

DRAFT

**Technical Support Document for the
Revised Turbidity Criterion to Protect
Florida Coral and Hardbottom Communities**



Prepared by:
Florida Department of Environmental Protection
Division of Environmental Assessment and Restoration
Water Quality Standards Program

2600 Blair Stone Rd.
Tallahassee, FL 32399
March 2021

Table of Contents

List of Acronyms and Abbreviations	3
1.0 Introduction.....	4
1.1 Purpose of the Report.....	4
1.2 Proposed Criterion Revision	4
2.0 Background	7
3.0 Stressor of Concern – Suspended Sediments	9
4.0 Conceptual Model.....	10
4.1 Effects of Suspended Sediment on Corals	11
4.2 Light Availability	12
4.3 Sediment Covering.....	12
4.4 Combined Effects of Proximal Stressors	13
5.0 Assessment of Effects	13
5.1 Sensitivity of Adult Florida Coral Species	16
5.2 Early Life Stages.....	19
6.0 Options for Criterion Revision.....	20
6.1 Develop Additional Narrative Components.....	21
6.1.1 Inclusion of Sabellariid Worm Reef Communities.....	22
6.2 Propose a Numeric Criterion Based on Available Florida Data	24
6.2.1 TSS, NTU, and Light Attenuation Translator Study, CRCP9	24
6.2.2 Potential Turbidity Threshold	25
6.3 Coordinate with Universities to Collect Dose-Response Data	33
6.4 Recommend Option(s)	37
7.0 Economic Benefits of Coral Reefs.....	38
8.0 References.....	41

Figures and Tables

Figure 1. Florida's Coral Reef (FCR).....	5
Figure 2. Spatial distribution of coral reefs on the southwest and southeast coasts of Florida (within state waters only).....	6
Figure 3. Conceptual model for suspended sediment effects on coral larvae and adult energy expenditure (Adapted from Jones et al., 2016).	11
Figure 4. 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, 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).	35
Figure 5. <i>Acropora tenuis</i> 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).	36
Table 1. 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.....	13
Table 2. 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.	25
Table 3. Annual value of protection provided by coral reefs by Florida region (From Storlazzi et al., 2019).	38
Table 4. Average sales, income, and employment for the year 2000 in four different South Florida counties. Number adjusted for inflation to reflect 2019 prices (Johns 2001).	40

List of Acronyms and Abbreviations

ATP - Adenosine Triphosphate
BMPs - Best Management Practices
COTF - Coastal Ocean Task Force
EC - Effective Concentration
EPA – Environmental Protection Agency
F.A.C. - Florida Administrative Code
FCR - Florida’s Coral Reef
FKNMS - Florida Keys National Marine Sanctuary
NMFS - National Marine Fisheries Service
NOAA - National Oceanographic and Atmospheric Administration
NPS - Ninhydrin Positive Substance
NSU - NOVA Southeastern University
NTU - Nephelometric Turbidity Unit
OFR - Our Florida Reefs
P:R - Photosynthesis to Respiration
RSMAS - Rosenstiel School of Marine and Atmospheric Science
SCTLD - Stony Coral Tissue Loss Disease
SEFCRI - Southeast Florida Coral Reef Initiative
SSC - Suspended Sediment Concentration (mg/l or mg/cm²)
USCRTF - US Coral Reef Task Force

1.0 Introduction

1.1 Purpose of the Report

The purpose of this document is to summarize the current scientific understanding of coral species sensitivities 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 retain the existing numeric turbidity criterion of 29 Nephelometric Turbidity Unit (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 of the state where coral reef or hardbottom communities are currently found or have been demonstrated to have occurred since November 28, 1975.

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

- a) Turbidity shall not be increased more than 29 NTU above natural background conditions.
- b) Turbidity shall not be increased above background conditions within areas of the state where coral reef or hardbottom communities are currently found or have been demonstrated to have occurred since November 28, 1975. To evaluate this criterion, background conditions shall take into account the natural variability of turbidity levels, not to exceed 29 NTU.

The majority of Florida's coral reefs and hardbottom communities occur within Florida's Coral Reef (FCR) (**Figure 1**). Though they are not well delineated, patchy distributions of coral reefs and hardbottom communities also occur outside of the FCR (**Figure 2**). Consideration of the historical presence of coral is of critical importance because the FCR 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 FCR; the turbidity criterion is intended to ensure that turbidity is not a limiting factor to their survival, recruitment, growth, or recovery of corals from SCTLD, regardless of whether these species currently occur within an area. Additionally, most of the FCR 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.

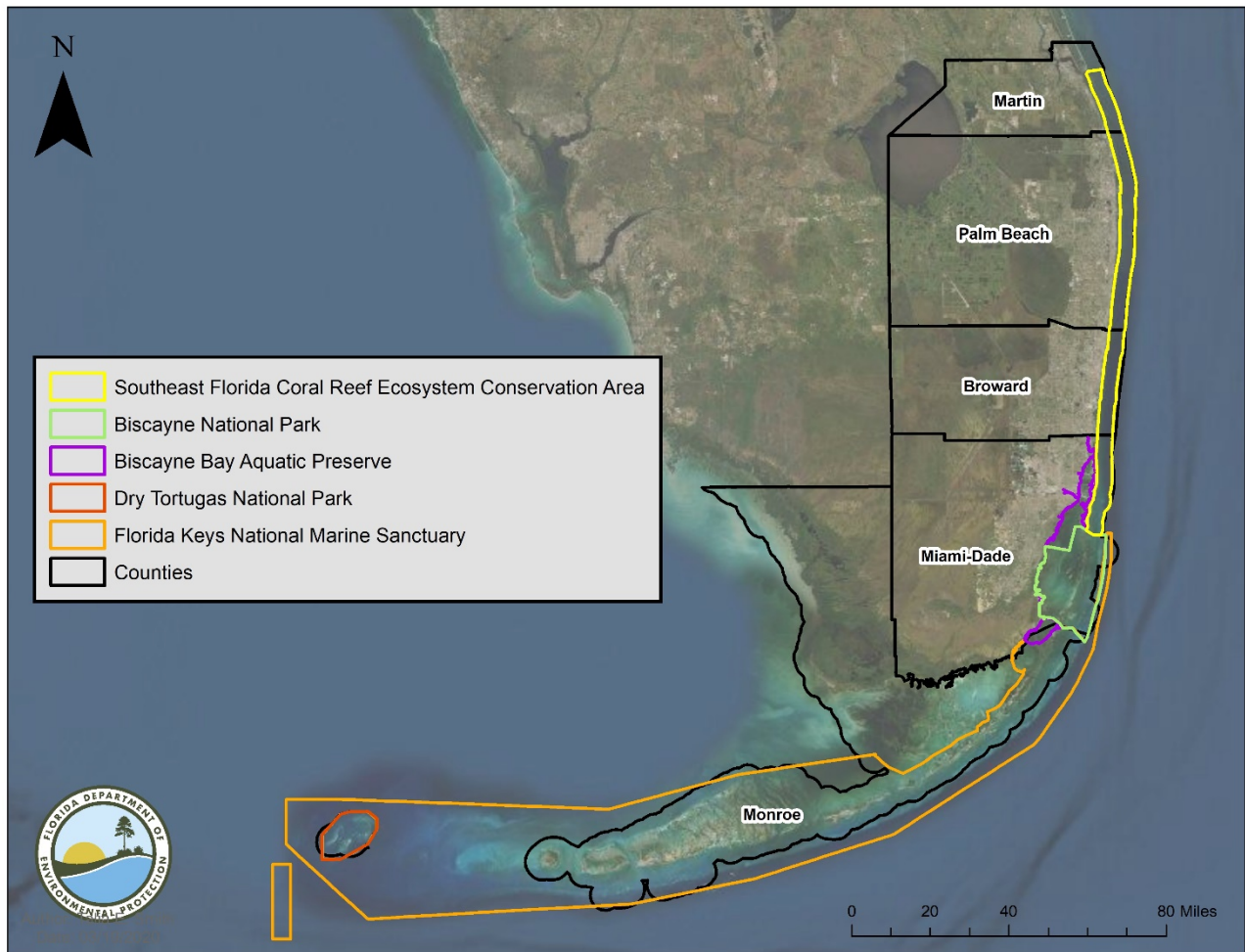


Figure 1. Florida's Coral Reef (FCR).

