Requirements for sediment plumes caused by dredging

Final thesis report

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Preface

This report concerns the study on requirements for sediment plumes caused by dredging. It has been carried out as a Master of Science thesis at the Delft University of Technology, faculty of Civil Engineering and Geosciences, department of Civil Engineering, section of Hydraulics.

The study is executed in co-operation with Hydronamic, the engineering department of Royal Boskalis Westminster dredging company.

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Abstract

In many dredging contracts, environmental restrictions on sediment plumes must be met. Sediment plumes cause reduced light penetration, increased concentration of suspended solids and sedimentation which all can affect benthic ecosystems. Contractors confronted with these requirements get the impression that these regulations are not well founded. Because the costs of dredging increase with stricter limits, it is important to know why restrictions are necessary.

Goal of this investigation was to review and clarify some aspects of the situation.

This report about requirements for sediment plumes caused by dredging is divided in three parts. In the first part consists of an inventory of the standards for sediment plumes caused by dredging as applied in different countries and limits set at dredging projects for sediment plumes with their backgrounds. The possible effects of sediment plumes on different ecological environments are listed and the extent to which limits are based on well documented environmental effects is discussed.

There is no international regulation or legislation about uncontaminated sediment plumes caused by dredging. It seems impossible to make limits universal because the effects of sediment plumes are site and time specific. Site specific because ecosystems and natural conditions vary from site to site and time specific because they depend on tide, day or night, seasons and hydrodynamic conditions (like monsoons, breeding and hatching seasons, currents). Per project has to be decided if the environment is sensitive to sediment plumes and whether limits are required.

It is concluded that requirements for sediment plumes in dredging contracts are often not well founded. Limits usually are copied from other projects or reports without much investigation and/or based on water criteria standards or community perception.

The second study focuses on the effects of sediment plumes on one specific ecosystem: coral reefs. Probably this is the most sensitive marine ecosystem. The literature on the effects of suspended sediment and turbidity on corals is reviewed and restated in the context of dredging. The effects are evaluated in terms of acceptable damage, for which a recovery time of one year is used, considering the long-term equilibrium situations, or natural conditions, of coral reefs. Most published experiments were focussed on the sublethal effects. It appears that, taking in account the observed species and sediment sizes, corals can clear themselves from 100 mg/cm^2/day and can handle concentrations of suspended solids up to 100mg/l for a few days.

Drastic lethal effects on corals were experimentally observed only when burial was complete. There must be an intermediate dose of sediment, but no data exist in this range. Corals can not handle burial caused by dredging activities for more than, depending on the natural conditions, 1 day to 1 week.

To put the data in perspective and to give direction to future discussions about norms and limits, it is proposed to work with dose-effect curves as used in toxicology. This approach also indicates that experiments with higher sediment doses where partial but significant damage occurs and where recovery times are registered must be done to achieve higher precision in the conclusions.

The impact of sediment plumes probably can be minimised by modifying dredging techniques. Dredging also can be confined to specific time windows from which sensitive seasons of the ecosystem and conditions that adversely affect the distribution and impact of the plume can be excluded. Another possibility to reduce the impact of sediment plumes caused by dredging is to remove the sediment with a flowdredge. Further an approach is given to calculate the extent of possible effects caused by dredging plumes.

The third part is a contribution to the methodology of how to implement and control a set limit in real time during a dredging operation. A probabilistic description of sediment plume behaviour in the Øresund Fixed Link Dredging project is given. Very many measurements were done during this project, which gives the opportunity to investigate the minimum but required frequency of measurements to check if the actual turbidity or concentration of suspended solids complies with the limits. When measurements are taken continuously the probability that the limits are exceeded without being noted is small, but continuous measurement methods are expensive.

The objective of this study is to optimise the number of measurements at a location, i.e. the number of ship crossings through a sediment plume, given the costs and the accuracy of the turbidity measurements, by a statistical data analysis.

Turbidity is assumed to be a random variable and the inherent uncertainty of turbidity is described by a Binomial-Exponential (BE) distribution function. The data contain natural background values as well and the BE distribution separates the background values from the turbidity due to dredging. The BE distribution has two distribution parameters, which are calculated. as well as their uncertainty in dependence on the number of ship crossings.

The statistical uncertainty of the probability distribution function of the parameters and of the turbidity depends on the number of ship crossings. The maximum allowable turbidity is probabilistically determined as function of the number of ship crossings. With this approach the number of ship crossings can be determined for a required reliability.

A method is proposed and illustrated with the data to optimise the number of ship crossings by optimising total costs, consisting of the costs of ship crossings and the gains of having a smaller uncertainty. Also a sensitivity analysis of the cost parameters is given.

With this method, when the costs (disadvantages) of having a smaller accuracy of the turbidity probabilistic distribution function are assessed in relation to the Øresund case and assuming the same plume behaviour, the number of ship crossings can be optimised for other cases.

List of relevant terminology

Background conditions
Natural turbidity and concentration of suspended solids

Benthic organisms, benthos
Organisms that spend all or most of their life at the bottom of the water column

Bleaching
A phenomenon in which *Zooxanthellae* microalgae leave a coral, resulting in coral whitening, under the stress of high water temperature, low salinity or high turbidity. If such a stress is removed the coral will recover but if bleaching continues for an extended period, coral will die.

Coral reef
A coral reef is defined as the topography formed by hermatypic organisms that are mainly composed of coral. In a coral reef, animals called coral live in a colony. The reef includes the area where corals grow and the seaweed and seagrass habitats and sandy or muddy places around the coral.

Cnidaria
A phylum of animals including corals and jellyfish

Hermatypic
The property of corals that produce a skeleton of calcium carbonate in a coral reef. Most of the corals that coexistent with *Zooxanthellae* are hermatypic.

Mitigation
The policy of trying to eliminate the effects of development on the environment, through avoidance, minimization, correction, reduction, and compensation.

Natural conditions
Climate-, background-, and hydrodynamic conditions

Phylum
A taxonomic group of similar classes having common properties

Planula
A coral or other cnidarian larva

Zooxanthellae
Single-cell algae, which are symbiotic with hermatypic corals and other animals

List of notation and abbreviations

Symbol	*Descripton*
n	number of ship-crossings
x_j	distance in m, at j=1,2,…,30 [0, 17, 34,…,493]
d_k	depth in m, at k=1,2,3,4 [0.5, 1, 2.5, 4.5]
$t_{n,j,k}$	turbidity at location (j,k) at ship crossing n
X	Random value
x	Realisation of X
f_X	PDF of X
F_X	CDF of X
μ	mean
ϱ	correlation coefficient
σ	standard deviation
p	percentage of zero's of the turbidity measurements
μ	mean value of the non-zero's of the turbidity
α	mean value of the normal distribution function of μ
β	standard deviation of the normal distribution function of μ
γ	mean value of the normal distribution function of p
δ	standard deviation of the normal distribution function of p
ε	mean value of the normal distribution function of t
ζ	standard deviation of the normal distribution function of t
BE	Binomial Exponential
CDF	Cumulative Distribution Function
corr	Correlation
cov	Covariance
CV	Coefficient of Variation
E	Expectation
PDF	Probability Density Function
TC	Total Costs
var	Variance
ADCP	Acoustic Doppler current profiling (acoustic backscatter)
FTU	Formazin Turbidity Units
JTN	Jackson Turbidity Units
NTU	Nephelometry Turbidity Units
OBS	Optical backscatter sensor
ppm	parts per million; milligrams of solids per kilograms of water (mg/kg), which equals mg/l in water with a density of 1000 kg/m3

1 Introduction

1.1 Backgrounds

Dredging in its simplest form consists of excavation of material from a sea, river or lake bed, and the relocation of the excavated material elsewhere. It is commonly used to improve the navigable depths in ports, harbours, and shipping channels, or to win minerals from underwater deposits. It may also be used to improve drainage, reclaim land, improve sea defence, or remove and relocate contaminated materials.

At present more attention is paid to the environmental aspects in general and the environmental impact of dredging in particular. In an increasing number of dredging contracts, environmental requirements concerning sediment plumes have to be met. Sediment plumes cause reduced light penetration, increased concentration of suspended solids and sedimentation which all can have adverse impacts on the benthic vegetation and fauna.

The environmental effects associated with sediment plumes are often secondary to those associated with the direct loss of the seabed. The loss of the seabed is a fundamental and unavoidable consequence of dredging as requested in contracts. The environmental effects associated with sediment plumes don't need to be. To prevent the adverse impact of sediment plumes, requirements for turbidity and concentration of suspended solids are made for dredging activities.

There are no internationally laid down standards about requirements for sediment plumes. Contractors of dredging and reclamation activities confronted with the requirements get the impression that these are not well founded. The goal of this report is to review and clarify some aspects of requirements for sediment plumes caused by dredging.

1.2 The report

This report only considers uncontaminated sediment and is divided in three parts.

Basic study
The first part investigates the requirements for sediment plumes caused by dredging in general. The objective of the Chapter 2 to 5 in this report is to investigate:
- standards for sediment plumes caused by dredging in different countries
- limits set at dredging projects for sediment plumes with their backgrounds
- the effects of sediment plumes on different ecological environments
- the relationship between the limits and the effects; are the limits based on the environmental effects

Chapter 2 describes the generation of sediment plumes, plume processes, methods of measurement, and options to mitigate the extent of sediment plumes. Chapter 3 reviews the relevant regulation and legislation in different countries, and describes stakeholders that have an interest in sediment plumes often driven by the requirements of legislation.
In Chapter 4 dredging projects with requirements for sediment plumes caused by dredging are collected and their backgrounds are analysed.
The scope of the potential environmental effects of sediment plumes is reviewed in Chapter 5.

This basic study created a large number of possible further investigations concerning requirements for sediment plumes. Research areas contained the source of sediment plumes (the forecast calculations), methods of measurement, and the effects of sediment plumes on different ecosystems in more detail. From these possibilities two follow-up studies were determined, described in chapter 6 and 7.

Effects on corals
Chapter 6 describes a literature review on the effects of sediment plumes on one specific ecosystem; corals. The objective of this study is to investigate the effects of sediment plumes on corals to be able to make recommendations on requirements for dredging projects near coral reefs.

Measurement optimisation
In Chapter 7 the frequency of measurements, to check if the actual turbidity or concentration of suspended solids complies with the limits, is investigated using existing turbidity measurements done at the Øresund Fixed Link project. The objective of this study is to optimise the number of turbidity measurements at a location, ie the number of ship crossings through a sediment plume, given the costs and the accuracy of the turbidity measurements, by a statistical data analysis.

Chapter 8 describes the conclusions of this report and Chapter 9 offers recommendations on further investigations

2 Sediment plumes

This chapter gives information about sediment plumes caused by dredging.

Section 2.1 shows an overview of sediment plumes caused by dredging. Section 2.2 explains the terms turbidity and concentration of suspended solids and their methods of measurement. Section 2.3 and 2.4 describe the way sediment plumes are generated and further processes of the plumes. Options to reduce the extent of sediment plumes are discussed in Section 2.5.

2.1 Overview

Figure 2-1 shows an overview of the generation and processes of sediment plumes caused by dredging.

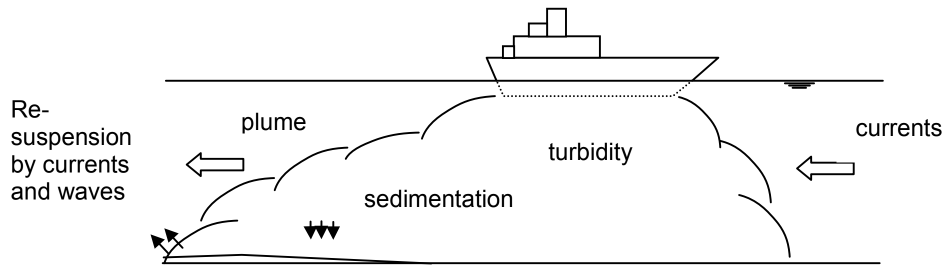


Figure 2-1 An overview

The dredge stirs up sediment and causes sediment plumes at one or more locations. The sediment-water mixture that forms the plume is influenced by its gravity and by currents. It settles at the seabed or stays in suspension and is carried away from the dredge by currents. Sediment plumes cause reduced light penetration, increased concentration of suspended solids and sedimentation, which can all have their own adverse impacts on the benthic vegetation and fauna. Some environments are very sensitive to sediment plumes, while in other environments sediment plumes hardly cause any harm.

2.2 Turbidity and concentration of suspended solids

The terms 'turbidity' and 'concentration of suspended solids' are different, although commonly interchanged:

Suspended solids concentration is the measure of the dry weight of suspended solids per unit volume of water, and is normally reported in milligrams of solids per litre of water (mg/l). Sometimes concentration of suspended solids is expressed in parts per million (ppm) (milligrams of solids per kilograms of water (mg/kg)), which equals mg/l in water with a density of 1000 kg/m^3. To derive suspended solids concentrations water samples are taken and analysed (Thackston and Palermo 2000).

Turbidity is an optical property of water, which causes light to be scattered and absorbed rather than transmitted in straight lines through a sample of water. It is caused by the molecules of the water itself, dissolved substances, and organic and inorganic suspended matter (Thackston and Palermo 2000).

Measurement of turbidity is often perceived as a generally lower cost option than extensive sampling and testing of suspensates. Turbidity can be measured in several ways; the simplest with a white circular 'Secchi Disc', some 300mm in diameter, lowered into the water column until no longer visible from the surface.

Electronic turbidity measuring methods are grouped into optical transmissivity, optical backscatter, and acoustical backscatter techniques.

The standard method for measuring turbidity is by optical backscatter techniques in which fixed angle scattering of light by particulates is compared to standards usually prepared from Formazine. Turbidity has been expressed in terms of Nephelometry Turbidity Units (NTU) or Jackson Turbidity Units (JTU), which are approximately equivalent, or Formazin Turbidity Units (FTU).

The optical transmissometer records the extinction in light caused by scattering and absorption between the emitter and receiver (Telesnicki and Goldberg 1995). This instrument displays data as percentage transmission. In comparison to the transmissometer the optical backscatter sensor (OBS) is simple and compact and capable of measuring much higher particle concentrations (Puckette 1998).

The acoustic backscatter, or Acoustic Doppler current profiling (ADCP) technique utilises the transmission of a beam of sound into the water column. Backscattered sounds from plankton, small particles, etc. are received by the transducer (Hitchcock et al. 1999).

Conversion of turbidity and suspended solids concentration are only possible when turbidity sensors are calibrated with a turbidity standard and with suspended matter from the monitoring site. The ability of a particle to scatter light depends on the size, the shape, and relative refractive index of the particle and on the wavelength of the light. Thus, two samples of water with equal suspended sediment concentrations, but different size distributions of particles, will produce different turbidity readings on the same turbidity meter.

Turbidity or acoustic backscatter readings are only valid for measuring suspended solids concentration when they are properly calibrated against suspended solids concentration values obtained from water samples on the same site, in the same suspension, at the same time (CEDA/ IADC 2001, Land and Bray 1998).

2.3 Generation of sediment plumes

There are three primary influences on the generation of sediment plumes; the dredging operation, the material, and the hydrodynamic conditions in which the dredging takes place.

Dredging techniques

The dredging type defines the geographical location where the plume forms. The types of dredging used in the report are discussed below:

Trailing suction hopper dredging

As they move forward, trailing suction hopper dredges (TSHD) pump a water/sediment mixture from the bed, via one or more suction pipes, into a hopper. In the hopper the coarse sediment settles to the bottom and the supernatant water is returned to the sea via an overflow weir. This overflow can be a significant source of sediment generation. Since the residence time in the hopper is short (decreasing as the hopper fills), much of the fine fraction of the sediment does not settle out and is released into the water with the overflow discharge. Other causes of sediment release are draghead disturbance at the seabed, discharge of screened material, and turbulence caused by the dredge propellor scouring the seabed.

Cutter suction dredging
Cutter suction dredges (CSD) are used when stiffer cohesive sediments and weak rock needs to be dredged, or when the material has to be pumped ashore (e.g. for reclamation). A rotating cutterhead is mounted on the end of a suction pipeline. The material is dislodged by the cutter head and pumped, as slurry, via a pipeline to the desired location. There is no overflow from the dredge. The main source of sediment plume generation is material disturbed around the cutterhead.

Dipper dredging
Dipper dredges are used for dredging cohesive and non-cohesive sediment. They are similar to land-based excavators, although the excavator is mounted on a pontoon, which has to be fixed into position using spuds pushed into the seabed. Dipper dredges re-suspend sediment when the bucket hits the seabed, and because of spillage as the bucket is lifted or lowered through the water column and when its contents are loaded into a barge.

Material
The properties of the material to be dredged influence the amount and size of the sediment that is released into suspension. The source strength, measured in terms of concentration by weight, of a dredged plume depends on the type of sediment being dredged, in particular its particle size distribution and the degree to which it aggregates when disturbed by dredging. The actual amount of disaggregation depends on the amount of energy put into the dredging operation.

The material type also affects the turbidity of the plume because of the different optical properties of silty and sandy water; the finer the sediment, the higher the turbidity for any given concentration by weight. Because of different settling properties of sand and silt, the larger the proportion of fine sediment in the dredged material, the longer it will take for the resulting plume to settle out. This means that silty materials produce more noticeable, longer lasting plumes, although this typically does not equate to a greater impact.

Hydrodynamic conditions
The hydrodynamic environment affects how the dredging operation is carried out and therefore the rate of sediment loss. Hydrodynamic conditions affect the choise of dredging plant. For example, cutter suction dredges can not operate in high wave conditions, where as TSHD are versatile in this respect. Losses will generally be higher if operating conditions are difficult. Waves and currents further influence the dispersion and advection of the plume.

2.4 Plume processes

Dredging releases sediment into the water column forming a sediment plume. There two types, or phases of plumes; the dynamic phase, where the plume moves under its own volition, and the passive phase, where the plume moves due to other influences acting upon it. These processes are shortly described in this section. For more information is referred to CIRIA 2000.

Dynamic plume
The main causes of dynamic plumes are TSHD overflow, pipeline and hopper discharge (pumped or through bottom opening). The water sediment mixture in the water column is of higher density than the surrounding water and descends rapidly towards the seabed. As the plume descends a small part is stripped from the plume and is advected by currents as part of a passive plume. The remainder moves radially outward across the seabed as a dense plume,

slowing with time and distance as the kinetic energy is spent overcoming friction. Eventually a weak deposit is formed (CIRIA 2000). Re-suspension can also take place during this flow phase.

The zone of impact of the dynamic plume phase is relatively small, usually affecting an area less than 100-200m from the dredge (CIRIA 2000, Hitchcock et al. 1999). The size of the impact zone is principally dependent on the initial density and momentum of the sediment/water mixture and the strength of the current flow. The suspended sediment concentration is higher than that within a passive plume; it can be thousands of milligrams of sediment per litre of water (mg/l).

Passive plume

The sources of passive plumes are the losses arising during dredging operations and dynamic plumes. Generation due to the dynamic phase is caused by turbulence or dispersion (spreading of the plume through the effect of different current velocities through the water column)

The sediment concentrations within a passive plume are relatively low and the settling velocity of the particles is sufficiently low for them to remain in suspension. For the finest particles this may be for several hours or days before settlement. The movement of the particles is thus dominated by water currents.

The zone of influence of the passive plume can be several kilometres and is dependent on the magnitude and direction of the currents and on the nature of the released sediment. Suspended sediment concentrations within the plume can be in the order of hundreds of mg/l in the vicinity of the dredge, reducing to tens of mg/l with distance from the dredge (CIRIA 2000).

Modelling

In assessing sediment plumes arising from dredging it is important to be able to predict the plume behaviour and its impact rather than just to measure it afterwards. This implies a need for well established and validated models. There are a different categories of models: flow, dredging process, dynamic plume, fluid mud flow, passive plume, and water quality models. Some parts of the processes can be simulated to an adequate degree, but others can not (yet). A review of techniques, the existing state of knowledge, and the future research needs are outside the scope of this report.

2.5 Mitigating measures

There are different options for mitigating the extent of sediment plumes. The choice and operation of dredging plant with respect to the environment to be dredged is fundamental to reducing sediment plumes. Environmental dredging focuses on limiting sediment re-suspension. Another fundamental area of mitigation is environmental windows.

Choice and operation of dredging plant

Sediment re-suspension caused by trailing suction hopper dredging can be mainly reduced by limiting overflow and re-suspension from cutter suction dredging can be reduced by optimising the swing and the rotation of the cutterhead. Table 2a summaries the measures to reduce sediment plumes arising from dredging.

Dredge	**Mitigation measure**
Trailing suction hopper dredge	Optimise trailing velocity, suction mouth and pump discharge Limit overflow and/or hopper filling Reduce intake water Use return flow Reduce air content in the overflow mixture
Cutter suction dredge	Optimise cutter speed, swing velocity and suction discharge Shield the cutter head or suction head Optimise cutter head design
Dipper dredge	Use a visor over the bucket Use a silt screen (see section 2.5.2)

Table 2a Measures to reduce sediment re-suspension from dredges

Environmental dredging

Some types of dredges and equipment have been designed specifically to operate with minimal suspension of sediment:

Types of cutter suction dredges
The environmental dredging techniques were developed to allow the dredging of thin layers of polluted mud with the smallest possible amount of re-suspension or spillage. They were all designed with the capacity to pump high-density material. Different types of dredges have been developed:
The auger dredge uses two horizontal augers instead of a conventional cutting head to move the sediment towards the suction head and uses a curtain against re-suspension. The disc bottom cutterhead dredge is a variant using a horizontal-mounted disc cutter. Scoop/sweep dredges use a specially designed cutting head that scrapes material towards the suction intake.

Silt screens
A silt screen is a curtain of cloth suspended from a floating framework down to the bed. The basic idea is that the cloth will be permeable to water but not to silt and aims to reduce the spreading of fine sediment. The effectiveness of silt screens, however, is limited to areas of small currents (<0,2 m/s) and low wave conditions. The sediments need enough time to settle, thus the screen can not be moved before this settling time. Careless handling of the screen may completely negate the advantages of its use. Hence, the use of silt screen is not always practical or

economic. Additional costs presented by the use of silt screens often means that other environmental measures are more suitable.

Retention basins

At the disposal area, if there is enough space, retention basins can be made where the sediments can settle on the bottom of the basin before the return flow reaches the surface water. The required length of stay depends on the settling rate of the sediment particles. When the settling rate is larger than the discharge per surface area of the basin (Q/BL) all particles will settle. In practice, such a basin takes a lot of space and other arrangements to prevent fines from being discharged in the surrounding waters. Examples of possible arrangements are dams to prevent direct currents from the inlet to the outflow of the basin, and delivery of the dredged material under the existing sediment layer by means of a pipe and a diffuser. This last example was successfully used in the Netherlands at the temporary disposal of the 'Ketelmeer' and the disposal of the 'Slufter'.

