# DREDGE PLUMES

## Ecological risk assessment

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# Preface

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# Summary

Nowadays, the ecological effects of dredge plumes are usually managed based on the precautionary principle. Predictions of suspended sediment levels are made, which have to be compared to thresholds set by the responsible authority. Failing to comply may cause a project to be delayed and thus lead to additional costs. The precautionary principle however is vague and incorrect, since it does not take into account the benefits of the dredging activity. The proper question to ask is whether the dredging activity should be allowed to harm the ecosystem or the ecosystem should be allowed to harm the dredging activity. To be able to answer this question, ecological risk is required to be assessed in a quantitative manner. A suitable framework to do so is provided by the Ecological Risk Assessment (ERA), which enables a risk agent to include uncertainties explicitly. An ERA consists of a description of the system and its components, hazard identification, effects assessment, exposure assessment, risk characterization and an evaluation which provides feedback for a possibly updated system description. The effects assessment relates suspended sediment concentration and exposure duration to the response of a sensitive receiver. A graphical representation of this relationship is a dose-response curve, which represents the resistance of the species, or 'strength'. Field measurements or laboratory experiments are necessary to enable the development of dose-response curves for important sensitive receivers. The exposure assessment starts with the formulation of the dredge plume source term. The complex dynamic phase of the plume is not modeled, but is incorporated in the source term by means of established empirical relations. The passive phase is modeled by a hydrodynamic and transport model, which results in a time series of suspended sediment concentration levels at the location of the sensitive receiver. This is translated into a concentration and an exposure duration, which can be interpreted as the 'load'. When effects and exposure have been estimated, the risk has to be characterized. There are several ways to do this, which depend on the treatment of uncertainty. A probabilistic approach incorporates variability in exposure and effects estimates and a deterministic approach estimates one representative value for exposure and compares this with one representative dose-response relationship. A probabilistic approach enables the determination of a 'failure probability'. This provides confidence levels for the obtained results and points to gaps in knowledge. In general, insight in probabilities is assumed to enable a better risk assessment. When these methods are applied in practice, it depends on the situation at hand which technique is most suitable to estimate risk. In the design and planning phase of dredging works a probabilistic analysis is the preferred option, to identify possible new areas of investigation or research or to support the development of a monitoring strategy. It is however computationally expensive to carry out a Monte Carlo analysis to assess long-term exposure. On the other hand, when dredging works are already in progress, a deterministic analysis satisfies the desire for a quick assessment of the risks. Execution methods can in that stage still be changed and mitigating measures might still be implemented. In conclusion, for a quantitative assessment of ecological risk it is necessary to carry out a probabilistic analysis. Costs and benefits of a dredging project can then be determined, which enables a complete economic analysis and a transparent decision making process.

