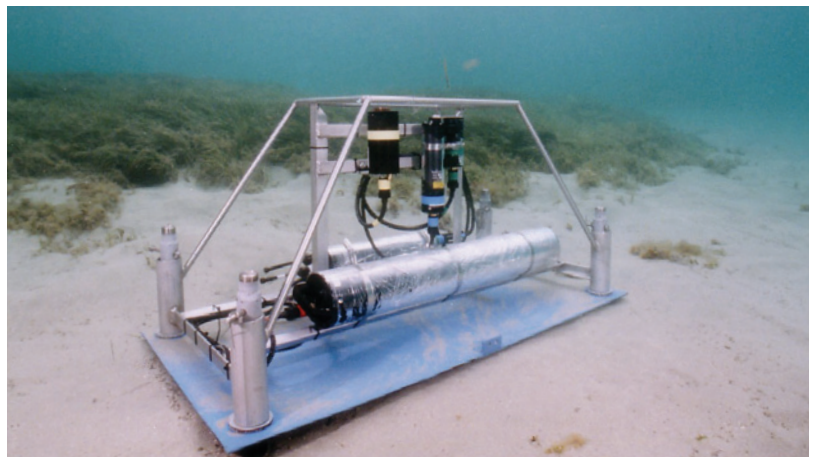


A CEDA Information Paper

ASSESSING AND EVALUATING ENVIRONMENTAL TURBIDITY LIMITS FOR DREDGING



A CEDA Information Paper

ASSESSING AND EVALUATING ENVIRONMENTAL TURBIDITY LIMITS FOR DREDGING

Copyright notice

The contents of this paper are © Central Dredging Association (CEDA). Permission is given to reproduce this document, in whole or in part, provided that the copyright of CEDA and the source are acknowledged. All rights reserved.

Citation

CEDA (2020). *Assessing and Evaluating Environmental Turbidity Limits for Dredging* [online]. Available at: <http://www.dredging.org/media/ceda/org/documents/resources/cedaonline/2020-05-AETL.pdf>

Central Dredging Association (CEDA)

Radex Innovation Centre
Rotterdamseweg 183c
2629 HD Delft
The Netherlands
T +31 (0)15 268 2575
E ceda@dredging.org

Table of Contents

1	Introduction	3
2	Approach.....	4
3	Definition of Turbidity Used in this Document	4
4	Building a System Understanding	4
4.1	General	4
4.2	Metocean conditions	4
4.3	Natural sediment dynamics	6
4.4	Biology.....	6
4.5	Anthropogenic conditions	6
5	Planned Works	7
5.1	General	7
5.2	Dredging methods, volumes and expected spills.....	7
6	Sensitive Receptors, Threshold and Trigger Levels... 7	
6.1	Identification of sensitive receptors.....	7
6.2	Identification of influencing factors	8
6.3	Definition of threshold values.....	10
6.4	Definition of trigger levels.....	11
6.5	Trigger level evaluation and monitoring programme definition	12
6.6	Monitoring parameters	12
6.7	Intensity and duration.....	13
6.8	Location	13
6.9	Frequency.....	14
6.10	Depth	14
7	Turbidity Monitoring	14
8	Discussion and Recommendations for Setting Turbidity Limits	15
	References	17
	Glossary	19

ASSESSING AND EVALUATING ENVIRONMENTAL TURBIDITY LIMITS FOR DREDGING

This paper has been prepared by the Central Dredging Association (CEDA) Working Group on Assessing Environmental Turbidity Limits (WGETL). The Working Group was initiated by the CEDA Environment Commission.

1 Introduction

Dredging is often essential for the maintenance and development of ports, harbours and waterways to allow for safe navigation, remediation and flood management. The process, which relocates large volumes of sediment, can be accompanied by the release of suspended sediments into the water column (sediment plumes). Excessive suspended sediment concentration has an impact on water transparency (as a result of increased turbidity) and may cause the degradation of water quality and marine ecosystems.

Mitigating these impacts is usually managed by limiting the amount of suspended sediments released at the dredging sites or entering sensitive areas. For dredging projects around the world, many different limit definitions and corresponding turbidity monitoring methods have been applied. However, the basis or background of these definitions is not always clear. Sometimes a very strict, or alternatively very ambiguous, definition of the turbidity limits can have a serious impact on the project execution methodology, proposed by bidding contractors, and thus on the cost of the project. A very loose definition of the turbidity limits can additionally have a huge impact on the local environment. In many cases, turbidity limits may even appear to be defined without consideration of the specific sensitive receptors that are supposed to be protected. One potential risk that may result is that, on the one hand, the turbidity limits may be overly conservative, while on the other hand, they may also be inadequate in protecting the sensitive receptors.

In 2016, the CEDA Environment Commission (CEC) conducted a survey, among a wide range of companies and institutes working with dredging, to investigate which environmental turbidity limits existed for dredging projects, how these limits were set and

how the environmental limits affected the projects both financially and time-wise. Interestingly, the survey showed that compliance monitoring on average contributed about 1–5% to the cost of the dredging project.

The majority of the respondents indicated that they understood and supported the need for environmental turbidity limits. However, the replies also showed that a major proportion of the limits did not seem to be scientifically or environmentally founded. Limits varied regionally and by project, but rarely seemed to be linked to local sensitive receptors. Taking into account the generally high costs of compliance monitoring, and the environmental risk that a limit is set incorrectly, the CEC raised the following question: *Is there a need for guidelines on how to set realistic and effective environmental turbidity limits for dredging?*

The results of the questionnaire imply that there is such a need. However, setting a reasonable turbidity limit for a given dredging operation that provides adequate protection for the environment, but that gives sufficient flexibility in the selection of a dredging approach, and does not entail excessive costs for monitoring the dredging operation, is not an easy task. It requires an understanding of the dredging operation, and dredging spill processes, as well as how the local environment works in terms of hydrodynamics, sediments and biology. Furthermore, it is necessary to consider socioeconomic aspects such as visual disturbances and impacts on water intakes.

This paper aims to highlight a general approach to set or discuss turbidity limits for dredging applications. Connections to background information, monitoring and management measures (as relevant where exceedance occurs) are provided.

2 Approach

This paper is based on the assumption that setting turbidity limits requires a general understanding of dredging processes as well as the surrounding environment. The approach is thus an integrated approach that takes all aspects into account. The main required aspects for a general integrated approach are an understanding of:

- the baseline conditions for hydrodynamics, sediments and biology;
- the dredging operations in terms of locations, volumes and spills;

- the sensitive receptors and their tolerance levels;
- possible monitoring programmes; and
- possible response options.

To implement this approach, a typical flowchart for managing environmental turbidity limits in a dredging operation is shown on the following page. In this figure the different parts of the flowchart (*Figure 2-1*) and the interactions between them are highlighted. This flowchart will form the basis of this paper.

3 Definition of Turbidity Used in this Document

The term 'turbidity' is well established in the dredging world and is adhered to throughout this document. It is often used for a number of aspects related to sediment in the water, from actual concentrations to water clarity (Department of Water, 2009; Fearn et al., 2017; United States Environmental Protection Agency, US EPA, 2012; United States Geological Survey, USGS, 2017). However, in its correct usage, the term 'turbidity' solely refers to the effect of suspended sediment measured by a turbidity sensor (ISO, 2014). Therefore, one must understand that 'turbidity' is a proxy for 'suspended sediment concentration'.

Turbidity can be measured and reported in terms of NTU, FTU, SSC, TSS and several other ways. However, it is important to note that NTU and FTU pertain to light scattering in the water, whereas SSC and TSS relate to the amount of sediment suspended (e.g. American Society for Testing and Materials, 2013; Neukermans et al., 2012).

In this document, the term 'turbidity' refers to the popular use of the word and thus covers all kinds of measurable environmental parameters (e.g. turbidity, suspended solids, sedimentation, light attenuation) that can be directly linked to the creation of suspended sediment plumes and associated environmental impacts.

4 Building a System Understanding

4.1 General

Before setting any limits, it is important to understand the physical and biological patterns of the local system in term of its background turbidity, natural variations and adaptation of local sensitive receptors. The following factors need to be investigated:

- metocean conditions;
- sediment dynamics;
- biological aspects; and
- anthropogenic conditions.

