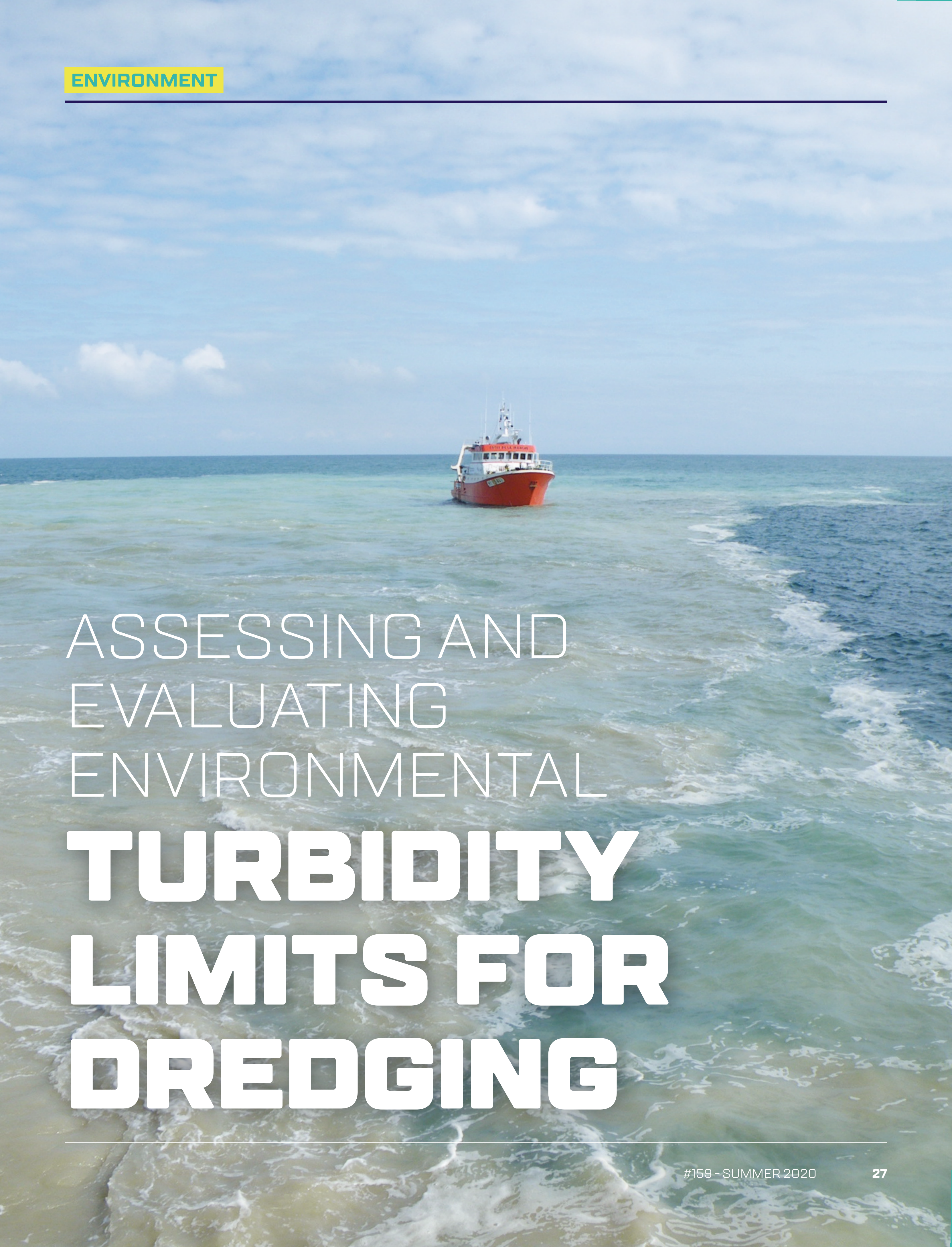

ASSESSING AND EVALUATING ENVIRONMENTAL TURBIDITY LIMITS FOR DREDGING

Dredging is 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 referred to as sediment plumes.

Introduction

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 the impacts of turbidity 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 their quoted price. 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.

FIGURE 1

The process of relocating large volumes of sediment can be accompanied by the release of suspended sediments into the water column referred to as sediment plumes.

This article is based on the assumption that setting turbidity limits requires a general understanding of dredging processes as well as the surrounding environment.

