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DEVELOPMENT OF GUIDELINES FOR DREDGED MATERIAL DISPOSAL BASED ON ABIOTIC DETERMINANTS OF CORAL REEF COMMUNITY STRUCTURE

Christopher McArthur, P.E.[1], M.ASCE, Roland Ferry, Ph.D.[2], John Proni, Ph.D.[3]

Abstract: To be protective of living marine resources the ocean disposal of dredged materials must be managed such that these activities do not significantly disrupt the natural environment upon which marine animal and plant communities depend. Two important controlling factors affecting the diversity, abundance and general health of hermatypic (stony) corals comprising reef communities in tropical and subtropical environments are sedimentation and the availability of sunlight for photosynthesis. Disposal activities result in residual sediment plumes which, when occurring near coral communities, can expose corals to increased suspended sediment levels and sedimentation rates and reduced light intensity. In order to avoid adverse impacts to corals, dredged material disposal guidelines should ensure that disposal activities do not add significantly to sedimentation and light attenuation caused by naturally occurring oceanographic and meteorological processes. The development of disposal guidelines requires an understanding of these processes and their influence on sedimentation and light availability. Studies of these processes are currently underway at the Miami, Florida Ocean Dredged material Disposal Site (ODMDS). Initial results of eight months of acoustical backscatter data collected from October 1998 to October 1999 suggest a marked seasonal difference in average natural background suspended sediment concentrations at reef locations inshore of the ODMDS. Fall seasonal averages were higher due in part to several hurricanes and tropical storms that caused high elevations of suspended sediments on reef communities for two to four day periods. Suspended sediment guidelines for dredged material disposal will depend on the importance of these major oceanographic and meteorological events as determining factors for coral reef structure and function.

INTRODUCTION

In coastal and marine ecosystem protection resource managers and regulators are often required to place conditions, limits and other controls on human activities in order to reduce stress to critical marine resources. The typical model for environmental decision making usually begins with a prediction of the resources' response to the proposed activity based on the information available, establishment of limits based on the preceding predictions and possibly some type of monitoring of performance and/or impacts. Very often conditions detailing maximum allowable limits are applied without a clear understanding of the effects this will ultimately have on the resource we wish to

1) U.S. Environmental Protection Agency Region 4, 61 Forsyth Street, SW, Atlanta, GA 30303, USA. mcarthur.christopher@epa.gov

2) U.S. Environmental Protection Agency Region 4, 61 Forsyth Street, SW, Atlanta, GA 30303, USA. ferry.roland@epa.gov

3) NOAA Atlantic Oceanographic and Meteorology Laboratory, 4301 Rickenbacker Causeway, Miami, FL 33149, USA. john.proni@noaa.gov

protect. The main reason for this is that the necessary scientific information for sound decision making is usually not available. Marine ecosystems are complex assemblages comprised of multiple plant and animal communities, each one often containing dozens or hundreds of species across several higher level phyletic groups. There is often scant reliable scientific information about the effects of the stressor in question on even a few, if any, species in the assemblage. In addition, the structure of marine communities changes across various spatial and temporal scales in response to natural abiotic (physical and chemical) factors and in response to other human activities. In an attempt to circumvent these problems the use of a few species or single species, for which some information is available, to serve as indicators of potential community impacts, is sometimes prescribed. The single species indicator approach is beset with a number of problems, including sensitivity and applicability which affect the reliability of such measurements (EPA, 1999).

Alternative methods for marine resource protection are needed in situations where a high degree of uncertainty exists regarding the scope and magnitude of community responses to varying levels of exposure to environmental stressors. Such methods should not depend on large volumes of difficult to obtain and often ambiguous biological response data in order to be effective. In this paper we propose an alternative method for the protection of coral reef communities in southeast Florida, from impacts due to the ocean disposal of dredged sediments. The proposed method makes few assumptions about the resource and its specific stress responses. The method does not require extensive community characterizations or impact analyses in order to provide effective guidelines for dredged material disposal. The method only requires a detailed knowledge of the natural range of the parameters of concern.

BACKGROUND

The Miami Ocean Dredged Material Disposal Site (ODMDS) was designated by the Environmental Protection Agency (EPA) Region 4 for the disposal of dredged material from the Port of Miami in 1995. It is located on the continental slope where the ocean circulation is strongly influenced by the Florida Current and within approximately 2.3 km of reef-like ridges containing a coral-octocoral hardbottom community. During the disposal site designation process and Environmental Impact Statement development in the late 1980's and early 1990's, significant concerns were raised regarding the potential for suspended dredged material disposal plumes to be carried to the reef areas by Florida Current spin-off eddies in sufficient concentrations and with sufficient frequency to cause adverse impacts (EPA, 1995).