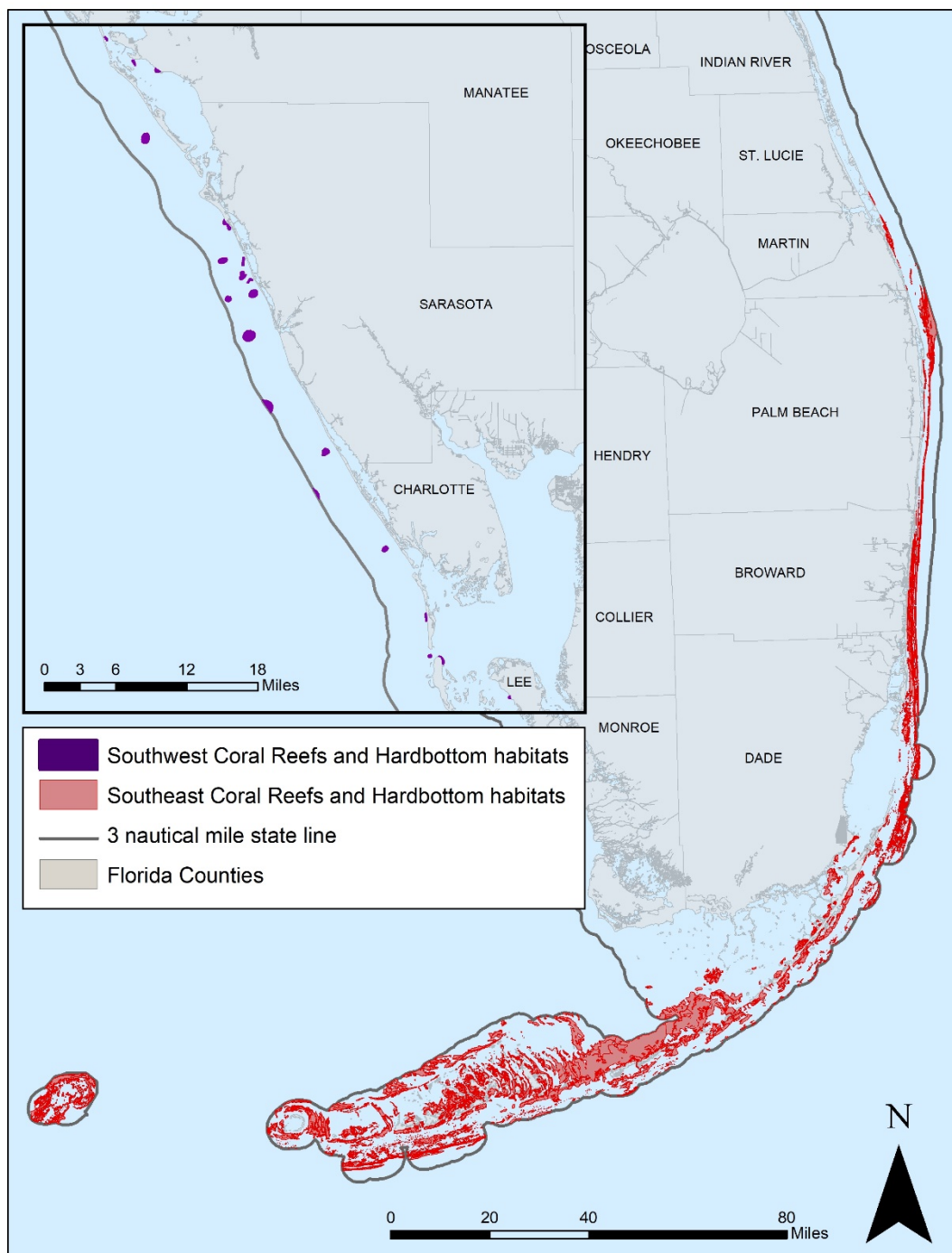


Figure 2. Spatial distribution of coral reefs on the southwest and southeast coasts of Florida (within state waters only).

For purposes of interpreting the turbidity criterion in paragraph 62-302.530(70)(b), F.A.C., “Coral reef”, shall mean a limestone structure composed wholly or partially of the living or dead skeletal remains of marine invertebrates in the Class Anthozoa and the Orders Scleractinia (stony corals), Stolonifera (organ-pipe corals), Antipatharia (black corals), and Hydrozoa (hydrocoral), and Hydrozoa (hydrocoral); and, “hardbottom community” shall be defined as a marine benthic community of organisms characterized by the presence of corals and associated reef organisms.

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) component of turbidity.

The State of Florida established a water quality criterion for turbidity in subsection 62-302.530(70), 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 NTU above natural background conditions. The State’s original turbidity criterion was 50 Jackson Candle Units, but in 1983 it was converted to 29 NTU. 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 related to natural processes 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 can 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 Florida Keys National Marine Sanctuary (FKNMS). In marine environments, dredging and construction activities increase Suspended

Sediment Concentration (SSC¹), sediment deposition, and turbidity, which can result in reductions in light, reduced gas exchange, and physical smothering or even burial of benthic communities. The settlement of the re-suspended sediment in particular is a well-known stressor, requiring epi-benthic organisms to expend energy self-cleaning or they become progressively smothered in sediments (Stark et al., 2017).

A variety of stakeholder groups, such as Our Florida Reefs (OFR), Coastal Ocean Task Force (COTF), US Coral Reef Task Force (USCRTF), and the Southeast Florida Coral Reef Initiative (SEFCRI), have recognized the value of the coral reef resources in Florida 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 their recommendations include:

1. 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 Best Management Practices (BMPs) that eliminate destructive impacts to coral reefs from coastal construction projects (beach nourishment, 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. 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. 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.

¹ Suspended Sediment Concentration (SSC) is equivalent to Total Suspended Sediments (TSS). The term “SSC” is most commonly used within the literature on coral responses and is therefore used in this document for consistency with these literature sources.

- 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, increased 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 sediment 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 between suspended sediments and 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 endpoint(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.