# Samenvatting

Tegenwoordig worden ecologische effecten van baggerpluimen meestal gemanaged op basis van het 'voorzorgprincipe'. Voorspellingen van concentraties van gesuspendeerd sediment worden gemaakt en vergeleken met grenzen die zijn gesteld door de verantwoordelijke autoriteit. Wanneer men zich niet houdt aan deze grenzen, kan een project vertraging oplopen met extra kosten als gevolg. Het voorzorgprincipe is echter vaag en incorrect, want het neemt de voordelen van een baggerproject niet in beschouwing. De correcte vraag die moet worden gesteld is of een baggeractiviteit mag worden gehinderd door een ecosysteem of dat een ecosysteem mag worden gehinderd door een baggerproject. Om deze vraag te kunnen beantwoorden moet ecologisch risico worden geanalyseerd op een kwantitatieve manier. Een geschikte methode om dit te doen is de Ecologische Risicoanalyse (ERA), die het voor een risicomanager mogelijk maakt onzekerheden expliciet te behandelen. Een ERA bestaat uit de beschrijving van het systeem en zijn componenten, identificatie van gevaren, analyse van effecten, analyse van blootstelling, karakterisering van het risico en een evaluatie die leidt tot feedback voor een mogelijke nieuwe systeembeschrijving. De analyse van effecten relateert de gesuspendeerd sediment concentratie en duur van blootstelling aan het effect bij de gevoelige flora en fauna. Een grafische weergave van deze relatie is een dosis-effect kromme, die de weerstand van een soort weergeeft, ofwel de 'sterkte'. Veldwerk of laboratorium experimenten moeten zorgen voor de ontwikkeling van dosis-effect krommen voor belangrijke gevoelige natuur. De analyse van blootstelling begint met de formulering van de baggerpluim bronterm. De complexe dynamische fase van de pluim wordt niet gemodelleerd, maar meegenomen in de bronterm door middel van bepaalde empirische relaties. De passieve fase wordt gemodelleerd door een hydrodynamisch en transportmodel, wat resulteert in een tijdreeks van gesuspendeerd sediment concentraties ter plaatse van gevoelige flora en fauna. Dit wordt vertaald in een concentratie en een duur van blootstelling, wat kan worden geïnterpreteerd als de 'belasting'. Wanneer effecten en blootstelling zijn ingeschat, moet het risico worden gekarakteriseerd. Er zijn verschillende manieren om dit te doen, wat afhangt van de behandeling van de onzekerheden. Een probabilistische analyse neemt variatie in blootstelling- en effectschattingen mee en een deterministische analyse schat één representatieve waarde voor blootstelling en vergelijkt dit met één representatieve dosis-effect relatie. Een probabilistische aanpak maakt het mogelijk een faalkans te bepalen. Dit geeft betrouwbaarheidsintervallen voor de verkregen resultaten en geeft hiaten in kennis aan. Over het algemeen wordt aangenomen dat meer inzicht in kansen leidt tot een betere inschatting van het risico. Wanneer deze methodes in de praktijk worden toegepast, is het afhankelijk van de situatie ter plaatse welke methode het meest geschikt is om het risico in te schatten. In de ontwerp- en planningfase van baggerwerken is een probabilistische analyse te verkiezen om nieuwe gebieden van onderzoek aan te wijzen of de ontwikkeling van een monitorstrategie te ondersteunen. Het is echter duur qua rekenkracht om een Monte Carlo analyse uit te voeren om lange termijn-blootstelling te analyseren.

Anderzijds, wanneer baggerwerken inmiddels zijn begonnen, is een deterministische analyse te verkiezen om snel een inschatting van het risico te kunnen maken. Uitvoeringsmethoden kunnen in die fase nog worden aangepast en mitigerende maatregelen kunnen nog steeds worden genomen. Tot slot, voor een kwantitatieve analyse van ecologisch risico is het noodzakelijk een probabilistische analyse uit te voeren. Kosten en baten van een baggerproject kunnen dan worden vastgesteld, wat een complete economische analyse en een transparant besluitvormingsproces mogelijk maakt.

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# Chapter 1

# Introduction

## 1.1 History of ecology

The coining of the term "ecology" is generally attributed to the German zoologist Ernst Haeckel, who used it in 1866 in his book "Generelle Morphologie der Organismen" (Haeckel, 1866). However, it is only since a few decades that ecology is familiar to people outside university and its autonomy as a science is often doubted (McIntosh, 1985). According to Peters (1976), ecology's main tenets (succession, diversity, competitive exclusion and spatial heterogeneity) are derived from the Darwinian evolution concept and are therefore merely tautologies: 'fitness', as used in the phrase "survival of the fittest" appears to be equivalent to survival itself. Nevertheless, ecology has matured into a predictive science with capabilities to deal with environmental concerns. Haeckel defined ecology as "the comprehensive science of the relationship of the organism to the environment", whereas the modern textbooks, e.g. Townsend et al. (2008), usually propose something like "the scientific study of the distribution and abundance of organisms and the interactions that determine distribution and abundance". In the definition of Heackel, the "environment" is explicitly mentioned. Dredging and dredging related activities undoubtedly have an influence on the environment and therefore affect at least temporarily the "distribution and abundance of organisms". The history of the relation between interventions in the environment, such as dredging, and the organisms that live in the environment can be described along the lines of a dialectic triad: for a long time, the Cartesian subject-object split underlayed the relation between mankind and its natural environment. This frame of thought proved unsatisfactory. The way nature had been manipulated turned out to be unsustainable and adverse effects of human interventions became apparent. This led to the affirmation of its negation: a general abstention from intervening in the environment. This reaction is based on the assumption that non-intervention will result in nature returning to its stable equilibrium. On reflection, this thesis proves inadequate as well and should be discarded. The idea of a return to a harmonious condition in absence of human interference is flawed and so is the thought that it is realistically possible to abstain from intervention. Man is an undeniable part of the system, which requires pragmatic solutions for today's ecological problems. It is expected that in 2050 roughly nine billion people will populate the earth, while resources such as food and energy are becoming increasingly scarce (United Nations, 2011). A synthesis is necessary, pushing towards a truly sustainable ecology. In the following paragraphs, this synthesis will be elaborated.