4.2 Metocean conditions

Metocean conditions cover the actions of weather, and waves and currents in an aquatic system. Waves and currents generate turbulence and hence control the erosion, transport and deposition of suspended sediments. One should always gather enough background knowledge to understand how the system works. More specifically:

- what kind of water system it is: marine, harbour, navigational channel, river, lake, transitional water, or combined system;
- morphology and bathymetry within the area;

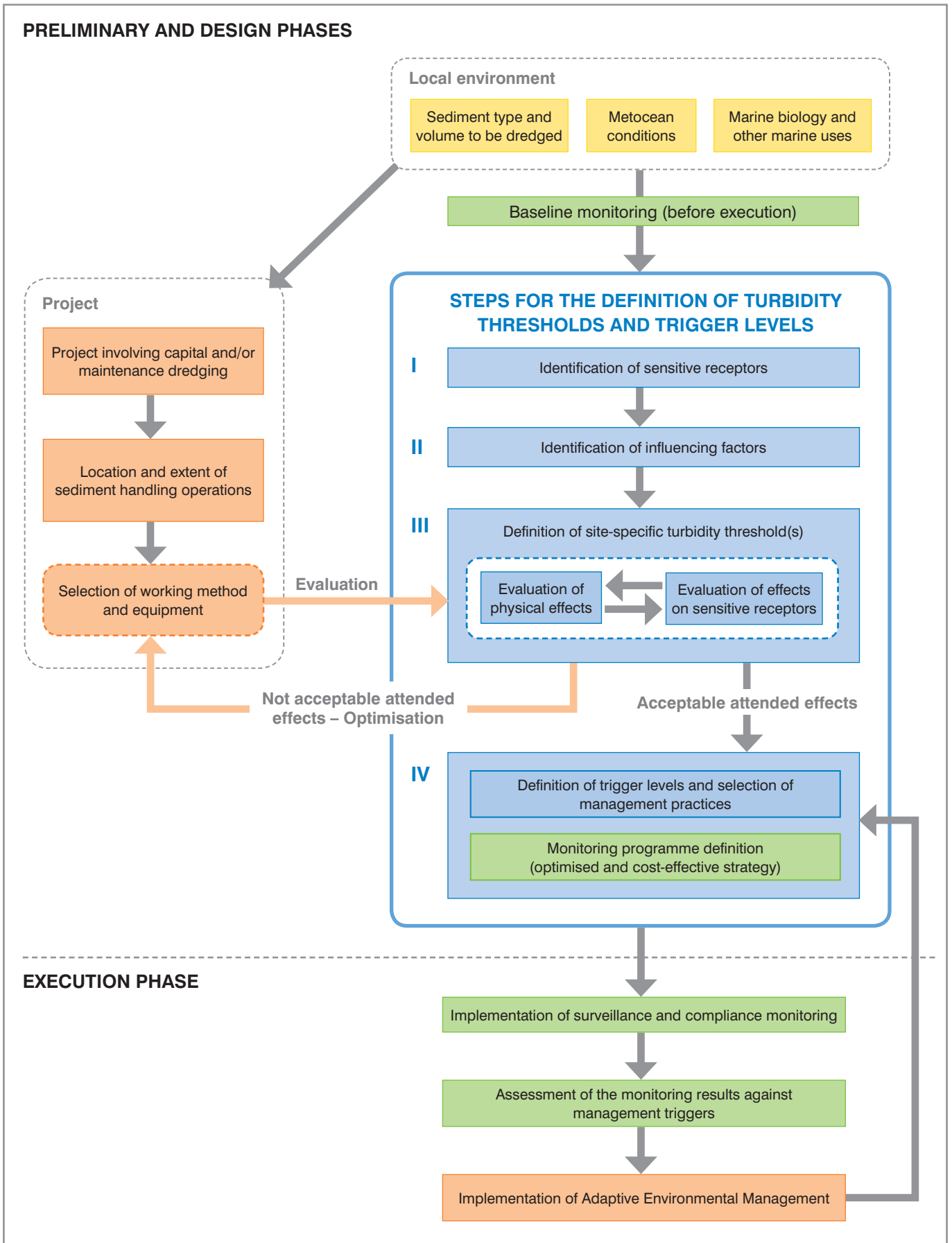


Figure 2-1: Typical flowchart for environmental management in a dredging operation.

Metocean conditions cont'd:

- flow, tidal and wave conditions;
- exposure of the area to waves: exposed, semi-sheltered or sheltered;
- river inflows, stratifications;
- timescale of variations in hydrodynamic conditions (e.g. rapidly changing, seasonal, yearly); and
- impact of the project design itself or adjacent project under construction.

This will provide a starting point to highlight which phenomena are important for the erosion, deposition and spreading of sediment. In many cases, simple observations of the hydrodynamics can provide valuable information on the sediment transport patterns prevailing in an area. For instance, deep waters are not usually influenced by waves. Moreover, a high-energy open coast will not allow the long-term sedimentation of fine sediments, whereas low-energy marsh areas probably will. It is also important to establish whether there are seasonal variations such as summer or winter, or a dry or wet season, as these may imply different impact levels for a dredging operation.

4.3 Natural sediment dynamics

Once the metocean conditions have been characterised, it is important to establish how they affect the natural background turbidity levels and what these are. The interaction between the behaviour of the sediment under the influence of the metocean conditions is too complex to be described here (see for instance, Whitehouse et al., 2000 for detailed information). Information on sediment types and characteristics, natural background concentration levels and their variability, as well as knowledge of local sources and sinks of sediments, are crucial. Local flora and fauna are generally adapted to the local light and coverage conditions and thus knowledge of these aspects is essential as they govern the existing conditions for life.

Local waves and velocity fields typically generate a bottom shear stress that affects the erosion and deposition of sediments. In particular, sediment starts to be eroded when a certain shear stress threshold is exceeded and keeps eroding until either no more sediment is available or the shear stress falls below the threshold. The eroded sediment is transported for as long as the energy conditions allow it. At a lower threshold energy level, the sediment will be deposited. The frequencies of this determine the local

concentration, light and coverage conditions.

In the case of fine sediment, flocculation may occur, influencing the settling velocities and thus deposition. Flocculation is a property of cohesive sediments during which individual particles tend to stick together to form flocks or larger aggregates (Grabowski et al, 2011; Winterwerp & Kesteren, 2004).

4.4 Biology

The critical thresholds for turbidity and sedimentation, as well as the duration of periods of high turbidity or excessive sedimentation that affect a species' survival, vary greatly among species and their distances from the intervention sites. Therefore, it is very important to recognise and evaluate the natural conditions of local flora and fauna before dredging activities start.

Flora and fauna species in the marine environment are generally acclimatised to the local light and coverage conditions and to the prevailing hydrodynamics, water quality and sediment composition. Thus, knowledge of these aspects is essential as they govern the existing conditions for life. For example, light-sensitive species, and species that are very sensitive to coverage by sediments, will not generally be found in highly turbid environments, while the opposite may be possible. Moreover, other species might have a different degree of sensitivity to turbidity variations in relation to their geographical distribution (e.g. Anchor Environmental C.A. L.P., 2003; Bridges et al., 2008; Erfteimeijer & Lewis, 2006; Erfteimeijer et al., 2012; Paganelli et al., 2014; Tillin et al., 2011). The presence of certain species may also provide information about the sediment types and dynamics in an area. Usually, the governing factors for aquatic life are available light and sensitivity to burial. It is important to note that there might be particular times of the year where the susceptibility to environmental stress caused by high turbidity may be greater, for example considering shellfish during the spawning period. Therefore, it is crucial to develop adequate knowledge of local light conditions and local species' sensitivity to changes in light. Furthermore, resilience to (cyclic) coverage by sediments needs to be studied. It is necessary to recognise the distribution and the ecology of the species present in an area, noting that the most sensitive species are often classified as sensitive receptors.

4.5 Anthropogenic conditions

Local anthropogenic activities are connected to the

various physical, legal and optical properties of the water body and are often vital to local communities and other sea users. Water intakes, local recreational areas, such as beaches, and tourist attractions may be of

great socioeconomic importance, relating for example to water clarity and aquaculture in general. Therefore, it is important to map these anthropogenic activities.