Numerous field measurement exercises (Proni et al., 1991; Proni et al., 1993; Tsai et al., 1992) and numerical modeling studies (Scheffner and Swain, 1989; Thevenot and Johnson, 1994) were conducted by the National Oceanic and Atmospheric Administration Atlantic Oceanographic and Meteorological Laboratory (NOAA/AOML) and the US Army Engineer Waterways Experiment Station’s Coastal Engineering Research Center (CERC) to attempt to address these concerns. Results from the field and numerical modeling studies indicated that initial disposal plume concentration exceed 1,000 mg/l throughout the water column and decrease to below 100 mg/l within 1 km of the discharge point and to below background within 13 km or 2.5 hours of discharge (Thevenot and Johnson, 1994; Thevenot, 1995). However, it was unknown with what frequency these elevated concentrations might reach the reefs and if they did what was an acceptable concentration and exposure time at the reefs. Threshold values for individual reef species and for the reef ecosystem as a whole are not available (Rogers, 1990). It is not known for example what suspended sediment level will result in a given percent decrease in the amount of living coral cover or cause death of coral species in the field. Normal suspended sediment concentrations and turbidity levels on coral reefs are available from the scientific literature, but by how much these values can be exceeded before reef organisms are adversely effected is unknown (Rogers, 1990).

Due to these uncertainties, the disposal site management plan restricts disposal at the ODMDS during periods when currents are in the direction of the reefs. This restriction requires an elaborate system of both real-time current measurements at the ODMDS and real-time communication of appropriate information regarding the current velocity criteria during dredging operations (Proni, et. al., 1998). To resolve the issues regarding acceptable suspended sediment concentrations at the Miami reefs, the EPA Region 4 and NOAA/AOML have initiated a long term monitoring effort following procedures described in Larcombe et. al (1995) to develop guidelines for suspended sediment concentrations specific to the Miami reefs.

APPROACH

All living organisms respond to a variety of biotic and abiotic environmental variables in ways that affect the overall fitness of the individual organism and the communities that they comprise. Physiological responses to most abiotic variables occur on a gradient along which exists a range of values describing the minimum and maximum tolerance levels in which each species can exist (Odum, 1971; Brewer, 1979). Within the tolerance range is a generally narrower range of values optimal for metabolic and primary biological functions, such as growth and reproduction, for each life history stage. In the case of hermatypic (reef building) corals, the communities are considered to have relatively narrow tolerance and optimum ranges for environmental variables such as water temperature, salinity, turbidity, and suspended sediment loads as is indicated by their geographic distribution (Jones and Endean, 1973).

The ocean disposal of dredged sediments may alter the coral environment through the addition of sediments into the water column. Suspended sediments can limit coral fitness by 1) reducing the amount of sun light available for coral photosynthesis, and 2) increasing the metabolic energy required for the removal of sediment particles from the coral exoskeleton (Hubbard and Pocock, 1972; Dodge and Vaisnys, 1977; Bak, 1978; Kendall et. al., 1985; Meesters et. al., 1992; Hubbard and Scaturo, 1985; Tomascik and Sanders, 1985). Though the sensitivity to changes in suspended sediment loads varies among the species present, South Florida corals are adapted to normal sediment loads occurring in coastal waters and can tolerate the occasional high sediment loads that occur during storm events and other disturbances.

We propose that ecologically sound suspended sediment guidelines can be developed for coral communities without specific detailed information regarding the importance of sediments as a limiting factor based on the concept that the combined effects of all major controlling factors, including suspended sediments, are integrated into the present community structure. We further propose, if the above statement is generally correct, that sound suspended sediment guidelines requires only detailed information on the variability in the suspended sediment loads to which these communities are exposed.

The principal goal for deriving ecologically sound suspended sediment guidelines for ocean disposal should be to prevent significantly greater exposure beyond that to which the coral community is presently adapted. Any suspended sediments resulting from disposal activities should fall within the natural limits for that environment and thus cause no added stress to individual corals or the coral community. The principal objective of the initial phase of this study was to determine the natural limits of coral community exposure to suspended sediments and the atmospheric and oceanographic processes that drive it.

