, the average money spent by visiting divers on the coral reefs is $84.70 per person per day. The overall annual value of recreational diving on the reefs within the national park is $658,359.00 (Trujillo 2017). Similarly, 200,000 divers and three million snorkelers visit Hawaii each year, bringing the total recreational value of Hanauma Bay to $31,021,099 per year (Beukering 2004).

A five-year study found that the average visitor made 6.31 trips, at an average value of $463 per visit, to Florida's coral reefs for the purposes of diving, snorkeling, or glass bottom boat tours (Bhat 2003, Brander and Beukering 2013). Protecting the area, or adding marine protected areas, leads to a 200% increase in fish abundance, 100% increase in water visibility, and a 100% increase in coral quality. Protection also increases the number of times a tourist will visit the ecosystem. Protection allows for 4.99 more trips on average for divers, 3.88 more trips on average for snorkelers, and 2.70 more trips on average for glass bottom boat tours (Bhat 2003, Brander and Beukering 2013). Johns et al. (2001) reported that reefs generate 70,400 full time and part time jobs per year and $4.4 billion in local sales in South Florida. The coral reef ecosystem is an integral part of Florida's economy and can vary in influence based on location.

A 2001 study conducted by Johns et al. examined four different counties in South Florida for the amount of reef related sales, income generated by reefs, and employment created by reefs (**Table 6**). The total income of the reef related sales for the four counties was nearly $2 billion.

Table 6. Average sales, income, and employment for the year 2000 in four different South Florida counties. Number adjusted for inflation to reflect 2019[2] prices (Johns 2001).

County	Reef Related Sales (millions of dollars)	Income (millions of dollars)	Employment (number of full time and part time jobs)
Palm Beach	530.9	211.2	4,500
Broward County	1,647	853.6	19,000
Miami-Dade County	1,305	623.1	13,000
Monroe County	539.8	157.6	8,000

Brander and Beukering (2013) determined that Florida coral reefs provide a mean annual value of $10,428[3] per hectare (2007 prices) for all tourism and recreational activities, which equates to $12,714 per hectare ($5,145/acre) in 2019 when adjusted for inflation. Additionally, Brander and Beukering (2013) estimated that total annual recreation value of the Florida reef track is $174 million dollars (2007 prices) or $258.4 million dollars adjusted for inflation (2019). Their estimate was based on a total coral area of 36,000 hectares (88,958 acres) and included recreational fishing, scuba diving, snorkeling, and glass-bottom boat rides.

[2] All inflation adjustments were calculated based on the Consumer Price Index (CPI) Inflation Calculator (https://data.bls.gov/cgi-bin/cpicalc.pl) based on a comparison between December 2007 and May 2019.

[3] Equates to $4220 per acre.

Coral reefs support a vast diversity of life. Countless varieties of fish, invertebrates, and mammals use coral reefs for foraging, territory, nursery grounds, and cleaning stations. This high volume of life allows commercial and recreational fishing industries to flourish. Many people in countries with vibrant coral reefs are dependent on the fish that reside within the reef. Tourists are able to fish from land, boat or even dive the reef to spearfish. For, example, in Guam, the value of the fishing industry totaled $3.96 million USD per year. This included both the recreational and commercial fishing industries (Beukering 2007). Other estimates place the value of coral reef fisheries at $5.7 billion annually worldwide (Cesar 2003). By protecting coral reefs, the fishing industry benefits as the reef serves as vital nursery grounds for many large fish.

Coral reefs play an essential role in the health and economy of coastal areas. By adopting protective measures, corals can protect the shoreline and existing infrastructure from harmful waves and storm surges, create a thriving tourism industry, and promote local fisheries which boosts the local economy.

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