5 Planned Works

5.1 General

Once an environment has been evaluated in terms of its metocean conditions, sediment and biology, and present anthropogenic activities, the expected effects of planned works on turbidity, and possible impacts on local conditions, can be assessed. This generally involves describing the anticipated dredging plan, volumes and methods, as well as the resulting turbidity generated and how its impacts can be managed.

5.2 Dredging methods, volumes and expected spills

It is important to clarify how the dredging operation will be performed. The turbidity created will be dependent on the dredging method and its duration. The possible long-term effects on the background turbidity depend on the volume of sediment released, and the time period over which it is released, in addition to the metocean conditions. It is therefore crucial to estimate

the short- and long-term turbidity variations that are due to the dredging operations. To estimate the impact on the environment, it is also essential to determine the type of material to be dredged or released, as the properties of the sediment may differ from the native surface sediment.

In addition, it is essential to establish how, where and when, the relocation of dredged material is planned to occur. Typical spill rates (amount of fines transferred to the far field) can be seen in John et al., (2000). The parameters that are important when establishing the spill rate and the overall spilled volume or mass are as follows (for example, see Becker et al., 2015):

- dredging method, location and planning;
- dredged volume;
- dredging production rates; and
- composition and optical and physical properties of dredged material.

6 Sensitive Receptors, Threshold and Trigger Levels

In the early phases of a project, a crucial step is to identify the presence of sensitive receptors, and to build a proper system understanding, in order to assess turbidity-related influencing factors, identify threshold levels (critical stress levels), and finally select trigger levels to protect the sensitive receptors. This four-step process is illustrated in Figure 6-1.

As far as possible, this approach should be performed based on local knowledge, available via, for instance, local consultants, research institutes, users of the water body in question, and historic information. Moreover, one should implement one or more proper environmental baseline survey(s). The different terms will be defined in the following sections.



Figure 6-1: Flowchart for selecting trigger levels with emphasis on sensitive receptors.

6.1 Identification of sensitive receptors

Identifying the sensitive receptors is a key step in the integrated approach to determine the turbidity limits. This step is marked in Figure 6-2.

Sensitive receptors (sometimes referred to as receivers) may include species, habitats, resources, and activities or items located in the area of influence of the project, that are identified as being of importance and that might be affected by the increased turbidity



Figure 6-2: Flowchart for selecting trigger levels with emphasis on sensitive receptors.

associated with the dredging operations.

The potential sensitivity of the receptors to dredging works (and induced turbidity) is determined by the combination of their own characteristics and functionalities, on the one hand, and the characteristics of the natural system, in which they are located and where the works will occur, such as coastal morphology, sediment type, metocean and anthropogenic pressures on the other. Sensitive receptors are generally adapted to their local ecosystem (e.g. offshore, coastal waters, coastal lagoon) and its natural variations (e.g. season, tide, flood). Any change could affect the sensitive receptors for a short duration (days to months), a

longer period (months to years), or even lead to irreversible damage. Thus, the identification of the presence of sensitive receptors is crucial to properly assess the relationship between the physical effects (described in terms of intensity, duration and frequency) and the potential impacts caused by dredging.

6.2 Identification of influencing factors

Following the identification of sensitive receptors, it is important to recognise the factors related to the works influencing or stressing each receptor in order to plan proper monitoring and management measures. See Figure 6-3.



Figure 6-3: Flowchart for selecting trigger levels with emphasis on the influencing parameters.

Elevated turbidity due to dredging can affect the sensitive receptors (i.e. through light reduction, sediment re-deposition, contaminant and nutrient release and burial phenomena). For instance, in the case of corals, both increased light reduction and burial phenomena due to sedimentation, are influencing factors, whereas for water intakes it is only the sedimentation and the increase in suspended sediment in the water column that are of concern. It should be taken into account that some sensitive receptors are more vulnerable during certain periods of the year (e.g. water quality is most important during the bathing season in bathing areas). For benthic species, critical or sensitive periods of the life cycle (e.g. recruitment, deposition, reproduction) must be taken into consideration in order to identify the optimal periods

(i.e. environmental windows) in which dredging can be performed with an acceptable impact on biological resources. For instance, some mammals are only present seasonally and seagrasses are most vulnerable to coverage during the growth period.

Table 1 presents a list of receptors that are potentially sensitive to increases in suspended sediment, and outlines the factors that influence them (i.e. increase in turbidity and re-deposition). This table should be considered as a guidance tool to be used by project managers, consultants and decision makers, in the early stages of a project. The information provided in the table should always be completed and confirmed with site-specific information, gathered during the environmental and social impact assessment studies to be performed during the design phases of the project.

Table 1: List of sensitive receptors (categorised as “Habitats and species” and “Marine uses”) that are potentially affected by increased turbidity and suspended sediment re-deposition. The reader should refer to specific scientific references for further details on receptors’ responses.

Sensitive receptor(s) type	How changes in turbidity or re-deposition may have negative impacts on sensitive receptor(s)	Sensitive to turbidity	Sensitive to re-deposition	Fixed receptor	Mobile receptor
Habitats and species					
Seabed habitats/ benthic communities	Increased turbidity and re-deposition may have temporary or permanent effects in terms of smothering, damage to feeding and respiratory systems, and changes in benthic community structure and composition (e.g. abundance, diversity, biomass).	●	●	●	
Coral reef	Increased turbidity may affect photosynthetic ability. Re-deposition may lead to smothering and burial of polyps, and growth of bacteria in coral mucus. Turbidity and re-deposition may also reduce recruitment and survival of coral larvae.	●	●	●	
Aquatic macrophytes/ seagrasses	Increased turbidity may lead to light attenuation with significant effects on seagrass plants, microphytobenthos and macroalgae. Increased re-deposition may result in burial phenomena on plants and reduce vitality or death among associated benthic fauna.	●	●	●	
Mangroves	Increased turbidity does not <i>per se</i> affect mangroves unless the sediments are contaminated. In addition, excessive re-deposition may smother the mangrove roots.		●	●	
Shellfish	Increased turbidity and re-deposition can affect filter-feeding systems of shellfish (e.g. oysters, mussels), with possible effects on pseudo-feces production, the amount of algal food ingested and on bivalve gills (clogging).		●	●	
Fish	Increased turbidity can affect visibility, reducing feeding and hunting ability, and growth rate in juveniles. High suspended sediment concentrations can affect fish gills, eggs and larvae.	●	●	●	●
Wildlife	Increased turbidity may affect the predatory capacity of wildlife (e.g. marine mammals, turtles, seabirds). Other potential effects may be related to noise production, food availability and collision risks.	●			●
Marine uses					
Bathing water quality	Increased turbidity can lead to temporary changes in water colour. Presence of contamination (e.g. faecal bacteria) associated with suspended sediment can directly affect public health, especially during the bathing season.	●		●	
Aquaculture/ shellfish farms	Increased turbidity can affect primary production and bivalve growth. Sediment re-deposition can damage farm structures (see fish and shellfish).	●	●	●	
Recreational areas and tourism	Increased turbidity can lead to temporary or long-lasting changes in water colour. Moreover, even in the absence of contamination, possible misunderstandings and complaints from beach users may see tourism and associated activities affected.	●		●	●
Infrastructure, navigation	Excessive re-deposition near structures (e.g. quay walls, jetties, outlets) and navigation channels may lead to functional issues (e.g. operability, maintenance).		●	●	
Fishery	For extensive dredging, increased turbidity can hinder some fishery practices. Fishery areas may be modified: on a short-term basis, if fish communities temporarily avoid turbid waters; on a long-term basis, if fish are affected during sensitive stages of the life cycle. Particular attention must be paid to the presence of nursery and reproduction areas (in particular for demersal species with commercial value).	●		●	●
Cultural heritage	Increased turbidity can lead to change in water colour and re-deposition, with socioeconomic impacts on cultural heritage and historical sites.	●	●	●	
Water intake	Increased turbidity and re-deposition can lead to water supply shortages (e.g. industrial/drinking water supply) with both socioeconomic and sanitary impacts (e.g. public health).	●	●	●	

6.3 Definition of threshold values

It is not only the sensitive receptors that need to be defined, but also the threshold values at which the receptors may exhibit increasing impacts. This is illustrated in Figure 6-4. The threshold values may be

defined specifically at the receptor or, alternatively, as a more general parameter for the area. Note that the threshold values can be defined in many ways. They are often defined as stress levels for a given receptor at a given site.