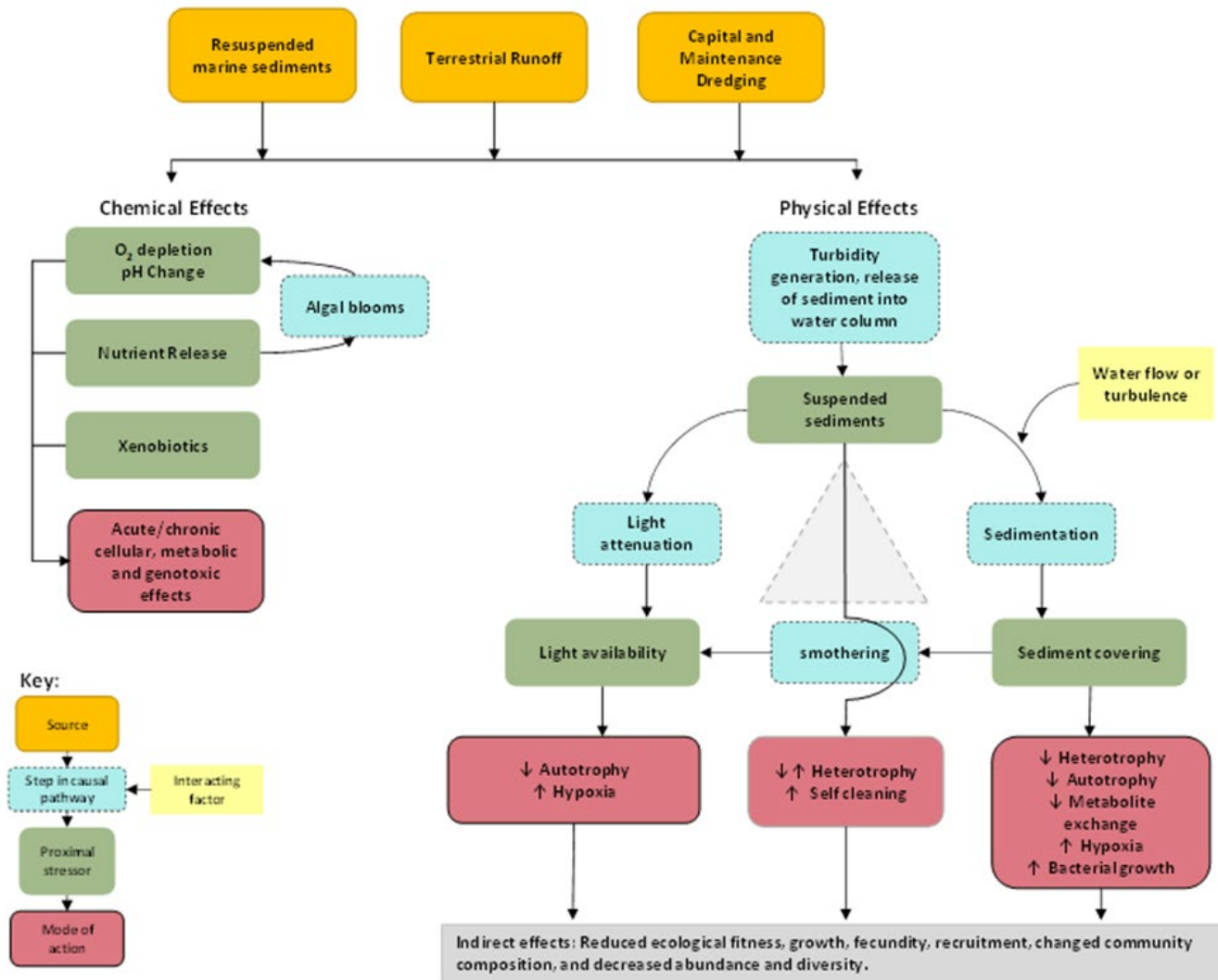


Figure 3. Conceptual model for suspended sediment effects on coral larvae and adult energy expenditure (Adapted from Jones et al., 2016).

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, which reduces ingestion rates. Similarly, Anthony (2000) indicated that at SSCs $> 30 \text{ mg L}^{-1}$, *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, sediment grain size, 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 inevitably 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 Voosenek 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**).

5.0 Assessment of Effects

As part of the literature review for this document, the Department compiled a global dataset of literature on the effects of suspended and deposited sediment on corals that spans three oceans, over 140 coral species, decades of research, and 86 field- and lab-based experiments. Adverse effects in response to deposited sediment occurred on the order of hours to days, while those in response to suspended sediment occurred on the order of days to weeks. (Tuttle and Donahue 2020). While there is limited literature available on the effects of turbidity and sedimentation on Florida reefs, 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**.

Table 1. 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
<i>Acropora cervicornis</i>	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)

Coral species	Experimental SSC, turbidity, or light level	Response	Growth Form	References
	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)
<i>Acropora spp.</i>	170 mg/l (hours) of marine snow/SPM	Mucus production in response to flocculation		Fabricius and Wolanski (2000)
<i>Agaricia agaricites</i>	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		Bak (1978)
	<1% SI (several days)	33% Decrease in calcification rate (for >1 month), but survival		Thompson and Bright (1980)
	1000 mg/l (for 65 h)	Mortality of colonies		
<i>Cladocora arbuscula</i>	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)
<i>Colpophyllia natans</i>	Severe light reduction (shading) for 5 wks	Partial bleaching (5 wks), limited recovery & some algal growth (15 wks)	M	Rogers (1979)
<i>Dichocoenia stokesii</i>	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)
<i>Diploria labyrinthiformis</i>	Severe light reduction (shading) for 5 wks	Substantial bleaching (5 wks), no recovery & some algal growth (15 wks)	M	Rogers (1979)
<i>Eusmilia fastigiata</i>	Severe light reduction (shading) for 5 wks	No visible effects	M	Rogers (1979)
<i>Isophyllia suniosa</i>	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)
<i>Madracis auretenra</i>	<1% SI (several days)	33% drop in calcification rate (for >1 month) but survived	B	Bak (1978)
<i>Manicina areolata</i>	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)
<i>Millepora alcicornis</i>	Severe light reduction (shading) for 5 wks	Partial bleaching (5 wks), algal growth (6 wks), no recovery of damaged tissue	B	Rogers (1979)
<i>Meandrina meandrites</i>	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		
<i>Montastraea annularis</i>	severe light reduction (shading) for 5 wks	substantial bleaching (5 wks), partial recovery (6-8 wks), some algae/mucus	M/E	Rogers (1979)

Coral species	Experimental SSC, turbidity, or light level	Response	Growth Form	References
	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)
<i>Montastraea cavernosa</i>	severe light reduction (shading) for 5 wks	No visible effects	M	Rogers (1979)
<i>Mussa angulosa</i>	Severe light reduction (shading) for 5 wks	No visible effects (1 colony showing minor bleaching after 8 wks)	M	Rogers (1979)
<i>Phyllangia Americana</i>	49, 101, 165, 199 mg/l	No effect on growth rate or survival (10 d), minor bleaching (20 d)	E	Rice and Hunter (1992)
<i>Porites astreoides</i>	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)
<i>Porites astreoides</i>	30–120 mg·cm ⁻² d ⁻¹ (0.07–42 NTU) ¹	After four weeks of exposure to low turbidity (<7 NTU), 80% of <i>P. astreoides</i> recruits remained alive; exposure to turbidity levels above 29 NTU led survival to drop to 10%.	L	Fourney and Figueiredo (2017)
<i>Porites divaricata</i>	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)
<i>Porites Furcata</i>	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)
<i>Porites porites</i>	Significant light reduction due to eutrophication	Reduced reproductive success (ova maturation, larval development)	M	Tomascik and Sander (1987)
<i>Scolymia cubensis</i>	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)
<i>Siderastrea radians</i>	49-199 mg/l (10 days)	Partial polyp death and partial bleaching (in some individuals)	M/E	Rice (1984)
<i>Siderastrea siderea</i>	Severe light reduction (shading) for 5 wks	Partial bleaching after 5 weeks, partial recovery in 6–8 weeks	M	Rogers (1979)
<i>Solenastrea hyades</i>	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)
	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)

Coral species	Experimental SSC, turbidity, or light level	Response	Growth Form	References
<i>Stephanocoenia intersepta</i>	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.

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](#)).

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/cm² of clean calcareous sediment (Rogers 1983). When exposed to 600 mg of sediment², *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).

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/cm² 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

² Sediment was dumped into a cup approximately the "size of a small 35 mm film canister"

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 (boulder 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/cm² 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 strigosa* (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/cm² (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 were 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 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; Fourny 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.

Fourny 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 (Fourny 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 (Fourny and Figueiredo 2017). After 4 weeks of exposure to low turbidity (< 7 NTU) levels, 80% of *Porites astreoides* recruits remained alive. However, 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.

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*) for Florida species. 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 (or mg/cm²) 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 measured using a nephelometer 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 is also evidence that measured turbidity (NTU) is a better measurement of suspended silt content in the water column. Reef sediments are typically composed of coarse sized grains, which promote higher survival rates of recruiters than sediments from land, which contain more silt sized grains (Fourney and Figueiredo 2017). The coarse sediment naturally lowers turbidity around reef areas because the sediments settle out quickly (Robbins 2018, Boyer and Briceno 2015).

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 FCR; 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, with designated uses including drinking water supply, fish and wildlife habitat, recreational use, agricultural and industrial supply): 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, with designated uses including marine, shellfish and wildlife habitat, shellfish harvesting for direct human consumption, recreation and all other legitimate uses including navigation): (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 BMPs are used to control turbidity and none exceeding levels necessary to protect and maintain all designated uses ([Connecticut Department of Energy and Environmental Protection](#)).
- 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 ([Environmental Protection Agency](#)).
- 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 ([New Mexico Environment Department](#)).

- 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 ([Environmental Protection Agency](#)).

DEP recommends retaining the current 29 NTU above natural background criterion for all waters in paragraph 62-302.530(70)(a), F.A.C., and adopting a second narrative provision in paragraph 62-302.530(70)(b), F.A.C., designed to provide additional protection to coral reefs and hardbottom communities. The provision would state that turbidity shall not be increased above background conditions within areas of the state where coral reef or hardbottom communities are currently found or have been demonstrated to have occurred since November 28, 1975. 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 areas of the state where coral reef or hardbottom communities are currently found or have been demonstrated to have occurred since November 28, 1975. To evaluate this criterion, background conditions shall take into account the natural variability of turbidity levels, not to exceed 29 NTU.

The determination of background under paragraph 62-302.530(70)(b), F.A.C., whether for implementation in permitting or Impaired Water assessments should include consideration of natural variability and allow for limited duration activities such as dredging or construction as long as turbidity levels do not exceed an upper percentile of natural variability of background levels (e.g., 90th percentile or interquartile range). 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 should maintain the background turbidity magnitude, frequency, and duration.