Environmental windows

Environmental windows are specific time periods to which a dredging project should be confined. In some time zones environments are more sensitive to the possible adverse effects of dredging. In terms of sediment plumes there are two fundamental sets of site-specific factors to take into account. The environmental interests at risk (the location of shellfish beds, fish migration routes and seasons) and the environmental factors affecting the distribution and impact of the plume and its subsequent settlement (tidal excursion, sediment type and quantity). To identify appropriate windows extensive knowledge of the site-specific factors is needed.

3 Standards

This chapter deals with international regulation or legislation specifically relating to uncontaminated sediment plumes caused by dredging activities.

First the regulations in the member states of the European Union will be discussed, with the Netherlands in particular. Then relevant regulation and legislation of other countries will be described. This comes down to The USA and Hong Kong.

In the second section of this chapter, stakeholders with an interest in sediment plumes will be introduced.

3.1 Regulation and legislation in Europe

Europe

Europe does not have any legislation specifically relating to sediment plumes caused by dredging activities (CIRIA 2000). As a result sediment plumes are usually considered in the context of environmental legislation relating to licensing and permitting of all aspects of dredging projects; the environmental impact assessment (EIA).

For the EIA's all member states of the European Union are subject to the provisions of EC directives; including EC Directive 85/337/EEC, as amended by Directive 97/11/EC, on the assessment of the effects of certain public and private projects on the environment and EC Directive 92/43/EEC on the conservation of natural habitats and wild fauna and flora. (ref.. web sites Europe) Each country may implement these provisions in different ways.

Under Directive 97/11/EC for example proposed harbour works require harbour empowerment and coastal protection act consent. An EIA requires consideration of the environmental effects of all aspects of a proposed project. If dredging is proposed within or adjacent to a European protected site then the provisions of EC Directive 92/43/EEC are applied. If it is considered that the works are likely to have a significant effect, an assessment has to be made of the effect of dredging (including the plume). If the works are likely to have an adversely effect on the site, they will not be able to proceed without mitigation or compensation. All EIA's include extensive consultation with stakeholders, including the regulators, conservation agencies and fishery organisations.

European Union does have regulations to protect the aquatic environment from and pollution caused by disposal at sea. The European Community and Member States are party to various international agreements containing important obligations on the protection of marine waters from pollution; in particular the Convention on the Protection of the Marine Environment of the Baltic Sea Area (Helsinki 1992, approved by Council Decision 94/157/EC), the Convention for the Protection of the Marine Environment of the North-East Atlantic (Paris 1992, approved by Council Decision 98/249/EC), and the Convention for the Protection of the Mediterranean Sea Against Pollution (Barcelona 1976, approved by Council Decision 77/585/EEC). Directive 2000/60/EC on the establishing of a framework for Community action in the field of water policy is to contribute to the progressive reduction of emissions of hazardous substances to water. For dredging and dumping of uncontaminated material no requirements are set.

For contamination caused by hazardous materials that are disposed in the aquatic environment of the Community the provisions of EC Directive 76/464/EEC are applied. According to these

European guidelines it is not mandatory to include emission norms in licences for discharges from temporary disposal sites.

Another approach to protect the water quality is to define the minimum quality requirements of water to limit the cumulative impact of emissions. The water quality guidelines of the EU for surface waters (ref. web sites Europe) are:
Guideline 75/440/EEG for drinking water: mean value <1-10 mg/l concentration of suspended solids.
Guideline 76/160/EEG for bathing water: mean value visibility of Secchi disc>1 meter.

The Netherlands

The Netherlands have, just like the rest of Europe, no legislation and regulatory processes specifically relating to sediment plumes. A few years ago regulations were tried to set up by determining a specific factor times the baseline conditions of turbidity. But these baseline conditions were hard to determine because nature causes very large variety in turbidity. Thus, at present for each project in tender specifications guidelines are given for the dredging methods.

For all dredging activities, permits are required. For some projects (no marine projects) suspended sediment or visibility norms are attached to these permits. The competent authorities; Rijkswaterstaat or polder boards (Hoogheemraadschappen or waterschappen) set the norms. Only one report was found about recommendations for norms for suspended solids or turbidity; the CIW/CUWVO report (1998). In this report recommendations for discharges from temporary disposal sites were made by a special commission under the terms of the Surface Waters Pollution Act (Wet verontreiniging oppervlaktewateren (WVO)). EC Directive 76/464/EEC (see section 3.1.1) is incorporated in this act.

The Surface Waters Pollution Act (WVO) has to prevent contamination of inland surface waters. It is not allowed, in any way, to bring waste, polluted or harmful matters into the surface water without a permit. These are matters that can attack the self-cleaning capacity of the water or that can lead to a decrease of the water quality. For temporary disposal sites a Wvo-permit is obliged.

Licence regime regarding the water quality policy:

- The Environmental Protection Act (Wet milieubeheer (Wm)) (sub-section 2 of section 8.40) and the Surface Water Pollution Act (Wet verontreiniging oppervlaktewateren (WVO)) (sections 2a through e) provide for the establishment of general rules. There appear to be possibilities for establishing general rules for disposal of clean or hardly polluted (class 0/1/2) dredged material.
- According to the European guidelines concerning emission norms and discharge licences it is not mandatory to include emission norms in licences for discharges for temporary disposal sites (section 3.1.1).

Recommendations from the CIW/CUWVO report (1998) concerning uncontaminated disposal of dredged material:

Distinguish between disposal sites for storing dredged material from one and the same watercourse (location disposal sites) and disposal sites for storing dredged material from the region or where more than one batch of dredged material is stored for a longer period of time (regional and passage disposal sites).

- It is recommended for the class 0/1/2 location disposal sites to employ a regime that is based on retaining the suspended solids using a discharge regulator and disposal site management with the requirement of 200mg/l for suspended solids in the discharge.
- It is recommended for the class 0/1/2 regional disposal sites and passage disposal sites to employ a regime that is based on retaining the suspended solids using discharge regulators and disposal site management with the requirement of 100mg/l for the content of suspended solids in the discharge.

- Enforce a requirement of 400mg/l suspended solids for water systems where there is no, or only a very limited, ecosystem functioning, which is particularly the case for new sand dredging pits or gravel pits. Or, make it obligatory that the delivery water, by means of a pipe and a diffuser, is to flow close to the bottom of the pit. The absence of any risk for an ecosystem that is functioning normally is the criteria in these cases.

These are recommendations. It is up to the competent authorities like a Hoogheemraadschap, waterschap or Rijkswaterstaat to set the norms.

3.2 Other countries

USA

In the United States the situation concerning the limits on turbidity set by regulatory agencies is very much determined on a project-by-project basis as well. The USA Corps of Engineers (USACE) and Environmental Protection Agency (EPA) are jointly responsible for permitting procedures under the Clean Water Act, Marine Protection, Research and Sanctuary Act, Resource Conservation and Recovery Act and the Water Resources Development Act. They co-ordinate individual dredging projects with both state and other federal agencies (National Marine Fisheries Service, US Fish and Wildlife Service). Federal agencies can request compliance with certain water quality criteria, but these are advisory unless the dredging falls under other federal legislation, such as the Endangered Species Act. Although dredged material is often placed or disposed at offshore sites, the dredging itself almost always occurs in state waters. Authority for setting criteria lies with the individual state.

Each state issues a Water Quality Certificate for a given dredging project, and stipulates acceptable turbidity conditions and required monitoring. The standards used to establish water quality criteria vary from state to state (EPA 1988). In some states the critical conditions are given as NTU units, in others as mg/l or in meters of visible depth of a Secchi disc. Sometimes the limits are absolute but most of the times above natural levels. The numbers for fish and aquatic life marine water for example vary from 5 NTU to 100 NTU above natural conditions to no limit. According to the USACE in many cases the values are quite arbitrary, based on prevailing perceptions of dredging-induced effects rather than quantitative evidence.

Hong Kong

In Hong Kong since 1998 the Environmental Impact Ordinance is established to avoid, minimise and control the adverse environmental impacts of designated projects through the EIA process and environmental permits. Permits are required for projects involving reclamation works and dredging operations exceeding 50.000 m^3. For smaller dredging operations a permit is required where a project is less than 500 m from environmentally sensitive site (eg a marine park or reserve, bathing beach, fish culture zone) or less than 100 m from a seawater intake point. To date, the Environmental Protection Department has issued several dredging permits. All permits include detailed monitoring and auditing conditions on dredging operations to prevent adverse environmental effects associated with the introduction of sediment into the water column.

3.3 **Conclusions**

There is no international regulation or legislation specifically relating to uncontaminated sediment plumes caused by dredging activities.

In a number of countries there are international conventions and legislation with respect to aquatic disposal of dredged material at sea and in inland waterways These assessment and licensing procedures are all aimed at prohibiting or controlling the amount of contaminants placed in the aquatic environment. The Dutch Surface Waters Pollution Act (WVO) is based on prevention of contamination of surface waters as well. The 100 and 200 mg/l as recommended in the CIW/CUWVO report seem strict limits for uncontaminated sediments and it is not clear why there has to be a limit for water systems where there is no ecosystem functioning.

Further there are water quality criteria registered in several countries. These criteria are not implicitly applicable for dredging projects. Dredging projects have only temporarily impacts and can be well planned by means of environmental windows (see Section 2.5.3), for example not in hatching etc. seasons or bathing seasons.

It seems impossible to make limits universal because the effects of sediment plumes caused by dredging vary from site to site. For a small country like the Netherlands this did not work out because the baseline conditions varied too much. This implies that for a large number of projects no limits would be required because the environment is used to varying suspended sediment concentrations and turbidity.

3.4 Stakeholders

Stakeholders include all parties with an interest in sediment plumes caused by dredging activities, including dredging companies and contractors, regulators and other affected parties.

Regulations are subject to government agencies and other interested parties include port and harbour authorities, seabed owners, fishermen's associations, non-governmental organisations, members of the public, environmental consultants and coastal process specialists.

Various associations look after many of the dredging industry's interests, such as those detailed below:

International Association of Dredging Contractors (IADC)
The IADC, based in the Netherlands, is a world-wide umbrella organisation for more than 120 private dredging companies. It seeks to promote the private dredging industry and establish fair, open market conditions for its members.

Central Dredging Association (CEDA)
CEDA is based in the Netherlands and had British, Belgium and Dutch national sections that promote education about dredging, disseminate quality information on dredging, develop guidelines and standards relating to good practice, initiate and support research, and be proactive in relevant policy-making.

Vereniging van Waterbouwers in Bagger-, Kust- en Oeverwerken (VBKO)
The VBKO is the Dutch association of contractors that undertake dredging, shore and bank protection works, representing more than 300 companies, and provides an outlet for education and business promotion.

Permanent International Association of Navigation Congresses (PIANC)
PIANC, based in Belgium, represents organisations involved in the safe and efficient operation of all types of commercial and recreational vessels, including the management and sustainable development of ports and navigational waterways.

These associations take care of information gathering and knowledge transfer. Recently, Dutch dredging companies and the Rijkswaterstaat, through the VBKO, have commissioned UK investigations into turbidity assessment software. The results will be in the public domain.

Another sort of stakeholder is the World Bank. The World Bank Group finances commercial and industrial projects. For projects for which no specific environmental guidelines have been written the World Bank Group has general environmental guidelines. Process wastewater, domestic sewage and contaminated stormwater and runoff must meet maximum limits before being discharged to surface waters. For total suspended solids the limit is 50 mg/l. Projects must comply with these policies and guidelines, which emphasize pollution prevention. Depending on the project, the requirements may need to be supplemented by additional requirements. The intent of the guidelines is to minimize resource consumption and to eliminate or reduce pollutants at the source. For ease of monitoring, maximum permitted emissions limits are often expressed in concentration terms-for example miligrams per liter (mg/l) for liquid effluents.

4 Limits

Limits for turbidity and concentration of suspended solids become quite common and the limits are getting stricter. For dredging contractors it is getting more difficult to cope with the restrictions and sometimes they get the impression the background reasons are lacking. The limits have to be well founded because the costs of dredging increase with stricter limits.

In this chapter an overview has been made of some dredging projects from all over the world at which limits for suspended solids and/or turbidity were set. The requirements were found in technical specifications of international dredging and reclamation tenders. The reasons for the requirements and the backgrounds were analysed and commented.

4.1 Projects

In appendix B an overview can be found with information on the dredging projects collected from all over the world with their limits for turbidity and/or concentration of suspended solids and other relevant information as available at the consulted companies and institutes. This information includes background conditions, characteristics of sediment, hydrodynamic conditions, during of dredging activities and dredging equipment. Table 4a shows a summary. The projects the author is acquainted with that are under construction at the moment or still in tender phase are not included in the appendix and table.

A large part of the projects in the overview were still in tender phase during this study. This indicates that requirements of turbidity and/or concentration of suspended solids become more common. It further means that the projects are not executed yet and no results are known. Because information about these projects in tender phase is delicate, it is difficult to find out about the backgrounds of the limits. This is an important reason why, in the overview often information is missing.

The 14 projects are located all over the world, most of them are harbour or infrastructure projects, in marine- and in freshwater. A summary of the findings from the dredging projects will follow below:

The reasons for the limits were for most projects to prevent environmental damage, most of the time corals, seagrass or fish. For some projects the reason is not accessed in this study.

For corals, most of the limits were set in suspended solids contents. They varied from < 2500 mg/l effluent from reclamation area (Beef Islands International Airport), to < 500 mg/l (Sohar) and 400 mg/l above ambient values 200 m around cutter and at discharge point (Ruwais). Concentration of suspended solids in surface waters over reef slopes varied from <10 mg/l above ambient concentration during daylight hours, <20 mg/l at night (Fuah Mulaku) and < 30 mg/l TSS (Jervoise Bay).
Sedimentation rates were required on coral reef slope <10 mg/cm^2 day (Fuah Mulaku) and for turbidity a limit of 20-29 NTU average over and above background conditions measured at a line 100-200 m seaward of the works was set (Puerto Caucedo).

For seagrasses a limit in concentration of suspended solids of < 30 mg/l was set (Jervoise Bay) and for the Øresund shading percentages were determined and converted to spill percentages. For the Jervoise Bay Secchi depths above/ nearby sensitive benthic communities had to be >20th percentile of background Secchi depths.

Project	Limit	Location	Level	Frequency
Øresund Link (1996 – 2000)	Total spill <5% Maximum weekly and daily spillage limits	Spill monitoring (OBS and ADCP) by vessels sailing through the spill plume	4 levels in the water column	24 hours/day
Ruwais (1999-2000)	Total spill <5% TSS<400mg/l above background levels (3 to 8 mg/l) at any time	At boundary lines 200m around cutter and at discharge point	Over the whole water column	13 hours/day
New Port and Fishery Harbour at Wilayat Sohar	suspended solids content of the final discharge water to the sea < 500 mg/l	At discharge point		Twice a day or as directed by the Engineer

Table 4a Limits of the dredging contracts

Other concerns and areas than corals or seagrasses give the following limits;<80 mg/l (Jervoise Bay), 25 ppm for fishery and park area and 75 ppm for industry area at selected positions (Bourgas), 100 mg/l at discharge point (Port 2000). For the Penny's Bay in Hong Kong a limit of 20 to 30% above reference values for turbidity and concentration of suspended solids was set and at the same time a maximum number of dredges was allowed because of fish farms and recreation. For the Øresund other reasons than seagrass were herring, birds, bathing water and mussels. For inland surface waters and rivers the limits were based on permits (Zevenhuizerplas, Haarrijnse plas, Port 2000); these permits are discussed in chapter 3.

The limits were expressed in different units; spillage in (kg/s) or percentage (%), concentration of suspended solids (mg/l or ppm), turbidity (NTU), visibility with a Secchi disc (m) and sedimentation (mg/cm^2 day).

The limits have been set at different locations. Sometimes at the location of possible negative environmental impact for example near coral reefs (Fuah Mulaku Harbour Project in the Republic of Maldives), at seagrass meadows or both (Jervoise Bay Infrastructure Project). For other projects the limits have been set at the discharge point or around the dredge (Beef Islands International Airport, Ruwais and at Wilayat Sohar).

The required frequencies of measurement varied from 24 hours/day (Øresund Link), 13 hours/day (Ruwais), twice a day (Sohor), to regularly at intervals not exceeding one week (Beef Islands), daily (Jervoise Bay) to 3 days/week (Penny's bay). At some projects the contractor has to develop a monitoring plan.

No conclusions can be drawn from these limit values, because of the different environments and methods of measurement. It just indicates the variety of ways to set limits and that there are no international standards.

4.2 Backgrounds

The backgrounds of the limits of the projects described in the overview were analysed. The Øresund Fixed Link was the only project for which a full environmental investigation to the effects on the ecosystem was exposed. For some projects the limits were based on background values, for others the physical backgrounds were lacking or based on experiences at other projects.

Investigations on the impact on the ecosystem

At the Øresund Link project limits were based on the marine environment's sensitivity to sediment spillage (Øresundkonsortiet 1997). The project is described in Box I; a summary is given below.

Large-scale field experiments and laboratory experiments were used to establish limitations for turbidity from dredging operations. The key species were eelgrass, herring, birds, and mussels.

For eelgrass field experiments have been conducted to reveal both spatial and seasonal variation in eelgrass variables as well as the effects of shading. A model of an eelgrass-dominated ecosystem was used to predict the potential impact of increased turbidity caused by dredging. For the other species similar methods were used.

A sediment transport model simulates the temporally and spatially varying sedimentation at the sea-bed, and the suspended sediment concentration. This was used directly as input to the ecological model. The model results have been translated into time and geographical spill limits, which were included in the tender documents and the contracts.

Experiences at other projects

Frequently, when consultants are asked for advice to set limits, there is no time or money available to do a full environmental study. Consultants have no other choice than to give advice based on experience on other projects and knowledge of the area. This was the case for the projects in Ruwais and Sohor (ref. Halcrow). When experience of other projects is used prudence is called for. Limits can not simply be copied from one project to another without a thorough study and comparison on all conditions of the environments. Limits are very site and time specific and important factors of influence hydrodynamic conditions, sediment characteristics, background conditions and specific species.

Sometimes it looks like limits in tender documents are arbitrarily copied from other projects. Especially the 5 per cent spill of the Øresund Link project.

For the Øresund environmental programme eelgrass (a type of seagrass) was one of the key species to protect from negative effects of turbidity. In the waters of Øresund the background turbidity is almost zero and the eelgrass is very vulnerable to turbidity. But seagrasses adapt to their local conditions. In the shallow North Lake of Tunis (project described in appendix B) the seagrass is not disturbed by the sediment resuspension and turbidity of the lake, which is said to be large in storm wave conditions (Oostinga 2001). In the much more turbid Dutch Wadden Sea there is eelgrass as well, even the same species as in the Baltic Sea. And while it is the same eelgrass it is not necessary to use the limits of the Øresund eelgrass for the Wadden Sea eelgrass.

The limits of the Øresund project are only valid for a similar environment (almost no natural turbidity, same species (herring, mussels, seagrass, foraging birds) with the same behaviour, same hydrodynamic conditions, same sediments, same dredge, etc.). On the other hand it is possible to use the same models with different input of parameters based on specific local conditions.

Øresund Fixed Link

The Øresund Fixed Link between Copenhagen in Denmark and Malmö in Sweden was constructed from1996 to 2000. The Øresund is the easternmost of the three straits connecting the Baltic Sea with the North Sea. During the design phase of the projects, environmental protection assumed a central role. Consequently, the contemporary political view, emphasising that infrastructures must be designed in interaction with the surrounding environment, has greatly influenced the final design of the Fixed Link.

For the Øresund Fixed Link project The Danish and Swedish authorities laid down very strict environmental regulations. The most important are:

- total amount of dredged material must not exceed 7,5 million cubic meters;
- average amount of sediment spillage must not exceed 5 percent of the dredged amount;
- total spillage must be determined with accuracy within 20 percent; and
- sediment spillage from dredging and reclamation works must be limited in intensity, time and space with due regard to the flora and fauna in Øresund.

In order to meet the second requirement the owner of the project, Øresundskonsortiet had carried out extensive investigations for the purpose of assessing the environmental consequences of the Fixed Link. The limitations were prepared on the basis of preliminary surveys of the marine environment's sensitivity to sediment spillage. Large-scale field experiments and laboratory experiments were used to establish limitations for turbidity from dredging operations.

The water of the Øresund is very clear and clean and the background turbidity is almost zero. The most sensitive parameters are eelgrass, herring, mussels and birds. Seagrasses are abundant down to10 m below sealevel. Field experiments have been conducted to reveal both spatial and seasonal variation in eelgrass variables as well as the effects of shading. A model of an eelgrass-dominated ecosystem was improved by DHI and used to predict the potential impact of increased turbidity caused by dredging. It calculates the growth of seagrasses (biomass roots, leaves and amount of corbonhydrates in the roots) as a function of water quality, temperature salinity etc. A sediment transport modelling complex simulates the temporally and spatially varying sedimentation at the sea-bed, and the suspended sediment concentration. This was used directly as input to the ecological model. This model has been used to calculate max dose of spill, which could be tolerated without violating the criteria for seagrasses laid down by the authorities: 'Eelgrass beds and other important vegetation are to be safeguarded by ensuring that the distribution and biomass are not reduced by more than 25 per cent after completion of the dredging operations. A larger reduction, however, is accepted at depths of more than 5 m.' Similar methods were used for calculating limits with respect to other organisms like mussels, fish, birds and bathing water quality:

- Herring migration through Øresund must be safeguarded by ensuring that a minimum of 2/3 of Drogden and the Flinte Channel are kept free of concentrations of suspended materials above 10 mg/l during migratory periods.
- Foraging birds in the shallow waters around Saltholm will be safeguarded by ensuring that concentrations of suspended material during April and July-August do not exceed 28 mg/l in 90 per cent and 70 per cent of the time respectively.
- Mussel beds must be safeguarded by ensuring that sedimentation in the outer impact zone does not exceed 15 kg/m2/month. And by ensuring that sedimentation does not exceed 60 kg/m2/day for more than 20 per cent of the time during the period from June to August, when mussel larvae settle.
- The bathing water quality at the bathing beaches along the Swedish and Danish coasts will be safeguarded by ensuring that the visibility will not be less than one meter in the bathing season.

Øresundskonsortiet has translated these operational threshold values for acceptable sediment concentrations into maximum daily and weekly spillage rates for different dredging areas depending on the season and the area's sensitivity. The established requirement of the authorities, maximum average spillage from all dredging operations of 5 per cent of the total dredged amount, was not directly related to the modelling of the impact on the ecosystem. This limit is well-known but the daily, weekly and seasonal limits to spill in zones across Øresund were the major management tool, which secured that the 7 million m3 dredging project could be accomplished under very strict environmental criteria and without causing any public alarm.