Figure 6-4: Flowchart for selecting trigger levels with emphasis on the threshold values.

There is a distinctive difference between turbidity thresholds and trigger levels. Threshold values for a dredging activity must be defined starting from information about site-specific environmental parameters, their variation and the tolerance of all receptors identified as sensitive. When a tolerance threshold value is exceeded, the sensitive receptor is expected to experience a certain amount of stress or disturbance. A nature-based approach demands that the acceptability of such effects must always be evaluated against the characteristics of the system where the dredging activities occur. A scientifically sound approach by which to do this is through the use

of a species response curve. Such curves describe the response of individual species (such as a specific coral type or seagrass type) as a function of the intensity and the duration of increased stress (after Erftemeijer et al., 2012). Figure 6-4 shows that a temporary slight elevation of turbidity may be considered unlikely to cause serious effects on a sensitive receptor. Instead, a short, high peak of turbidity (leading, for example, to the total sediment coverage of a biotope caused by sediment re-deposition), or a slight elevation of turbidity over a long period of time, may ultimately have serious consequences.

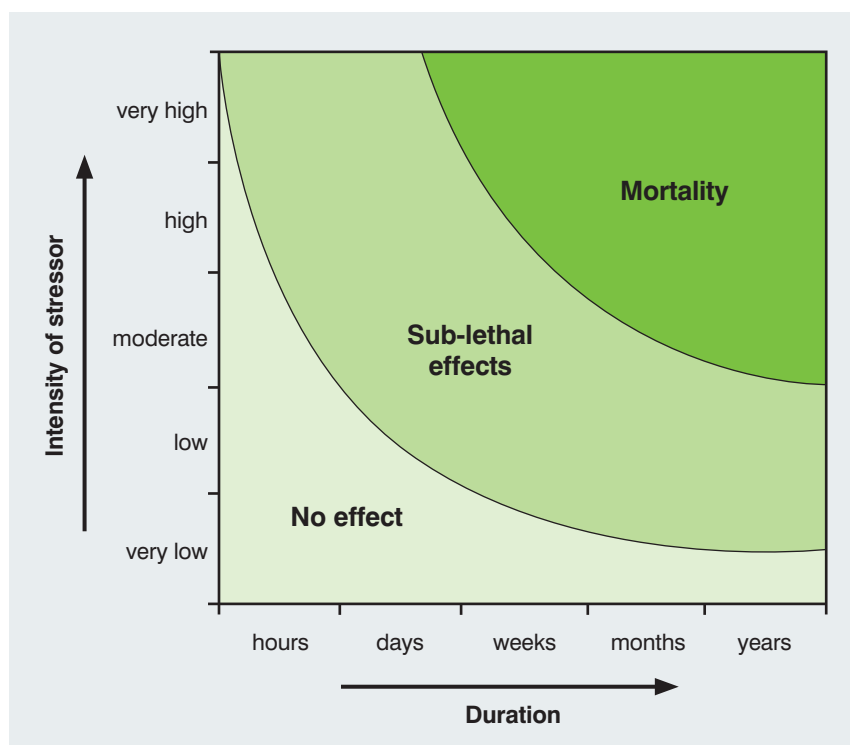


Figure 6-5: Intensity-duration relationship (after Erftemeijer et al., 2012) based on the species response curve for species and biological sensitive receptors.

Using the species response curve approach, and borrowing the classification proposed by the Australian Environmental Protection Agency (EPA, 2016) as a starting point, the next step is to define the threshold levels at which the receptor shifts from a status of acceptable effect to an impact with increasing severity (moderate and high).

The relationship between the intensity, duration and frequency of perturbation and the associated environmental effects on the specific receptor, can be

derived on the basis of site-specific data, the literature data, or by expert judgement concerning the site-specific receptor's tolerance limits. For this purpose, site-specific data should be available and/or inferred from specific stress response curves related to the expected water quality variation during execution (see Figure 6-5). These studies should ideally be based on either direct experience in the context of dredging from previous projects or specific tests performed on sensitive receptors.

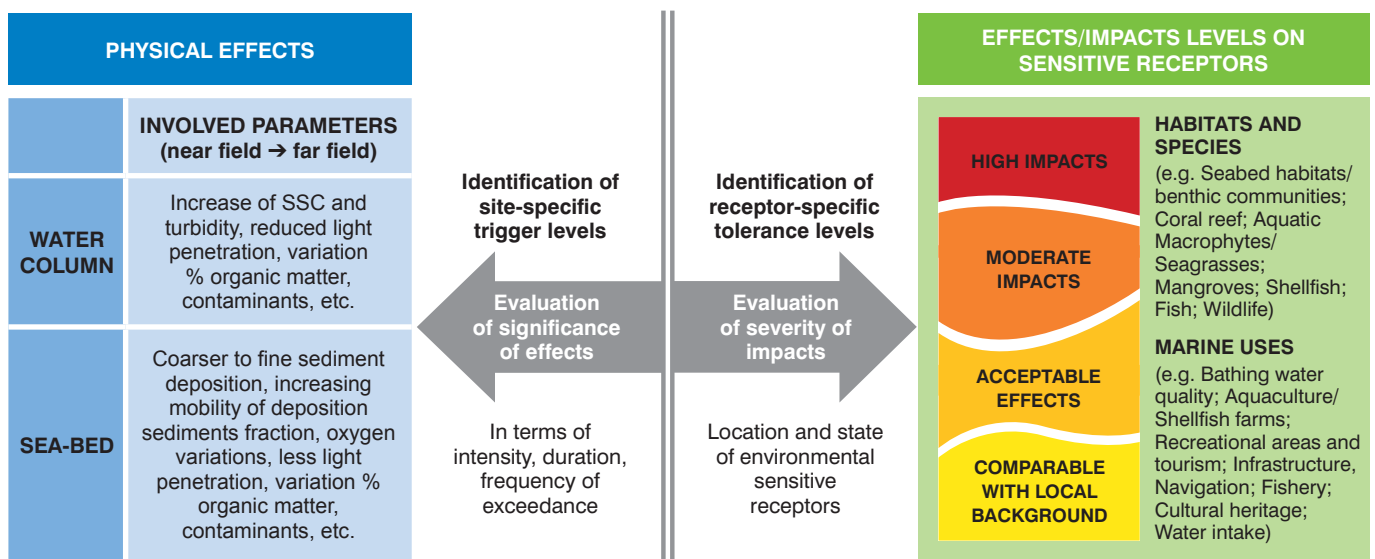


Figure 6-6: Scheme of the relationships between the significant physical effects, and the impacts on the sensitive receptors, related to the threshold levels defined as a function of the status of the sensitive receptors. Refer to the EPA (2016) for the classification of moderate and high impacts related to changes from the background conditions. Modified from Lisi et al. (2019).

Nevertheless, information from the literature is not always available or useful. It may therefore be necessary to deduce site-specific thresholds from a baseline monitoring campaign, preceding the execution of the dredging works, in order to determine the variation in the natural levels of turbidity. The reasoning here is that if a biological sensitive receptor is able to live in a certain location, it must be adapted to withstand the natural stress levels occurring, hence baseline monitoring can be crucial to determining reasonable and realistic thresholds (e.g. Clarke et al., 2000; Erftemeijer et al., 2012). Depending on the environment and planning in question, it may be challenging to obtain a sufficiently large set of data when no proper assessment has been performed

during the design phase of the project. It must be noted however, that the processing and the interpretation of a baseline monitoring data set, for the establishment of site-specific threshold levels, represents a complicated matter. The more dynamic the natural background concentration levels, the more difficult it is to adequately define this reference state with only a moderately long time series. Therefore, this is a task that requires local insight and specialist knowledge.

6.4 Definition of trigger levels

Once the thresholds levels related to the sensitive receptor(s) present in the area of influence of the works have been determined, it is good practice to define a set of trigger levels for each type of material to be

dredged and each receptor. In addition, one should define each trigger's response in terms of how the

dredging operations should proceed. This is illustrated in Figure 6-7.