Three factors were determined to be important aspects of coral and coral community effects of exposure to suspended sediments; 1) intensity, 2) duration, and 3) frequency.

Intensity: High suspended sediment concentrations place stress on corals, therefore suspended sediment values near the high end of the normal range of concentrations to which South Florida coral communities are exposed are most likely to have adverse effects on community structure. Suspended sediment concentrations due to natural conditions plus dredged sediment disposal should not exceed the highest values to which South Florida coral communities are normally exposed. The highest allowable values have been selected as the 99th percentile observed concentration. A lower value, the 95th percentile observed concentration, has been selected as a threshold concentration. This threshold concentration can be exceeded only for specified durations and frequencies as discussed below. Concentrations below this threshold value are not considered to significantly affect coral communities because of their naturally higher frequency of occurrence.

Duration: The average suspended sediment concentrations that persist in the environment throughout the year can be considered “background” levels of continuous or near continuous duration. These typical concentrations are not expected to adversely affect coral communities. High sediment concentrations may cause an adverse impact if the corals are exposed to these concentrations for sufficient time periods. Any significant increase in the time of exposure or duration of high sediment concentrations may result in excess stress in individual coral species and changes in community structure. Coral exposures to suspended sediment concentrations (dredged sediments plus native sediments) above the threshold value should not exceed the naturally occurring 95th percentile duration event.

Frequency: Suspended sediment concentrations that coral communities are most frequently exposed throughout the year are those to which corals are principally adapted and, therefore, are not expected to have an adverse impact. Higher values are those caused by storm events and other anomalies, which occur less frequently. Corals are able to tolerate occasional heavy sediment concentrations provided there is sufficient time for recovery between high sediment events. Any significant increase in the frequency of high sediment concentrations may cause a change in community structure due to the disappearance of those species with lower sediment tolerance. Suspended sediment concentrations above the threshold value due to dredged sediment disposal, for a specific duration, should not occur at a frequency such that the combined frequency of the dredging and natural events are significantly greater than would normally occur. The level of significance or frequency guideline has been selected as the upper 95^{th} percent confidence interval.

METHODS AND MATERIALS

Study Area

The Miami ODMDS is located approximately, 7.2 kilometers east of Virginia Key, Florida. Approximately 2.3 km to the west of the ODMDS lie reef-like ridges containing a coral-octocoral hardbottom community (Goldberg, 1973; Courtney et al., 1974; Marszalek, 1981). According to Lee and Mayer (1977), the study area is heavily influenced by the Florida Current and its associated spin-off eddies. The three site locations selected for the placement of sensors are shown in figure 1. Site 1 was selected as the primary data station due to its proximity to the ODMDS. It is located just offshore of Key Biscayne and about 3.7 kilometers from the boundary of the Miami disposal site at a depth of 19 meters. Hard substrate at the site has a vertical relief of up to 1 meter. The coral colonies located here are scattered and interspersed with gorgonians and sponges. Site 2 was selected to measure wind data and atmospheric radiation. It is located at a range tower located approximately 5.6 kilometers north of Site 1. Site 3 was established to provide a supplementary data station north of the inlet and in a reef area most likely to be impacted by disposal plumes. It is located approximately 5.6 kilometers north of Site 2 also at a depth of 19 meters. The area around Site 3 represents sand bottom interspersed with low relief ridges of hard bottom and scattered coral.

Data Collection

Sensors placed at Site 1 include: a 1200 kHz acoustic Doppler current profiler (ADCP), two optical backscatter devices (OBS), an electromagnetic current and wave sensor, and a photosynthetically available radiation (PAR) meter. Mounted on the tower above the water surface at Site 2 is a PAR meter and wind (speed and direction) meter. Site 3 contains an OBS and PAR sensor.

The bottom mounted upward looking ADCP was used to collect current and acoustic backscatter data at one half meter intervals from the bottom to the surface. The ADCP was setup with 1 minute ensembles taken every 10 minutes. Backscatter measurement were taken from the first bin corresponding to 1.7 meters above the bottom and used to estimate suspended solids concentration (SSC). The OBSs were used to estimate SSC by measuring turbidity by detecting infrared radiation scattered from suspended matter. The subsurface PARs use a spherical quantum sensor to measure photon flux from all directions with a spectral response of 400 to 700 nm to measure light reduction due to suspended sediments. The OBSs, subsurface PARs, and electromagnetic current and wave sensor were all located 1.5 meters above the bottom and sampled one minute averages every 20 minutes.