The project was finished one year ahead of the time schedule and within the original budget. All environmental restrictions were met. It has thus been proven that the execution of large-scale dredging and reclamation projects in environmentally sensitive areas without disturbing the environment is possible.

Box I The Øresund Fixed Link

Reports

In the tender specifications of the Port of Bourgas Expansion Project in the Black Sea limits are set for concentration of suspended sediment at several locations. As stated in the specification for the fishery area EIFAC (European Inland Fisheries Advisory Committee) criteria are used and a limit of 25 ppm is set. For the other areas the backgrounds are not known. In the report on Finely Divided Solids and Inland Fisheries, EIFAC Technical paper (1964) the following criteria are presented:

a. There is no evidence that concentrations of suspended solids less than 25 mg/l have any harmful effect on fisheries
b. It should usually be possible to maintain good or moderate fisheries in waters, which normally contain 25-80 mg/l suspended solids. Other factors being equal, however, the yield of fish from such waters might be somewhat lower than from those from those in category a.
c. Waters normally containing from 80-400 mg/l suspended solids are unlikely to support good freshwater fisheries, although fisheries may sometimes be found at the lower concentrations within this range.
d. At the best, only poor fisheries are likely to be found in waters, which normally contain more than 400 mg/l suspended solids.

These freshwater criteria are drawn up for lakes and rivers. It seems not appropriate to use the criteria for the water of the Black Sea without further investigations.

The limit of 25 ppm seems quite strict. As described at point b, 80 mg/l would still cause no harmful effects. The criteria are stated for normal water conditions while dredging will only cause a temporally increased concentration of suspended solids.

There is no information given about the background circumstances of the area. 25 mg/l seems like a very low value for an environment like the Black Sea. It would not be useful to set limits for turbidity caused by dredging activities containing lower levels than the normal circumstances.

Background conditions

Sometimes a limit is set a factor times the background level (limits for Ruwais, Caucedo, Fuah Mulaku and Penny's Bay). For example in Hong Kong there is not a fixed limit but usually the limit is 30% above the ambient or background level. The ambient level usually is established from long term monitoring data.

Sometimes it is difficult to determine background values because nature can cause very high variations. But this seems a logical and reasonable way to set limits.

Permits

At the Penny's Bay Reclamation project in Hong Kong the Environmental Permit imposes the maximum number of dredging and reclamation units. The restriction logically followed the recommendations of the Environmental Impact Assessment. This is inconsistent with the equally imposed system of background and impact monitoring related to action and limit levels. For the technical development and competition possibilities it is better to let the dredging contractors do the interpretation of the soil characteristics and its disintegration by the dredging process, leading to the sediment release rates of the dredge. This enables them to select, allocate and possibly adapt their resources in the best suitable way.

At the Zevenhuizerplas, the limit was based on bathing water criteria. The clay layer on top of the sand that was to be mined and had to be dumped at the bottom of the existing lake. This lake was at a recreation area. With a discharge diffuser, at about one meter above the bottom of the lake, the limits at the required 4 depths were met (see appendix B).

At the Haarrijnse plas, the limit was based on the WVO permit. The polder board (Hoogheemraadschap de Stichtse Rijnlanden) used the recommendations of the CIW/CUWVO report (chapter 3); 400mg/l suspended solids for a new dredging pit, a water system where no ecosystem is functioning.

Community perception

Turbidity plumes are highly visible and can lead to a poor community perception about the project's ability to be managed in an environmentally suitable manner (Jervoise Bay). At some projects limits are set to prevent complaints from environmentalists or inhabitants of the neighbourhood.

This may lead to technically almost not feasible or at least not realistic specifications in tender documents. At the Freeport harbour mouth widening in the Bahamas the specification implied that the outflow from the reclamation area had to be clear, sediment-free water. The material to be dredged was coralline rock. When this material is dredged by a cuttersuction dredge it will be crushed to fine powder. In water it will stay in suspension for a long time, it will look like a milky fluid and there will be a wide spread of the sediment plume. To prevent this would be unrealistic. There are of course ways to diminish the outflow of sediments but in this case it would bring along very high costs. The dredging contractor convinced the consultant of this project to abandon the specification. Finally no water flowed back into the ocean at all, because it could be diverted to underground cavities in the limestone rock, of which all of the Bahamian islands consist. This opportunity was not recognized beforehand by either party.

At the Øresund Fixed Link project the clean, clear water was very important to the countries bordering the Baltic Sea, and herring is a great source of income. The plan to make the fixed link was already there in 1934. There was resistance from environmental organisations etc. The clean and clear water in the Øresund is a difficult environment to carry out large dredging operations. Even minor sediment plumes are clearly visible and the relative strong currents transport the spill over long distances. For years there was a complicated political situation that finally resulted in the decision to pay a price for the environment

4.3 Conclusions and remarks

Conclusions

The requirements for sediment plumes in dredging contracts vary in reasons, limit values with different units, method of measurement, location, and frequency of measurement, and the backgrounds for many projects are not well founded. Political reasons such as community perception often play an important role in determining limits rather than environmental effects. This sometimes even results in unnecessary requirements or limits that can not be realised with regular working methods.

Remarks

This section contains some remarks about possible reasons for the lacking of the backgrounds of limits and for problems at projects with requirements for sediment plumes. Possible solutions for the problems are suggested as well.

Lack of knowledge

The main problem with setting up limits is that there is not enough knowledge of the backgrounds. The limits should be based on the impact of sediment load on the ecosystem but biologists do not agree on how much the ecosystem can handle. When the limits are determined they have to be translated to a way of dredging. The engineers have sediment plume models but do not know how much sediment is stirred up exactly. This makes it very hard to bring these parties together and find a solution within the boundaries of the resilience of the ecosystem. And when there is environmental damage, there will be a conflict because the cause of the damage is very hard to prove. More research is needed on the thresholds and duration that different ecosystems can be exposed to and on the models that can predict the amount of re-suspended sediment.

Costs

Requirements for turbidity and/or suspended solids caused by dredging activities bring along costs; for investigations to determine limits and for monitoring. For the Øresund project about 45 people were working on the environmental monitoring for 24hr per day. A rough estimate of the relative costs imposed by the strict environmental requirements on the design and construct of the Link is approximately 10 percent. (IADC/CEDA 2000).

The employer should realise that requirements implicate high costs, and that requirements are not always needed. Sediment plumes do not always have negative impacts on the environment. That is why for every project first a rough judgement has to be made, whether negative impact is to be expected. Only in the event of expected negative impact a quantification of limits is appropriate. This can save the employer money for unnecessary requirements.

Type of contract

Another problem is the procedure of making dredging contracts. The employer, with the help of a consultant, makes a tender document with the environmental specifications. Several contractors can make a bid and the contractor (combination) with the lowest bid gets the contract.

In these traditional contracts the competition is on price only. Dredging contractors have to do the works for the agreed lump sum, also if problems delay the works, and changes increase the costs. Thus they prefer to dredge non-stop without difficulties caused by environmental limits. In a different kind of contract, whereby the contractors are more encouraged to accept risks related to the achievement of the environmental objects, the contractors could use their engineering capacities to make proposals for projects with environmental objects.

Another possible solution could be that the contractors make prices for different options. The employer can choose an option for his project, which will be a compromise between the level of environmental impact and the costs made to prevent this.

Other water quality limits

The limits for turbidity and suspended solids should be balanced with water quality limits at other industries like commercial shipping (ferries create resuspension of sediments), trawler fishing or chemical industries. It seems unbalanced that at some projects limits for sediment plumes are very strict while sewage and waste is dumped directly into the same water. For example the primary threat of the quality of the Hong Kong waters is the outflow of untreated sewage from the city (Oostinga 2001).

5 Effects on the ecosystem

This chapter numbers the possible negative impacts of sediment plumes and discusses the vulnerability of different ecosystems to sediment plumes.

The global effects of sediment plumes on the aquatic environment, mentioned in Section 5.1, are well known. In more detail, to determine a direct relation between sediment plume and effect is very complicated. The vulnerability of an ecosystem to sediment plumes, discussed in Section 5.2.1, depends on the characteristics of the plume, and on the natural conditions and the present species. Section 5.2.2 shows that for a large part of the dredging projects no limits are needed.

5.1 Effects of sediment plumes

Sediment plumes can be caused by dredging but also by natural conditions such as storms, river run off or high water flows, or by other activities, such as bottom trawling.

A number of negative impacts of sediment plumes on water quality, marine ecology, fish and shellfish can be expected and has been demonstrated:

- Elevated turbidity causes reduction of photosynthesis by phytoplankton, algae and rooted vegetation and reduction of visibility, which makes feeding difficult to certain fish.
- Increased suspended sediment concentrations will cause reduction of dissolved oxygen levels, and release of adsorbed heavy metals or toxic organics from fine-grained suspended solids (outside the scope of this report); and will cause
- interference with respiration and (filter-)feeding of (shell)fish, impediment to mobility, or irritation to tissue, making infection or invasion by parasites more likely.
- Sedimentation will cause covering of the bottom near the dredging site, smothering bottom-dwelling organisms (including eggs and larvae), reducing or eliminating food supply, or reducing habitat diversity -particularly vulnerable are tropical species such as corals, sea grasses and mangroves.

The level, duration and location of the elevated turbidity and concentration of suspended solids in the plume determine the load on the ecosystem. The impact of this load depends on the tolerance of the ecosystem (see Section 5.2.2).

5.2 Vulnerability of the environment

Factors of influence

The vulnerability of a specific environment to sediment plumes depends on the natural conditions and the characteristics of the present species. If some species are sensitive to elevated turbidity or concentration of suspended solids levels, this has its influence on the whole ecosystem.

Natural conditions

Species are adapted to natural conditions such as the climate conditions, the background turbidity and the hydrodynamic setting.

Climate in higher latitudes is generally more dynamic and less hospitable than the climate in lower latitudes. The ecosystem in a climate in higher latitudes with large differences in temperature, hydrodynamic and turbidity conditions will have high tolerances. The biodiversity is lower, and the plants and animals are capable of surviving extreme conditions. In tropical areas, where the conditions are more constant, biodiversity is greater, but the ecosystem will be more vulnerable to changes (CEDA/IADC 2001).

The background turbidity is of interest to tolerance of ecosystems. Ecosystems adapt to the natural light and sediment conditions over longer periods. If the ecosystem is used to large variation of turbidity levels and sedimentation rates caused by storms or currents, its tolerance will be large and changes, for example caused by dredging, do not necessarily raise environmental problems. Table 5a (Hitchcock 1999) shows natural variation in suspended solid concentration for different areas. The number of decimals in some of the numbers in this table seems unrealistic.

Reference	**Location**	**Comments**	**Conc.SS(mg/l)**
Bassindale (1943)	Bristol Channel, UK	At Weston-Super-Mare	30-900
Postma (1961)	Wadden Sea	coastal	1000
Manheim et al (1972)	Gulf of Mexico, USA	surface (offshore)	0.125
Chave (1965)	SW Florida, Carib.	surface	5
Chester & Stoner (1972)	English Channel Irish Sea	surface surface	1.719 1.680
Buss & Rudolfo (1972)	Cape Hatteras, USA	surface (offshore) midwater (offshore) bottom (offshore)	0.1 1-2 0.5-2
Gajewski & Uscinowicz (1993)	Baltic Sea	depth average	1.8
HR Wallingford (1997)	Owers Bank, UK Rye Bay & Harwich	depth average depth average, storms	0-30 220-410
Dyer & Moffat (1992)	Southern North Sea	depth average - summer depth average – winter	5-30 38-42
Environment Agency (1992)	English Channel	surface, bottom midwater	2-76 3-97

Table 5a Selected values of suspended solid concentrations. (Modified from Moore, 1977; Dyer & Moffat, 1992; HR Wallingford, 1993; Environmental Agency, 1997, Hitchcock, 1999)

The hydrodynamic conditions determine how much stress is due to sedimentation and how much is due to turbidity. In regions of low hydrodynamic energy, settling of suspended sediment is of more influence than light attenuation. In regions of high hydrodynamic energy where sediment tends to remain in suspension, the reverse is true. Sediments are less likely to cause a problem when strong currents are present. Currents can take away sedimentation but on the other hand strong tidal flows are capable of re-suspending sand and silt and cause increased turbidity.

Characteristics of the present species
Sediment plumes can affect benthic flora en fauna, water column ecology, fish and shellfish. Corals are especially vulnerable to increased levels of turbidity and sedimentation. Sea grass is an example of highly light sensitive flora. Filter-feeding bivalves such as mussels can't take high sedimentation rates. Fish are potentially sensitive to sediment plumes in terms of suspended sediment in the water column and sediment settlement on the seabed, especially during their early life stages.

Sensitive species have their effects on the whole ecosystem. Increases in sedimentation rates can alter the interactions between organisms and their habitats. In tropical coastal areas for example, juveniles of many fish species and other organisms depend on mangroves and seagrass beds for food and shelter, moving to deeper waters and offshore reefs as they mature. Deterioration of any of these ecosystems can lead to decline in fish populations. Cutting of mangrove trees, which normally entrap sediment, can result in siltation for nearby seagrass beds and reefs from runoff after heavy rains. Destruction of red mangroves with submerged prop roots decreases the habitat for juvenile fishes. Excessive sedimentation can affect the complex food web on the reef by killing not only corals, but also commercially important fish and shellfish. Further, with deterioration of mangroves and coral, the natural coastal protection decreases.

Types of aquatic environments and their sensitivity to sediment plumes caused by dredging

Different types of aquatic environments can be distinguished (CEDA/IADC 2000). On a worldwide scale the geographical distribution of marine biota is fixed by water temperature, light availability and the tolerance towards changes. At regional scale, tidal amplitude, water movement including mixing of salt and fresh water, wave action, desiccation and sediment type are important physical factors for zonation and distribution of shore organisms together with biological factors, such as competition and predation. In the littoral zone particular irradiation, exposure time, desiccation, grazing and predation are important factors. In deep water, temperature is the main factor and in estuaries, the salinity gradient is the dominant factor. Per environment the vulnerability to the possible effects of sediment plumes will be discussed.

In typical tide- or current dominated environments such as tidal inlets, estuaries, bays and straits, the background turbidity often is of the same magnitude or higher than the turbidity created by dredging. If this is the case, increased turbidity of uncontaminated material should not necessarily be regarded as an environmental problem.

In open sea or wave-exposed coasts or shelf areas effects of spill generated by dredging projects are usually of a temporary nature. Light sensitive flora is not normally found in such areas and the dispersion of the spill is often so high that the resulting turbidity will be very small. Increased sedimentation caused by spill may locally affect mussels, fish eggs and other benthic fauna.

5.3 Conclusions

Many environments are not vulnerable to sediment plumes caused by dredging. This means for dredging projects in these environments that it is not necessary to set up limits. In environments where negative impact is to be expected, investigations are needed on the quantification of the limits.

The quantification of limits for the increased turbidity, concentration of suspended solids or sedimentation has to be project specific because there are too many factors of influence for general standards.

The effects are site and time specific. Site specific because the species and natural conditions vary from site to site. The effects are time specific because they depend on tide, day or night, seasons with different hydrodynamic conditions, for example monsoons, breeding and hatching seasons, currents.

6 Effects on corals

Coral reefs are, unlike many other marine species, very sensitive to increased sedimentation and turbidity. Coral reefs form important ecosystems in tropical seas and often form natural barrier against the sea. Destruction of coral reefs either directly by dredging or by increased sedimentation may lead to increased coastal erosion and to a significant reduction in fish population.

This Chapter describes a literature review on the effects of sediment plumes on corals and investigates how sensitive corals actually are, to be able to make recommendations on requirements for dredging projects near coral reefs.

6.1 Examples of damage caused by sediment plumes

The effects of sedimentation and elevated turbidity on reef corals have been discussed and reviewed in the literature (see Rogers 1990 for a review). But there are relatively few papers, which specifically address the effects of dredging on coral reefs at sites where corals have been monitored before, during and after the event.

A few dredging projects have caused environmental damage. Dredging and filling destroyed 440 ha of reef at Johnson Atoll and resulted in siltation, which adversely affected 6 times this area (Brock et al.1966). In Bermuda (Atlantic Ocean), Dodge and Vaisnys (1977) attributed lower amounts of living coral in Castle Harbour compared with other study reefs to extensive dredging 35 yr earlier. Reef flat communities in Guam succumbed to siltation after dredging of nearby areas (Marsh & Gordon 1974/Rogers 1990).

For some other dredging projects where corals have been monitored no extensive damage was reported. Marzalek (1981) surveyed reef areas before and after a large-scale dredging project off Florida, USA, where dredging took place for 3 months every year over a 5 year period. Several colonies showed partial mortality and excessive muscus secretion but no mass mortality was reported. Similarly, no long lasting effects of sedimentation were evident on coral reefs at Diego Garcia (Indian Ocean) following blasting and dredging in the lagoon (Sheppard 1980). In 1986-1987 an intertidal reef flat at Phuket, Thailand was subject to increased sedimentation from a 9 months dredging operation. One year after the start of dredging the corals showed a 30 % reduction in living coral cover and a significant decline in species diversity. After the event, the reef recovered rapidly with coral cover and diversity values restored to former level 12 months after dredging was completed (Brown et al 1990).

For the effects of runoff on coral reefs even fewer detailed scientific assessments are available. In some cases, it is difficult to determine the cause of coral death. Excessive rainfall during a storm in Hawaii led to death of coral reef organisms from a combination of high turbidity, low salinity and other factors. Increased runoff after Hurricane Flora led to bleaching of corals in shallow water off Jamaica. Increased river discharge may be responsible for the less than 2% coral cover on Algarrobo Reef off the west coast of Puerto Rico and for the death of all corals on a nearby reef (Rogers 1990).

These examples demonstrate that sediment plumes can damage coral reefs. It also shows that not all dredging projects are detrimental. Therefore, it is important to investigate under what circumstances dredging causes unacceptable damage and how this can be prevented.

6.2 Corals

Corals are very small animals (only a few mm) with typically a cylindrical body, topped with a ring of tentacles, which are used to capture food from the surrounding waters (see Figure 6-1).

In this report only the hermatypic, adhesive colony corals are discussed because they greatly contribute to the making of coral reefs. The life and colony types of hermatypic or reef building coral (Nishihira, 1988) can be found in tabel 6a.

Figure 6-1 Individual polyps (of only a few mm) of the great star coral Montastrea carvenosa, clearly showing a cylindrical body with a ring of tentacles

The adhesive corals securely adhere to hard basement such as rocks or dead coral, and also to artificial materials left in the water. Most hermatypic corals live in colonies and build up a communal stony skeleton of calcium carbonate. These adhesive colony-type corals have four basic colony types; encrusting, massive, foliaceous and branching (see Figure 6-2). The individual corals are only a few millimetres but the colonies have dimensions of several metres.

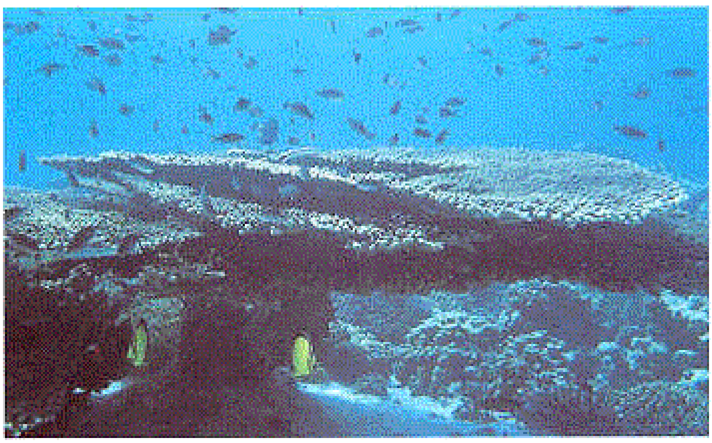
Life type		**Colony type**	**Typical species and classification groups**
Adhesive	Single coral	-	*Lithophyllon lobata*, etc.
	Colony coral	Encrusting	*Astreopora* spp., etc.
		Massive	*Favia* spp., *Porites* spp., etc.
		Foliaceous	*Echinopora lamellosa*, *Montipora foliosa*, etc.
		Branching	*Acropora* spp., etc.
Non-adhesive (free-living)	Single coral	-	*Cycloseris* spp., *Fungia* spp., etc.
	Colony coral	Elliptical, elongated	*Sandalolitha* spp., *Herpolitha* spp., etc.

Table 6a The life and colony types of hermatypic or reef building coral (Nishihira, 1988)

The following species will be discussed in more detail in this study; *Acropora cervicornis*, *Acropora palmata*, *Montastraea annularis*, and *Porites*.. *Acropora* is a branching coral. Figures 6-3 to 6-5 show pictures of the species. *A. palmata* has wide, flattened braches, like lettuce leaves with ridges and is called elkhorn coral, *A. cervicornis*, or staghorn coral, has small polyps. *Montastraea annularis* , or boulder star coral, has medium sized polyps and builds massive colonies. *Porites*, is a massive coral.

Hermatypic corals usually spawn on the night of a full moon around the beginning of the summer. After the fertilization of eggs by sperm, the coral larvae, called planula, settle on a substrate.