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.

The article 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.

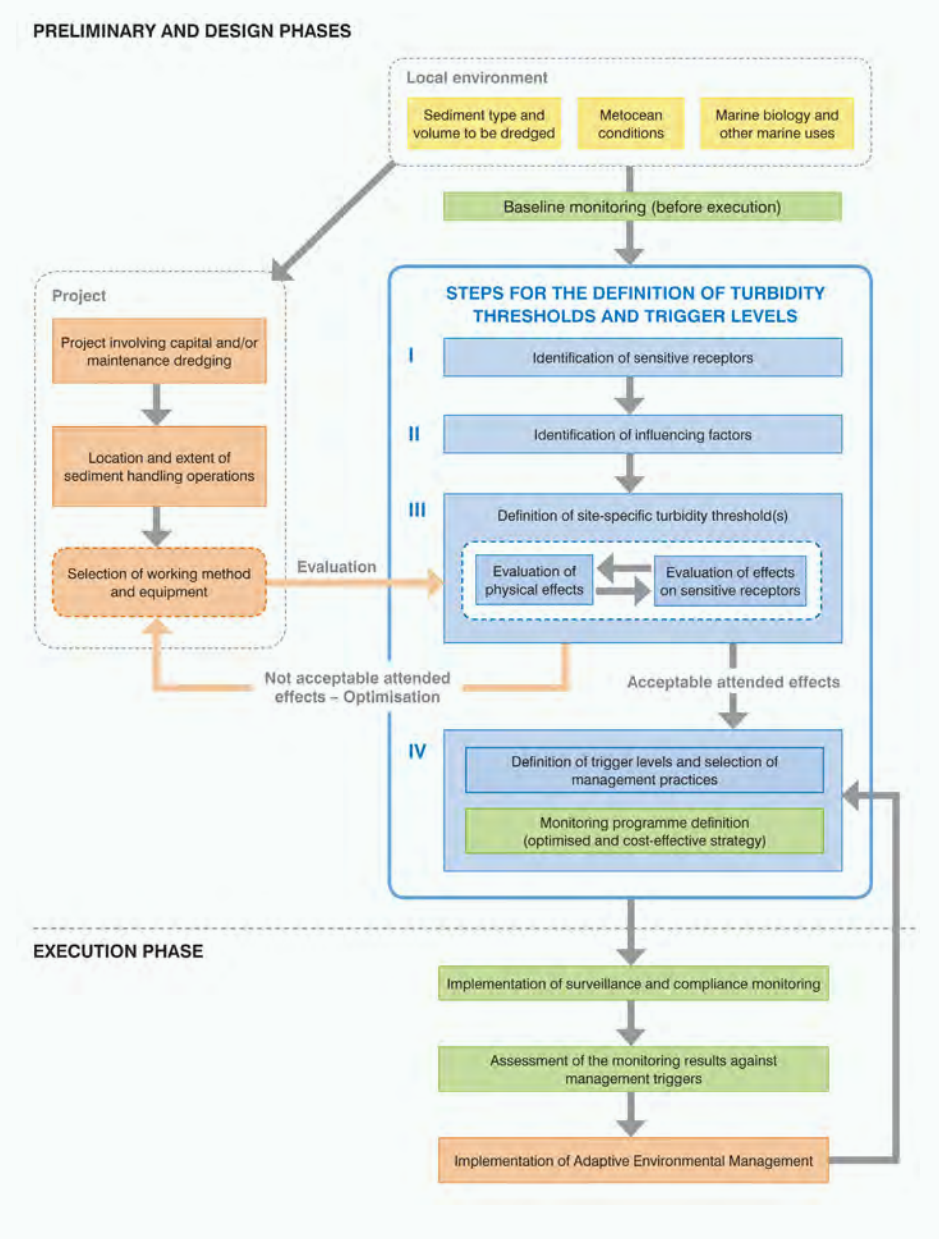

FIGURE 2

Typical flowchart for environmental management in a dredging operation.

Approach

This article 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;
- An understanding of the dredging operations in terms of locations, volumes and spills;
- An understanding of the sensitive receptors and their tolerance levels;
- An understanding of possible monitoring programmes; and
- An understanding of possible response options.

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.