### The mastery of nature

In former times, the prevailing paradigm was that whatever interventions were carried out by mankind, they would be mediated and in the end dominated by the course of history (Žižek, 2007). Regardless of the intentions of the actor, everything and everybody else would go on undisturbed. Obviously, this was true before the industrial revolution, when the scope of interfering activities was relatively small. Since the industrial revolution however, the rate and size of interferences has increased sharply. The possibilities for countries and their populations to obtain larger economic growth and a higher standard of living suddenly were ample. At the same time their ability to make long term changes in their environments, beneficial as well as harmful, also increased. Especially in the field of technology (e.g. agriculture, biogenetics, nuclear energy or the fishing industry), the accomplishments have been impressive. Consequently, the possible adverse effects can be equally impressive. Large infrastructure, which is an important aspect of the modern economy, has the ability to change the natural environment as well. The dredging industry has been a part of this development, by building and maintaining navigation channels, land reclamation, sea defenses etc. During these projects, adverse effects of human interventions became apparent. As a result, the paradigm seems to be no longer true; people can no longer count on the limited scope of their interventions and it might be well possible that a single act or intervention will trigger an ecological disaster.

### Nature!

Nature is being manipulated and can no longer be considered a historical constant. The fact that nature can be definitively altered leads people to think that nature is not natural any more. The knowledge about this fragility of nature has led to a widespread discontent. This gives a new dimension to Freud's "Das Unbehagen in der Kultur" (Freud, 1930), namely a discontent about the fact that there is no balanced natural ecosystem which people can rely on. The result is an ecological movement opposed to every form of change, with a desire to go back to a state of harmony and equilibrium, to a balanced nature. That is why the predominant trend in ecology is very conservative, where the protection of nature against disaster is the main incentive. It takes almost religious proportions by giving ecology an unquestionable authority and imposing strict limits on human activity.

The broader movement underlying this prevalent view on ecology is contemporary postmodern sentimentalism (De Dijn, 2003). In this view, modern technology is unable to provide satisfactory solutions for problems that exist in today's society. And it goes beyond that: the idea of progress, associated with the Enlightenment, is said to be the main reason for those problems. The main narrative is that rationality and modern technology can have unintended consequences, such as the degradation of the natural environment, which cannot be solved by rationality itself. The proposed alternative is an aesthetic-ethical stand, wonderfully articulated by the Russian entomologist Andrei Petrovich Semenov-tian-shanskii (Weiner, 1988). Already in the early 1920s he firmly criticized modern industrial society. The conservative point-of-view is clear: "Educated minds cannot but recognize that free nature undefiled in all of its portions by mankind is a great synthetic museum, indispensable for our further enlightenment and mental development, a museum which, in the event of its destruction, cannot be reconstructed by the hand of man." The concept of 'Gaia', after the Greek goddess of the earth, as later elaborated by Lovelock (1979), already seems to be manifest in Semenov-tian-shanskii's writings: "In snuffing out the hearth of nature's life, in plundering and squandering her basic stock, we are digging our own graves, preparing a miserable future for our progeny."