Figure 6-7: Flowchart for selecting trigger levels with emphasis on the trigger values.

The trigger level is the turbidity level that needs to be respected to ensure that the threshold levels are not reached. It is thus a specified criterion used for the management of the dredging operations. When a trigger level is exceeded, the need for a management action will be assessed and, if necessary, implemented to prevent undesired/negative impacts.

A typical approach is to define three different types of trigger levels:

- warning level: indicating an increase in turbidity levels, providing time to investigate the causes and anticipate/identify possible solutions;
- action level: indicating that the levels have continued to rise and that mitigation measures need to be taken to prevent the impact level from being reached; and
- impact level: indicating that the increased turbidity levels have the potential to harm the sensitive receptors and that urgent action needs to be taken to reduce them below the impact level or the action level.

Trigger levels should be monitored either at the receptor or at a location at which the response at the receptor is known.

6.5 Trigger level evaluation and monitoring programme definition

There are many different ways in which trigger levels and monitoring programmes are defined worldwide.

Typical environmental questions to be answered in the early preliminary planning phases are:

- What types of sediment spill sources could be expected/distinguished (e.g. single spill event, continuous point spill over a certain period)?
- Will suspended sediments leave the dredging or relocation site?
- Where will the material go and how much material will remain in the water column after a certain period of time?
- Which sensitive receptors could be involved and how?

Listed below are the criteria that need to be addressed in order to provide a clear definition of limits and to develop a monitoring programme that can effectively implement them:

- parameters;
- intensity and duration;
- location;
- frequency; and
- depth.

A good monitoring strategy involves an analysis of the sensitive receptors at risk and the selection of relevant monitoring parameters, equipment and locations (CEDA, 2015; CEDA/IADC, 2018). It is also important to recognise here that the monitoring of sensitive receptors, that are not directly at risk, may help to constantly redefine the baseline (or background) conditions and prove the validity of assumptions, regarding the absence of impacts on the sensitive target receptors, specifically selected before the operations proceed.

6.6 Monitoring parameters

The parameters that need to be monitored must be clearly defined. This is typically undertaken when determining the influencing factors, as these parameters govern the possible impacts. Typical (not limited) monitoring parameters may be defined in terms of:

- turbidity (e.g. NTU, FTU);
- total suspended solids (TSS, SSC);
- photosynthetically active radiation (PAR);
- metocean conditions (e.g. wind, waves, tide, currents, temperature, salinity);
- sediment properties and deposition rate; and
- biological response (e.g. marine conditions of habitats and species) and other parameters related to environmental impacts.

Even though reduced PAR, elevated sedimentation and elevated TSS levels constitute the parameters

that are ultimately related to environmental impacts, their principles of measurement have limitations and present challenges that are not within the scope of this article (for these, the reader should refer to CEDA/IADC, 2018). For this reason, one often defines limits in terms of the simplest parameter that can be measured, such as NTU.

Measurements of physical parameters not directly related to water quality (e.g. currents, waves, tides) can provide information on the plume dispersion, in a particular area, as well as on the factors that cause additional turbidity.

6.7 Intensity and duration

Trigger levels may be defined as absolute values, levels relative to background or baseline conditions in terms of a so-called 'spill budget', or in more complex ways. All these approaches have specific advantages and limitations.

When using absolute fixed turbidity trigger levels, one can argue that naturally elevated turbidity levels (due for example to tidal and storm events) may result in limitations when dredging the site, regardless of the contractor's efforts, resulting in a considerable degree of uncertainty with respect to operational downtimes.

Turbidity trigger levels defined as a fixed value above background conditions have the advantage of allowing the contractor to develop an understanding of the additional turbidity that can be generated by the works. On the other hand, it is important to understand that, regardless of the source of the elevated turbidity, sensitive receptors may undergo a certain amount of stress once their specific turbidity threshold levels are exceeded (e.g. Erftemeijer & Lewis, 2006; Feola et al., 2016; Fisher et al., 2018; Fraser et al., 2017; Jones et al., 2016; World Association for Waterborne Transport Infrastructure, PIANC, 2010; Wilber et al., 2001). In other words, it is questionable whether it is wise to allow additional stress on the sensitive receptors at a time when they are already experiencing naturally elevated turbidity levels. Care should also be taken with levels that are expressed in terms of a percentage increase in turbidity above background, as these may lead to unrealistically low trigger values during periods of very low natural turbidity (for example 50% of 0 NTU = 0 NTU) and unrealistically high trigger levels during periods of high turbidity. While establishing trigger levels expressed as excess concentration, attention should also be paid to natural spatial heterogeneity in terms of the turbidity of certain areas.

As mentioned before, any evaluation of the significance of effects must necessarily consider different aspects of the induced perturbations to the environment, not only in terms of intensity, but also in terms of the duration and frequency of events exceeding the defined levels. Mathematical models are regarded as valuable tools in forecasting variations in turbidity and supporting decision makers (before, during and after execution) to optimise the interventions and monitoring actions, with regard to environmental and project objectives, while maintaining desired production rates (Lisi et al., 2019).

Another method used for defining trigger levels is the 'spill budget' method. The contractor is limited to the release of a certain amount of (fine) material that can be put into suspension over a certain period of time and within a certain spatial boundary. The 'spill budget' is usually estimated through modelling studies because, in reality, the execution of accurate monitoring campaigns within the dredging (spill) are very difficult. Given that modelling hypotheses can give an unrealistic estimation if spill data is unavailable for validation, best practice should include an optimised interaction, between models and monitoring, as part of a cost-effective approach. The reader is referred to CEDA/IADC (2018) for more details on the subject.

6.8 Location

A further item that needs to be clearly addressed, is the area within which the trigger levels are to be controlled and respected. Sometimes limits are defined within the dredging zone itself. However, in most cases this does not make sense as the creation of turbidity is inherently connected to the dredging process and turbidity levels, close to the dredger, may become very high and are related to near-field processes. While assessing turbidity levels and impacts, we should consider far-field processes (unless dredging occurs very close to a sensitive receptor) and their temporal scale (especially in the case of contaminated sediment).

Another location where trigger levels are often defined is at a certain fixed distance from the dredger (for example at 500 m, which may still be within the dredging zone). Here it must also be noted that most dredgers (CSD and TSHD) move during the dredging process. Not only does this make it difficult to define the exact location, it creates additional difficulties with respect to safe work and sailing practices. One example of a more pragmatic method is to define trigger levels at a specified distance from the dredging zone perimeter.

The most logical location at which to measure environmental impacts is close to the sensitive receptor itself. Depending on the location of the sensitive receptor, relative to the dredging zone, the monitoring locations can be placed in between the dredging zone and the sensitive receptor and can act as early warning sites. The distances between the monitoring locations should also be taken into account, in the monitoring strategy, as considerable sailing distances may render a plan unpractical or unnecessarily costly.

Understanding the advantages and limitations, of the various available sampling techniques, is important in determining the most cost-effective approach for sediment plume monitoring. In general, fixed stations are required for comprehensive and regular monitoring over time, for collecting the background conditions during different environmental conditions before the execution of the works, and for verifying the selected reference levels during their execution.

Furthermore, during the execution phase, mobile sampling stations (e.g. samplings from a vessel) may also be required to track the near-field plume through the water column and to perform measurements at various locations over short periods.

6.9 Frequency

Frequency criteria regarding monitoring should be clearly defined. Distinctions need to be made between:

- sampling frequency of monitoring devices;
- monitoring campaign frequency; and

- frequency at which the trigger levels are checked to ensure compliance.

Trigger levels can, for example, be compared to a moving average taken over several hours of data measured every minute. The monitoring campaign frequency may range, for instance, from once before or after the project, to a continuous regime of acquiring data. Indeed, the frequencies imposed in checking compliance often determine the eventual monitoring method that will be chosen. When a turbidity measurement is only sought once per day, or per week, it may make sense to use a monitoring vessel to travel to each location in turn and collect a reading. By contrast, when monitoring is to be carried out more frequently, it may be necessary to install continuous monitoring sensors, either on buoys or monitoring beacons, often with a telemetry link to deliver the data in real time onboard the dredger.