Figure 6-2 Acropora Above: Branches of Acropora cervicornis. Right: The elkhorn coral Acropora palmata. Below: Table coral Acropora clathrata



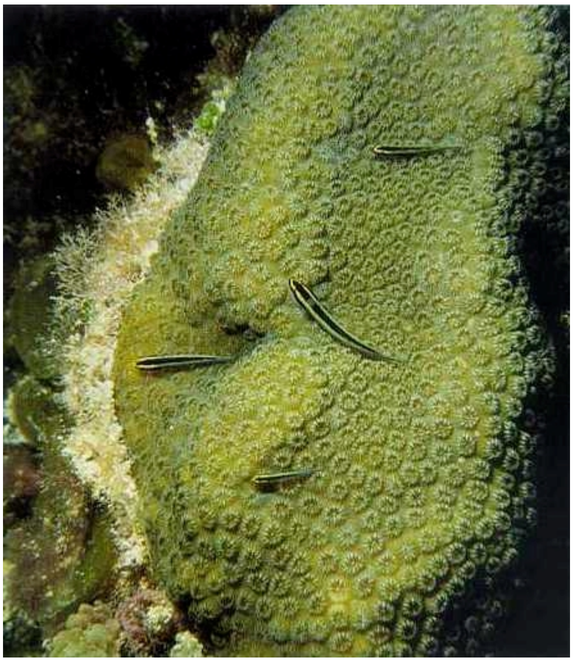
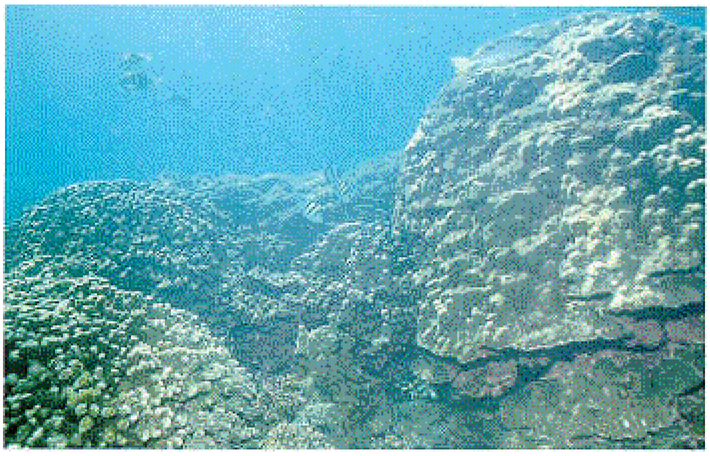
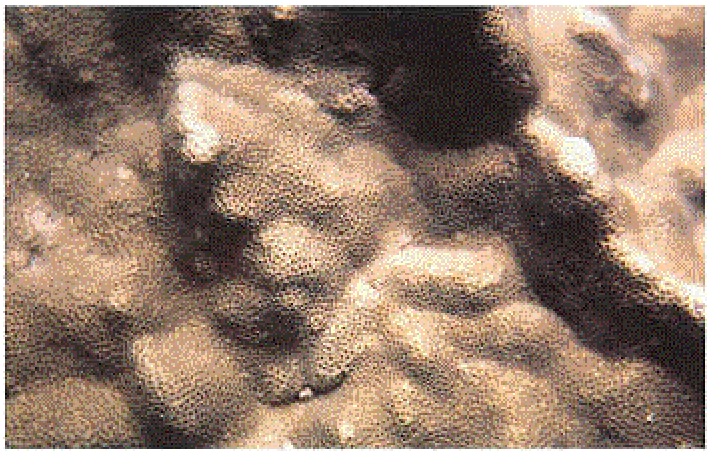


Figure 6-3 Boulder star coral Montastrea annularis

Figure 6-4 Porites Lutea (bump coral) and Porites compressa (finger coral). Below: Porites Lutea





Hermatypic coral has symbiotic algae called Zooxanthellae living in its tissue. The corals grow by eating zooplankton and the photosynthetic products of the Zooxanthellae. Because light is required for photosynthesis by Zooxanthellae, it constitutes an essential factor for the growth (rapid deposition of calcium carbonate for skeletal growth, for production of oxygen and other metabolites) of hermatypic coral.

Even in ideal conditions, these hermatypic corals are slow growing. The upward growth of the skeleton is generally between 1-10 millimetres per year. The faster growing tips of branching corals may extend at rates of 150 millimetres per year or more. Corals may live for several decades or centuries.

6.3 Effects of sediment plumes on corals

Sedimentation and sediment re-suspension are among the important factors that may influence coral abundance and coral species distribution.

Sediment can inhibit coral growth in four general ways:

1. Redirection of coral energy expenditures for self-clearance of settling sediments
2. Rapid sediment deposition (actual smothering of coral tissue) may lead to coral burial and death.
3. The presence of sediment in water column or on a colony's surface may slow growth.
4. Sediment-covered surface may prevent planula settlement

Ad 1) It has been demonstrated that although relatively high rates of sediment fouling will kill coral species, most corals can withstand a low sediment input by active physical removal of the sediment. Sediments smother corals, forcing them to expend much of their energy to expel these particles. When sediment loading exceeds the rate of sediment removal, a sediment layer builds up which may become anoxic and kill the underlying tissue (Lasker, 1980).

Ad 2) Increased turbidity reduces the light. Under the stress of high water temperature, low salinity or high turbidity *Zooxanthellae* microalgae leave a coral, resulting in coral whitening. This phenomenon is called bleaching (see Figure 6.6). If such a stress is removed the coral will recover. Recovery rates appear to differ between species from 2 months to one year. If bleaching continues for an extended period, coral will die.

Figure 6-5 Coral bleaching

As corals gain much of their nourishment from microscopic algae living in their tissues, sediments make corals work harder with less food supply (Abdal-Salam and Porter 1988).

The bleaching events reported prior to the 1980s were generally attributed to localized phenomena such as major storm events, severe tidal exposures, sedimentation, rapid salinity changes, pollution, or thermal shock. Since 1980 elevated water temperatures have been implicated in the majority of the major bleaching events. The most significant mass bleaching, event to date was associated with the warm water upwellings during the 1997-98 El Niño Southern Oscillation (ENSO) event, where there were reports from bleaching from all over the world (Spalding et al. 2001). In the Central Indian Ocean this event was followed by mass mortality; up to 90% of all corals died over thousands of square kilometres. New coral growth has been observed but full recovery of such a large-scale event will take many years or decades. The local events caused by short-time temperature variability provide a clear indication of the wider long-term impacts of rising sea surface temperatures. Some corals have adapted to warmer or variable temperatures but it remains to be seen what will happen during the predicted global warming of the next decades.

Ad 3) Coral larvae, or planula, adhere to a substrate. They are not very selective regarding the material to which they adhere, but they can not adhere to sand or sediment-covered surfaces, nor on algae-covered surfaces.

The effects of sediment plumes can adversely affect the structure and function of the whole coral reef ecosystem by altering both physical and biological processes. For example, sedimentation can kill major-reef building corals, leading to eventual collapse of the reef framework. A decline in the amount of shelter the reef provides leads to reduction both in number of individuals and in the number of species of commercially important fish and shellfish. Decline of tropical fisheries, evident for the Caribbean and the Pacific is at least partially a result of degradation of coral reefs, seagrass beds and mangroves due to sedimentation (Rogers 1990).

6.4 S-curve

The effects of stress on organisms in general can be described by an S-curve (Figure 6-7), borrowed from the science of toxicology.

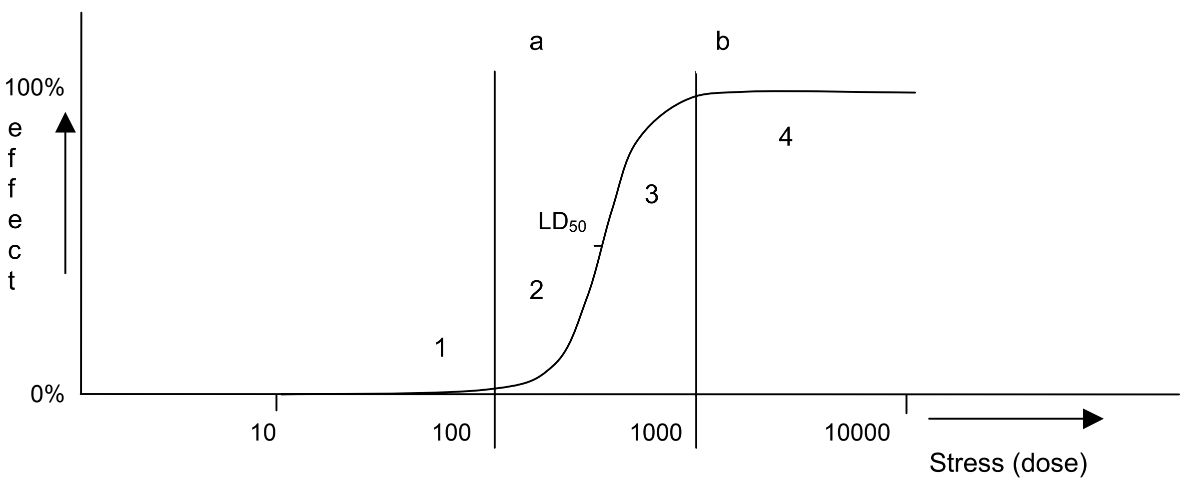


Figure 6-6 The S-curve

In toxicology the dose of a substance determines whether it is poisonous. In the S-curve the dose, or the amount of stress, is plotted on the logarithmic horizontal axis. The effect is plotted on the vertical axis as a percentages ranging from no effect, zero, to maximal effect, 100%. Any measured effect can be plotted this way, like behavioural, physiological (rate of respiration is often used with corals and other organisms) and percentage of mortality. Mortality after a fixed time is the parameter most often used. The curve obtained is described by its midpoint, called LD_{50} (Lethal Dose 50%) when mortality is studied, and more generally ED_{50} (Effect Dose 50%) in other cases, and by its slope. Not much theory on this slope exists; but the dose-range in which effect goes from zero to 100% usually is within a factor of ten.
A small amount of stress causes no effects (up to line a) but a large amount causes mortality (on the right side of line b). At the point of LD_{50} the probability for an individual to die is 50%.

Examples are the effects of alcohol or salt on people, and the effects of sedimentation or turbidity on different organisms. If someone drinks one alcoholic drink in one hour nothing will happen. Many people do this every day. If someone drinks ten alcoholic drinks in one hour, only sublethal effects will occur. With 30 drinks, a litre strong spirits, in an hour, the chance she or he will survive is about 50%; this is point 3. When people drink 100 drinks in one hour the effect is 100% mortality. For sedimentation on organisms the same line of argument can be used.

In toxicology standards are based on the LD_{50} of a substance, multiplied with a safety factor.
If standards are desired for dredging plumes, the same approach can be used.

6.5 Acceptable damage

When damage caused by dredging is to be prevented, first acceptable damage has to be defined. Whether damage is acceptable or not is related to 'normal' or natural damage, for example caused by storms and in perspective to the development of the particular ecosystem over longer time-scales.

Acceptable damage for coral reefs

The majority of reef structures that exist today is not the result of continuous growth, but of pulses of growth interspersed with quiescent periods, or even periods of erosion. Sea levels in the oceans have varied, particularly during the recent ice ages, and many reefs have intermittently become dry land, or have been flooded by waters too deep to allow corals to grow. Between these extremes, however, corals recolonize some of these fossil structures and reef development recommences.

On a smaller time scale, no reef is in a constant state of growth. During major tropical storm events all reefs undergo losses in coral cover and often erosion of their physical structure. Over years or decades the extent of actively growing coral cover also varies considerably. Recently observed events, including coral disease (reported since 1970 especially in the Caribbean, Belize 1985-1996 (Spalding et al. 2001)), coral bleaching (see Section 6.3), and outbreaks of the coral-feeding crown-of-thorns starfish (plagues observed in the GBR, Guam, Japan, Hawaii, Micronesia throughout 1960s and 1970s (Spalding et al. 2001)), have all produced considerable losses of live coral cover to some reefs. Recovery from such events points to a natural resilience. It also shows that any understanding of a 'reef' measured from only one moment in time will be limited. Along these lines, in this report recovery time is used as a measure for acceptable damage. A recovery time of one year is used as the acceptable limit. This is viewed in perspective to normal damage caused by yearly storms, from which corals recover. Storms have impacts on coral reefs through winds and high rainfall. Wind induced waves can damage coral reefs physically and by transporting sediment that may smother or bury of organisms. Heavy rainfall causing erosion and flood run off can damage reefs by sedimentation and by lower salinity. Since dredging is a rare phenomenon compared to such natural processes, the recovery time of one year can be used.

Unacceptable damage can be described from the S-curve as well. In Section 1-2 no damage occurs, which is an acceptable effect. In Section 2-3 corals experience some effects like changing respiration and calcification rates, and bleaching. When corals bleach, they are not in optimal condition, but they still can recover. Recovery rates appear to differ with species and the time required to attain full recovery may vary from 2 months to one year. These effects are still acceptable. When the level of environmental stress is high and sustained the coral may die. If, on a particular reef only a few scattered corals will die, the reefs will recover within a few years as a result of the arrival of new corals, which settle in the empty spaces vacated by the dead corals. At point 3 there is a chance of mortality of 50%. At point 4 the effect is mass mortality. There is no recovery and this is of course not acceptable.

Recovery

Complete recovery to pre-disturbance conditions implies restoration of the same community structure and function, that is, recovery of all organisms on the reef and natural processes. For hard corals this means restoration of percent cover, species diversity (evenness and richness), species similarity, and colony size distribution. Recovery takes place through:

1. Settlement, survival and growth of sexually produced coral recruits
2. Healing and regeneration of damaged colonies
3. Growth of coral fragments (for storms)

Recovery will be impeded if the substrate for settlement is covered by a sand layer. Algae are the first obvious colonizers of new substrate. If grazing is not intense enough, the algae will dominate (see figure 6-8), corals can not settle and recovery of the reef will take longer.

Recovery times of coral reefs are not well documented. For hurricanes some recovery times with diverse results are reported (see Rogers 1991). A hurricane is a type of tropical cyclone and can be considered for a specific coral reef as a very rare, severe storm. For recovery of the British Honduras reef following Hurricane Hattie (1961) several decades were estimated while for Florida reefs recovery was reported after only 5 years. The understanding of the recovery process on coral reefs is limited. Recovery is presumably faster if the dominant corals are fast-growing branching corals. On the other hand, these species are more fragile and suffer the most damage from storms. This physical damage plays no part at dredging projects.

It is well documented that reefs that are in a healthy state recover from damage more quickly compared to those that suffer from chronic problems such as pollution or an ecological imbalance.

This means it is of importance to keep coral reefs from such problems. This can be done by prevention of pollution, good management of land use on islands and mainland watersheds to minimise losses of soils, sewage and fertilisers to the sea and by limiting fishing to make sure abundant seaweed-grazing fish, snails and sea urchins are left behind.

Figure 6-7 Algae are quick to colonize bare surfaces following coral mortality

For the planning of dredging projects the state of the reef has to be considered to make sure that, for example, a reef that is just recovering from a damaging hurricane does not have to take the extra impact of a dredging project.

6.6 Literature study

To make recommendations for dredging limits near coral reefs it is important to know how increased sedimentation and decrease of light availability affects corals. This section presents an overview of research that has been done on these effects and on the conditions corals naturally live in.

Remarks

In this study articles by biologists were used to solve an engineering problem. It is difficult to integrate biological and engineering information to objectively evaluate potential impacts because the two sorts of information are not adjusted to each other. There are only few adequate data available quantifying biological responses to appropriate threshold concentration/exposure duration dosages. Many past investigations focused upon detrimental effects induced by dosages well above those likely to occur at dredging project sites. Or, on the other side, on the first visible sublethal effects, such as respiration rates and growth, induced by dosages that occur in natural conditions. In the S-curve, explained in Section 6.4, these stages are the vertical lines plotted in the graphic, while the part of interest lies in between these lines. Further, many investigations provide no follow-up information on reef status after the initial effects were monitored, and thus data are lacking.

Given the specific conditions of a dredging project; type of dredge, sediment characteristics, local hydrodynamics, and distributions of resources in space and time, exposures can be conceived to fall within a matrix of concentration/ duration combinations (Figure6-9, Clarke and Wilber 2000).

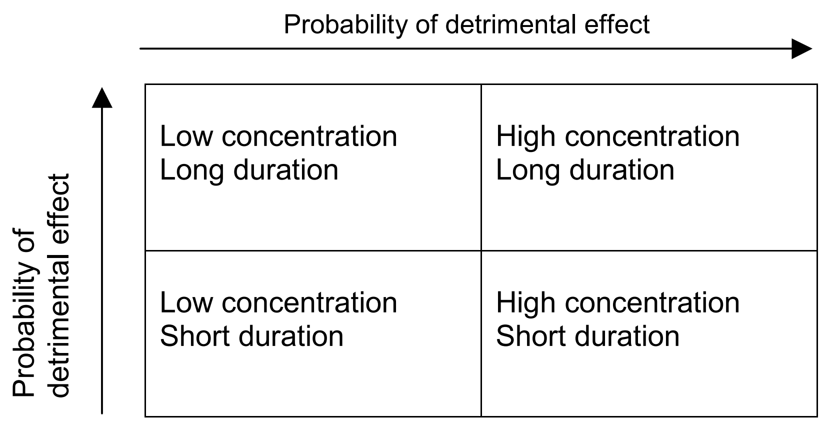


Figure 6-8 Matrix of concentration/ duration combinations (Clarke and Wilber 2000).

Clearly minimal sediment concentrations for short intervals pose minimal risk and projects generating persistent, high suspended sediment concentrations represent the most problematic circumstances. Acute exposures at high concentrations for short intervals of time might occur in association with many dredging project scenarios; these would be often limited in spatial scale.

How dredging-related conditions may affect organisms requires knowledge of:
- The thresholds at which (relevant life history stages of) organisms respond negatively to suspended sediments.

- Reliable estimates of dredging induced suspended-sediment plume temporal and spatial dynamics.
- The probability that organisms encountering a dredging-related suspended sediment plume that will exceed a concentration and/or exposure duration tolerance threshold.

In the next part of Section 6.6 tables are used to describe the findings from literature on corals. The following information can be found from these tables:
The source of the information, the location of the coral reefs, the background, or natural turbidity conditions, the coral species used for experiments, the treatment of the corals, and in the last three columns the results of the measurements of the experiments. The bottom limit implies no damage occurred. The upper limit means the coral died. In between means, some changes were visible but the corals recovered from this damage within one year after treatment.

Sedimentation

The negative effects of sedimentation are described in Section 6.3. In Tabel 6b experiments are described in which the corals are buried completely. Trends from these and other field and laboratory studies indicate that many coral species can tolerate burial only for relatively short periods of time. No literature reports were found that suggested that any coral specimen could survive total burial for more than 15 days and most species tested could not tolerate more than 2 days of burial. Coverage for longer periods is lethal to all species.

Table 6c describes experiments with applications of sand with lethal and sublethal effects and Table 6d shows experiments on the self-cleaning ability of coral species. Whether corals can withstand sediment input depends on their self-cleaning ability and on the natural condition, such as currents, waves and sedimentation rates.

The field studies and laboratory experiments on the response of coral to sediment application indicate large differences in their ability to reject sediments. Sediment rejection is a function of morphology, orientation, growth habit, and behaviour, and of the amount and type of sediment (Bak and Elgershuizen 1976).

The results of the experiments are difficult to compare because various species have been investigated and not always the same sort of sediment was used, but they show some trends. The species *Acropora cervicornis*, *Acropora palmata*, *Montastraea annularis*, and *Porites* are discussed in more detail. *Porites* shows the best ability to withstand sediment, followed by *Montastraea annularis, Acropora cervicornis* and *Acropora palmata*.

Hemispherical corals with a small radius, such as *Porites*, and *Montastraea annularis* in shallow water (and *Diploria strigosa)*, have a higher chance of quickly removing particles; this may contribute to their broader depth range. They show similar clearing rates significantly higher than that for *Acropora palmata*. *Acropora palmata* grows in shallow water, where water movement is high and washes the sediment away. In deep water its clearing effort may not be subsidized by wave energy (Abdel-Salam et al. 1988). This is supported by the study of Rogers (1983) that showed that *Acropora palmata* was the least resistant to sediment application. Lasker (1980) suggested that broad surfaces of *Acropora palmata* increase the probability that a sediment particle will lodge on the colony surface, and therefore increase the energetic cost of sediment rejection for this species. Rogers (1983) found that sediment particles could not adhere to the cylindrical branches of *Acropora cervicornis* but were able to accumulate on flat portions of *Acropora palmata*. This means that for the same sedimentation rate *Acropora palmata* collects a great amount of particles that are to be rejected and most of the particles that fall on *Acropora cervicornis* roll off to the ground and do not have to be rejected. This might explain the differences in response to sediment between the species.

A different type of experiment is the use of environmental limits as the input in a computer model. For the case study of Bali Turtle Island Development (DHI) feedback monitoring was used. Environmental limits had to be used. The proposed threshold sediment deposition rate for corals (key species Acropora sp) was10 mg/cm2/d and 0,42mg/cm2/h (Driscoll et al. 1997). During the project the impact criteria were exceeded and still no negative impacts had been observed. There were some reductions in growth rates, but no mortalities. Limits would have been revised and refined but the monitoring as well as the project itself was cut short due to the financial crises in Indonesia.

Conclusions:

Burial caused by dredging activities for more than, depending on the natural conditions, 1 day to 1 week can't be accepted.

In general, taking in account the observed species and sediment sizes, corals have the ability to clear themselves from 100 $mg/cm^2/day$. (Lasker (1980) examined the sediment rejection-ability of corals only under natural field conditions). This means approximately $1kg/m^2/day$ or a thin layer of 2 mm sediment per day. Obviously, when waves or currents bring settled sediment in re-suspension or prevent sediment from settling the corals can withstand more. In natural environments with currents and/or waves problems with sedimentation caused by dredging are less likely.

The results of the sedimentation experiments on corals can be put out in the S-curve described in Section 6.4. The values for the amount of stress in Figure 6-7 at line a and b will be:
For sensitive species: line a at 100 mg/cm^2, line b at 1000 mg/cm^2
For more tolerant species: line a at 400 mg/cm^2, at line b no experiment results are available; 4000 mg/cm^2 is to be expected.

Turbidity

The negative effects of elevated turbidity are described in Section 6.3. In Tabel 6e the experiments with decrease in light penetration are described. Only one experiment reports mortality for some species without recovery; 1000 ppm for 65 h. *Acropora cervicornis* did not recover from bleaching after total shading for 3 weeks. In this case the corals were covered with black plastic so they did not get any light. These conditions do not appear during dredging projects.

For the case study of Bali Turtle Island Development a suspended sediment concentration limit of 10 mg/l above the ambient levels was applied as the input for environmental limits in a computer model. The reduction in irradiance was in the order of 20% at a depth of 1m, while at a depth of 10m the reduction would be about 80%. Again the preliminary impact criteria were exceeded and still no negative impacts have been observed. In the article it is stated that some degree of relaxation would be allowed (Driscoll et al. 1997).

Conclusions:

At dredging projects, sedimentation will be important near the dredge (larger particles settle) and turbidity at a larger distance (fines stay in suspension) as described in Chapter 2. Often, because of changes in current direction, the turbidity will not stay at the same location for a long time. And at a larger distance the plume will be more dispersed. Each project has to be investigated (case by case approach) but this study indicates that, speaking of unacceptable damage caused by sediment plumes, sedimentation is a far more important factor than reduced light intensity. This is supported by Salvat 1987; light is not a limiting factor in turbid waters except in deeper water where it becomes critical.

The results of the turbidity experiments on corals can be put out in the S-curve described in Section 4. The values for the amount of stress in Figure 6-7 at line a and b will be:

Line a at 100 mg/l, line b at 1000mg/l; for sensitive species for 3 days and for more tolerant species for 3 weeks.