The idea of nature that can be contained and kept in equilibrium can already be found in 18th century sentimentalist literature, notably Goethe's play "Der Triumph der Empfindsamkeit" (The triumph of sentimentality, 1777), which satirizes the sentimental view of nature displayed in his earlier, famous novel "Die Leiden des jungen Werthers" (The sorrows of young Werther, 1774) (Heins, 2006). The main character, Prince Oronaro, tends to forget the difference between art and nature, commonly known as the quixotic problem, after the 1605 novel "Don Quijote" by Cervantes. Oronaro is presented as a disturbed individual, who believes that his own products of imagination are real. The sentimentality becomes particularly apparent in his conception of nature. This conception is associated with English landscape gardening, a certain art form popular at the time. Goethe suggests that the belief in the naturalness of landscape gardening is a projection of the sentimental mind. A wonderful metaphor for this view of nature is Prince Oronaro's 'Reisenatur', a mechanical theater set which resembles a garden. He never travels without his nature in a box, where it cannot be harmed nor harm us. According to Goethe, sentimental gardening portrays nature as a mild and harmonious system, when in reality, nature is unruly and violent. The aesthetic illusion that underlies this conception of nature is exposed when Oronaro is being asked by his court ladies to take a walk outside. His guard answers the ladies:

> "Da ist eins zu bedauern, meine vortrefflichen Damen! Mein Prinz ist von so zärtlichen, äußerst empfindsamen Nerven, daß er sich gar sehr vor der Luft und vor schnellen Abwechselungen der Tageszeiten hüten muß. Freilich, unter freiem Himmel kann man's nicht immer so temperiert haben, wie man wünscht. Die Feuchtigkeit des Morgen- und Abendtaues halten die Leibärzte für höchst schädlich, den Duft des Mooses und der Quellen bei heißen Sommertagen für nicht minder gefährlich! Die Ausdünstungen der Täler, wie leicht geben die einen Schnupfen! Und in den schönsten wärmsten Mondnächten sind die Mücken just am unerträglichsten. Hat man sich auf dem Rasen seinen Gedanken überlassen, gleich sind die Kleider voll Ameisen, und die zärtlichste Empfindung in einer Laube wird oft durch eine herabfahrende Spinne gestört. Der Prinz hat durch seine Akademien Preise ausgesetzt, um zu erfahren, ob diesen Beschwerden, zum Besten der zärtlichen Welt, nicht abgeholfen werden könne? Es sind auch verschiedene Abhandlungen gekrönt worden; die Sache aber ist bis jetzt noch um kein Haar weiter."

The guard explains that Oronaro is too sensitive to confront nature because of a variety of hazards: morning dew, the scent of moss, mosquitoes, ants and spiders are just a few. He goes on to say that on a number of occasions the prince has offered rewards to solve these problems, but nothing has come up yet.

Afraid of nature, the self-proclaimed most nature loving man on earth refuses to go out. The quixotic problem is exposed and the sentimental idea of nature proves itself to be a fallacy. The artifice becomes the object of Oronaro's desire, instead of nature itself. This is typical for the sentimentalist view: when the subjective effect has become an end in itself, the question whether the means is real or not is no longer important.

### Ecology without nature

The fallacious belief of nature as a harmonious continuity needs to be rejected, to be able to have a proper view on ecology. To put it in stronger terms: the very idea of nature hampers the development of a sustainable ecology (Morton, 2007). What are the possible ecological strategies when neither nature nor human activity can be contained entirely? A pragmatic view can lead to sustainable development, which is necessary to obtain an environment where the world population can safely survive. A view that accepts the open, unruly, unpredictable, but above all unnatural, character of the natural environment is needed to generate solutions that incorporate the desire for biodiversity, food security, safety, economic growth and a healthy living space. New ideas are currently being pushed forward by interdisciplinary thought, combining ecology with economy, philosophy, technology and social sciences. These ideas focus on services that a system can provide, rather than conservation of system integrity. Ecosystems provide services such as the supply of clean air, clean water and fertile soil, waste processing and protection against extreme weather (Hawken et al., 1999). Instead of determining maximum stress levels a system can withstand, it might be more suitable to investigate whether systems can cope when stress is applied and whether they can still provide their services.