To implement this approach, a typical flowchart for managing environmental turbidity limits in a dredging operation is shown below. In this figure, the different parts of the flowchart and the interactions between them are highlighted (see figure 1). This flowchart will form the basis of this article.

Definition of turbidity used in this article

The term 'turbidity' is well established in the dredging world and is adhered to throughout this article. 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; Fearns 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.

Building a system understanding

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.

Metocean conditions

Metocean conditions cover the actions of weather, 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;
- 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 as these may imply different impact levels for a dredging operation such as summer or winter or dry or wet season.

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 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).

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; Erftemeijer & Lewis, 2006; Erftemeijer 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 driving factors are available light and sensitivity to burial and 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.

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.

Planned works

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 that is expected to be created and how its impacts can be managed.

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 owe 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 will occur. Typical spill rates can be seen in John et al. (2000). The parameters that are important when establishing the spill rate – amount of fines transferred to the far field – and the overall spilled volume or mass are the following (see e.g. Becker et al., 2015):

- Dredging method, location and planning,
- Dredged volume,
- Dredging production rates, and
- Composition and optical and physical properties of dredged material.

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 critical stress levels and finally select trigger levels to protect the sensitive receptors.

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 several proper environmental baseline survey(s). The different terms will be defined in the following. A flowchart is shown in figure 3.

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 3.

Sensitive receptors – sometimes referred to as receivers – may include species, habitats, resources, 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 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

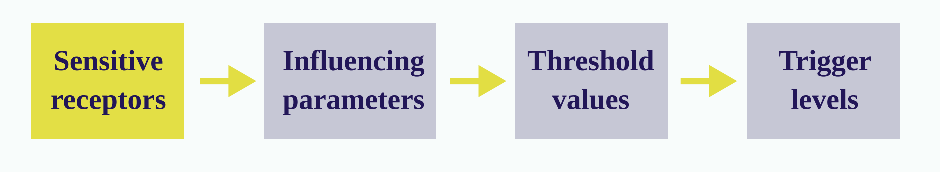

FIGURE 3

Flowchart for selecting trigger levels with emphasis on sensitive receptors.

FIGURE 4
Flowchart for selecting trigger levels with emphasis on the influencing parameters.

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 (e.g. 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.

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 4).

Elevated turbidity due to dredging can affect the sensitive receptors, for example 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.

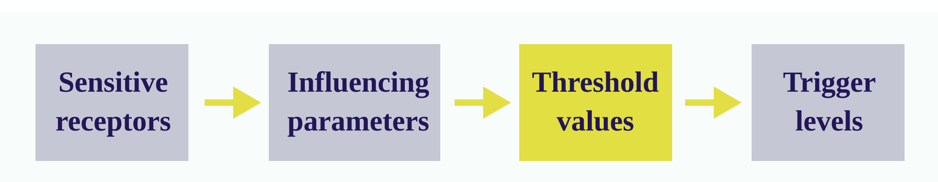

FIGURE 5
Flowchart for selecting trigger levels with emphasis on the threshold values.

Table 1 presents a list of receptors that are potentially sensitive to increases in suspended sediment and outlines the factors that influence them such as 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.

Definition of threshold values

It is not only the sensitive receptors but also the threshold values at which the receptors may exhibit increasing impacts that need to be defined (see figure 5). 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.

There is an important 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 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 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.

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 sector 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).	X	X	X	
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.	X	X	X	
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.	X	X	X	
Mangroves	Increased turbidity does not per se affect mangroves unless the sediments are contaminated. Moreover, excessive re-deposition may smother the mangrove roots.		X	X	
Shellfish	Increased turbidity and re-deposition can affect filter-feeding systems of shellfish (e.g. oysters, mussels), with possible effects on pseudo-faces production, the amount of algal food ingested and on bivalve gills (clogging).		X	X	
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.	X	X	X	X
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.	X			X
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.	X		X	
Aquaculture/ shellfish farm	Increased turbidity can affect primary production and bivalve growth. Sediment re-deposition can damage farm structures (see fish and shellfish).	X	X	X	
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.	X		X	X
Infrastructure, navigation	Excessive re-deposition near structures (e.g. quay wall, jetties, outlets) and navigation channels may lead to functional issues (e.g. operability, maintenance).		X	X	
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 demersal species with commercial value).	X		X	X
Cultural heritage	Increased turbidity can lead to change in water colour and re-deposition, with socioeconomic impacts on cultural heritage and historical sites.	X	X	X	
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).	X	X	X	