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 withstand 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 mortality 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 summary, *P. lapidosa* can tolerate high silt load levels for at least four days, can only tolerate burial by sediment for 24 hours at high temperatures, and may tolerate burial for at least 72 hours at cooler temperatures (17 - 23 °C). The available literature suggests that sabellariid worms are not particularly sensitive to turbidity or suspended sediments, but can be sensitive to sediment burial or smothering. The Department expects that the background levels near the worm reefs will be higher than those typically found in coral communities, which would be reflected in the variability in baseline conditions that would be used to derive permit limits for dredging operations if the proposed narrative criterion was applied to worm reefs. However, the Department ultimately decided that applying the turbidity criterion to worm reefs is not needed given they typically occur in environments with highly dynamic natural turbidity conditions and do not typically support benthic communities found in other hardbottom substrates,

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 SSC (mg/L), rather than turbidity.

6.2.1 TSS, NTU, and Light Attenuation Translator Study, CRCP9

The Standards Development Section (SDS), the Coral Reef Conservation Program (CRCP) in the Office of Resilience and Coastal Protection (RCP), and Beaches Inlets and Ports Program (BIPP) designed and completed a study (CRCP 9) that collected concurrent samples of SSC (mg/L), turbidity (NTU) and light attenuation (PAR, converted to Kd) in the vicinity of beach nourishment projects located in Southeast Florida. The primary objective of CRCP 9 was 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. While the results found positive correlations between turbidity and TSS, the relationships appear to be site specific and a site-specific translator based on the specific sediment characteristics of the site would be needed if a criterion based on TSS was implemented as a turbidity permit limit.

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.

Table 2. 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	<i>P. Astreoides</i>	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.
Telesnicki and Goldberg 1995	Hollywood, FL	<i>D. Stokesii</i> , <i>M. meandrites</i>	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 <i>M. meandrites</i> .
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.
Hodel, E. 2007	Broward County, FL and in lab	<i>A. cervicornis</i>	0 – 200 mg/cm2/day (sedimentation, phosphate, and	Histopathologic changes observed (both in lab and in the field): increased

Citation	Location	Species	Experimental turbidity levels	Summary
			combination of the two)	mucus production, epidermal thickness decreased, mucocyte abundance decreased, reduced number of spirocysts, and loss of gonads. Some oocytes were degraded.
Kendall et al. 1983	Carysfort Reef, FL	<i>A. cervicornis</i>	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), NPS at 100 ppm, zooxanthellae density (at 500 ppm).
Kendall et al. 1985	Carysfort Reef, FL	<i>A. cervicornis</i>	50, 100 mg/l kaolin for 24 hrs followed 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	<i>M. cavernosa</i>	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
Lirman and Fong 2007	Florida's Coral Reef	community study	<i>In situ</i> observations	reefs closer to shore have greater coral

Citation	Location	Species	Experimental turbidity levels	Summary
				cover despite more stressors
Walker et al. 2012	Ports of Miami, Everglades and Palm Beach	community study	<i>In situ</i> observations	Dredging at 3 FL ports effected 176 hectares of reef through burial
Jordan et al. 2010	Florida	community study	<i>In situ</i> 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	<i>In situ</i> 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	<i>In situ</i> 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,

Citation	Location	Species	Experimental turbidity levels	Summary
				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 sediment. Some species shifted towards shallower waters due to light availability.
CSA International – survey conducted in February 2004 (PBS&J 2008)	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	<i>M. cavernosa</i> , <i>S. bournoni</i> , and <i>S. siderea</i>	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	<i>S. radians</i>	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.

Citation	Location	Species	Experimental turbidity levels	Summary
				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	<i>S. radians</i> (2-3cm diameter)	burial for 4, 7 and 10 days, under salinity of 20 psu and 15 psu	<i>S. radians</i> are highly tolerant and recover rapidly. At 20 psu and 4 days of burial coral showed slight reduction in 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	<i>M. cavernosa</i>	<i>In situ</i> (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.

Citation	Location	Species	Experimental turbidity levels	Summary
Rogers 1983	Puerto Rico	<i>A. palmata</i> , <i>A. cervicornis</i> , <i>O. annularis</i> , <i>D. strigosa</i> , <i>D. clivosa</i>	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 <i>A. palmata</i> had algal growth, at 400mg/cm ² <i>O. annularis</i> and <i>A. cervicornis</i> had mild bleaching, <i>D. strigosa</i> was tolerant. <i>D. clivosa</i> was damaged by repeated exposure other species were not
Abdel-Salam and Porter 1988	USVI	<i>A. palmata</i> , <i>D. strigosa</i> , <i>M. annularis</i>	600 mg of sediment	All three species showed significant increases in respiration rates and photosynthetic rates for <i>M. annularis</i> and <i>A. palmata</i> . <i>Annularis</i> and <i>Strigosa</i> were better at clearing sediment than <i>A. palmata</i> .
Torres 2001	SW Puerto Rico	<i>O. annularis</i>	Field sampling	Corals at high sedimentation sites had lower skeletal extension rates.
Torres and Morelock 2002	Puerto Rico	<i>O. annularis</i> , <i>S. siderea</i> , <i>P. astreoides</i>	<i>In situ</i> observations	<i>M. annularis</i> cover decreased in reefs with high terrigenous sediments. Linear extension was unaffected. <i>S. siderea</i> and <i>P. astreoides</i> have higher resilience to terrigenous sediments.
Acevedo et al. 1989	Ponce, PR	community study	<i>In situ</i> observations based on distance from terrigenous sediment influx	Species diversity and coral cover decreased with increased proximity to sediment influx. <i>M. cavernosa</i> dominated sites near influx and <i>A. palmata</i> were largely absent. <i>O. annularis</i> and <i>A.</i>

Citation	Location	Species	Experimental turbidity levels	Summary
				<i>agaricities</i> were less common near influx.
Begin et al. 2016	Saint Lucia	community study	<i>In situ</i> 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	<i>Acropora palmata</i>	<i>In situ</i> 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. <i>O. annualaris</i> decreased 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	<i>A. Faveolata</i>	measured skeletal growth rates at sites	Corals exposed to high levels of local

Citation	Location	Species	Experimental turbidity levels	Summary
			with varying effects from local stressors. Sedimentation was one of the local stressors included.	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	<i>O. annularis</i>	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	<i>M. cavernosa</i> , <i>O. annularis</i> , <i>S. radians</i> , <i>S. siderea</i> , <i>M. meandrites</i>	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. <i>M. cavernosa</i> dominated the high turbidity site. <i>S. radians</i> , <i>S. siderea</i> and <i>M. meandrites</i> were abundant, but <i>O. annularis</i> prevalence was low and colony sizes were smaller.
Nemeth and Nowlis 2001	St. Thomas, USVI	community study	High sedimentation rates were 10-14mg/cm ² /day. Low rates were 4-8mg/cm ² /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 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

Citation	Location	Species	Experimental turbidity levels	Summary
				concentrations for healthy reefs are <1-10mg/cm ² /day and <10 mg/l, respectively. Chronic exposure to higher rates reduced coral cover, diversity, growth rates, calcification rates, and recruitment and increased branching morphology.

The best available science currently in the literature supports a revised turbidity criterion for areas with coral reef habitat at approximately < 7 NTU, based primarily on the work by Fournay and Figueiredo (2017) and Telesnicki and Goldberg (1995). These levels would be more protective of coral recruits, especially for sensitive *Acropora* sp. However, the value may be reconsidered based on pending study results from NOVA Southeastern University, which currently suggest a criterion of approximately 4.5 NTU for *Acropora cervicornis* recruits (Robbins 2018). The recommended duration of the criterion is either an instantaneous value (single sample maximum) or weekly median value (Joana Figueiredo, personal communication 2/9/21). Although this study was conducted 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. Any numeric criterion based on this work would also need to account for natural variability in turbidity.

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 NSU, 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 NSU. 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 4**). 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 and duration 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 5**) that were used to determine EC₅₀ (Effective Concentration; Concentration of a substance that causes a 50% response) thresholds for fertilization success. Thresholds like an EC₅₀ are typically used to develop acute and chronic water quality criteria. Most typically, a lower level of effect (e.g., EC₂₀) 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 develop a criterion with a magnitude, duration (averaging period), and frequency (of allowable excursions) components (Erftemeijer et al., 2012).