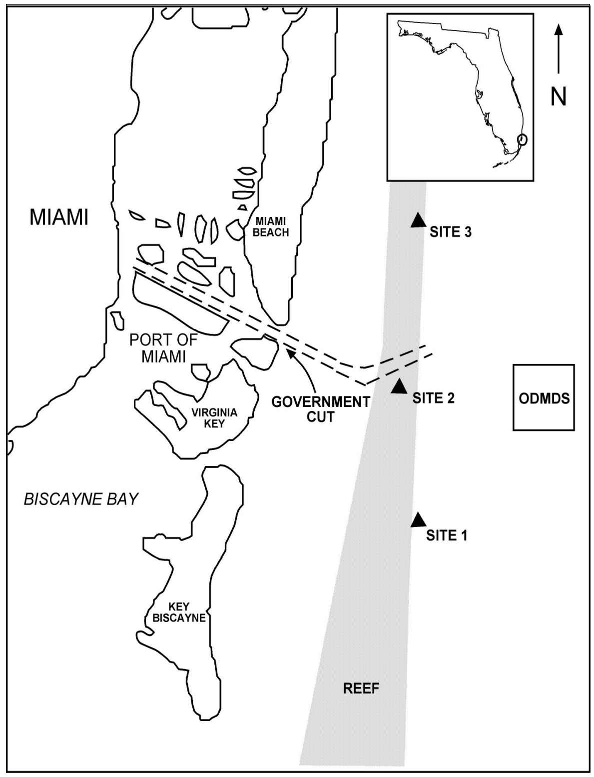

Figure 1: Study area and sensor locations.

Analysis

Estimated SSC values were calculated from the OBS turbidity and the ADCP backscatter data. The OBSs were calibrated in the laboratory following methods employed by Nelson et al (2000) using suspension created from sediments collected at Site 1. Site specific calibration of the OBSs is needed because the OBS output is dependent upon the nature and grain size distribution of the sediment suspension (Larcombe et. al, 1995). Laboratory calibrations resulted in a linear correlation of 0.99 between SSC and OBS turbidity. The OBS deployments were limited to approximately 2 weeks due to biofouling. To obtain an estimate of SSC for the entire instrument deployment, the following relationship between ADCP backscatter and SSC concentrations was utilized (Deines 1999; Gartner and Cheng 2001):

$$SSC_{(est)} = 10^{(A+B*RB)}$$

where $SSC_{(est)}$ is estimated SSC concentration, RB is the relative acoustic backscatter intensity and A and B are the intercept and slope, respectively, determined by regression of concurrent acoustical backscatter with known total suspended solids on a semi-log plane. Backscatter from the first bin of the ADCP corresponding to the depth of the OBS was used. Following methods described in Deines (1999) and Gartner and Cheng (2001), A and B were determined for a range of turbidities measured by an OBS during the passage of Hurricane Floyd. For this two day period, the linear regression correlation coefficient for the calibration was 0.87. For a 1200 kHz ADCP, this method is considered appropriate for particle size distributions between 10 :m and 400 :m, corresponding to silts and fine sands (Gartner and Cheng, 2001). We found that 95% of the suspended particulate matter is within this range.

The estimated SSCs from the ADCP backscatter provided the most reliable data set for the calculation of the guideline values. The data set was broken into three two month periods for analysis representing the summer, fall and winter seasons. The 99th and 95th percentile SSCs were calculated to determine the intensity guideline and the threshold concentration used for the duration and frequency guidelines, respectively. Figure 2 shows the SSC frequency distribution and calculated intensity guideline and threshold concentration for the summer season. The data set was then analyzed to determine the distribution of all duration events (exposure times) during which the threshold value was exceeded. The 95th percentile longest event was calculated as the duration guideline. The distribution and guideline value are shown in figure 3 for the summer season. To develop frequency guidelines, all events exceeding the threshold value were grouped into classes by