The traditional economic analysis of a situation where an ecosystem experiences stress only considered the harm that a stressor inflicted on a receiver. But this approach ignores the reciprocal nature of the problem (Coase, 1960). To avoid stress to a receiver, the activities leading to stress have to be restricted. These activities however provide valuable services as well, which are sacrificed when the assessment is incomplete. An example of this problem, which will be the topic of this thesis, is the effect of dredging on ecosystems. The proper question to ask is whether the dredging activity should be allowed to harm the ecosystem or the ecosystem should be allowed to harm the dredging activity. This question can only be answered when the obtained value of the dredging project is compared with the value of the damage to the ecosystem (discontinuation of services) required to execute the project. Provided that a pricing system will come into existence that works orderly, the problem can be systematically analyzed. It is then possible to decide whether the total effect is desired or not, depending on an analysis of costs and benefits. The valuation of ecosystem services and biodiversity however is complex and controversial, but substantial progress has been made in past decades (TEEB, 2010). Contingent valuation, as described by Hanemann (1994), might be a helpful tool when the market failed to set prices. A survey can be used to obtain the public's *willingness to pay*, which makes it possible to determine the economic value of the services that ecosystems provide.

In a cost-benefit analysis all effects have to be included: the cost of the damage to ecosystem attributes, the benefit of the realized project and the benefit due to (unintended) positive ecological effects of the project. The latter might be obtained by integration of ecosystem services in the value chains of businesses, which can create both major cost savings and extra revenues (e.g. *Building with Nature*). Quantification of costs and benefits can be a problem due to lack of information, great uncertainty or situations characterized by non-marginal change, leading to *tipping points*. Ecological policy decisions therefore have to be carefully prepared and uncertainties have to be treated explicitly. This applies to all stakeholders, including inter-governmental and other international bodies, national governments, local and regional authorities, business, civil society organizations and the scientific community.

## 1.2 Thesis

### 1.2.1 Objective

Nowadays, dredging projects are usually managed based on the precautionary principle. A widely publicized definition is the Wingspread Declaration, from a meeting of environmentalists in 1998: "When an activity raises threats of harm to the environment or human health, precautionary measures should be taken even if some cause and effect relationships are not fully established scientifically". This principle however is vague and incorrect, since it does not take into account the benefits of the activity. It is non-economic and thus often paralyzing, tends to obstruct the development of regulation and, most serious of all, offers no guidance: it forbids all courses of action, including inaction (Sunstein, 2003). It provides help only when many aspects of risk-related situations are discarded and a narrow subset is focused on.

The general approach that is currently applied in the dredging industry consists of a prediction of suspended sediment levels, which have to be compared to thresholds set by the client. Failing to comply may cause a project to be delayed and thus lead to additional costs. It is therefore considered important to predict the increase in sediment concentration as a result of dredging and take precautionary action regarding design and execution method. A lot of uncertainties are involved in this procedure. As a result, several conservative assumptions are applied leading to predictions in a worst case scenario. This method guarantees compliance to environmental criteria, but leads to undesirably high cost. If the influence of uncertainty on suspended sediment levels would be clarified, conservative assumptions do not have to be applied.

However, even if the influence of uncertainty is clarified, another significant problem remains. The environmental criteria are rigid, often quite arbitrary and fail to link the dredging activity to ecological effects for a sensitive receiver (key ecosystem attribute) in an effective way. To be able to avoid the more serious harm, to either the ecosystem or the dredging project, methods to estimate risk, necessary to quantify the costs of damage, have to be developed. This can be done within the framework of an Ecological Risk Assessment (ERA). EPA (1998) defines this as follows: "Ecological risk assessment is a process that evaluates the likelihood that adverse ecological effects may occur or are occurring as a result of exposure to one or more stressors." This leads to the following objective for this thesis:

> **Development of a risk-based approach to assess the effects of dredge plumes on sensitive receivers**

#### Research questions

Questions that follow from the research objective are:

I How can receiver sensitivity to stresses be quantified?

II How can stresses be quantified?

III How can risk be quantified, taking into account the role of uncertainty?