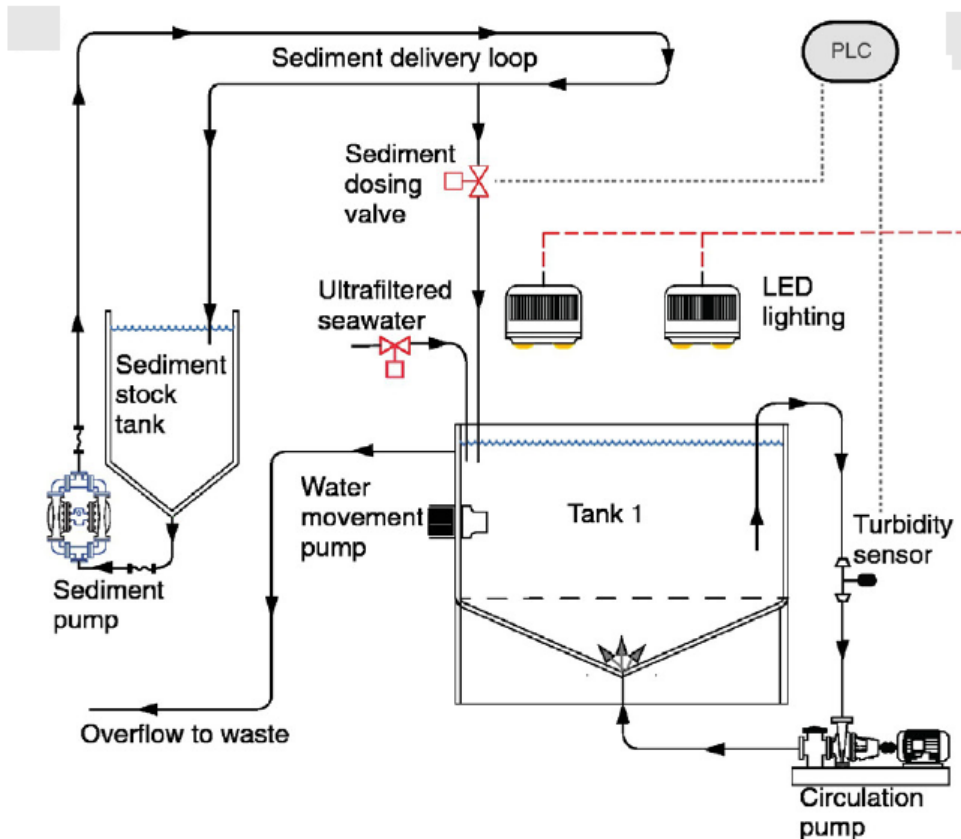


Figure 4. Schematic of the experimental dosing system used by Bessell-Browne et al. (2017) showing the sediment delivery (stock) tanks, and the position of the recirculation pump, water movement pump and in-line turbidity sensor. Delivery of sediment from the stock tanks, and the position of the recirculation 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).



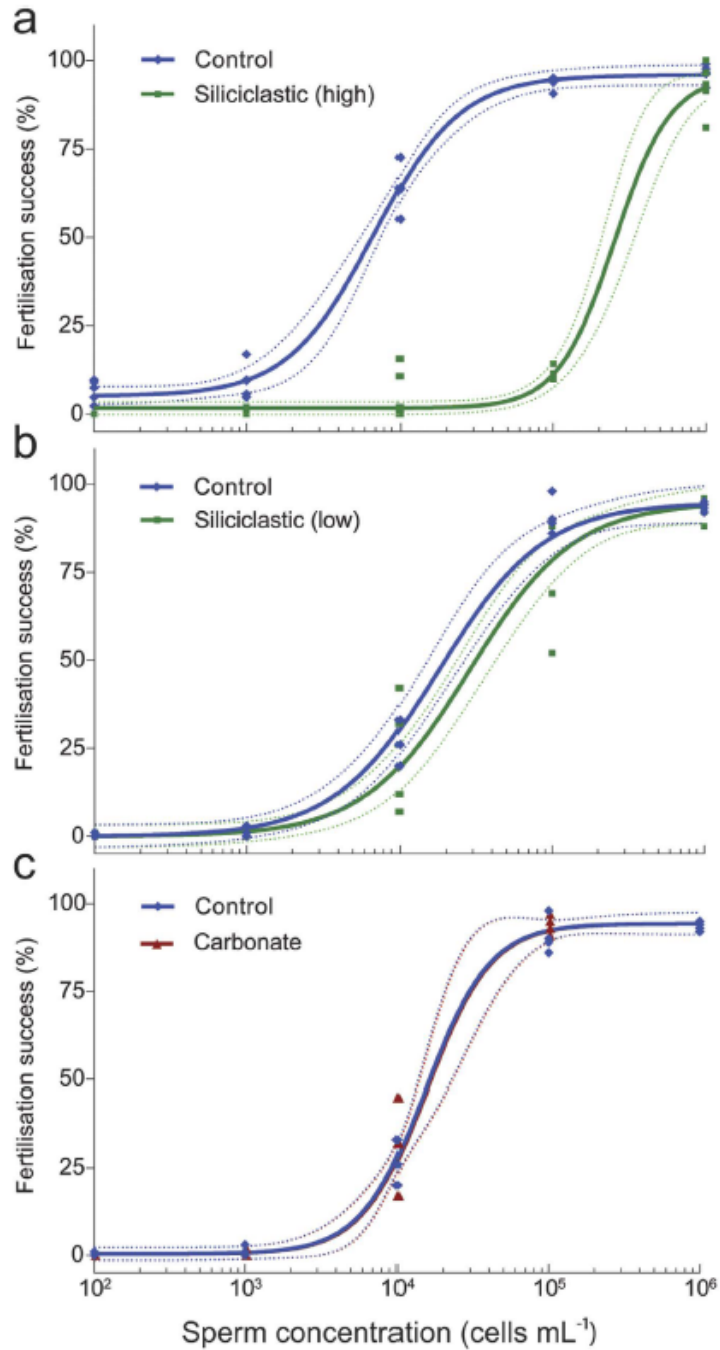


Figure 5. *Acropora tenuis* fertilization success (%) curves fitted to four-parameter logistic models plotted over a range of sperm concentrations (10^2 – 10^6 sperm m^{-1}). (a) Siliciclastic (high): 700 $mg L^{-1}$, green; control: 0 $mg L^{-1}$, blue and (b) siliciclastic (low): 230 $mg L^{-1}$, green; 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: **Option 1)** add narrative components to supplement and strengthen the existing turbidity criterion; **Option 2)** adopt a criterion based on the currently limited Florida and Caribbean data; or, **Option 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 Triennial Review. Second, we recommend that the Department reach out, perhaps through the Office of Resilience and Coastal Protection's Coral Reef Conservation Program, to researchers at 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 (IWR), 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 that would be protective 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 sensitivities 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.

Where 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, but that the total cost would increase to an annual damage cost of \$12.7 million USD without the services provided by coral reefs (Beukering et al., 2007). 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 from extreme weather events. They estimated that coral reefs provide over \$420 million in protective services to Florida on an annual basis (**Table 3**).

Table 3. 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

Measure	Florida Peninsula	Florida Keys
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 ecotourists 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.

Johns et al. (2001) examined four different counties in South Florida for the amount of reef-related sales, income generated by reefs, and employment created by reefs (**Table 4**). The total income of the reef-related sales for the four counties was nearly \$2 billion.

Table 4. Average sales, income, and employment for the year 2000 in four different South Florida counties. Number adjusted for inflation to reflect 2019³ 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 \$10,428⁴ 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 FCR 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.

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. 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.

³ 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.

⁴ Equates to \$4220 per acre.