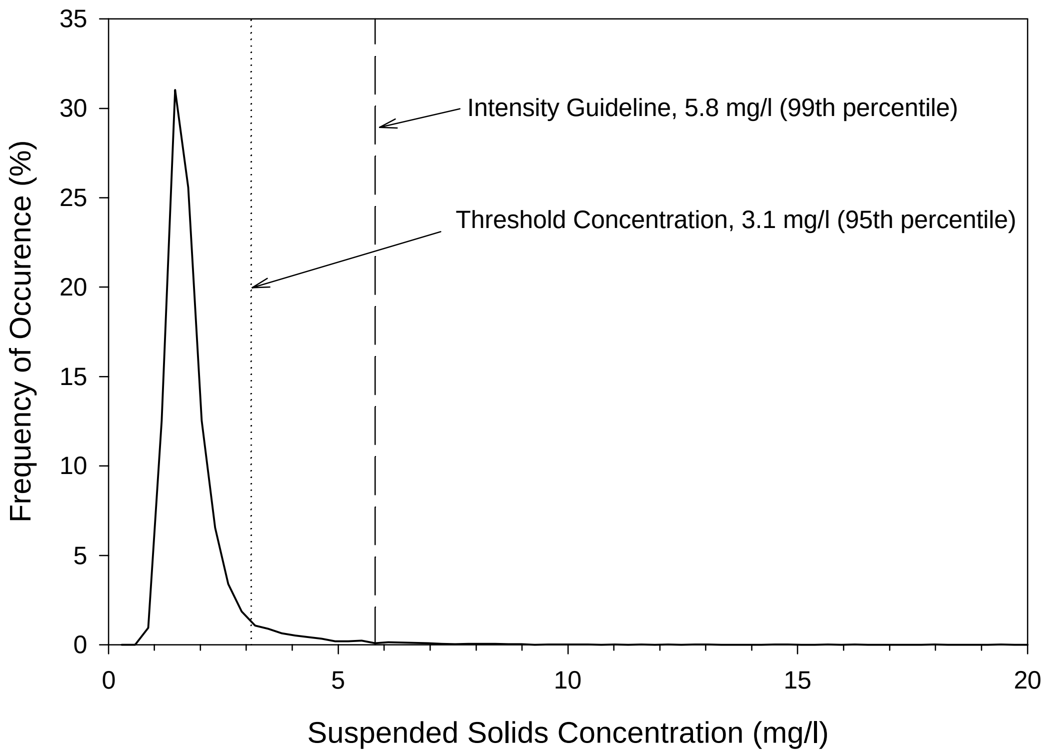

Figure 2: Summer season suspended solids concentration frequency distribution and calculated intensity guideline and threshold concentration.