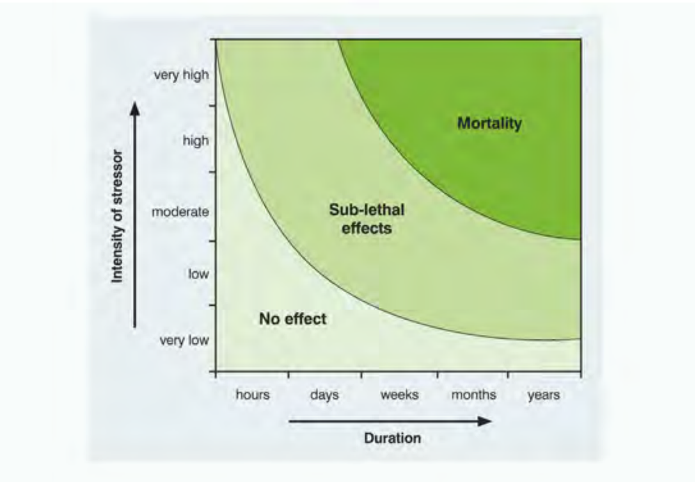

FIGURE 6

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 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, on 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 7). 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.

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 represent 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.

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 their receptors; moreover, one should

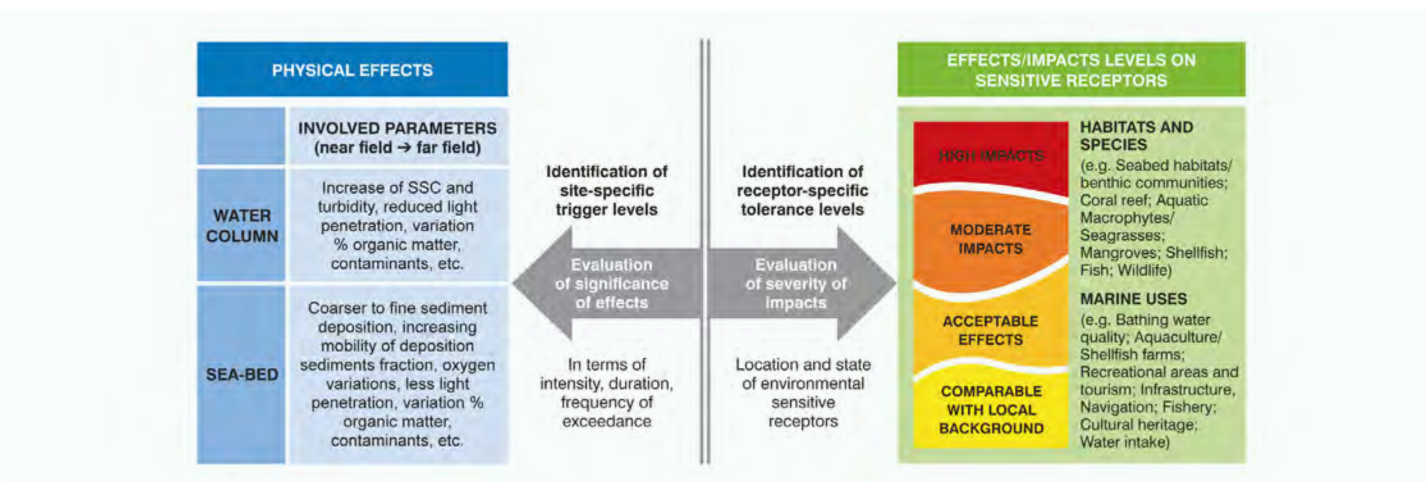

FIGURE 7

Scheme of the relationships between the significant physical effects and the effects 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).

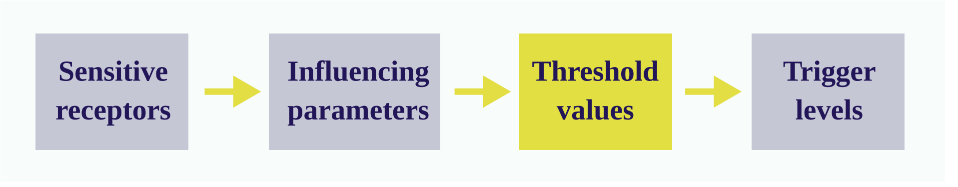

FIGURE 8

Flowchart for selecting trigger levels with emphasis on the trigger values.

define each trigger's response in terms of how the dredging operations should proceed (see figure 8).