In some limits set up for dredging projects (see Chapter 4) 100 ppm is used as a threshold value. From this study can be concluded that at 100 ppm often changes can be seen, but no mortality of corals occurs. In the S-curve this falls within the part of acceptable damage.

Natural conditions

Another way of investigating the effects of turbidity and sedimentation on corals is to look at the thresholds of corals under natural conditions; a long-term equilibrium situation. In Table 6f findings about natural conditions are described.

In the Atlantic, tolerable levels for shallow water corals were estimated at 5-10 ppm and 'normal' sedimentation rates for coral reefs appear to be on the order of 10 $mg/cm^2/d$ or less. In the Indo pacific region Pastorok and Bilyard (1985) found natural ranges up to 230 $mg/cm^2/d$ and in the Great Barrier Reef, Hopely et al. (1991) suggested that reefs have become acclimatised to higher sediment loads, commonly exceeding 100 mg/l. To some extent corals adjust to their natural conditions. Particular species live both in the Atlantic, as well as in the Great Barrier Reef under different natural conditions, but patterns in coral species distribution related to sediment conditions can be seen.

Relationship between natural sediment conditions and coral distribution
The relationship between natural suspended sediment and sedimentation levels, and coral distribution can be investigated by a sediment gradient analysis. Kleypas (1996) researched the fringing coral reef development in the southern Great Barrier Reef in an environment with a natural gradient of increasing turbidity. Differences in reef colonisation and growth across a gradient of increasing tidal range and turbidity were examined.

Effects of elevated turbidity were not only in the fringing reef development but also in the community structure. The following changes were found in the benthic community structure with increasing tidal range and turbidity: 1). an overall decrease in colony size of hard corals; 2). a decrease in both hard and soft coral diversity; 3). a shift in some coral morphologies towards encrusting and plate-like forms; and 4). a lack of major framework builders.

It is not known how much these patterns reflect greater sedimentation versus reduced light penetration. Under naturally high sediment loads, smaller colony size is expected because smaller colonies are more efficient at sediment rejection, and larger corals suffer greater mortality under increased sedimentation and turbidity (Dodge and Vaisnys 1977; Rogers 1990).

Reduced diversity under high turbidity stress is also to be expected since fewer species would be able to tolerate such conditions. The shift in species dominance with proximity to Broad Sound reflects both a shift to more turbidity tolerant species, and the elimination of major framework builders, such as branching *Acropora* spp. and massive *Porites* spp. The most turbid regions had reefs dominated by turbidity tolerant species, such as *Turbinaria mesentaria* or *T. reniformis*.

Relationship between natural conditions and tolerance of corals
The natural distribution of corals may provide an indication of general tolerance of a species to environmental factors. The experiments of Rice and Hunter (1992) on the effects of suspended sediment and burial on corals from west central Florida patch reefs (see Tables 6b and 6e) illustrate this. Seven species of corals were exposed to increasing levels of suspended sediment in the laboratory and seven species were subjected to prolonged burial in sediment. The results of these experiments indicated that the species tested are among the most resistant corals in the Caribbean region with respect to suspended sediment and physical burial.

Compared to more tropical habitats, the patch reefs off west central Florida are exposed to more severe environmental conditions, such as low winter temperatures, high turbidity and decreased light penetration. Many of the corals inhabiting patch reef communities off west central Florida have been found to occupy the least favourable habitats in more tropical settings such as lagoons and near-shore reefs. It is not surprising that species that inhabit these areas demonstrate high tolerances to environmental stress. But it may also be that these species are living near their physiological tolerance limits of environmental conditions and may be more sensitive to additional prolonged conditions (i.e., chronic siltation stress) than their tropical congeners.

Conclusions:

Corals (and other organisms) are adapted to their natural conditions; level and variability of turbidity and sedimentation rates, and other environmental factors such as temperature. This is an equilibrium situation. Dredging causes short term increases of turbidity and sedimentation. Corals that are naturally exposed to variable background conditions for example because of storms will probably show high tolerances to short increases in turbidity or sedimentation caused by dredging. For more constant background conditions a possible approach to assess the effects of dredging is to multiply the levels of the equilibrium situation with still to be determined factors. This is not further worked out in this study.

6.7 Dredging

The study described in Section 6.6 was done to get a better understanding of the negative impact of sedimentation and elevated turbidity on reef corals caused by dredging activities. This section considers the range of impacts due to dredging activities.

An example calculation of possible damage

The next example calculation shows by rough calculations and estimates how much damage a dredging project near coral reefs actually can cause. Because in Section 6.6 was concluded that sedimentation is a far larger problem for corals than turbidity this example is focused on sedimentation. It describes a dredging project with a stationary vessel that is dredging 24 hr/d. The dredge causes re-suspension of the sea bed material. The spilled material settles again or stays in suspension, and is transported or dispersed. Settled material can be re-suspended by currents and waves. To model these processes to eventually determine sedimentation rates, the following factors of influence have to be known:

- type of dredging vessel
- production
- duration of dredging
- concentration suspended solids at the dredge
- characteristics of the spilled sediment (grain size)
- current velocity and direction
- fall velocity of the spilled material
- depth
- hydrodynamic conditions

As regards the modelling of plumes arising from dredging, there are some significant gaps of knowledge. The absence of reliable field data created uncertainty in the development of models and the physical processes in the initial stages of plume development are not clear. Research is done for example as part of the VBKO research initiative (see Section 3.2). For this example assumptions are made for a certain amount (m^3) of stirred up sediment, or spill.

Example calculation for a stationary dredge

The production of a dredging vessel: 2000 m^3/h

The average spill: 5% of total dry bulk
The density of the material to be dredged, wet in situ (with a porosity of 0,4): 2000 kg/m^3
The density of the material to be dredged, dry in situ: 1606 kg/m^3

The production is 3212 ton dry bulk/hour
The allowed spill percentage of 5% that leaves the work zone results in 161 ton dry bulk spillage/hour, or 3864 ton dry bulk/day.

Corals can handle a sedimentation rate of 100 mg/cm^2/d (Section 6.6.2), or 1 kg/m^2/d. If the 3864 ton spreads out evenly an area of 3,8 km^2 will be covered. The density of the deposited wet material will be 1300 kg/m^3 (with a porosity of 0,8, the density of the deposited dry material will be 500 kg/m^3).
This means a layer of 2 mm per day.

Larger particles settle out first. It is assumed that the material settles in vicinity of the dredge, in the direction of the currents. When the process of settling does not go fast, the plume will disperse more and more and when the particles eventually settle, there will not be a problem.

If the spilled material settles evenly in a layer of 2 mm, the sedimentation area will be max 3,8 km^2 and no damage will be caused. If the material settles out in a thinner layer, this will be a larger area and again no damage will be caused. If it settles at some places in a thicker layer those location can be damaged but then the by spillage affected area will always be smaller than 3,8 km^2 (see Figure 6-10).

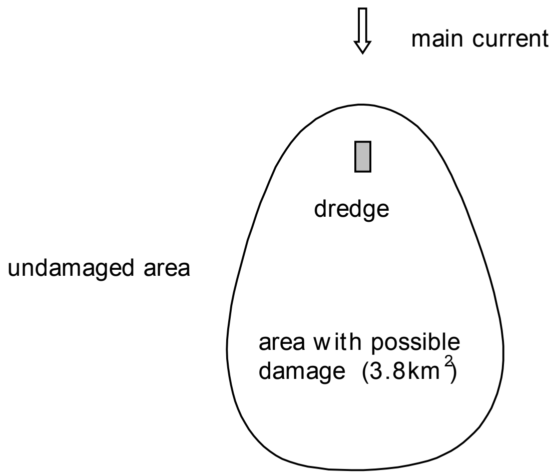


Figure 6-9 Area with possible damage caused by dredging sediment plumes

When dredging goes on for days and currents change, the sediment can damage different areas. But this will also mean that on the previous impacted areas the corals have time to recover, and may be helped by currents and waves that re-suspend the material. The sedimentation rate of 100 mg/cm^2/d is the amount coral can handle without help of current or waves etc. This means it includes a safety factor. More precise calculations imply much more complicated calculations; these are outside the scope of this report.

For the example calculation a stationary dredge was assumed. For a moving dredge the calculation is more complicated because every day a different area can be affected.

Comparison with an example of damage

The dredging example calculation shows an approach to determine how much damage sediment plumes can cause on corals. The approach was checked using the example of damage at Johnston Atoll (Brock at al. 1966) described in Section 6.1.

At the atoll dredging of 280 ha and reclamation of 160 ha, together 4,4 km^2 of reef affected 26,4 km^2 of corals in the adjacent area. The effects were reduction in the percentage of living coral was none to 40%, with an average of 10%. Following proposed the approach, assuming the same production, spill percentage, sediment characteristics etc., the affected area caused by dredging at one location has to smaller than 3,8 km^2. This implies that the dredged and reclaimed 4,4 km^2 had to be spread over minimal 7 different locations at distances of a few kilometres.

Since the example calculation was made for only one location and the report on the Johnston Atoll did not give information about the type of dredge, the production rates of the dredge, spillage rates, or the duration of dredging, this comparison could not be accurate and only gives a rough indication.

Possibility water jet

Because sedimentation is a larger problem for corals than turbidity, another possibility to keep the corals from extensive damage is to remove the sediment with a jet of water. With a flowdredging technique (Van der Schrieck 2001), a low-pressure water jet (flow velocity 5 m/s) with a large diameter (3 m) the sediment could be sprayed away. This technique uses the seabed erosion by the water jet and is applied for example to make trenches pipelines. Coral reefs are liable to develop in the direction of rough waves. Because coral have a calcium carbonate skeleton and securely adhere to rocks, they are more adapted to rough waves and streams than other attached animals or algae.

To investigate this possibility experiments should be done with jets on corals to find out how much the corals can handle. Further has to be examined where the sediment will be transported to, and the costs have to be calculated.

6.8 Conclusions

Detailed conclusions of the literature review are described after each section (6.6.2 to 6.6.4). The rest of the conclusions of the study on the effects of sediment plumes on corals are described below.

Limits for sediment plumes

To determine limits for sediment plumes caused by dredging a research strategy like in the toxicology can be used. But when the results of the experiments cited in Section 6.6 per species are plotted this way, it appears that existing data do as yet not allow the construction of a complete dose-effect relationship curve. Most of the experiments were focussed on the sublethal effects. To determine limits, the part in the S-curve between the lines is interesting and thus experiments with higher doses of stress would be very useful to determine limits.

Further, in most experiments recovery times were not determined. Experimental work would gain in value if the recovery after a few months and after a year were also checked in the future.

The same is true for reported damage caused by sediment plumes. For the example of damage in Section 6.1 at Johston Atoll Brock et al. (1966) report the effects spill: reduction in the percentage of living coral of none to 40%, with an average of 10%, but no information is available about potential recovery after dredging. Recovery seems likely, compared to the dredging projects described in this section where no extensive damage was reported. Brown et al. (1990) reported a reduction in the percentage of living coral of 30% with a recovery time of one year after dredging was completed.

Evaluation of the limits for dredging projects discussed in Chapter 4 near coral reefs

The limits set at the location of the corals seem, assuming the background conditions to be low and reasonably constant, very strict; suspended solids contents < 10, 20 or 30 mg/l above background conditions (Fuah Mulaku and Jervoise Bay) and sedimentation rates <10 mg/cm2 day (Fuah Mulaku).

To evaluate the limits set around the dredge or at discharge points first the resulting sedimentation at the coral areas has to be calculated.

The extent of possible damage

The dredging example calculation shows an approach to determine how much damage sediment plumes can cause on corals. This approach is not applicable to set up of limits but may be useful for an environmental impact assessment (EIA).

7 Probabilistic description of sediment plume behaviour at the Øresund Fixed Link Dredging project

Previous chapters discussed the thresholds of the sediment limits for dredging projects. Another important subject is the way limits are checked. In dredging contracts monitoring programs prescribe the way to check whether the actual turbidity or concentration of suspended solids complies with the limits. Table 4a gives an overview of the monitoring programs of the projects discussed in Chapter 4. Various sorts of monitoring programs can be seen; locations at selected points or mobile sampling locations at plume tracking positions, at one or more depths, with a frequency of measurements ranging from 24 hours/day to 3 days/week to twice a day. For some projects the contractor has been asked to develop a monitoring program.

The monitoring programs vary a lot. The reason for this is not clear and the limits do not always seem to have a scientific basis. When measurements are taken continuously at several depths much information can be gathered and the chances that the limits are exceeded without registration by measuring is small. But this method is also very expensive.

The objective of this study is to optimise the number of turbidity measurements at a location, ie the number of ship crossings through a sediment plume, given the costs and the accuracy of the turbidity measurements, by a statistical data analysis. The used data come from turbidity measurements done at the Øresund Fixed Link project.

Section 7.1 describes the Øresund Fixed Link projects to provide background information on the used turbidity measurements. To be able to use the turbidity data of the project for a statistical analysis, simplifications were made on the raw data. This is described in Section 7.2 and Section 7.3 considers the statistical analysis of the simplified data. In Section 7.4 a method is proposed to optimise the number of ship crossings on the basis of a cost optimisation.

7.1 Project

The used data come from the Øresund Fixed Link project (see Chapter 4). Figure 7-1 shows the location of the Øresund Fixed Link. Dredging works at this project included a trench for the tunnel, work harbours, navigation, construction and access channels and compensation dredging (deepening of certain parts of the Øresund to maintain the overall exchange of water; the zero solution). Reclamation works included the artificial peninsula at Kastrup on the Danish coast and the artificial island south of Saltholm.

Figure 0-1 The location of the Øresund Fixed Link

Sediment spill

The limits at the project are sediment spill limits. An overall spill limit of 5% (by weight) of the design quantity to be dredged and more detailed limitations, weekly and daily percentages of spill were prescribed. The contractors are contractually obliged to measure sediment spillage and are responsible for monitoring the amount of spillage.

Spill is defined as the portion of dredged or excavated material brought in suspension during dredging, transport or filling, which leaves the work zone or land reclamation areas. The work zone is the area that has to be dredged plus a surrounding 200m zone. Spill is measured by dry weight of suspended materials (kg).

The sediment spillage by the dredge will appear as plumes travelling in the direction of the current, away from the dredging area. Figure 7-2 shows examples of sediment plumes.

Figure 0-2 Sediment plumes

Essential data for the calculation of the spill are the current and turbidity values within the plume leaving the workzone. The spillage measurements are carried out from vessels that sail across the plume from 'clear water' to 'clear water' at right angles to the current, collecting current and turbidity data. At the reclamation areas the outflow from the sedimentation basins is measured inside pipelines.

Methods of measurement

Depending on the waterdepth, the current velocity is measured by acoustic (ADCP) or electro-magnetic current measurements. Four Optical BackScatter (OBS) sensors measure the turbidity, one mounted at the front of the vessel, three placed on a streamer cable with an output in FTU (formazin Turbidity Unit). Figure 7-3 shows the spillage monitoring.

Since the amount of spill was calculated in terms of weight the turbidity measurements were translated into concentrations of suspended sediment. For each area a correlation between turbidity and concentration of suspended sediment was calculated on the basis of water samples taken during the measurements.

The concentration of suspended sediment converted to kg/m^3, multiplied by the current velocity [m/s] integrated in spaces gives a spill flux or intensity (F_s [kg/s]). The amount of spill can then be calculated by integration of all transects in time. At the end of every day an average amount of kg/day was calculated.

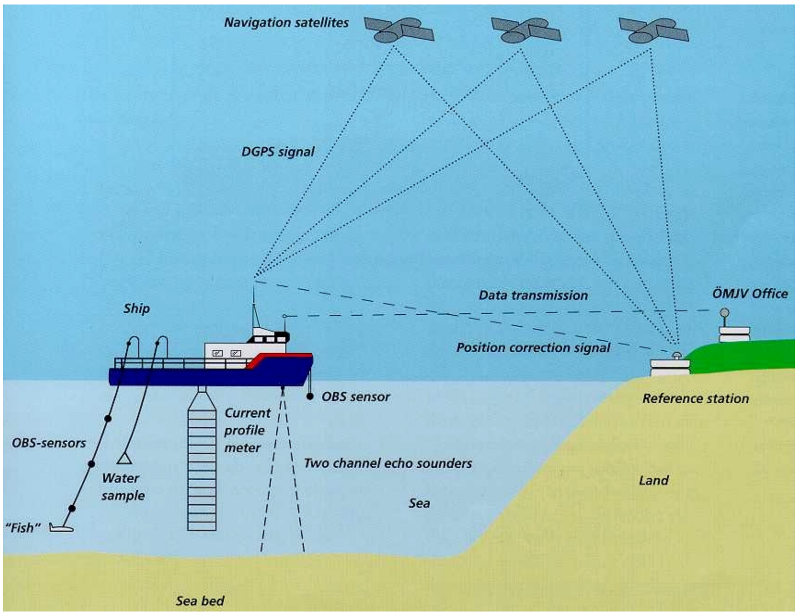


Figure 0-3 Spillage monitoring

This set-up was used during the whole project. The costs of the monitoring program were very high. At the Øresund Fixed Link project the employer was willing to pay these costs to be sure the Swedish and Danish authorities' environmental requirements were met.

7.2 Data

Turbidity data of the Øresund project

The used data are turbidity measurements of one day; 15 January 1996. The tidal influence in the Øresund is low; currents are mainly wind driven. During this day the wind velocity was 4,6 to 6,2 m/s (wind-force 3 to 4) and the direction was south to southeast. Background values were low; approximately 0,1 FTU. The dredged material consisted of clay and limestone.

The dipper dredger 'Chicago" was dredging a work harbour on the west side of the artificial island (see figure 7-4).

Figure 0-4 Construction of the initial stages of the artificial island

This location falls under spillage area 3 (see Figure 7-5).

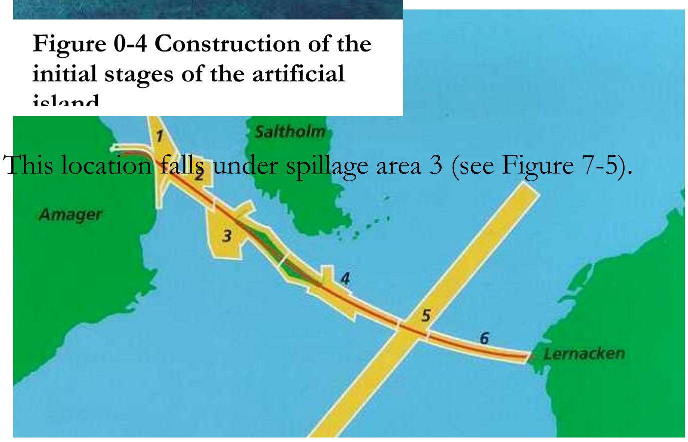


Figure 0-5 Spillage area 3

The 'Chicago' (see figure 7-6) has a dipper bucket capacity of 22 m^3 and a daily maximum production between 2.000 and 8.000 m^3. The dredge loaded 2.000-ton material barges to be towed to the reclamation areas for offloading behind stone revetments.

The vessel 'Coastal Flyer' was measuring the spillage. An overview of the main sailed lines and the position of the dredge is given in Figure7-7, and Figure 7-8 shows a picture of the 'Chicago' and the 'Coastal Flyer' at work.

Figure 0-6 Dipper dredge 'Chicago'

The vessel 'Coastal Flyer' was measuring the spillage. An overview of the main sailed lines and the position of the dredge is given in Figure7-7, and Figure 7-8 shows a picture of the 'Chicago' and the 'Coastal Flyer' at work.

During 15 January 1996, the measuring vessel sailed 72 ship crossings in 24 hours. There were 58 ship crossings at line 1 and the rest of the crossings was divided over the other lines. Under influence of the wind driven current, the sediment plume travelled to the north-east and turbidity in the plume was measured at line 1. At line 3 and 5 upstream background turbidity was measured.

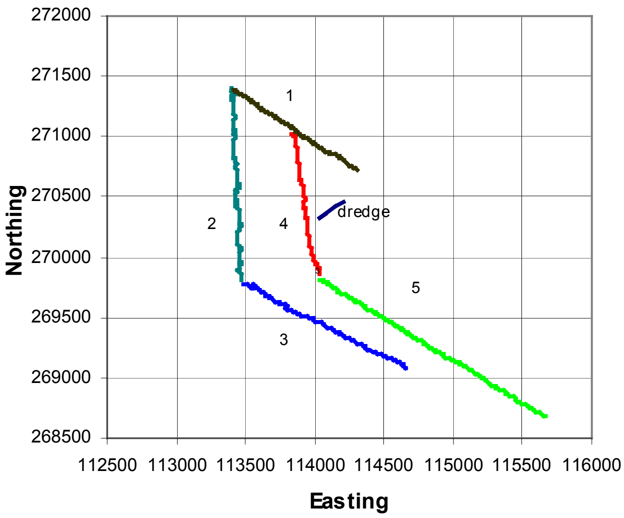


Figure 0-7 Co-ordinates in meters of the sailed lines by the measuring vessel 'Coastal Flyer' and the position of the dredge

Figure 0-8 The 'Chicago' and 'Coastal Flyer' at work. The sediment plume is clearly visible

Simplification of the data

To be able to describe the turbidity process structure in the cross section in time the structure of the data is adjusted. To restructure the data assumptions were made:

- At every ship crossing the vessel measures at the exact same locations in distance and depth. Therefore only the part of crossing line 1 with a reasonably constant depth of the seabed is used for the data analysis.
- It is assumed that all measurements in one cross section are taken at the same time.

This results in a data structure with the format:
n, x_j , d_1, d_2, d_3, d_4, t_1, t_2, t_3, t_4.
With:
n: number of ship-crossings [1:58]
x_j : distance in m, at j=1,2,…,30 [0, 17, 34,…,493]
d_k :depth in m, at k=1,2,3,4 [0.5, 1, 2.5, 4.5]
$t_{n,j,k}$: turbidity at location (j,k) at ship crossing n
The ship makes 58 crossing from j=1 (x=0 m) to j=30 (x=493 m). During 24 hours the sediment plume passes by and turbidity is measured 58 times at each location (x,d).