IV How can a risk-based approach be applied to current dredging practice?

| Term | Description |
| --- | --- |
| Dose | Total amount of an agent administered to, taken up by, or absorbed by an organism, system, or (sub)population. |
| Dose-response relationship | Relationship between the amount of an agent administered to, taken up by, or absorbed by an organism, system, or (sub)population and the change developed in that organism, system, or (sub)population in reaction to the agent. |
| Effect | Change in the state or dynamics of an organism, system, or (sub)population caused by the exposure to an agent. |
| Exposure | Concentration or amount of a particular agent that reaches a target organism, system, or (sub)population in a specific frequency for a defined duration. |
| Hazard | Inherent property of an agent or situation having the potential to cause adverse effects when an organism, system, or (sub)population is exposed to that agent. |

Table 1.1: Key generic terms in an Ecological Risk Assessment (ERA) and their definitions (WHO, 2004)

### 1.2.2 Approach

The Ecological Risk Assessment (ERA) provides a suitable framework to approach the problem. To understand the ERA properly, it is necessary to define certain important terms. Whereas in practice some of the terms are used interchangeably, they will be used in this thesis as defined in Table 1.1. An ERA consists of the following steps (CUR, 1997):

1. System description
2. Hazard identification
3. Effects assessment
4. Exposure assessment
5. Risk characterization
6. Evaluation

From a high level perspective, the system includes the dredging activity, sensitive receivers in its vicinity, their respective functions and related processes. This system can then be divided into subsystems or components. There are several types of sensitive receivers, each with their own features and failure modes. There are large communities of flora and fauna, individual organisms, attributes that are very important to the food chain, stronger and weaker attributes etc. A number of hazards is present in the aquatic environment where dredging takes place, such as anchoring, oil spills, underwater sound and dredge plumes. As discussed in the previous paragraphs, the hazard analyzed in this thesis is the suspended sediment plume. This hazard can be divided into an increase in turbidity, leading to a reduction in light penetration, an increase in suspended sediment concentration and an increase in sedimentation rate (Doorn-Groen and Foster, 2007).

The responses to these stresses are different for each type of sensitive receiver and depend on several parameters, such as exposure duration and exposure intensity. A useful tool to analyze this interaction is a dose-response curve, which represents the resistance of the species. This curve depicts response as a function of exposure duration and intensity. It is a suitable way to assess the ecological effects of an increased suspended sediment concentration. The dose-response curve can be interpreted as the 'strength' of the sensitive receiver, which is a common feature in engineering problems of the same nature.

The starting-point of the exposure assessment is an overview of the state of the art regarding system description and formulation of the dredge plume source term. This term can be formulated either as a stationary source such as an outflow from a dredge material deposit or settlement basin or as a (semi-)moving source such as hoppers, cutters, backhoes etc. Subsequently, the source term has to be included in a hydrodynamic and transport model, such as Delft3D. *OpenEarth*, an open source data and knowledge platform, provides tools to do this (Van Koningsveld et al., 2010). The Dredge Plume toolbox in DelftDashboard, a pre-processing tool coupled with Delft3D, can be used to include a dredge plume source term in the hydrodynamic model. The spatial and temporal distribution of the dredge plume in the area of interest can then be calculated. The dose, possibly consisting of several components, with which a sensitive receiver is exposed can be interpreted as the 'load', which enables a comparison with the receiver's strength.

The results of the plume modeling exercise and the obtained dose-response curves have to be brought together to be able to carry out a risk characterization. There are several methods to do this. One method is to estimate one representative value for exposure and compare this with one representative dose-response relationship; another one is to incorporate variability in exposure and effects estimates. It depends on the application which one is more suitable. In either situation, uncertainties have to be analyzed to yield an estimate of risk. In a deterministic analysis conservative assumptions are applied to solve the problem of uncertainty. In a probabilistic analysis on the other hand, uncertainties are treated explicitly. Model parameters are represented by stochastic variables, which enables applying the Monte Carlo method. This is true for both plume modeling and response data analysis. The input parameters for the hydrodynamic and transport model are drawn from an a-priori specified distribution. After processing the results from these simulations, distributions for suspended sediment concentrations at relevant locations (i.e. sensitive receivers) can be developed. This exposure distribution can be translated into a combination of duration and intensity. The dose-response curves are fitted based on existing data sets. Fitting parameters are stochastic variables, which represent the uncertain nature of the sensitive receiver's response and the lack of sufficient data. A probabilistic analysis provides insight in the elements which introduce uncertainty and which have the greatest influence on the results. In addition, it enables the determination of a 'failure probability'. This provides confidence levels for the obtained results and points to gaps in knowledge. In general, insight in probabilities is assumed to enable a better risk assessment.