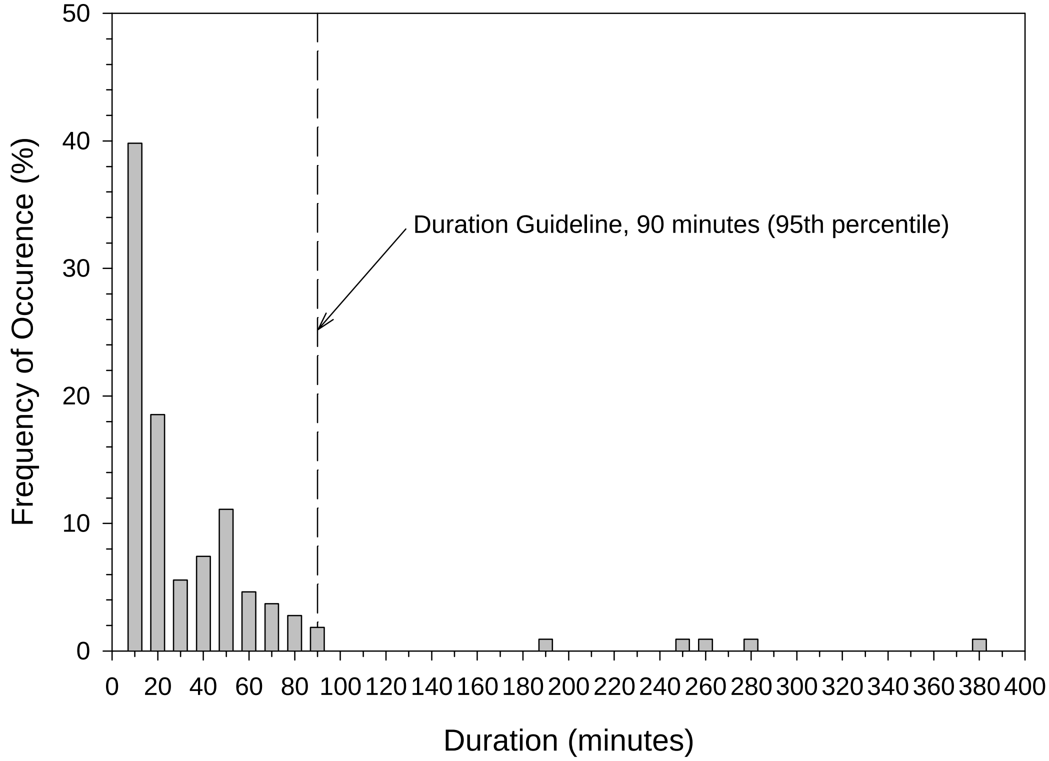

Figure 3: Duration histogram and guideline value for the summer season. Duration represents the length of each event in which the suspended solids concentration exceeded the threshold concentration.

duration. For each duration class, a frequency distribution was developed over the time frame of interest. In this case, the time frame selected is a week. The 95% confidence limit was then selected as the total allowable frequency. The principle behind the guidelines requires that natural SSCs plus that due to disposal cannot exceed the natural bounds. Therefore, the mean frequency is subtracted from the total allowable frequency to determine the frequency guideline for dredged material disposal.

Current data was analyzed from the first bin of the ADCP corresponding to the approximate depths of the other instruments. Mean current velocities were within 5% of those measured by the electromagnetic current meter. The wave statistics information was obtained by Fast Fourier Transform analysis of the pressure data.

RESULTS

Oceanographic Conditions

During the eight months of data collection, conditions ranged from calm summer conditions with little wave activity and low SSCs to hurricane category 4 conditions with elevated SSC. Three hurricanes and one tropical storm passed near South Florida during the deployments. Ninety percent of the current measurements were below 22 cm/sec and were predominately north and southerly directed. The mean current magnitudes for each season was within six percent of the overall average. Wave heights ranged to 5.5 meters with 95% of the measurements below 1 meter. Larger wave heights occurred in the fall during hurricane season. Summer wave heights did not exceed 1 meter. Figure 4 shows the wave heights for the passage of four tropical systems in 1999.

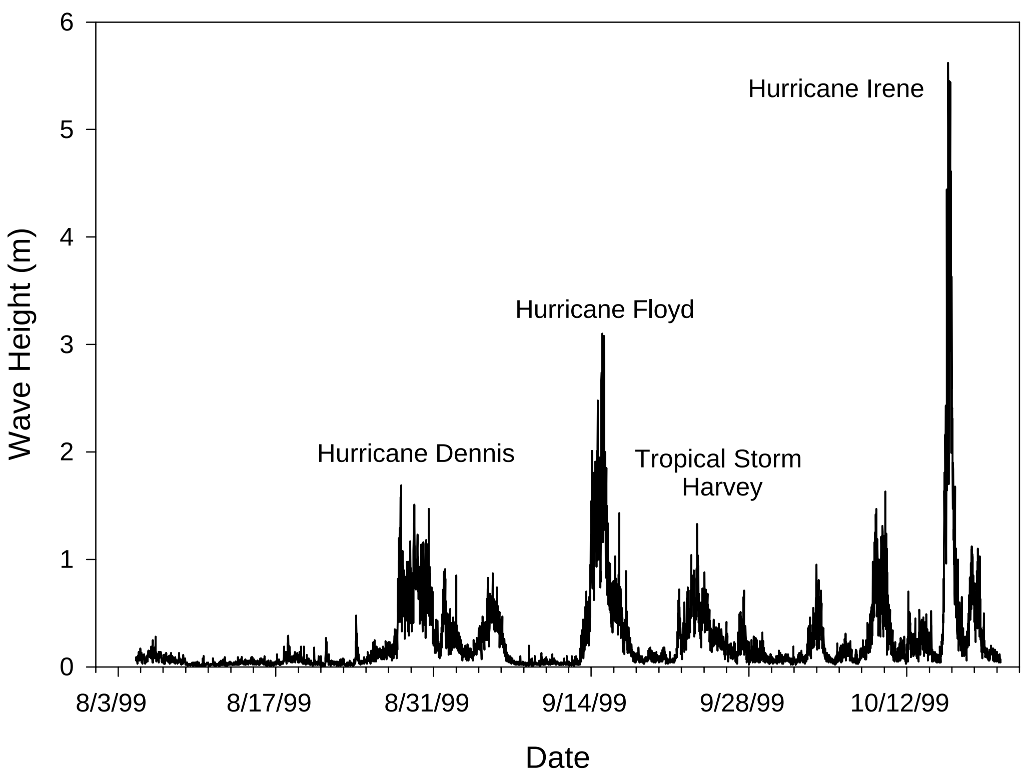

Figure 4: Wave heights during the passage of four tropical systems.