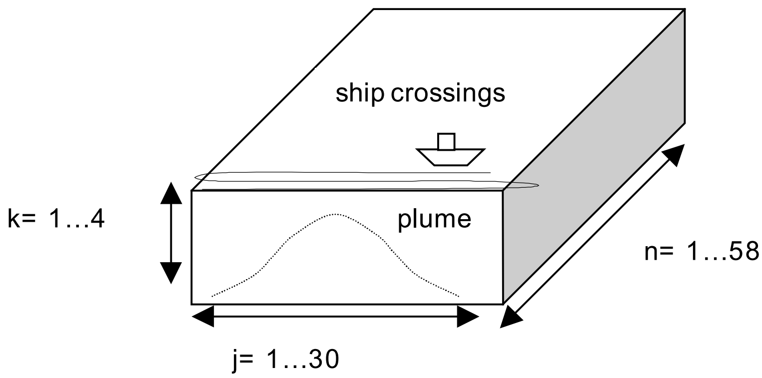


Figure 7-10 and Figure 7-11 show examples of the simplification at ship crossing 1 and 35. The first graph shows the raw Øresund data. In the second graph the part that was used for the data analysis is marked with vertical lines. The depth between these lines is assumed to be constant. The bottom graph shows the simplified data, used for the statistical data analysis.

Figure 0-9 An overview of the data. During one ship crossing the vessel measures the turbidity 30 times at 4 depths. The vessel makes 58 crossings

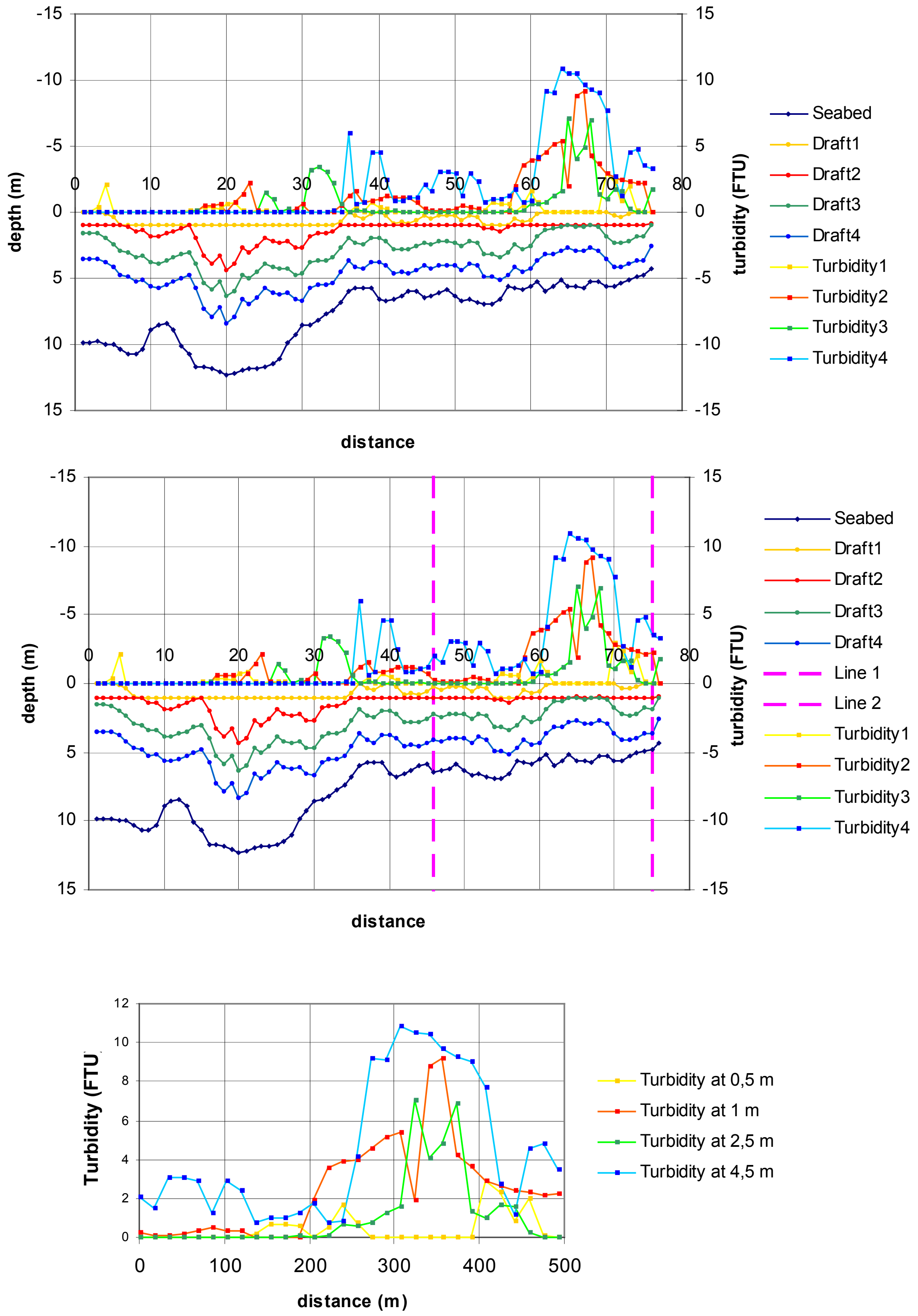
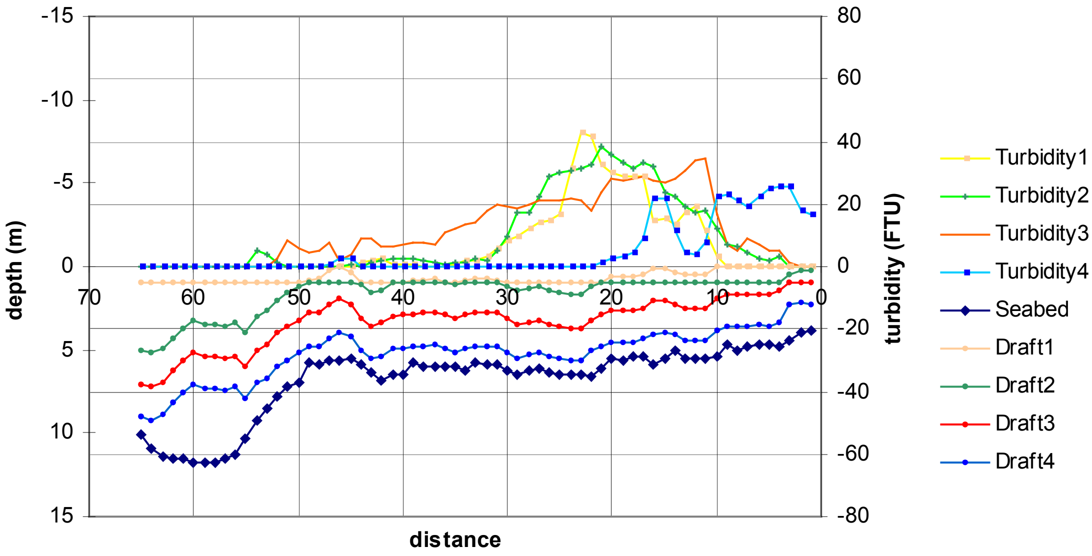
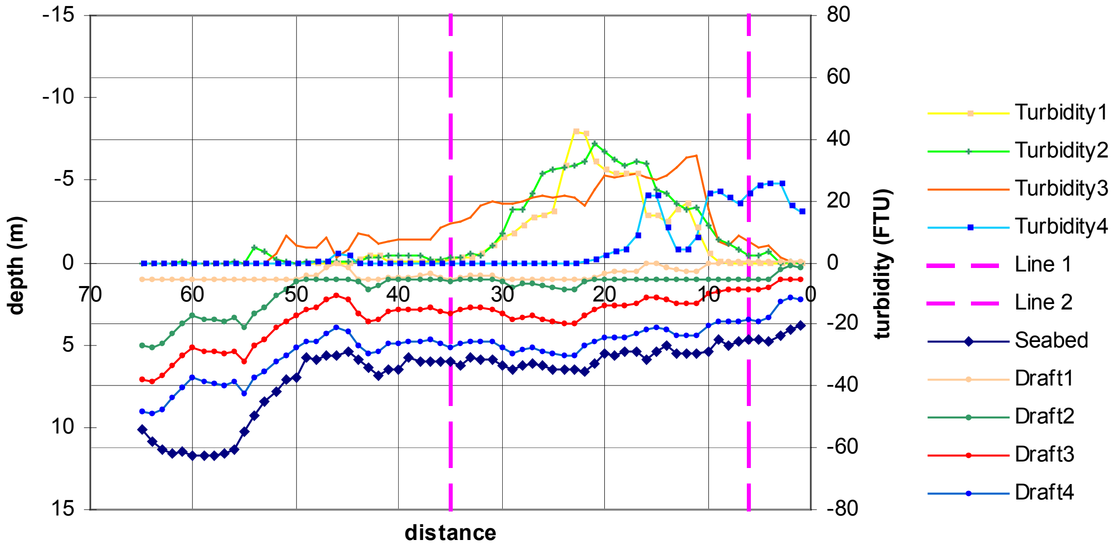


Figure 0-10 Simplification of the data of ship crossing 1; only the part between the lines was used and the depth was assumed to be at a constant 6m





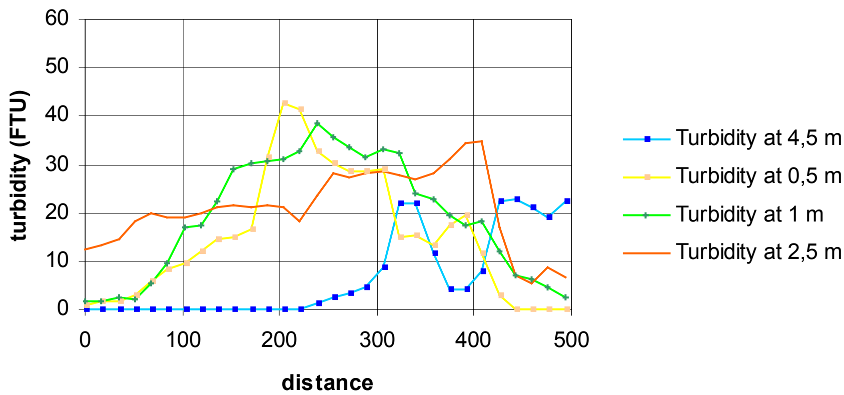


Figure 0-11 Simplification of the data of ship crossing 35; only the part between the lines was used and the depth was assumed to be at a constant 6m

7.3 Statistical data analysis

Approach

First the inherent uncertainty of the turbidity data is explained in Section 7.3.2

In Section 7.3.3 a distribution function is determined for the inherent uncertainty of turbidity. A statistical analysis on the turbidity data determines how often a given turbidity value is expected. This can be modelled by the probability density function (PDF) of a distribution function.

The statistical or parameter uncertainty of the probability calculated for the likelihood of a given turbidity depends on the amount of available data (the number of measurements). Section 7.3.4 shows how the uncertainty as function of the number of measurements can be quantified. Section 7.3.5 describes how the statistical uncertainty of turbidity can be derived and determines the maximum allowable turbidity in a probabilistic framework.

The optimisation of the number of measurements can be determined from the optimisation of costs. This is described in Section 7.4.

The basic probabilistic theories used for these Sections are derived from CUR (1997), Van Gelder (1999) and Vrijling (1990).

Inherent uncertainty

The approach of the statistical data analysis depends on the correlation of the data. If the data are correlated less measurements are needed, because one measurement value can be based on the previously measured value. Turbidity is assumed to be a random variable. Currents, dispersion, turbulence, and the amount of suspended sediment released by dredging influence the process of turbidity and make it inherently uncertain. Figure 7-10 and 7-11 shows examples of turbidity as function of the distance. Figure 7-12 shows some examples of turbidity as function of the number of ship crossings.

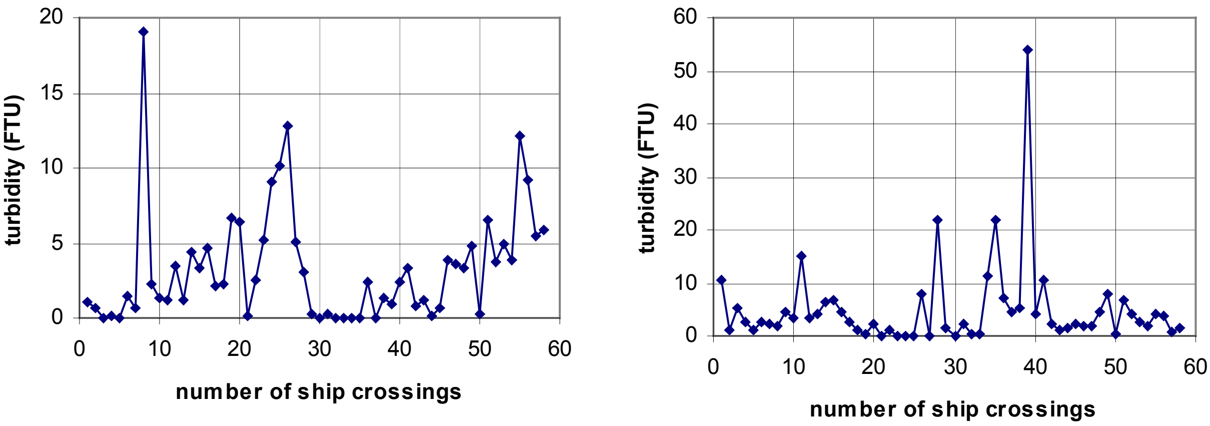
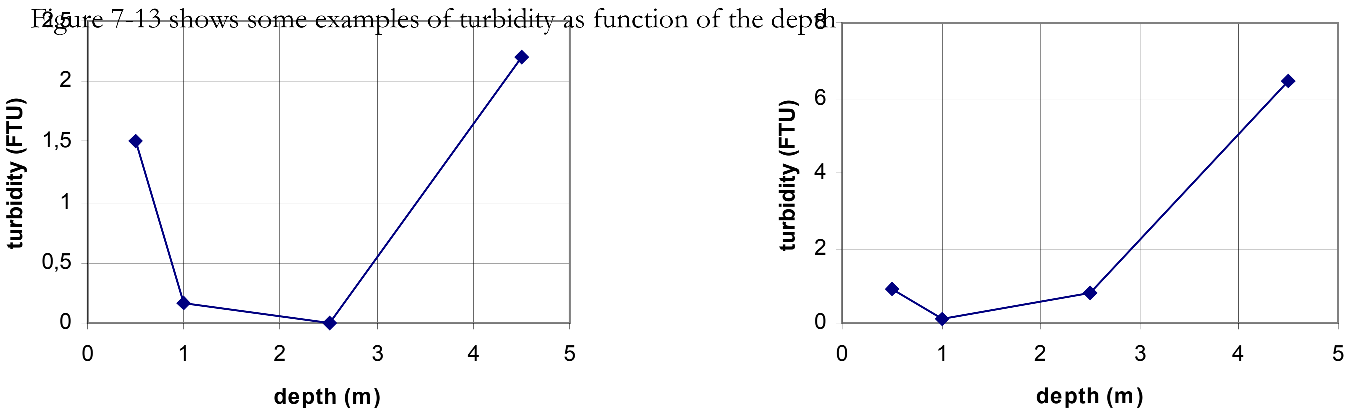


Figure 0-12 Turbidity as function of the number of ship crossings left: j=10, k=4; right j=20, k=4

Figure 7-13 shows some examples of turbidity as function of the depth



By means of auto correlation functions the inherent uncertainty can be shown. Auto correlation will be explained below.

Autocorrelation

Correlation is the linear dependence between two random variables; auto correlation is the correlation between the values of one random variable. The correlation coefficient is defined by:

$$\rho_{X1,X2} = \frac{\mathrm{cov}(X_1, X_2)}{\sigma_{X_1}\sigma_{X_2}}$$

Cov is the mixed central moment or covariance, and σ is the standard deviation.

The auto correlation of the ship crossing is the correlation between the turbidity at location (x,d) during ship crossing n, and the turbidity at the same location (x,d) during ship crossing n+i; corr (t(j,k,n) , t(j,k,n+i)), in which i varies between 1 and 58:

$$\text{Autocorrelation} = \text{corr (t(j,k,n) , t(j,k,n+i))} = \frac{\mathrm{cov}(t(j,k,n), t(j,k,n+i))}{\sigma_{t(j,k,n)}\sigma_{t(j,k,n+i)}}$$

For i=1 the correlation between two adjacent measurements n=(2,3), n=(3,4), etc., is calculated. For i=2 the correlation between n=(2,4), n=(3,5), etc. is calculated. Figure 7-14 shows this for location j=10, k=4. For i=1 to 58 correlations are calculated in this way. This results in the 58 points of the auto correlation function in Figure 7-15.

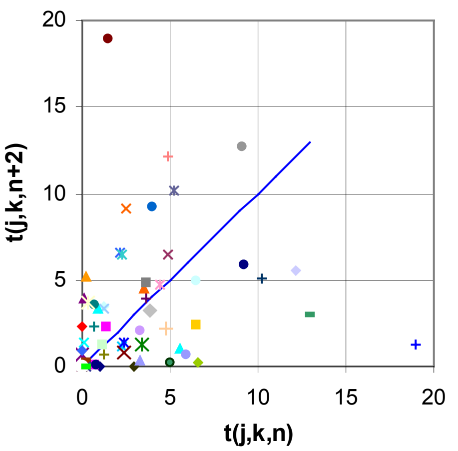


Figure 0-14 The auto correlation for i=2 at j=10, k=4 is 0.55. The line represents the theoretical example of a correlation of 1.

When all points fall within one line (correlation =1) the variables are dependent (see Figure 7-14). A correlation of zero means that the variables are independent.

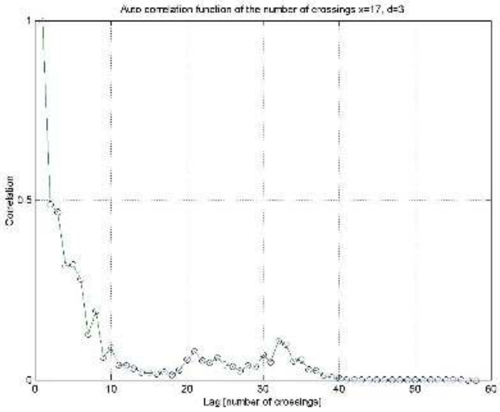
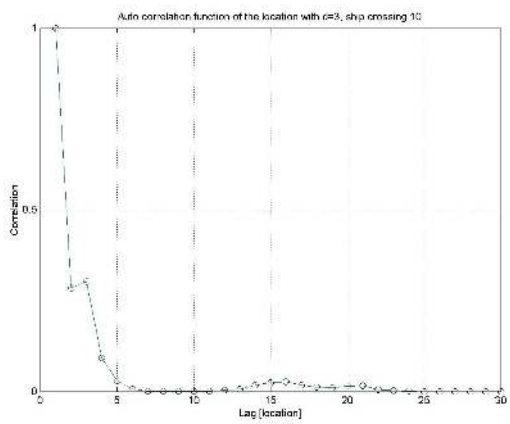
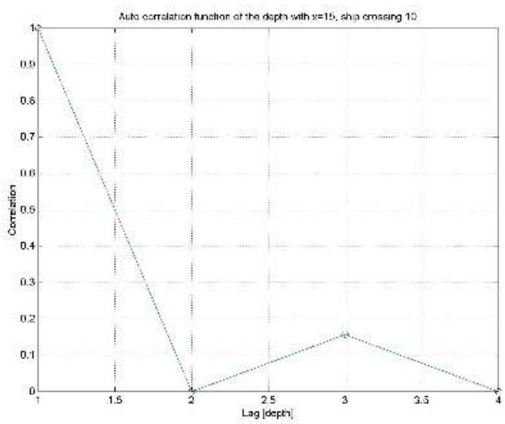


Figure 0-15 Auto correlation function of the ship crossing at location j=10, k=4. The correlation at lag=2 was determined in Figure 7-14

Auto correlation functions were also made of the location and of the depth. Figure 7-16 shows examples of auto correlation functions of the location at (j,3,10) and of the depth at (15,k,10).





Results
The auto correlation functions show low correlation values (< 0,5). This means that the turbidity values can not be interpreted from each other and are inherently uncertain as expected. Higher correlation values imply that less measurements are needed. With a correlation of 100% only one measurement is required. For the further approach of this study the correlation will be assumed to be zero. When the actual correlation is assumed, a more advanced statistical analysis has to be used.

Figure 0-16 Auto correlation functions of the location at k=3, n=10 and of the depth at j=15 , n=10

Distribution function for the inherent uncertainty of turbidity

The previous section concluded that the turbidity data are not correlated, which means that the turbidity is inherently uncertain. In this section the inherent uncertainty will be modelled by a distribution function.

A statistical analysis on the turbidity data determines how often a given turbidity value is expected. The turbidity T at location (x,d) can be modelled by a probability density function f(T). First the distribution function has to be determined.

The turbidity data contain a large number of very low values, or zeros. These are the natural, or background values that are measured by the measuring vessel at the edges of the plume, or when no clear plume can be observed. A way to separate the background values from the extra turbidity is to use a Binomial-Exponential distribution.

To check whether data fit well in the distribution function a computer program called 'Bestfit' was used. 'Bestfit' used a χ-square method (Van Gelder 1999). The program fitted the 58 measurements of T at location (x,d) in several distribution functions and determined the best fit. Because the distribution functions of 'Bestfit' do not include the BE-distribution, the background, or zero values were left out and for 20 tested locations the exponential distribution function came out as a good fit.

For all 120 locations the turbidity data are fitted in a Binomial-Exponential distribution. Appendix B shows that at most locations the turbidity measurements fits well in the distribution. Figure 7-17 shows an example of a good fit.

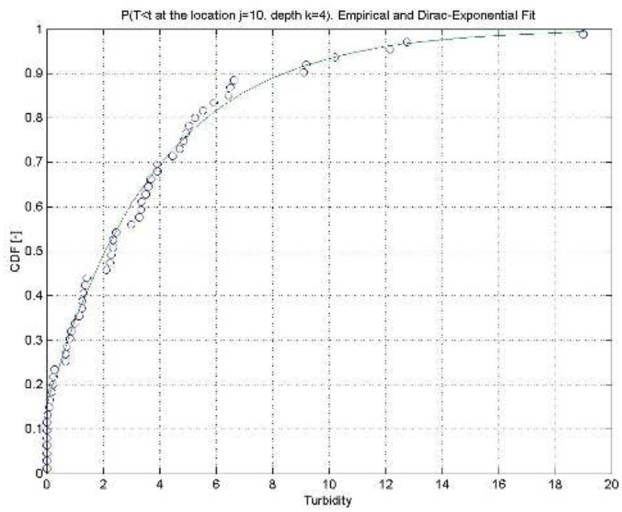


Figure 0-17 An example of a fit of turbidity data in a Binomial-Exonential distribution function

In this figure the data seem to be grouped. No explanation is found for this than that it may be caused by the measurement equipment. Since the effect is only small and does not affect further conclusions this is not investigated in more detail.