6.10 Depth

The depth at which the trigger level applies (i.e. depth of turbidity measurements) also needs to be clearly defined. In terms of technical challenges (and thus costs), there is a big difference between the installation of surface sensors, that can be mounted directly below a single moored turbidity buoy, and sensors placed near the bed, that require a more robust mooring solution to prevent damage to the instrument and power cables arising from the motions of the surface buoy as a result of the forces acting upon it.

7 Turbidity Monitoring

Turbidity measurements are described in detail in CEDA/IADC (2018), but can roughly be divided into direct and indirect measurements (e.g. Cutroneo et al., 2012). Direct measurements are measurements that do not require transfer functions. Examples include:

- water samples as well as sediment analyses (e.g. SSC) in the laboratory;
- light dampening and scattering of light (e.g. NTU, FTU);
- sediment traps as well as sediment analyses in the laboratory; and
- grain-size distributions (LISST, Malvern).

Indirect measurements can be derived from transfer functions. Typical examples are:

- calculated SSC values (typically from NTU or ADCP); and
- remote sensing (e.g. satellite images).

If carried out correctly, the results of direct measurements are indisputable, whereas indirect measurements require an understanding of the limitations of the transfer function, which often implies a significant level of uncertainty. Transfer functions may depend on the suspended sediment's grain-size distribution, type of material (mineral, organic), shape, concentration, gradation and colour (Downing, 2006). Furthermore, under dynamic conditions, the relationship

may change across time and space (see Bundgaard et al., (2019) and Fettweis et al., (2019) for further information). This means that the correlation has to be properly determined, for each measuring device, to cover both quiescent conditions and the more hydrodynamically energetic conditions that might occur under storm waves.

It is therefore very important to understand that indirect measurements are only useful for environmental

limits if the transfer function is valid for the local environment and the specific device. A turbidity limit based on indirect measurements should thus be based on a locally determined transfer function valid for local sediment as well as dredged sediment. The physical limitations of sensors must also be considered. In these ways, understanding the technical limitations to measurements when choosing a parameter for a turbidity limit is crucial.



Figure 7.1: Monitoring turbidity plume generated by a TSHD

8 Discussion and Recommendations for Setting Turbidity Limits

The goal of this paper has been to provide the crucial concepts for setting turbidity limits, with a balance between protecting the environment and still allowing for dredging in a cost-effective way. The paper has presented the various steps of a methodology, ultimately leading to a set of limits that together protect the environment and allow for a given dredging operation to commence in an environmentally safe way.

In particular, the turbidity limit is considered as consisting of two parts: a series of trigger levels and a threshold level. A threshold level for a specific sensitive receptor is defined as the level at which an impact can

start to occur. More generally, it can be specified as multiple levels with increasing criticality and identified in reference to the intensity and the duration of the stressor. The trigger levels consist of a series of intermediate levels established in order to prevent, at an early stage, the occurrence of threshold values.

The methodology involves four steps to identify: sensitive receptors; what they are influenced by; their threshold levels (critical stress levels); and ultimately reasonable trigger levels beyond which measures must be taken before the threshold levels are reached. This is shown in Figure 8-1.



Figure 8-1: Flowchart for selecting trigger levels with emphasis on sensitive receptors.

Defining case-specific threshold values and trigger levels should be based on an understanding of the local system and the impact arising from dredging operations. The limits represent a balancing decision based on the relevant environmental concerns, the needs of the project, and the stakeholders. This paper has aimed to list the key aspects of the system and the project needs. The basis for defining threshold values and trigger levels is a combination of these. It has been demonstrated that any impact should be assessed in relation to the biological and anthropogenic sensitive receptor(s) and therefore requires a good understanding of the system. For each receptor, it is necessary to determine the influencing factors and the corresponding threshold levels. This includes ascertaining time and space variations. Once one knows the sensitive receptors and their expected responses to dredging activities, both in space and time, it is possible to plan the dredging process accordingly.

The selection of the dredging plan, and the series of trigger levels that both protect the environment and allow for an 'executable' project, implies an evaluation of the dredging-induced excess in turbidity (in terms of type, amount and intensity in both the near and the far field) acceptable for the environment. To this end, it is necessary to estimate the impact of turbidity limits on the dredging operation and align the dredging project to match the environmental concerns.

Finally, it is necessary to understand what can actually be measured and monitored. Not everything can be measured, in a practical, cost-effective way, and not all sites can be monitored. A proper set of parameters is important to match the requested environmental protection.

Briefly, the turbidity limit should be:

- based on a system understanding of local hydrodynamics, sediments and biology;
- manageable in a dredging operation and provide reasonable response times;
- based on a clear definition of where to measure and what to measure; and
- site-specific and based on the critical stress levels for the local sensitive receptors.

We propose the following steps, which can be derived from a dedicated study, an ESIA, or a local survey undertaken in connection with the project. All of these steps are applicable in time and space.

1. Develop a system understanding.
2. Identify receptors sensitive to turbidity.
3. Determine critical stress levels for sensitive receptors (threshold value).
4. Choose a measurable turbidity limit based on the critical stress levels for the receptors and select a relevant measurable parameter.
5. Determine the trigger levels that need to be respected to avoid reaching the threshold levels and related management.
6. Determine where the turbidity limit applies based on the influence areas, the sensitive receptors and the dredging plan.
7. Define a sufficient, practical and cost-efficient monitoring strategy.

Regular and transparent communication with local stakeholders and experts, during the establishment of turbidity thresholds and trigger levels for a project, often increases the possibilities of mutual understanding and success during its execution.

Environmental turbidity limits for dredging operations should always be site-specific, and based on ecosystem functioning, in order to protect sensitive environmental receptors. By setting realistic limits, monitoring can be made more cost-effective and both environmentally and socially relevant.