8.0 References

- Abdel-Salam, H. A., Porter, J. W., & Hatcher, B. G. (1988). Physiological effects of sediment rejection on photosynthesis and respiration in three Caribbean reef corals. In *Proc 6th Int. Coral Reef Symp.*, 2, 285-292.
- Acevedo, R., Morelock, J., & Olivieri, R. (1989). Modification of Coral Reef Zonation by Terrigenous Sediment Stress. *PALAIOS*, 4(1), 92-100. doi:10.2307/3514736.
- Anthony, K. (1999). Coral suspension feeding on fine particulate matter. *J. Exp. Mar. Biol. Ecol.*, 232(1), 85–106. doi: 10.1016/S0022-0981(98)00099-9.
- Anthony, K. (2000). Enhanced particle-feeding capacity of coral on turbid reefs (Great Barrier Reef, Australia). *Coral Reefs*, 19, 59–67. doi: 10.1007/s003380050227.
- Anthony, K. (2006). Enhanced energy status of corals on coastal, high-turbidity reefs. *Mar. Ecol. Prog. Ser.*, 319, 111–116. doi: 10.3354/meps319111.
- Anthony, K., & Fabricius, K. (2000). Shifting roles of heterotrophy and autotrophy in coral energetics under varying turbidity. *J. Exp. Mar. Biol. Ecol.*, 252(2), 221–253. doi: 10.1016/S0022-0981(00)00237-9.
- Bailey-Serres, J., & Voosenek, L.A.C.J., (2008). Flooding stress: acclimations and genetic diversity. *Annu. Rev. Plant Biol.*, 59, 313–339. doi: 10.1146/annurev.arplant.59.032607.092752.
- Bak, R. P. M., & Elgershuizen, J. H. B. W. (1976). Patterns of oil-sediment rejection in corals. *Marine Biology*, 37, 105-113. doi: 10.1007/BF00389121.
- Bak, R. P. M. (1978). Lethal and sublethal effects of dredging on reef corals. *Mar. Pollut. Bull.*, 9(1), 14-16.
- Barnes, B. B., Hu, C., Kovach, C., & Silverstein, R. N. (2016, February). Sediment plumes resulting from the Port of Miami Dredging: Analysis and Interpretation using satellite data and long-term monitoring programs. American Geophysical Union, Ocean Sciences Meeting 2016, New Orleans, Louisiana.
- Bégin, C., Brooks, G., Larson, R. A., Dragičević, S., Scharrón, C. E. R., & Côté, I. M. (2014). Increased sediment loads over coral reefs in Saint Lucia in relation to land use change in contributing watersheds. *Ocean & Coastal Management*, 95, 35-45.
- Bégin, C., Schelten, C. K., Nugues, M. M., Hawkins, J., Roberts, C., & Côté, I. M. (2016). Effects of protection and sediment stress on coral reefs in Saint Lucia. *PLoS ONE*, 11(2), e0146855. doi: 10.1371/journal.pone.0146855.
- Bégin, C., Wurzbacher, J., & Côté, I. M. (2013). Variation in benthic communities of eastern Caribbean coral reefs in relation to surface sediment composition. *Mar Biology*, 160(2), 343-353. doi: 10.1007/s00227-012-2092-5.

- Bessell-Browne, P., Negri AP., Fisher R., P Clode PL., Duckworth A., & Jones R. (2017). Impacts of turbidity on corals: The relative importance of light limitation and suspended sediments. *Mar. Pollut. Bull.*, 117(1-2), 161-170. doi: 10.1016/j.marpolbul.2017.01.050.
- Van Beukering P. J. H., & Cesar, H. S. J. (2004). Ecological Economic Modeling of Coral Reefs: Evaluating Tourist Overuse at Hanauma Bay and Algae Blooms at the Kihei Coast, Hawai'i. *Pacific Science*, 58(2), 243-260. doi: 10.1353/psc.2004.0012
- Van Beukering P. J. H., Haider W., Longland M., Cesar, H. S. J., Shjegstad S., Beardmore B., Liu Y., & Garces G.O.. (2007). The Economic Value of Guam's Coral Reefs. *University of Guam Marine Laboratory Technical Report No. 116*.
- Bhat, M.G. (2003). Application of non-market valuation to the Florida Keys marine reserve management. *Journal of Environmental Management*, 67(4), 315–325. doi: 10.1016/S0301-4797(02)00207-4
- .Brander, L. M., & Van Beukering, P. (2013). The Total Economic Value of U.S. Coral Reefs: A Review of the Literature. NOAA Coral Reef Conservation Program, Silver Spring, MD. 32 p.
- Carilli, J. E., Norris, R. D., Black, B. A., Walsh, S. M., & McField, M. (2009). Local Stressors Reduce Coral Resilience to Bleaching. *PLoS ONE*, 4(7), e6324. doi: 10.1371/journal.pone.0006324
- Cesar, H. S. J., (1996). Economic Analysis of Indonesian Coral Reefs. *The World Bank, Washington, D. C.*
- Cesar, H. S. J., Burke, L., & Pet-Soede, L. (2003). The Economics of Worldwide Coral Reef Degradation. *Cesar Environmental Economics Consulting*, 6-22.
- Connecticut Department of Energy and Environmental Protection, *Water Quality Standards and Classifications Fact Sheet*. <https://portal.ct.gov/DEEP/Water/Water-Quality/Fact-Sheet-for-the-Water-Quality-Standards-and-Classifications>. Last updated February 28th, 2020.
- Dallmeyer, D. G., Porter, J. W., & Smith, G. J. (1982). Effects of particulate peat on the behavior and physiology of the Jamaican reef-building coral *Montastrea annularis*. *Marine Biology*, 68(3), 229-233. doi: 10.1007/BF00409589
- Dustan, P., & Halas, J., C. (1987). Changes in the reef coral community of Carysfort Reef, Key Largo, Florida: 1974 to 1982. *Coral Reefs*, 6(2), 91-106.
- Environmental Assessment Guidelines for Marine Dredging Programs EAG7. (2011). *Perth, Western Australia: Environmental Protection Authority (EPA)*, pp. 36.
- Erftemeijer, P. L., Riegl, B., Hoeksema, B. W., & Todd, P. A. (2012). Environmental impacts of dredging and other sediment disturbances on corals: A review. *Mar. Pollut. Bull.*, 64(9), 1737-1765. doi: 10.1016/j.marpolbul.2012.05.008.

- Fabrizius, K. E. (2005). Effects of terrestrial runoff on the ecology of corals and coral reefs: review and synthesis. *Mar. Pollut. Bull.*, 50(2), 125-146. doi: 10.1016/j.marpolbul.2004.11.028.
- Fabrizius, K. E., & Wolanski, E. (2000). Rapid Smothering of Coral Reef Organisms by Muddy Marine Snow. *Estuarine, Coastal and Shelf Science*, 50(1), 115-120. doi: 10.1006/ecss.1999.0538.
- Fisher, L., Banks, K., Gilliam, D. S., Dodge, R. E., Stout, D., Vargas-Ángel, B., & Walker, B. K. (2008). Real-time coral stress observations before, during, and after beach nourishment dredging offshore SE Florida. *Marine and Environmental Sciences Faculty Proceedings, Presentations, Speeches, Lecture. 42*. https://nsuworks.nova.edu/occ_facpresentations/42.
- Flores F, Hoogenboom MO, Smith LD, Cooper TF, Abrego D, & Negri AP (2012) Chronic Exposure of Corals to Fine Sediments: Lethal and Sub-Lethal Impacts. *PLoS ONE*, 7(5): e37795. doi: 10.1371/journal.pone.0037795.
- Fourney, F., & Figueiredo, J. (2017). Additive negative effects of anthropogenic sedimentation and warming on the survival of coral recruits. *Scientific Reports*, 7(1), 12380. doi: 10.1038/s41598-017-12607-w.
- Fukao, T., & Bailey-Serres, J. (2004). Plant responses to hypoxia — is survival a balancing act? *Trends Plant Sci.*, 9(9), 449–456. doi: 10.1016/j.tplants.2004.07.005.
- NOAA Fisheries. (2012). General Fact Sheet Atlantic Acropora Corals., *Department of Defense, Natural Resources*, <https://denix.osd.mil/nr/otherconservationtopics/coastalandoceanresources/fact-sheets/acropora-fact-sheet/>.
- Hernandez, Edwin & Yahaira, Mercy & Laureano, Ricardo & Hernández-Pacheco, Raissa & Ruiz, Tagrid & Oms, Julio & Díaz, Pedro. (2010). Sediment Stress, Water Turbidity, and Sewage Impacts on Threatened Elkhorn Coral (*Acropora palmata*) Stands at Vega Baja, Puerto Rico. *Proceedings of the 63rd Gulf and Caribbean Fisheries Ins.* 63.
- Humanes, A., Ricardo, G. F., Willis, B. L., Fabrizio, K. E., & Negri, A. P. (2017). Cumulative effects of suspended sediments, organic nutrients and temperature stress on early life history stages of the coral *Acropora tenuis*. *Scientific Reports*, 7, 44101. doi: 10.1038/srep44101.
- Hodel, E. (2007). Histopathological Assessment and Comparison of Sedimentation and Phosphate Stress in the Caribbean Staghorn Coral, *Acropora cervicornis*. Master's thesis. Nova Southeastern University. Retrieved from NSUWorks, Oceanographic Center. (264). https://nsuworks.nova.edu/occ_stuetd/264.
- Houlbrèque, F., & Ferrier-Pagès, C., (2008). Heterotrophy in tropical scleractinian corals. *Biol. Rev. Camb. Philos. Soc.*, 84(1), 1–17. doi: 10.1111/j.1469-185X.2008.00058.x.