Suspended solids concentrations averaged 3.2 mg/l with maximums reaching 176 mg/l during Hurricane Irene. Concentrations remained below 40 mg/l outside of the passage of the tropical systems. Sustained elevated SSCs occurred primarily under conditions of elevated wave activity. Figure 5 shows the SSCs for the same tropical systems shown in figure 4. There appears to be a threshold wave height of approximately 0.5 meters below which SCCs remain below 15 mg/l. It is also noted that the shorter period waves (ie. wind waves) produce lower SSCs than do corresponding longer period waves (swell) of similar wave heights.

Seasonal differences in the SSCs are apparent. For example, for the two summer months analyzed, the mean SSC was 1.7 mg/l with a maximum of 20 mg/l. For the two months in the fall during the peak hurricane period, the average SSC increased to 4.7 mg/l with a maximum of 176 mg/l. Winter months conditions fell between summer and fall. The average SSC for the winter period was 3.1 mg/l with a maximum of 39 mg/l.

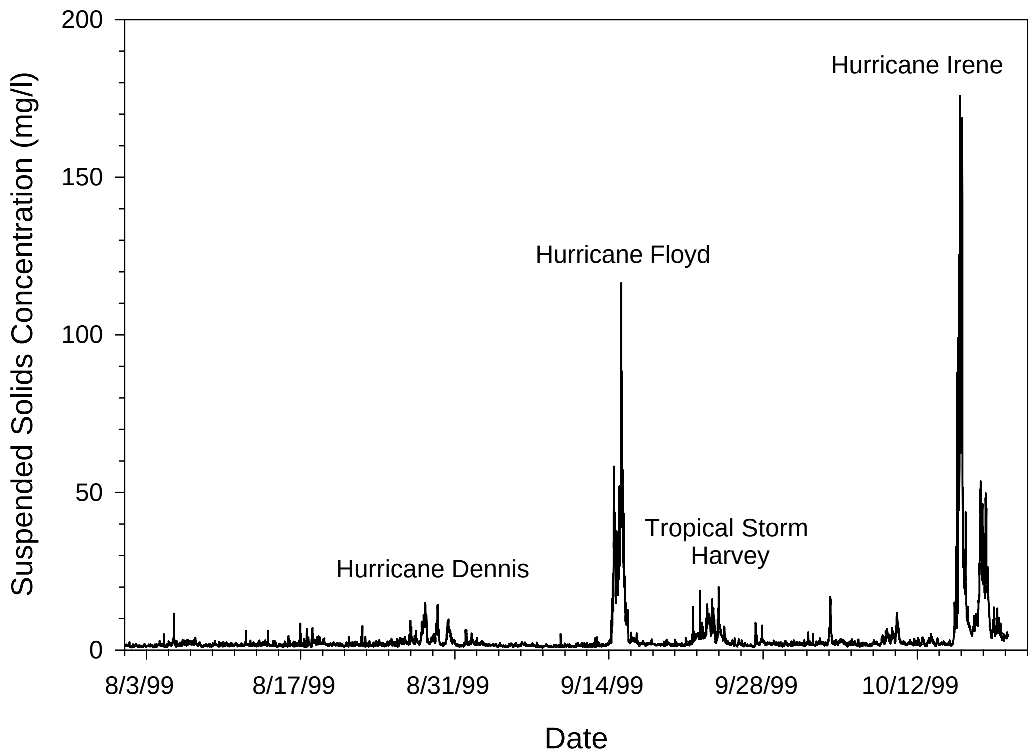

Figure 5: Suspended solids concentration during the passage of four tropical systems.

Guidelines

Preliminary guidelines based on the data to date have been developed for the summer, fall and winter seasons for illustrative purposes. The intensity guidelines and the duration and intensity threshold concentrations are shown in Table 1. The maximum duration (duration guideline) for exceedence of the threshold concentrations are 90 minutes for summer, 1050 minutes for fall and 480 minutes for winter. Shorter periods in excess of this threshold concentration are allowed, but only at the frequencies specified in Tables 2 through 4.