References

- American Society for Testing and Materials, (2013). *D3977-97(2013) e1, Standard Test Methods for Determining Sediment Concentration in Water Samples*. West Conshohocken, PA: ASTM International.
- Anchor Environmental C.A. L.P., (2003). *Literature Review of Effects of Resuspended Sediments Due to Dredging Operations*. Los Angeles, CA: Los Angeles Contaminated Sediments Task Force.
- Bridges, T.S., Ells, S., Hayes, D., Nadeau, S., Palermo, M.R., Patmont, C., and Schroeder, P., (2008). *The Four Rs of Environmental Dredging: Resuspension, Release, Residual, and Risk. Technical Report ERDC/EL TR-08-4*. Vicksburg, MS: U.S. Army Engineer Research and Development Center.
- Becker, J.H., van Eekelen, E., van Wiechen, J., De Lange, W., Damsma, T., Smolders, T. and van Koningsveld, M., (2015). *Estimating Source Terms for Far Field Dredge Plume Modelling. Journal of Environmental Management*. Vol. 149, pp. 282-293.
- Bundgaard, K., Lumborg, U. and Nyborg, L., (2019). *Challenges of Optical Backscatter Monitoring in Mixed Sediment Environments. Terra et Aqua*. Spring, Vol. 154.
- CEDA, (2015). *Environmental Monitoring Procedures*. Information Paper [online]. Available from: http://www.dredging.org/media/ceda/org/documents/resources/cedaonline/2015-02-ceda_informationpaper-environmental_monitoring_procedures.pdf
- CEDA/IADC, (2018). *Dredging for Sustainable Infrastructure*. The Hague, the Netherlands: CEDA/IADC.
- Clarke, D.G. and Wilber, D.H., (2000). *Assessment of Potential Impacts of Dredging Operations Due to Sediment Resuspension*. DOER Technical Notes Collection (ERDC TN-DOER-E9). [online]. Vicksburg, MS: U.S. Army Engineer Research and Development Center. Available from: www.wes.army.mil/el/dots/doer.
- Cutroneo, L., Castellano, M., Pieracci, A., Povero, P., Tucci, S. and Capello, M., (2012). *The Use of a Combined Monitoring System for Following a Turbid Plume Generated by Dredging Activities in a Port. Journal of Soils and Sediments*. Vol. 12 (5), pp. 797-809.
- Department of Water, (2009). *Surface Water Sampling Methods and Analysis – Technical Appendices. Standard Operating Procedures for Water Sampling – Methods and Analysis*. [Online]. Available from: <http://www.water.wa.gov.au/PublicationStore/first/87152.pdf>
- Downing, J., (2006). *Twenty-five Years with OBS Sensors: The Good, the Bad and the Ugly. Continental Shelf Research*. Vol. 26, pp. 2299-2318.
- Environmental Protection Agency (EPA), (2016). *Environmental Impact Assessment of Marine Dredging Proposals: Technical Guidance*. WA: Environmental Protection Authority, Western Australia.
- Ertemeijer, P.L.A. and Lewis, R.R., (2006). *Environmental Impacts of Dredging on Seagrasses: A Review. Marine Pollution Bulletin*. Vol. 52 (12), pp. 1553-1572.
- Ertemeijer, P.L.A., Riegl, B., Hoeksema, B.W. and Todd, P.A., (2012). *Environmental Impacts of Dredging and Other Sediment Disturbances on Corals: A Review. Marine Pollution Bulletin*. Vol. 64 (9), pp. 1737-1765.
- Fearn, P., Broomhall, M. and Dorji, P., (2017). *Optical Remote Sensing for Dredge Plume Monitoring: A Review. Report of Theme 3 - Project 3.1.1*. Prepared for the Dredging Science Node, Western Australian Marine Science Institution. Perth, WA.
- Feola, A., Lisi, I., Salmeri, A., Venti, F., Pedroncini, A and Romano, E., (2016). *Platform of Integrated Tools to Support Environmental Studies and Management of Dredging Activities, Journal of Environmental Management*. Vol. 166.
- Fettweis, M., Riethmüller, R., Verney, R., Becker, M., Backers, J., Baeye, M., Chapalain, M., Claeys, S., Claus, J., Cox, T., Deloffre, J., Depreiter, D., Druine, F., Flöser, G., Grünler, S., Jourdin, F., Lafite, R., Nauw, J. and Vereecken, H., (2019). *Uncertainties Associated with In-situ High-Frequency Long-Term Observations of Suspended Particulate Matter Concentration Using Optical and Acoustic Sensors. Progress in Oceanography*. Vol. 178, 102162. doi:10.1016/j.pcean.2019.102162.
- Fisher, R., Walshe, T., Bessell-Browne, P. and Jones, R., (2018). *Accounting for Environmental Uncertainty in the Management of Dredging Impacts Using Probabilistic Dose-Response Relationships and Thresholds. Journal of Applied Ecology*. Vol. 55, pp. 415-425. doi:10.1111/1365-2664.12936.
- Fraser, M.W., Short, J., Kendrick, G., McLean, D., Keesing, J., Byrne, M., Caley, M.J., Clarke, D., Davis, A.R., Ertemeijer, P.L.A., Field, S., Gustin-Craig, S., Huisman, J., Keough, M., Lavery, P.S., Masini, R., McMahon, K., Mengersen, K., Rasheed, M., Statton, J., Stoddart, J. and Wu, P., (2017). *Effects of Dredging on Critical Ecological Processes for Marine Invertebrates, Seagrasses and Macroalgae, and the Potential for Management with Environmental Windows Using Western Australia as a Case Study. Ecological Indicators*. Vol. 78, pp. 229-242.

- Grabowski, R.C., Droppo, I.G. and Wharton, G., (2011). *Erodibility of Cohesive Sediment: The Importance of Sediment Properties*. *Earth-Science Reviews*. Vol. 105, pp. 101-120.
- ISO (2014). *Water Quality – Determination of Turbidity – Part 1: Quantitative Methods*. 296
- John, S.A., Challinor, S.L., Simpson, M., Burt, T.N. and Spearman, J., (2000). *Scoping the Assessment of Dredging Plumes*. *CIRIA Report C547*.
- Jones, R., Bessell-Browne, P., Fisher, R., Klonowski, W. and Slivkoff, M., (2016). *Assessing the Impacts of Sediments from Dredging on Corals*. *Marine Pollution Bulletin*. Vol. 102, pp. 9-29.
- Lisi, I., Feola, A., Bruschi, A., Pedroncini, A., Pasquali, D. and Di Risio, M., (2019). *Mathematical Modeling Framework of Physical Effects Induced by Sediments Handling Operations in Marine and Coastal Areas*. *Journal of Marine Science and Engineering*. Vol. 7, p. 149.
- McArthur, C., Ferry, R. and Proni, J., (2002). *Development of Guidelines for Dredged Material Disposal Based on Abiotic Determinants of Coral Reef Community Structure*. *Dredging '02, Proceedings of the Third Specialty Conference on Dredging and Dredged Material Disposal*. Coasts, Oceans, Ports and Rivers Institute (COPRI) of ASCE, May 5, 2002, Orlando, FL, USA, pp. 1-15.
- Neukermans, G., Ruddick, K., Loisel, H. and Roose, P., (2012). *Optimization and Quality Control of Suspended Particulate Matter Concentration Measurement Using Turbidity Measurements*. *Limnology and Oceanography: Methods*. Vol. 10, pp. 1011-1023.
- Paganelli, D., La Valle, P., Ercole, S., Lisi, I., Teofili, C. and Nicoletti, L., (2014). *Guidelines for Environmental Studies Related to the Construction of Coastal Defence Works*. ISPRA, Handbooks and Guidelines 105-bis/2014.
- Tillin, H.M., Houghton, A.J., Saunders, J.E. and Hull, S.C., (2011). *Direct and Indirect Impacts of Marine Aggregate Dredging*. In: R.C. Newell and J. Measures, eds. *Marine ALSF Science Monograph Series No. 1*. MEPF 10/P144.
- United States Environmental Protection Agency (US EPA), (2012). *Water: Monitoring and Assessment. 5.5 Turbidity*. Washington D.C.: US EPA. Available from: <http://water.epa.gov/type/rsl/monitoring/vms55.cfm>
- United States Geological Survey (USGS), (2017). *Turbidity: Units of Measurement*. [Online]. USGS Office of Water Quality. Available from: <https://or.water.usgs.gov/grapher/fnu.html>
- Whitehouse, R.J.S., Soulsby, R.L., Roberts, W. and Mitchener, H.J., (2000). *Dynamics of Marine Muds*. *Wallingford Technical Report*. Thomas Telford. Available from: <http://www.icevirtuallibrary.com/content/book/100317>
- Wilber, D.H. and Clarke, D.G., (2001). *Biological Effects of Suspended Sediments: A Review of Suspended Sediment Impacts on Fish and Shellfish with Relation to Dredging in Estuaries*. *North American Journal of Fisheries Management*. Vol. 21, pp. 855-875.
- Winterwerp, J.C. and van Kesteren, W.G.M., (2004). *Introduction to the Physics of Cohesive Sediment in the Marine Environment*. *Developments in Sedimentology*. Vol. 56, pp. 1-466.
- World Association for Waterborne Transport Infrastructure (PIANC), (2010). *Dredging and Port Construction Around Coral Reefs*. PIANC EnviCom, Report 108.

Glossary

ADCP	Acoustic Doppler Current Profiler
CEDA	Central Dredging Association
CSD	Cutter Suction Dredger
Dredging works	Dredging in this paper is the maritime transportation of natural materials from one part of the water environment to another by specialised dredging vessels. It involves collecting and bringing up, fishing up or clearing away, or out, material or another object from the bed of a river, sea, etc., transporting it to the relocation site and unloading the material or object.
ESIA	Environmental Social Impact Assessment
FTU	Light dampening – <i>Formazin Nephelometric Unit</i>
IADC	International Association of Dredging Companies
ISO	International Organization for Standardisation
LISST	Laser In-situ Scattering and Transmissometry
NTU	Light dampening – <i>Nephelometric Turbidity Unit</i>
SSC	Concentration – <i>Suspended Sediment Concentration</i>
TSS	Concentration – <i>Total Suspended Sediment</i>
PAR	Light dampening – <i>Photosynthetically Active Radiation</i>
PIANC	World Association for Waterborne Transport Infrastructure
PPT	Concentration – <i>Parts Per Thousand</i>
Receptor	Receptors comprise species, habitats, resources, activities or items identified as being of importance, that may be affected by dredging.
Sediment spill	The release of sediments into the water body during dredging or reclamation activities.
Threshold level	The level at which a receptor can show an impact.
Trigger level	The levels at which management actions can, or should, be implemented to avoid environmental impacts based on identified sensitive receptors.
TSHD	Trailing Suction Hopper Dredger
Turbidity	A popular term for water clarity or sediment concentration. Turbidity is a measure of water clarity that indicates how much the material suspended in the water decreases the passage of light through it (United States Environmental Protection Agency, US EPA, 2012).
Turbidity plume	The horizontal (2D) and vertical extent of the water body containing suspended sediments. Due to the complexity of sediment-water interactions, variability in sediment properties, variations in dredging activities and natural hydrodynamics, turbidity plumes exhibit very dynamic behaviour in terms of both extent and sediment concentration (CEDA/IADC, 2018).