- Hubbard, J.A., & Pocock, Y.P. (1972). Sediment rejection by recent scleractinian corals: a key to palaeo-environmental reconstruction. *Geol. Rundsch.*, 61(2), 598–626.
- Johns, G. M., Leeworthy V. R., Bell F. W., & Bonn M. A. (2001, October). *Socioeconomic Study of Reefs in Southeast Florida: Final Report October 19, 2001*. NOAA Coral Reef Conservation Program. Silver Springs, MD.
- Jones, R., & Hoegh-Guldberg, O. (2001). Diurnal changes in the photochemical efficiency of the symbiotic dinoflagellates (Dinophyceae) of corals: photoprotection, photoinactivation and the relationship to coral bleaching. *Plant Cell Environ.*, 24, 89–99. doi: 10.1046/j.1365-3040.2001.00648.x
- Jones, R., Bessell-Browne P., Fisher R., Klonowski W., & Slivkoff M. (2016). Accessing the impacts of sediments from dredging on coral. *Mar. Pollut. Bull.*, 102(1), 9–29. doi: 10.1016/j.marpolbul.2015.10.049.
- Jordan, L. K., Banks, K. W., Fisher, L. E., Walker, B. K., & Gilliam, D. S. (2010). Elevated sedimentation on coral reefs adjacent to a beach nourishment project. *Mar. Pollut. Bull.*, 60(2), 261–271. doi: 10.1016/j.marpolbul.2009.08.032.
- Kendall Jr, J. J., Powell, E. N., Connor, S. J., & Bright, T. J. (1983). The effects of drilling fluids (muds) and turbidity on the growth and metabolic state of the coral *Acropora cervicornis*, with comments on methods of normalization for coral data. *Bull. Mar. Sci.*, 33(2), 336–352.
- Kendall, J. J., Powell, E. N., Connor, S. J., Bright, T. J., & Zastrow, C. E. (1985). Effects of turbidity on calcification rate, protein concentration and the free amino acid pool of the coral *Acropora cervicornis*. *Marine Biology*, 87(1), 33–46. doi: 10.1007/BF00397003
- Kirtley, D. & W. Tanner. (1968). Sabellariid Worms: Builders of a major reef type. *Journal of Sedimentary Research*, 38(1), 73–38. doi: 10.1306/74D718D9-2B21-11D7-8648000102C1865D
- Kühl, M., Cohen, Y., Dalsgaard, T., Jørgensen, B.B., & Revsbech, N.P. (1995). Microenvironment and photosynthesis of zooxanthellae in scleractinian corals studied with microensors for O₂, pH and light. *Mar. Ecol. Prog. Ser.*, 117, 159–177.
- Lasker, H. R. (1980). Sediment rejection by reef corals: the roles of behavior and morphology in *Montastrea cavernosa* (Linnaeus). *J. Exp. Mar. Biol. Ecol.*, 47(1), 77–87.
- Lewis, J., & Price, W.. (1975). Feeding mechanisms and feeding strategies of Atlantic reef corals. *J. Zool.*, 176(4), 527–544. doi: 10.1111/j.1469-7998.1975.tb03219.x.
- Lewis, J.. (1976). Experimental tests of suspension feeding in Atlantic reef corals. *Marine Biology*, 36, 147–150. doi: 10.1007/BF00388437.
- Linderman, K. C., & Snyder, D.B. (1999). Nearshore hardbottom fishes of southeast Florida and effects of habitat burial caused by dredging. *Fishery Bulletin*, 97(3), 508–525.

- Lirman, D., & Fong, P. (2007). Is proximity to land-based sources of coral stressors an appropriate measure of risk to coral reefs? An example from the Florida Reef Tract. *Mar. Pollut. Bull.*, 54(6), 779-791. doi: 10.1016/j.marpolbul.2006.12.014.
- Lirman, D., & Manzello, D. (2009). Patterns of resistance and resilience of the stress-tolerant coral *Siderastrea radians* (Pallas) to sub-optimal salinity and sediment burial. *J. Exp. Mar. Biol. Ecol.*, 369(1), 72-77. doi: 10.1016/j.jembe.2008.10.024.
- Lirman, D., Manzello, D., & Maciá, S. (2002). Back from the dead: the resilience of *Siderastrea radians* to severe stress. *Coral Reefs*, 21(3), 291-292. doi: 10.1007/s00338-002-0244-7.
- Lirman, D., Orlando B., Maciá, S., Manzello, D., Kaufman, L., Biber, P., & Jones, T. (2003). Coral communities of Biscayne Bay, Florida and adjacent offshore areas: Diversity, abundance, distribution, and environmental correlates. *Aquat. Conserv.: Mar. Freshw. Ecosyst.*, 13, 121-135.
- Logan, A. (1988). Sediment-shifting capability in the recent solitary coral *Scolymia cubensis* (Milne-Edwards and Haime) from Bermuda. *Bull. Mar. Sci.*, 43, 241-248.
- Logan, A., Yang, L., & Tomascik, T. (1994). Linear skeletal extension rates in two species of *Diploria* from high-latitude reefs in Bermuda. *Coral Reefs*, 13, 225-230. doi: 10.1007/BF00303636.
- Lopez, G.R., & Levinton, J.S. (1987). Ecology of deposit-feeding animals in marine sediments. *The Quarterly Review of Biology*, 62(3), 235-260.
- Louisiana Administrative Code (LAC) Title 22, Part IX. Water Quality Chapter 11, Section 1113. Criteria (9) Turbidity. (Accessed March 2021). Environmental Protection Agency. <https://www.epa.gov/sites/production/files/2014-12/documents/lawqs.pdf>.
- Loya, Y. (1976). Effects of water turbidity and sedimentation on the community structure of Puerto Rican corals. *Bull. Mar. Sci.*, 26(4), 450-466.
- Maliao, R.J., Turingan, R. G., & Lin, J. (2008). Phase-shift in coral reef communities in the Florida Keys National Marine Sanctuary (FKNMS), USA. *Marine Biology*, 154(5), 841-853. doi: 10.1007/s00227-008-0977-0
- Marshall, S.M., & Orr, A.P. (1931). Sedimentation on Low Isles Reef and its relation to coral growth. *Sci. Rep. Gt Barrier Reef Exped.*, 1, 93-133
- Marshall, N. (1965). Detritus over the reef and its potential contribution to adjacent waters of Eniwetok Atoll. *Ecology*, 46, 343-344. doi: 10.2307/1936340
- Marszalek, D. S. (1981). Impact of dredging on a subtropical reef community, southeast Florida, USA. In *Proceedings Fourth International Coral Reef Symp.*, 1, 147-153.
- Mehta, A. J. (1973). Coastal engineering study of sabellariid reefs: report of hydraulic model study to the Harbor Branch Foundation Laboratory, Ft. Pierce, Fl. Gainesville, Coastal and Oceanographic Engineering Lab, *Eng. And Indust. Exper. Sta.*, Univ. Florida. 67p.