Table 1. Mean SSCs, Intensity Guidelines and Threshold Concentrations

Season	Mean SSC (mg/l)	Intensity Guideline[1] (mg/l)	Threshold Concentration[2] (mg/l)
Summer	1.7	5.8	3.1
Fall	4.7	54	17
Winter	3.1	14	8.1

[1]Maximum SSC allowed at coral community
[2] SSC to be exceeded only for periods and frequencies provided in Table 2, 3 and 4

Table 2. Summer Duration and Frequency Guidelines

Duration Class (Consecutive minutes in excess of 3.1 mg/l)	Allowable Exceedences per Week
<10	17
11 - 20	11
21 - 40	9
41 - 50	7
51 - 70	5
71 - 90	3
> 90[1]	0

[1]Duration Guideline

Table 3. Fall Duration and Frequency Guidelines

Duration Class (Consecutive minutes in excess of 17 mg/l)	Allowable Exceedences Per Week
<10	7
11 - 20	4
21 - 170	3
171 - 410	2
411 - 1050	1
> 1050[1]	0

[1]Duration Guideline

Table 4. Winter Duration and Frequency Guidelines

Duration Class (Consecutive minutes in excess of 8.1 mg/l)	Allowable Exceedences Per Week
<30	4
31 - 50	3
51 - 170	2
171 - 480	1
>480[1]	0

[1]Duration Guideline

DISCUSSION

The preliminary guidelines calculated above show distinct seasonal differences. The least restrictive guidelines occur during the fall when the passage of tropical systems is most likely. This results in elevated SSCs for longer durations. Comparison of the seasonal intensity guideline and threshold concentrations to those values predicted by Thevenot (1995) indicates that dredged material disposal plumes are unlikely to match those created by nature during the frequent tropical systems found in the fall. Modeling by Thevenot (1995) estimated that maximum concentrations at the reefs due to disposal are expected in the 6 to 10 mg/l when currents are in the direction of the reefs. During the winter season, the intensity guideline is unlikely to be exceeded due to disposal. However, it is possible that the threshold concentration could be exceeded and the duration and frequency guidelines would have to be considered. Summer appears to be the critical season as it is when the most restrictive guidelines occur. Both the intensity guideline and threshold concentration are low and the duration guideline is short. Peak concentrations predicted by Thevenot exceed the threshold value and are in the range of the intensity guideline. However, the frequency guideline is much greater allowing more numerous exceedences of the threshold concentration.

It has yet to be determined exactly how the guidelines will be used to manage the Miami ODMDS. One option is to establish a single set of guideline values for an entire year. However, it is more likely that a limiting season or seasonal guidelines will be used. A factor to be considered is the most critical time for coral growth and reproduction or other important life history stages. The use of yearly guidelines during a critical season is likely to be inappropriate. A more likely management option is that unrestricted disposal will be allowed outside the summer season. For disposal during the summer window, the existing requirement of a real-time current monitoring system or other management measure to insure compliance with the guidelines would likely have to remain in effect.

CONCLUSION

An alternative method for the protection of coral reef communities in South Florida from impacts due to dredged material disposal has been proposed. This method assumes only that suspended sediment loads are one of the abiotic determinants of coral reef community structure and that excess loads may have deleterious effects on coral health and community fitness. It makes no assumptions regarding:

- the biological structure of the coral community;
- the present condition of the coral community with regard to health or trends (decline, growth, etc.);
- the presence and effects of other types and sources of coral community stress; or
- physical or chemical characteristics of the disposed dredged material such as particle size or shape that may affect coral health and community fitness.

Implementation of the method has shown that modeled suspended solids loads due to dredged material disposal are in the range of natural occurring SSCs at the Miami, Florida coral reef communities. The naturally occurring SSCs are variable with extreme events lasting more than a day. Most elevations in SSCs are due to elevations in wave activity. The most extreme events are associated with tropical storms and hurricanes occurring during the fall, whereas summer and winter are relatively calm.

Although preliminary, analysis of the time series data to date shows that guidelines for intensity, duration and frequency of elevated SSCs due to dredged material disposal can be developed based on the natural variability at the area of concern. These limits will assure that disposal will not disrupt the natural conditions. Additional data collection is needed to extend the data set into the spring season and to account for annual differences. To implement the guidelines, additional modeling of the disposal plumes and their visitation frequencies will be required. Once completed, appropriate management options can be developed to protect the reef communities and allow disposal without or with a reduced need for the existing expensive real-time current monitoring system.

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