For all locations the same distribution is used because the same process, i.e. turbidity is described. The cumulative distribution function (CDF) and the probability density function (PDF) for the BE-distribution function are described as (see Figure 7-18):

$F_t(t) = 1-(1-p)\cdot e^{\frac{-t}{\mu}}$ $f_t(t) = \frac{(1-p)}{\mu}\cdot e^{\frac{-t}{\mu}}$

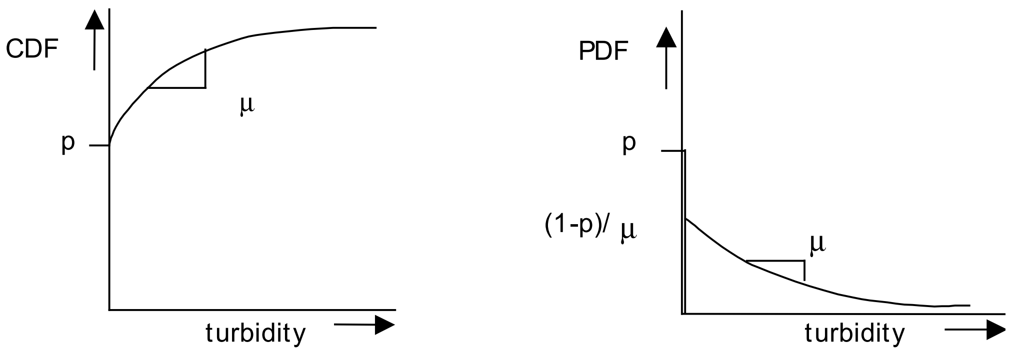


Figure 0-18 The cumulative and the probability density function of the Binomial-Exponential distribution function. The parameters p, i.e. the number of zero's, and μ that determines the curvature of the line are displayed in the figure.

The BE distribution has two distribution parameters; p and μ. p is the percentage of zero's of the turbidity measurements (background values) and μ is the mean value of the non-zero's of the turbidity. For all locations the two parameters of this distribution are calculated for the 58 values.

Statistical uncertainty

For further analysis the BE-distribution function will be used. The parameters of the distribution are now determined with a limited number of data. In this situation statistical or parameter uncertainty (or inaccuracy) occurs. The smaller the number of data, the larger the parameter uncertainty. The inherent uncertainty, described by a distribution function (see Section 7.3.2) can not be changed. An example to illustrate this is the weather forecast; we don't know the temperature at a specific day next year (inherent uncertainty). It can only be modelled by a probability density function probably normally distributed. With a larger number of measurements this probability density function with its mean and standard deviation does not change. But accuracy of the prediction gets larger (statistical uncertainty). The probability density function can be described more accurately.

Statistical uncertainty of parameter p shows itself in the point where the curved line starts and uncertainty of μ in the curvature of this line. This is illustrated in Figure 7-19.

The smaller the number of data, the larger the parameter uncertainty.

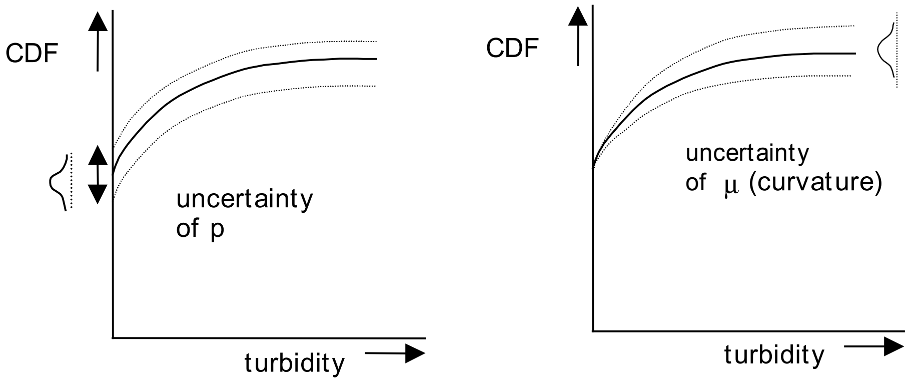


Figure 0-19 The uncertainty of the parameters visualised in the Cumulative distribution function.

Quantification of parameter uncertainty

A parameter of a distribution function is estimated from the data and thus is a random variable. The parameter uncertainty can be described by a distribution function, which can generally be modelled by a normal distribution function (see Figure 7-19).

The uncertainty can be quantified by the coefficient of variation value (CV). The coefficient is defined by the standard deviation divided by the mean:

μ = mean
σ= standard deviation

$$CV = \frac{\sigma}{\mu}$$

The derivation of parameter uncertainties can be done analytical and numerical.

Analytical method

For an overview of analytical expressions is referred to Van Gelder (1999). The Binomial-Exponential function consists of a continuous (exponential) and a discrete (binomial) part. To calculate the coefficient of variance for the estimator μ expressions for the exponential distribution function can be used. The following calculations are described in more detail in Appendix C. As these calculations can be applied in general, the expressions X defined as a random value and x defined as a realisation of X are used.

For the exponential distribution function:

If $F_x(x) = 1 - e^{-\frac{x}{\mu}}$, and $f_x(x) = \frac{1}{\mu} \cdot e^{-\frac{x}{\mu}}$

then $E(X) = \int_0^\infty f(x) x dx = \mu$

and $\quad E(X^2) = \int_0^\infty f(x) x^2 dx = 2 \cdot \mu^2$

thus $\quad var(X) = E(X^2) - E^2(X) = 2 \cdot \mu^2 - \mu^2 = \mu^2$

thus $\quad \sigma(X) = \mu$

If $X_1, X_2, \ldots, X_n \in Exp(\mu)$,

Than $\mu^* = \frac{\sum_{i=1}^{n} X_i}{n}$

μ^* is the estimator for the unknown μ.

μ^* is a function of n random variables, and thus is a random variable itself.

$$E(\mu^*) = \frac{E\sum X_i}{n} = \frac{1}{n} \cdot \sum EX_i = \frac{1}{n} \cdot n \cdot \mu = \mu$$

And $\sigma(\mu^*) = \frac{1}{n} \cdot \sqrt{\sum \sigma^2(X_i)} = \frac{1}{n}\sqrt{n \cdot \mu^2} = \frac{\mu}{\sqrt{n}}$

For the Binomial-Exponential function the average of the non zero values (in total n(1-p)) is needed and

$E(\mu^*) = \mu$

and $\sigma(\mu^*) = \frac{\mu}{\sqrt{(1-p) \cdot n}}$

thus $CV(\mu^*) = \frac{1}{\sqrt{(1-p)n}}$

Following the same reasoning for the coefficient of variance of the estimator of parameter p the binomial distribution function can be used with:

$E(X) = n \cdot p$

$var(X) = n \cdot p(1-p)$

The binomial distribution function is a model for an experiment with two possible outcomes; one with chance p and the other with a chance (1-p). If X is the random variable for the total number of positive outcomes, then for the Binomial-Exponential function the chance of a zero value is estimated by $p^* = \#zero's/n = X/n$. This results in:

$E(p^*) = p$

and with $var\left(\frac{X}{n}\right) = \frac{1}{n^2} \cdot var(X)$

$$var(p^*) = \frac{p(1-p)}{n}$$

var(p*)= (std(p*))², thus std(p*)= $\sqrt{\frac{(1-p)p}{n}}$

and CV(p*)= $\sqrt{\frac{1-p}{p \cdot n}}$

Numerical method

The analytical derived values were tested by a numerical parametric statistical estimation method. The following steps describe this numerical method:

1. The turbidity data can be simulated as follows: generate a random sample from a uniform distribution function, use this as the CDF-value of the BE-distribution and determine the corresponding turbidity (see Figure 7-20).

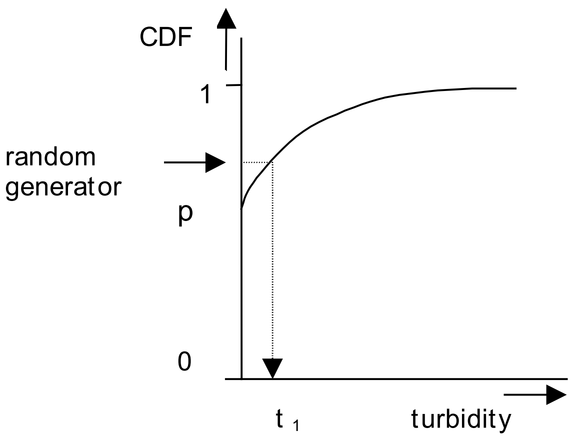


Figure 0-20 Simulation of turbidity measurements

Repeat this a hundred times.

2. Determine the amount of zero values and the mean value.

Repeat step 1 and 2 a hundred times and the distribution function of these 100 values for both the parameters can be derived. Figure 7-21 shows an example.

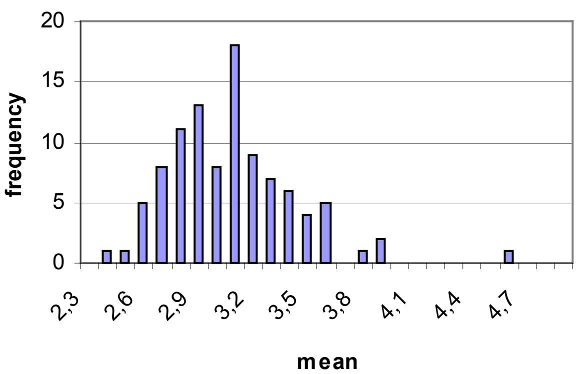


Figure 0-21 The distribution function of mean values, derived from a simulation of the BE distribution function with μ = 3 and p = 0,1 can be modelled by a normal

In practice, this distribution can be satisfactory modelled by a normal distribution function. The mean and standard deviation, and thus the CV of this distribution function can be calculated. From now on this will be described by:

$\mu \sim N(\alpha,\beta)$ with mean value α and standard deviation β, $CV(\mu) = \beta/\alpha$

$p \sim N(\gamma,\delta)$ with mean value γ and standard deviation δ, $CV(p) = \delta/\gamma$

Parameter uncertainty as function of the number of ship crossings

For 20 locations the parameter uncertainty was calculated. Fig 7-22 shows how the uncertainty of the parameter p and μ depends on the number of measurements for p=0.4 and μ=4, which is the average for all locations.

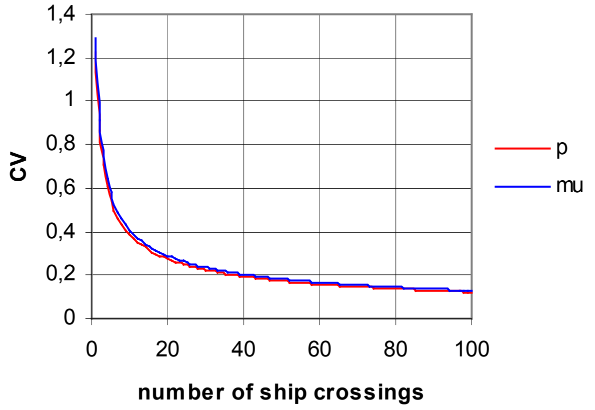


Figure 0-22 The uncertainty of the parameters as function of the number of ship crossings.

The CV is defined by the standard deviation divided by the mean as described earlier in this section. When the number of measurements increases the CV decreases (and the accuracy increases).

The uncertainty can be larger than 100%; this happens when the standard deviation is larger than the mean value ($\beta > \alpha$ or $\delta > \gamma$). Figure 7-23 illustrates this.

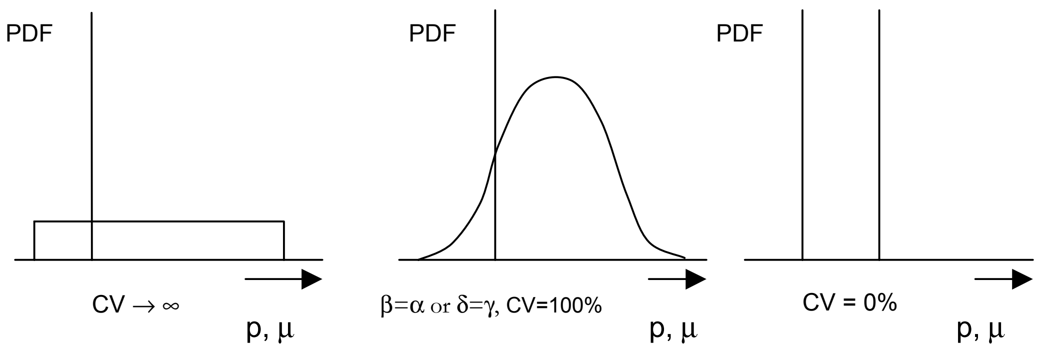


Figure 0-23 Probability density functions of a normal distribution function with limit situations for the CV value

Determination of the maximum allowable turbidity in a probabilistic framework

To determine the maximum allowable turbidity a method of failure chances is used. This theory is also applied to probabilistically determine dike heights (CUR 1997). The Limit State is the state when the resistance (R) is equal to the load (S) on the dike. When the load is larger than the resistance (S>R) the construction will fail. The state of the construction can be described by a reliability function Z=R-S. In this application failure occurs when the turbidity gets larger than a specific t (T >t) and the reliability function can be described by Z =t-T.

The maximum allowable turbidity in the field of investigation is described in a probabilistic way, for instance P(T<t)=98% (this is the chance of non failure). This means that in average 2 out of 100 measurements may exceed the maximum allowable turbidity t. Or similarly, out of 100 locations (j,k), there may be 2 locations where the turbidity exceeds the maximum allowable turbidity.

The cumulative distribution function (CDF) (shown by Figure 7-24) is described by:

$$F_t(t) = 1-(1- p)\cdot e^{\frac{-t}{\mu}}$$

With a required reliability of 98%

$$P\ (T<t) = 0.98$$

$$(1-\ p)\cdot e^{\frac{-t}{\mu}} = 0.02$$

$$e^{\frac{-t}{\mu}} = \frac{0.02}{1-p\cdot}$$

$$t = -\mu\cdot \ln\left(\frac{0.02}{1-p}\right)$$

Because the distributions of μ and p are modelled by a normal distribution function, t may be assumed also a normal distribution by first order reliability theory.

$\mu \sim N(\alpha,\beta)$ with mean value α and standard deviation β,
$p \sim N(\gamma,\delta)$ with mean value γ and standard deviation δ,
$t \sim N(\varepsilon,\zeta)$ with mean value ε and standard deviation ζ,

ε and ζ (as well as $\alpha,\beta,\gamma,\delta$) are dependent on the number of ship crossings n. If $n \rightarrow \infty$, $\zeta \rightarrow 0$. Figure 7-24 shows how uncertainties of μ and p (as described in Section 7.3.4) determine the uncertainty of t.

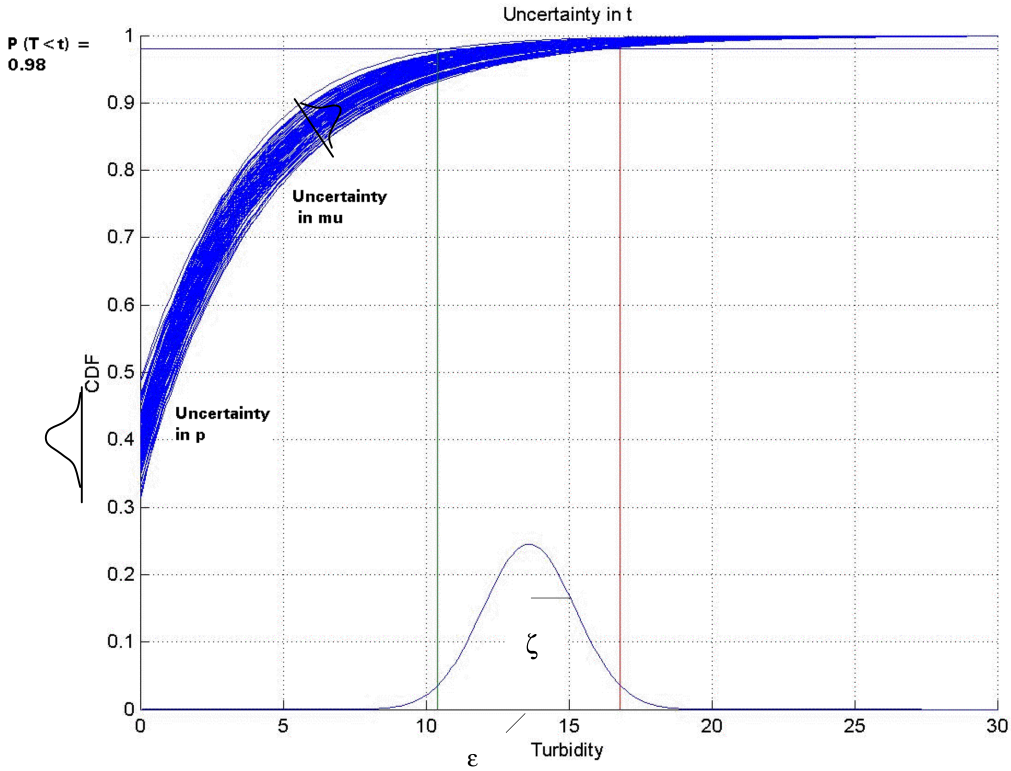


Figure 0-24 Cumulative Distribution Function of a B-E distribution with parameters p=0.4 and μ=4. The parameter uncertainties and the required reliability of 98% determine the allowable turbidity. In this figure 100 measurements were included. With more measurements the curve of the distribution of becomes more narrow and higher and the interval becomes smaller. This also happens for a lower reliability percentage but the curve will move to the left as well.

By a linear approximation of the relationship between t and its parameters μ and p with Taylor series expressions for ε and ζ can be determined (see CUR 1997). The outcomes are described below:

$$\varepsilon = -\alpha \cdot \ln\left(\frac{0.02}{1-\gamma}\right)$$

$$\zeta = -\beta \cdot \ln\left|\ln\left(\frac{0.02}{1-\gamma}\right)\right| + \delta \cdot \left|\frac{\alpha}{\gamma-1}\right|$$

Figure 7-24 shows these parameters as well. Assuming t has to be specified with 95% accuracy, then the interval of turbidity values is derived with:

$t = (\varepsilon - 1.965 \cdot \zeta,\ \varepsilon + 1.965 \cdot \zeta)$

In general, assumed that t has to be specified with (1 – p)% accuracy, then
$t = (\varepsilon - \Phi^{-1}(p/2) \cdot \zeta,\ \varepsilon + \Phi^{-1}(p/2) \cdot \zeta)$

The chance p in this formula differs from the parameter p of the BE-distribution. The minimal number of ship crossings can be determined when the interval of turbidity values for an accuracy of 95% is specified. This interval is the probabilistic allowable level of turbidity.

Figure 7-25 shows the interval as function of the number of measurements at a location with distribution parameters p=0.4 and μ=4.

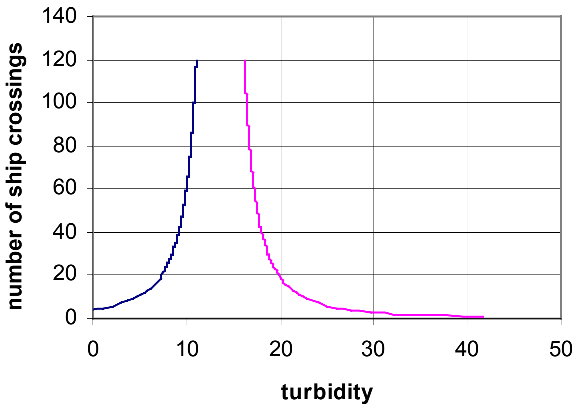


Figure 0-25 The interval of the allowable level of turbidity decreases with increasing number of ship crossings, p=0.4, μ=4

For 58 ship crossings, for a reliability of 98%, the 95% accurate interval of turbidity values is [9.9 , 17.3]FTU. Figure shows the outcomes for 100 shipcrossings.

When P (T<t) is smaller the allowable turbidity interval decreases (98% may be a very strict requirement).

To be able to minimise the number of measurements with this method the following requirements have to be specified:

- the required reliability (chance that the turbidity at location (j,k) is smaller than t)
- the required percentage of accuracy of t
- the reliability interval

7.4 Optimisation of costs

The number of ship crossings can be optimised as follows:
Assume the costs of one ship crossing is A
Assume the costs (disadvantages) of having a larger CV-value is B
Then the total costs can be described by:

$TC(n) = A \cdot n + B \cdot CV(p^*) + B \cdot CV(\mu^*)$, with n = the number of measurements in 24 hours,

$$TC(n) = A \cdot n + B\sqrt{\frac{1-p}{p \cdot n}} + B \cdot \frac{1}{\sqrt{(1-p)n}} \qquad (1)$$

The used data of the Øresund project are measurements of one day. Thus the process of turbidity of 24 hours is described and the cost optimisation is for 24 hours as well.

When TC'(n) is the derivative of the function TC(n), the optimal number of ship crossings follows from TC'(n) = 0, with

$$\text{Giving } n_{opt} = \sqrt[3]{\left(\frac{B \cdot \left((1-p)+\sqrt{p}\right)}{2A \cdot \sqrt{p \cdot (1-p)}}\right)^2} \qquad (2)$$

Quantification of costs

The costs of ship crossings can be assumed. A measuring vessel for 12 hrs/day approximately costs Dfl. 10.000,- per week and a vessel for 24 hrs/day costs approximately Dfl. 15.000,- per week. The gains of having a smaller CV-value are more difficult to determine. With a smaller accuracy the chance that limits are exceeded without registration by measuring is larger. For example when the measured mean value is smaller than the actual mean value, the chances that the ecosystem will be affected raise. But when the measured mean value is higher than the actual mean value, unnecessary problems between contractor and employer will rise. With larger uncertainties it is more difficult to prove whether effects on the environment are caused by dredging or not. The quantification of the costs will make the optimisation of number of ship crossings workable in practice but it is outside the scope of this report. To show how the optimisation of costs can be used global calculations are made for the Øresund case and a sensitivity analysis is done.

Results Øresund case and a sensitivity analysis

At the Øresund Fixed Link dredging project the environmental protection played a central role (see Chapter 4, Box I). Turbidity measurements were taken 24 hr/day and the costs imposed by the environmental requirements are assumed to be relatively high.

For the following example it is assumed that the optimal number of measurements for the Øresund case is 58. With assumptions for p and A, a value for B can be calculated by equation 2:
n_{opt}= 58 ship crossings
p= 0.4 , this is the average of the p-values for all locations
A= 1 , to show the relation between A and B

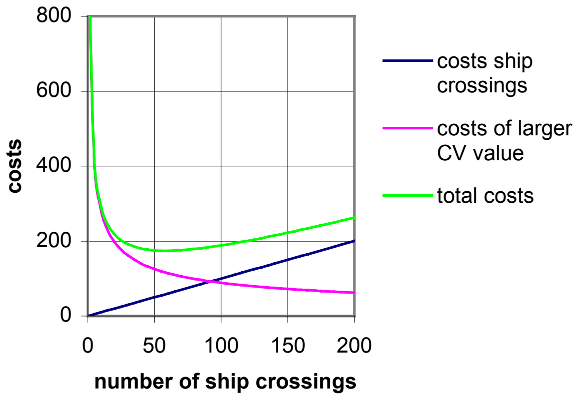
Gives:

B=352
These are the assumed relative costs of having a lower accuracy. Because the environment had a high priority at the Øresund projects this value of 352 is assumed to be high.