The Corporate Members of CEDA

We are grateful to our members who make a major contribution to our activities. In doing so they can be proud of the fact that they are also supporting the entire dredging community – regardless of membership status. Without our members we would not be able to do such excellent work. We hope others will be encouraged to follow their example and join us in fulfilling our mission to spread knowledge, share expertise and encourage best practice in the dredging profession.

Agence IKLIL com, *Morocco*
 Alia Instruments BV, *the Netherlands*
 Agence Nationale des Ports, *Morocco*
 Antea Group, *Belgium*
 Aqua Vision, *the Netherlands*
 Aquatex Ltd, *Latvia*
 ARCADIS Nederland BV, *the Netherlands*
 Atlantic Dredging, *Morocco*
 Atlas Services Group BV, *the Netherlands*
 Baggerwerken Decloedt & Zoon NV (Member of DEME Group), *Belgium*
 Bakker Sliedrecht Electro Industrie BV, *the Netherlands*
 Bell Dredging Pumps BV, *the Netherlands*
 BMT, *Australia*
 C.C. Jensen Benelux BV, *the Netherlands*
 Centre for Environment, Fisheries and Aquaculture Science (CEFAS), *UK*
 CEREMA, *France*
 Conway Advocaten & Attorneys-at-law, *the Netherlands*
 Damen Dredging Equipment BV, *the Netherlands*
 Damen Shipyards Gorinchem, *the Netherlands*
 Danish Coastal Authority, *Denmark*
 DC Industrial NV, *Belgium*
 Delft University of Technology, Faculty 3mE, *the Netherlands*
 Delta Coastal Services, *the Netherlands*
 Deltares, *the Netherlands*
 DHI A/S, *Denmark*
 Dragus int., *Portugal*
 Drapor Dragages des Ports, *Morocco*
 Dredge Yard, *the Netherlands*
 Dredging International NV (Member of DEME Group), *Belgium*
 Dumez Maroc, *Morocco*
 Dutch Dredging BV, *the Netherlands*
 Dutch Dredging Components B.V., *the Netherlands*
 EMO DRAGA Mozambican Dredging Company, *Mozambique*
 Femern A/S, *Denmark*
 Flender BV, *the Netherlands*
 Gareloch Support Services BV, *the Netherlands*
 Geomil Equipment BV, *the Netherlands*
 German Ministry of Transport and Digital Infrastructure, *Germany*
 Ghent Dredging NV, *Belgium*
 GIE Dragages-Ports, *France*
 Gulf Cobla LLC, *United Arab Emirates*
 Hafentechnische Gesellschaft e.v., *Germany*
 Hamburg Port Authority AöR, *Germany*
 Hanzehogeschool, Hogeschool van Groningen, *the Netherlands*
 Havenbedrijf Antwerpen NV van publiek recht, *Belgium*
 Van Heck BV, *the Netherlands*
 Herbosch-Kiere, *Belgium*
 HKA, *UK*
 Holland Marine Technologies BV, *the Netherlands*
 Hoogheemraadschap van Schieland & de Krimpenerwaard, *the Netherlands*
 De Hoop Terneuzen BV, *the Netherlands*
 HR Wallingford Group Ltd., *UK*
 Hydrogeo SARL, *Morocco*
 In2Dredging, *Australia*
 Industrial Tomography Systems plc, *UK*
 International Marine & Dredging Consultants NV (IMDC), *Belgium*
 iPS Powerful People, *the Netherlands*
 IRO, *the Netherlands*
 ISPRA - Institution for Environmental Protection and Research, *Italy*
 Jan de Nul NV, *Belgium*
 L&M Keating, *Ireland*
 Lagersmit, *the Netherlands*
 Land and Water Group, *UK*
 Machinefabriek De Hollandsche Yssel BV, *the Netherlands*
 MAN Energy Solutions SE, *Germany*
 Marine and Coastal Construction Service (MACCS), *UK*
 Marine Scotland, *UK*
 Metalogenia SA, *Spain*
 MeteoGroup Nederland BV, *the Netherlands*
 Ministry of Infrastructure & Water Management, *the Netherlands*
 Ministry of the Flemish Community Maritime Access Division, *Belgium*
 Ministry of the Flemish Community/Agency for Mar and Coast Serv., *Belgium*
 National Marine Dredging Co., *United Arab Emirates*
 Nortek BV, *the Netherlands*
 North Sea Port Netherlands NV, *the Netherlands*
 N-Seatec Subsea Systems BV, *the Netherlands*
 Port of Rotterdam NV, *the Netherlands*
 Rabobank Nederland Corporate Clients, *the Netherlands*
 Rohde Nielsen A/S, *Denmark*
 Rohr-Idreco Dredge Systems BV, *the Netherlands*
 Royal Boskalis Westminster NV, *the Netherlands*
 Royal Haskoning DHV, *the Netherlands*
 Royal IHC, *the Netherlands*
 Scheepvaart en Transport College, *the Netherlands*
 Skilltrade BV, *the Netherlands*
 Smals Dredging BV, *the Netherlands*
 Stema Systems, *the Netherlands*
 Svasek Hydraulics, *the Netherlands*
 Teledyne Reson, *the Netherlands*
 TenCate Geosynthetics, *the Netherlands*
 Terramare Oy, *Finland*
 The Crown Estate, *UK*
 Trustlube, *the Netherlands*
 UK Dredging (ABP), *UK*
 Van den Herik Sliedrecht, *the Netherlands*
 Van der Kamp International BV, *the Netherlands*
 Van Oord Dredging & Marine Contractors BV, *the Netherlands*
 VandeGrijp International Gear Suppliers BV, *the Netherlands*
 VOSTA LMG, *the Netherlands*
 Vuyk Engineering Rotterdam BV, *the Netherlands*
 Vereniging van Waterbouwers, *the Netherlands*
 Wärtsilä Nederland BV, *the Netherlands*
 Wasa Dredging Oy Ltd., *Finland*
 Witteveen+Bos

Acknowledgements

This information paper is presented by the Central Dredging Association (CEDA), an independent, international organisation with an extensive professional network, a centre of expertise on dredging and reclamation, and an easy-to-access forum for knowledge exchange. The paper has been prepared by a working group of international experts of broadly diverse backgrounds and range of expertise, under the remit of the CEDA Environment Commission.

Members of the CEDA Working Group on *Guidelines for Assessing and Evaluating Environmental Turbidity Limits*

Mark Bollen, IMDC, Belgium (until February 2019)

Klavs Bundgaard, NIRAS, Denmark (Chair)

Styn Claeys, Flanders Hydraulics Research, Belgium

Jos de Cubber, Jan De Nul, Belgium

Lucie Evaux, Van Oord, the Netherlands

Alessandra Feola, ISPRA, Italy (corresponding member)

Frederik Goethals, DEME, Belgium

Johan Henrotte, Boskalis, the Netherlands

Joël L'Her, Cerema, France

Iolanda Lisi, ISPRA, Italy (corresponding member)

Yves Planke, Port of Antwerp, Belgium

Bastian Schlenz, Femern A/S, Denmark

Jonathan Taylor, HR Wallingford, United Kingdom

Lynnyrd de Wit, Svasek Hydraulics, (at the time of going to press, Deltares)
the Netherlands

Central Dredging Association (CEDA)

Radex Innovation Centre
Rotterdamseweg 183c
2629 HD Delft
The Netherlands
T +31 (0)15 268 2575
E ceda@dredging.org