- Meyer, J. L., & Schultz, E. T. (1985). Tissue condition and growth rate of corals associated with schooling fish. *Limnol. Oceanogr*, 30(1), 157-166. doi: 10.4319/lo.1985.30.1.0157
- Miller, Margaret W. (2016). Detecting sedimentation impacts to coral reefs resulting from dredging the Port of Miami, Florida. USA. *PeerJ*, 4, e2711. doi: 10.7717/peerj.2711
- Mills, M., & Sebens, K., 1997. Particle ingestion efficiency of the corals *Siderastrea siderea* and *Agaricia agaricites*: effects of flow speed and sediment loads. *Proceedings of the 8th International Coral Reef Symp., Panama*, 2, 1059–1064.
- Mills, M.M., Lipschultz, F., & Sebens, K.P. (2004). Particulate matter ingestion and associated nitrogen uptake by four species of scleractinian corals. *Coral Reefs*, 23, 311–323. doi: 10.1007/s00338-004-0380-3
- Moeller, M., Nietzer, S., Schils, T., & Schupp, P. J. (2017). Low sediment loads affect survival of coral recruits: the first weeks are crucial. *Coral Reefs*, 36(1), 39-49. doi: 10.1007/s00338-016-1513-1
- Nelson, W. G., & Main, M. B. (1985). Criteria for Beach Nourishment: Biological Guidelines for Sabellariid Worm Reef. Florida Sea Grant College, Technical Paper No. 33.
- Nemeth, R. S., & Nowlis, J. S. (2001). Monitoring the effects of land development on the near-shore reef environment of St. Thomas, USVI. *Bull. Mar. Sci.*, 69(2), 759-775.
- New Mexico Environment Department. (Accessed March 2021). Integrated Rule Effective for State Purposes, Title 20, Chapter 6, Part 4. 20.6.4.13 (J) Turbidity. <https://www.env.nm.gov/surface-water-quality/wp-content/uploads/sites/25/2017/06/Integrated-Rule-Effective-for-State-Purposes-20200522.pdf>
- Otero, E. (2009). Spatial and temporal patterns of water quality indicators in reef systems of southwestern Puerto Rico. *Caribb. J. Sci.*, 45(2-3), 168-180. doi: 10.18475/cjos.v45i2.a5.
- PBS&J. (2008). Best management practices (BMPs) for construction, dredge and fill and other activities adjacent to coral reefs. Southeast Florida Coral Reef Initiative, Maritime Industry and Coastal Construction Impacts Focus Team. PBS&J, February 2008, 126pp.
- Perez III, K., Rodgers, K. S., Jokiel, P. L., Lager, C. V., & Lager, D. J. (2014). Effects of terrigenous sediment on settlement and survival of the reef coral *Pocillopora damicornis*. *PeerJ*, 2, e387.
- Ricardo, G. F., Jones, R. J., Clode, P. L., Humanes, A., & Negri, A. P. (2016). Suspended sediments limit coral sperm availability. *Scientific Reports*, 5, 18084.
- Rice, S. A. (1984). Effects of suspended sediment and burial upon survival and growth of eastern Gulf of Mexico corals. *Mote Marine Laboratory, Sarasota, Florida*.
- Rice, S. A., & Hunter, C. L. (1992). Effects of suspended sediment and burial on scleractinian corals from west central Florida patch reefs. *Bull. Mar. Sci.*, 51(3), 429-442.

- Jena Robbins. (2018). Effects of ocean warming, sedimentation, and parental genotype on the post-settlement survival and growth of *Acropora cervicornis* recruits. Master's thesis. Nova Southeastern University. Retrieved from NSUWorks, (483) https://nsuworks.nova.edu/occ_stuethd/483.
- Rogers, C. S. (1979). The effect of shading on coral reef structure and function. *J. exp. mar. Biol. Ecol.*, 41(3), 269-288. doi: 10.1016/0022-0981(79)90136-9.
- Rogers, C. S. (1983). Sublethal and lethal effects of sediments applied to common Caribbean reef corals in the field. *Mar. Pollut. Bull.*, 14(10), 378-382. doi: 10.1016/0025-326X(83)90602-1
- Rogers, C. S. (1990). Responses of coral reefs and reef organisms to sedimentation. *Mar. Ecol. Prog. Ser.*, 62, 185-202.
- Rosenfeld, M., Bresler, V., & Abelson, A. (1999). Sediment as a possible source of food for corals. *Ecol. Lett.* 2, 345–348. doi: 10.1046/j.1461-0248.1999.00097.x
- Schuhmacher, H., 1977. Ability of fungiid corals to overcome sedimentation. *Proceedings of the 3rd International Coral Reef Symp., Miami, US*, (1)503–510.
- Shashar, N., Kinane, S., Jokiel, P.L., & Patterson, M.R. (1996). Hydromechanical boundary layers over a coral reef. *J. Exp. Mar. Biol. Ecol.*, 199(1), 17–28. doi: 10.1016/0022-0981(95)00156-5
- Stafford-Smith, M., & Ormond, R. (1992). Sediment-rejection mechanisms of 42 species of Australian scleractinian corals. *Mar. Freshw. Res.*, 43, 683–705. doi: 10.1071/MF9920683
- Stafford-Smith, M. (1993). Sediment-rejection efficiency of 22 species of Australian scleractinian corals. *Marine Biology*, 115, 229-243. doi: 10.1007/BF00346340
- Storlazzi, C.D., Reguero, B.G., Cole, A.D., Lowe, E., Shope, J.B., Gibbs, A.E., Nickel, B.A., McCall, R.T., Van Dongeren, A.R., & Beck, M.W. (2019). Rigorously valuing the role of U.S. coral reefs in coastal hazard risk reduction: U.S. Geological Survey Open-File Report 2019–1027, 42, doi: 10.3133/ofr20191027
- Szmant-Froelich, S., Johnson, V., & Hoehn, T. (1981). The physiological effects of oil drilling muds on the Caribbean coral *Montastrea annularis*. In: *Proceedings Fourth International Coral Reef Symposium, Manila, vol. 1*, pp. 163–168.
- Telesnicki, G.J., & Goldberg, W.M. (1995). Effects of turbidity on the photosynthesis and respiration of two South Florida reef coral species. *Bull. Mar. Sci.*, 57, 527–539.
- Tennessee Department of Environment and Conservation, Chapter 0400-40-03, General Water Quality Criteria, -.03 Criteria for Water Uses. (Accessed March 2021). Environmental

- Protection Agency. <https://www.epa.gov/sites/production/files/2014-12/documents/tn-chapter1200-4-3.pdf>
- Thompson Jr., J.H. (1980). Responses of selected scleractinian corals to drilling fluids used in the marine environment. *PhD dissertation, Texas A and M University, College Station*.
- Thompson, Jr., J.H., & Bright, T.J., (1980). Effects of an offshore drilling fluid on selected corals. *Proc. Research on Environmental fate and Effects of Drilling Fluids and Cuttings, Lake Buena Vista, FL*, (2), 1044–1078
- Tomascik, T., & Sander, F. (1985). Effects of eutrophication on reef-building corals. *Mar. Biol.* 87, 143–155.
- Tomascik, T. and Sander, F., 1987. Effects of eutrophication on reef corals. II. Structure of scleractinian coral communities on fringing reefs, Barbados, West Indies. *Marine Biology*, 94, 53-75.
- Torres, J. L. (2001). Impacts of sedimentation on the growth rates of *Montastraea annularis* in southwest Puerto Rico. *Bulletin of Marine Science*, 69(2), 631-637.
- Torres, J. L., and Morelock, J. A. C. K. (2002). Effect of terrigenous sediment influx on coral cover and linear extension rates of three Caribbean massive coral species. *Caribb J. Sci.*, 38(3-4), 222-229.
- Trujillo, J. C., Navas, E. J., & Vargas, D. M. (2017). Valuing Coral reef Protection in a Caribbean Marine Protected Area. Economic Impact of Scuba Diving in Coral of Rosario and San Bernardo National Natural Park, Colombia. *Cuadernos de Desarrollo Rural*, 14(79), 1-14. Doi: 10.11144/Javeriana.cdr14-79.vcrp
- Vargas-Ángel, B., Peters, E. C., Kramarsky-Winter, E., Gilliam, D. S., & Dodge, R. E. (2007). Cellular reactions to sedimentation and temperature stress in the Caribbean coral *Montastraea cavernosa*. *J. Invertebr. Pathol.*, 95(2), 140-145. doi: 10.1016/j.jip.2007.01.003
- Vaughan, T.W. (1916). The results of investigations of the ecology of the Floridian and Bahaman Shoal-Water Corals. *Proc. Natl. Acad. Sci. U. S. A.*, 2(2), 95–100. doi: 10.1073/pnas.2.2.95.
- Walker, B. K., Gilliam, D. S., Dodge, R. E., & Walczak, J. (2012). Dredging and shipping impacts on Southeast Florida coral reefs. *Marine & Environmental Sciences Faculty Proceedings, Presentations, Speeches, Lectures*. 45. https://nsuworks.nova.edu/occ_facpresentations/45
- Wild, C., Huettel, M., Klueter, A., Kremb, S.G., Rasheed, M.Y., & Jørgensen, B.B. (2004). Coral mucus functions as an energy carrier and particle trap in the reef ecosystem. *Nature*, 428(6978), 66–70. doi: 10.1038/nature02344

Yonge, C.M., & Nicholls, A., 1931. Studies on the physiology of corals. V. The Effects of Starvation in Light and in Darkness on the Relationship Between Corals and Zooxanthellae Great Barrier Reef Expedition 1928–29, *Scientific Sci.c Rep.* 1, 177-211

DRAFT