The quantified accuracy for the assumed number of measurements is: CV(p*)=0.16 and CV(μ*)= 0.17 (see Figure 7.23).

Figure 7-26 shows the total costs for the optimal number of ship crossings of 58.

Figure 0-26The optimal number of ship crossings



When less measurements can be performed while the rest of the parameters stays the same, the accuracy will decrease, and the total costs will increase. Table 7a shows examples with less measurements for p=0.4, A=1 and B=352. Equations 1 and 2 were used for the calculations.

n	CV(p*)	CV(μ*)	TC(n)	% related to TC(58)	Compensation of A
58	0.161	0.170	174.3	100%	1
50	0.173	0.183	175.2	100.5%	0.98
40	0.194	0.201	180.0	103.3%	0.86
30	0.224	0.236	191.7	110%	0.42
20	0.274	0.289	218.0	125%	-1.19

Table 7a The influence of performing less measurements on the uncertainty and the total costs, with A=1, B=352, p=0.4

Thus when for example only 30 measurements are performed, the total costs of the ship crossings and of the disadvantages of having a larger CV value will raise with 10%.

This may be compensated by using cheaper methods of measurements. When the total costs and B stay the same, A has to decrease (see the last column of Table 7a). For 30 measurements the costs of one ship crossing has to be reduced with approximately 60%, and for 20 measurements it is not possible to fully compensate the increase of total costs by reduce the costs of the ship crossings.

In the described example the optimal number of ship crossings was assumed (to be 58) and B was determined. When it is possible to quantify B then the optimal number of ship crossings follows just from B and then the uncertainties can be calculated. Figure 7-27 shows a sensitivity analysis of the cost parameters. A is kept at a constant value of 1 to determine the influence of B on the optimal number of ship crossings. When accuracy is not important (B=0), no ship crossings are necessary. When accuracy gets more important, the optimal number of ship crossings increases almost linear.

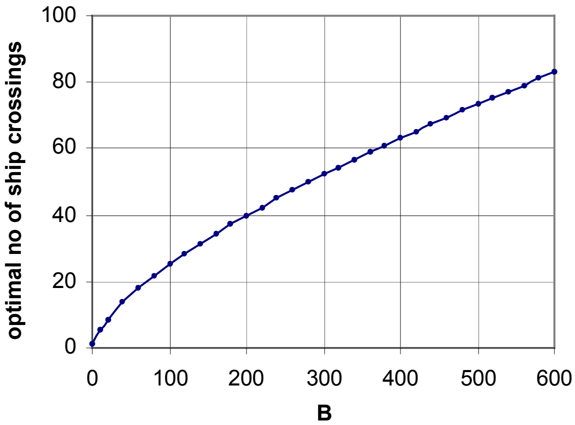


Figure 0-27 The influence of B on the optimal number of ship crossings. A is kept at a constant value of 1

When the factor B can be assessed in relation to the Øresund case, assuming the same sediment plume behaviour, the number of ship crossings can be optimised for other cases.

8 Conclusions

8.1 Basic study

1. There is no international regulation or legislation specifically relating to uncontaminated sediment plumes caused by dredging activities.

2. It seems impossible to make limits universal because the effects of sediment plumes caused by dredging are site and time specific. Site specific because ecosystems and natural conditions vary from site to site and time specific because they depend on tide, day or night, seasons with different hydrodynamic conditions (like monsoons, breeding and hatching seasons, currents).

3. For a large number of projects no limits are required because no adverse impacts are to be expected; the environment can be insensitive to sediment plumes because it is used to varying suspended sediment concentrations and turbidity or because no sensitive species are present. In environments where negative impact is to be expected, project specific investigations are needed on the quantification of the limits.

4. Requirements for sediment plumes in dredging contracts are often not well founded. Limits usually are copied from other projects or reports without much investigation or based on water criteria standards or community perception.

8.2 Effects on corals

1. Sediment plumes cause reduced light penetration and sedimentation, which may affect corals. For dredging near corals sedimentation is a far more important factor than reduced light intensity.

2. To determine limits for sediment plumes caused by dredging a research strategy like in the toxicology can be used. Because not enough adequate data are available to allow the construction of a complete dose-effect relationship, limits could not be determined yet.

3. Most experiments were focussed on the sublethal effects. Taking in account the observed species and sediment sizes, corals have the ability to clear themselves from 100 mg/ cm^2/day and can handle concentrations of suspended solids of 100mg/l for a few days. To determine limits the effects of higher doses with partial but significant damage also must be known.

4. Lethal effects on corals were experimentally observed only when burial was complete. Corals can not handle burial caused by dredging activities for more than 1 day to 1 week, depending on the natural conditions.

5. Coral reefs are probably the most sensitive marine ecosystems. This implies that limits based on other ecosystems can be less strict.

8.3 Measurement optimisation

The conclusions concern the simplified data of the Øresund Fixed Link project.

1. The inherent uncertainty of turbidity can be described by a Binomial- Exponential distribution function.

2. The exceeding of a certain turbidity level can be tackled with models that are also used in the safety and reliability issues of water defence design.

3. The maximum allowable turbidity can be probabilistically determined as function of the number of ship crossings. For a required reliability and accuracy the number of ship crossings can be determined.

4. The number of ship crossings can be optimised on the basis of the total costs. The total costs consist of the costs of ship crossings and the costs (disadvantages) of having a smaller accuracy of the turbidity probabilistic distribution function. This last factor is assessed in relation to the Øresund case.

9 Recommendations

Recommendations are divided in recommendations on further research and more practical recommendations for the dredging operations.

9.1 Basic study

- Further research

The main problem with setting up limits is that there is not enough knowledge of the backgrounds. More research is recommended on the thresholds and duration that different ecosystems can be exposed to and on the models that can predict the amount of re-suspended sediment.

- For the dredging operation

As long as there is not enough knowledge of backgrounds to set up restrictions it is not useful to set up standards. In sensitive environments where negative impact is to be expected, project specific investigations are needed on the quantification of the limits. Data of background conditions must cover natural variations and seasonal patterns in order to provide the context of the change. When the environment is very sensitive at specific time zones, environmental windows can be determined.

To prevent problems between employers and contractors during the project sensible arrangements have to be made in advance. Contract types whereby the contractors are more encouraged to accept risks may be more appropriate for dredging projects with environmental objectives. Another possibility could be that the contractors make prices for different options and the employer can choose an option, which will be a compromise between the level of environmental impact and the costs made to prevent this.

9.2 Effects on corals

- Further research

Set up experiments
To determine limits for sediment plumes caused by dredging a research strategy like in the toxicology can be used. But not enough adequate data are available to allow the construction of a complete dose-effect relationship. Further experiments on the effects of sediment plumes caused by dredging on coral are needed with higher doses of stress (percentages of mortality).

In this report recovery time of one year is used as a measure for acceptable damage. In many experiments reviewed in this study no recovery times are reported. Experiments would gain in value if the recovery after a few months and after a year were also checked in the future.

A possible approach to assess the effects of dredging is to multiply the levels of equilibrium situations with factors. To determine these factors more investigations is recommended on the relationship between long and short term effects of sediment plumes.

Other ecosystems
This study was focussed on a species that is vulnerable to the effects of sediment plumes; corals. For other sensitive species or ecosystems similar studies are useful.

Removal of sediment by a water jet
Investigations are recommended on the possibility to remove settled sediment from corals with a flowdredging technique. Experiments should be done with jets on corals to find out how much the corals can handle. For specific projects it should be examined where the sediment will be transported to, and what the costs will be.

- For the dredging operation

Approach to determine the extent of damage
The dredging example calculation shows an approach to determine how much damage sediment plumes can cause on corals. This approach is not applicable to the set up of limits but may be useful for an environmental impact assessment (EIA).

9.3 Measurement optimisation

- Further research

More data analyses
The data used for the statistical analysis come from turbidity measurements of the Øresund project of one day. To be able to perform the analysis the data were simplified. To investigate if turbidity can be described by a Binomial- Exponential distribution function in general, more analyses with other data have to be performed. The following sorts of data are proposed:
- the raw data of the Øresund project;
- data of another day at the Øresund project of the same dredge
- data of the Øresund project of a different dredge
- data of other projects with different natural conditions, dredges, and soil characteristics.

Quantification of the costs
To be able to use the results of this study in practice, a quantification of the costs has to be made. An indication for the costs of ship crossings was given in this report but the gains of having a higher accuracy of turbidity distribution functions are more difficult to quantify. In the report this is assumed in relation to the Øresund case. Further investigations into this would be interesting.

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Appendix A Projects

This appendix describes the projects that are discussed in chapter 4:

Marine projects that are completed:
Øresund Link (1996-2000)
Adnoc-Borouge polyethylene plant Ruwais (1999-2000)
New Port and Fishery Harbour at Wilayat Sohar (2000-2001)

The projects the author is acquainted with that are under construction at the moment or still in tender phase are not included in this appendix.

Other projects that are that are referred to in chapter 4
Freeport harbour mouth widening Bahamas (1989-1990)
Restoration of the North Lake of Tunis (1985-1988)

Project:	**Øresund Link (1996 – 2000)**
Location project:	Denmark and Sweden, Baltic Sea
Employer:	Danish and Swedish authorities, Øresundskonsortiet
Consultant:	DHI
Contractor:	for dredging Øresund Marine Joint Venture; Per Aarsleff A/S, Ballast Nedam Dredging and Great Lakes Dredge & Dock Company
Dredging activities:	dredging for a tunnel trench, construction and navigation channels and harbours, and reclamation for the construction of the artificial island and peninsula (a total amount of 7 million m^3)
Characteristics material:	gravel and stones, clay till and limestone with flint layers
Equipment:	Mechanical dipper dredger, hydraulic cutter suction dredger, smaller backhoes
Duration dredg activities:	5 years on the entire link
Hydrodynamic conditions:	limited wave action, currents of 2 nautical miles per hour (1,3 m/s)
Baseline conditions:	Natural content of particles 2-20 mg/l Visibility of more than 10 m
Limit:	Maximum daily and weekly spillage rates. The total spill from all activities of the contract must not exceed 5% of the dry weight of materials expressly required to be dredged
Unit of limit:	spill is measured by dry weight of suspended materials
Environmental reason:	clean, clear water, with eelgrass, mussels, herring, foraging birds and bathing water quality
Method of measurement:	Spill monitoring (OBS and ADCP) by vessels sailing through the spill plume Feedback monitoring programme in the marine environment around the dredging areas
Frequency:	24 hours/day
Location limit:	transects perpendicular to the plume several levels in the water column
Mitigation measures:	a program when to dredge where to control the sediment plumes feedback monitoring program
Backgrounds:	investigations on the impact on environment; experiments, ecological and sediment transport models
Result:	dredging was temporarily stopped a few times because of the limits

Project:	**Adnoc-Borouge polyethylene plant Ruwais (1999-2000)**
Location project:	United Arabic Emirates, Persian Gulf coast
Employer:	Adnoc Borouge (Abu Dhabi National Oil Company)
Consultant:	Halcrow
Contractor:	Boskalis Westminster
Dredging activities:	dredging of a harbour, total amount of 1,5 million m^3
Characteristics material:	ranged from sand to caprock
Equipment:	Cutter suction dredge
Duration dredg activities:	2 months
Hydrodynamic conditions:	very weak currents 5 to 10 cm/s, tidal current
Baseline conditions:	concentration of suspended solids 3–8mg/l
Limit:	400mg/l above background levels (3 to 8 mg/l) at boundary lines 200m around cutter and at discharge point Only 5% of the total dredging volume was allowed to cross the 200m boundaries as suspended solids
Unit of limit:	mg/l
Environmental reason:	corals, seagrass, oysters
Method of measurement:	OBS, ADCP, water sampler
Frequency:	Throughout the first two weeks of the dredging works 13 hours/day Later 13 hours/week
Location limit:	200 m out of and parallel to the dredging area boundaries Over the whole water column
Mitigation measures:	silt screens around cutter were required by the employer but not needed because the limit was not exceeded retention area
Backgrounds:	no full environmental study, based on knowledge of the area and experience on other projects, the client required the highest environmental standards (referred to Halcrow)
Result:	the spill limit was not exceeded

Project:	**New Port and Fishery Harbour at Wilayat Sohar (2000-2001)**
Location project:	Oman
Employer:	Sultanate of Oman, Ministry of communications, Directorate General of Ports and Marine Affairs
Consultant:	Ibn Khaldun in association with Halcrow
Contractor:	Hyundai
Dredging activities:	reclamation (750 ha), placing of fill won from the dredged approach channel and harbour bassin and other areas
Characteristics material:	
Equipment:	
Duration dredg activities:	
Hydrodynamic conditions:	
Baseline conditions:	
Limit:	suspended solids content of the final discharge water to the sea shall not exceed 500 mg/l
Unit of limit:	mg/l
Environmental reason:	corals
Method of measurement:	contractor shall submit a method statement for measurement of suspended solids in discharge water
Frequency:	twice a day or as directed by the Engineer
Location limit:	at the weir boxes
Mitigation measures:	if necessary temporary stilling ponds
Backgrounds:	see Ruwais
Result:	

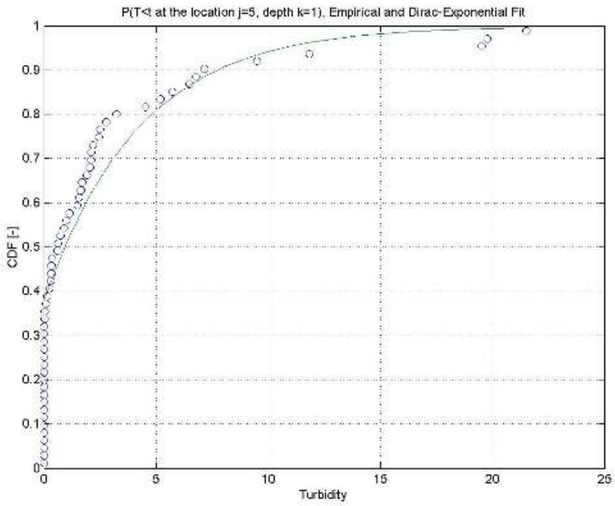
Project:	**Freeport harbour mouth widening (1989-1990)**
Location of project:	Bahamas
Employer:	
Consultant:	
Contractor:	HAM Dredging
Dredging activities:	dredging and reclamation
Characteristics material:	coralline rock
Equipment:	cutter suction dredger
Limit:	outflow from the reclamation area had to be clear water (sediment-free water) This specification abandoned
Result:	Water didn't flow into the ocean but in the underground cavities in the limestone rock

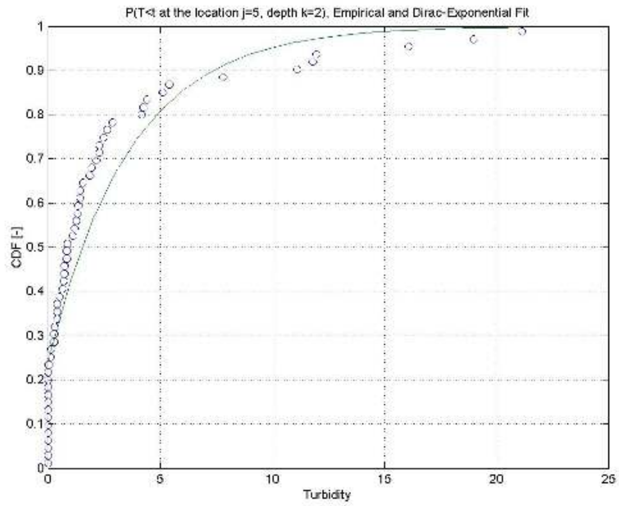
Project:	**Restoration of the North Lake of Tunis (1985-1988)**
Location project:	Tunis City ,Tunisia, North Lake of Tunis
Employer:	SPL (Societé de Promotion du Lac de Tunis)
Consultant:	Halcrow
Contractor:	The Lake Group joint venture (five Dutch dredging contractors)
Dredging activities:	Restoration of the polluted lake, dredging (20 million m^3) and reclamation (800 ha land)
Problem:	Dumping of waste and sewage outfall had polluted the lake. During the summer months the lake developed extreme symptoms of eutrophication. Further, space was needed for expansion of Tunis City
Design:	A lake water circulation system was developed
Result:	The eutrophication disappeared and and seagrasses started to expand through the lake. The sediment resuspension and turbidity of this shallow lake, which is large in storm wave conditions was not obstructing this environmental recovery

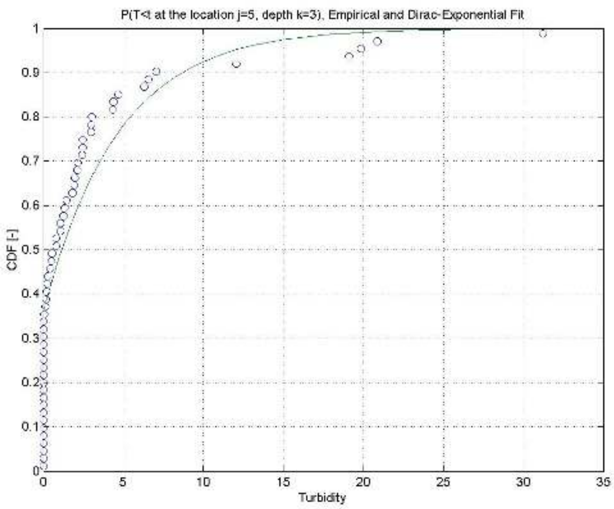
Appendix B Fits in Binomial-Exponential distribution functions

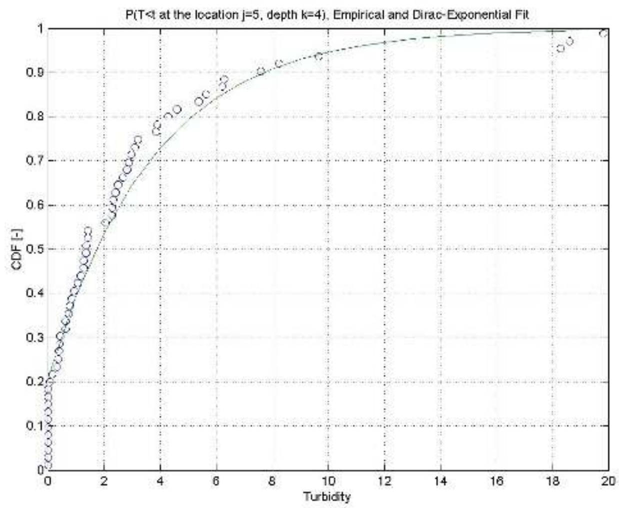
This appendix consists of fits at 20 locations: j = 5, 10, 15, 20, 25 k = 1,2,3,4

Fit in Binomial-Exponential distribution at j=5









Appendix C Analytical derivation of parameter uncertainties

The Binomial-Exponential function consists of a continuous and a discrete part. To calculate the coefficient of variance for the estimator μ the exponential distribution function can be used.

For the exponential distribution function:

If $F_x(x) = 1 - e^{-\frac{x}{\mu}}$, and $f_x(x) = \frac{1}{\mu} \cdot e^{-\frac{x}{\mu}}$

than $E(X) = \int_0^\infty f(x) x dx = \int_0^\infty \frac{1}{\mu} \cdot x \cdot e^{-\frac{x}{\mu}} dx = \left[-x \cdot e^{-\frac{x}{\mu}} \right]_0^\infty - \int_0^\infty -e^{-\frac{x}{\mu}} dx =$

$\left[-x \cdot e^{-\frac{x}{\mu}} \right]_0^\infty - \left[\mu \cdot e^{-\frac{x}{\mu}} \right]_0^\infty = \mu$

and $E(X^2) = \int_0^\infty f(x) x^2 dx = \int_0^\infty \frac{1}{\mu} \cdot x^2 \cdot e^{-\frac{x}{\mu}} dx = \left[-x^2 \cdot e^{-\frac{x}{\mu}} \right]_0^\infty - \int_0^\infty -2x \cdot e^{-\frac{x}{\mu}} dx =$

$\left[-x^2 \cdot e^{-\frac{x}{\mu}} \right]_0^\infty - \left[\frac{1}{2} x \cdot \mu \cdot e^{-\frac{x}{\mu}} \right]_0^\infty - \int_0^\infty 2 \cdot \mu \cdot e^{-\frac{x}{\mu}} dx =$

$\left[-x^2 \cdot e^{-\frac{x}{\mu}} \right]_0^\infty - \left[\frac{1}{2} x \cdot \mu \cdot e^{-\frac{x}{\mu}} \right]_0^\infty - \left[2\mu^2 \cdot e^{-\frac{x}{\mu}} \right]_0^\infty = 2 \cdot \mu^2$

thus $\text{var}(X) = E(X^2) - E^2(X) = 2 \cdot \mu^2 - \mu^2 = \mu^2$

thus $\sigma(X) = \mu$

If $X_1, X_2, \ldots, X_n \in \text{Exp}(\mu)$,

Than $\mu^* = \frac{\sum_{i=1}^{n} X_i}{n}$

μ^* is the estimator for the unknown μ.

μ^* is a function of n stochastic functions, and thus is a stochastic function itself.

$E(\mu^*) = \frac{E\sum X_i}{n} = \frac{1}{n} \cdot \sum EX_i = \frac{1}{n} \cdot n \cdot \mu = \mu$

And $\sigma(\mu^*) = \frac{1}{n} \cdot \sqrt{\sum \sigma^2(X_i)} = \frac{1}{n}\sqrt{n \cdot \mu^2} = \frac{\mu}{\sqrt{n}}$

For the Binomial-Exponential function the average of the non zero values is needed and

$$\sigma(\mu^*) = \frac{\mu}{\sqrt{(1-p) \cdot n}}$$

Following the same reasoning for the coefficient of variance of the estimator of parameter p the binomial distribution function can be used with:

$E(X) = n \cdot p$

var(X) = $n \cdot p(1-p)$

The binomial distribution function is model for an experiment with two possible outcomes; one with chance p and the other with a chance (1-p). For the Binomial-Exponential function the chance of a zero value is estimated by p^* =#zero's/n. This results in:

E(p^*) = p

and var (p^*) = $\frac{p(1-p)}{n}$ because var (X/n) = i/n^2var(X)