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;
- **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.

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 point 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 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.

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.

The trigger level is the turbidity level that needs to be respected to ensure that the threshold levels are not reached.

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 term of intensity, but also in terms of the duration and frequency of events exceeding the defined levels.

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.

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; Permanent International Association of Navigation Congresses, 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 term 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 are unavailable for validation, best practice should include an optimised interaction between models and monitoring as part of a cost-effective approach.

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 metres which may still be within the dredging zone). Here it must also be noted that most dredgers – Cutter Suction Dredgers and Trailing Suction Hopper Dredgers – move during the dredging process, possibly making it difficult to define the exact location, in addition 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, it is possible to define monitoring locations in between the dredging zone and the sensitive receptor to 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.

Frequency

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

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 data and power cables arising from the motions of the surface buoy as a result of the forces acting upon it.

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

TABLE 2

Overview of parameters which can be used as measures of turbidity limit and possible measurement methods. *Only using a locally obtained transfer function. **Only with proper local calibration data.

Turbidity limit related to	Optical (NTU/FTU)	Light dampening	Water samples	Sediment traps	Remote sensing
Light	X	X	(x)*	-	(x)**
Coverage	-	-	-	X	-
Visibility	X	X	(x)*	-	X
Sedimentation	- -	-	-	X	-
SSC	(x)*	-	X	-	(x)**

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. An overview of applicable parameters for various types of turbidity limits is displayed in Table 2. The trigger level regarding sedimentation and SSC can be assessed with the table or sediment traps can be used to check for compliance.

Discussion and recommendations for setting turbidity limits

The goal of this article has been to provide the crucial concepts for setting turbidity limits, intended as a balance between protecting the environment and still allowing for dredging in a cost-effective way. The article has presented the various steps of a methodology, ultimately leading to a set of limits that together both 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 referring to the intensity and the duration of the stressor. The trigger levels consist of a series of intermediate levels established so as to prevent, at an early stage, the occurrence of threshold values.

The methodology involves four steps, identifying: sensitive receptors, what they are influenced by, their stress levels, and what reasonable trigger levels are beyond the measurements that must be taken before the threshold levels are reached (see figure 9).

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 article 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.
- be manageable in a dredging operation and provide reasonable response times.
- be based on a clear definition of where to measure and what to measure.
- be 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.

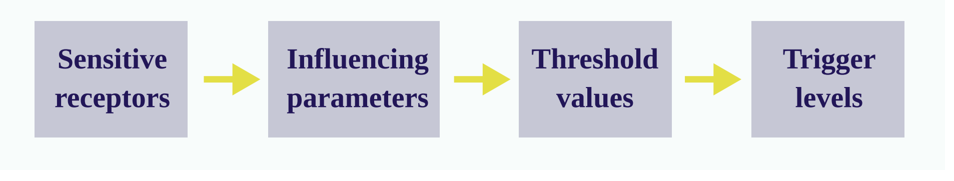

FIGURE 9

Flowchart for selecting trigger levels with emphasis on sensitive receptors.

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.

FIGURE 10

Monitoring turbidity plume generated by a TSHD.

TABLE 3

Glossary of Terms.

Receptor	Receptors comprise species, habitats, resources, activities or items identified as being of importance that may be affected by dredging.	
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).	
NTU	Light dampening	Nephelometric turbidity unit
FTU	Light dampening	Formazin nephelometric unit
SSC	Concentration	Suspended sediment concentration
TSS	Concentration	Total suspended sediment
PPT	Concentration	Parts per thousand
PAR	Light dampening	Photosynthetically active radiation
CSD	Cutter Suction Dredger	
TSHD	Trailer Suction Hopper Dredger	
Trigger level	The levels at which management actions can or should be implemented to avoid environmental impacts based on identified sensitive receptors.	
Threshold level	The level at which a receptor can show an impact.	
Dredging works	Dredging in this article 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.	
Sediment spill	The release of sediments into the water body during dredging or reclamation activities.	
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).	

Summary

Dredging relocates large volumes of sediment and can be accompanied by the release of suspended sediments into the water column referred to as 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 the impacts of turbidity 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.

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.

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. The article 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.

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