Different situations require different techniques to estimate risk. In the early stages of the decision making process, where a cost-benefit analysis is carried out to determine whe-

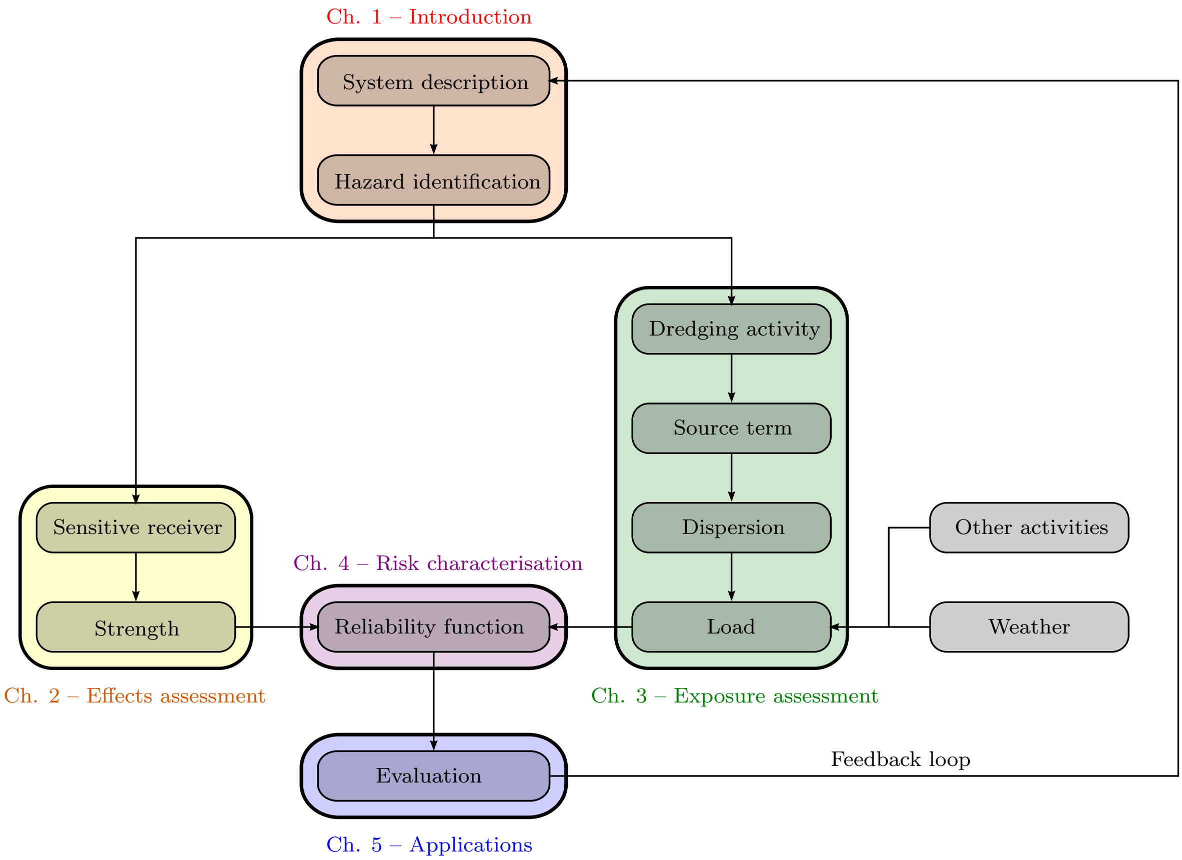


Figure 1.1: Organization of the thesis. The Ecological Risk Assessment (ERA) is used as a framework.

ther a dredging project is economically feasible, a probabilistic analysis is the most suitable method. In the design and planning phase of dredging works a probabilistic analysis still seems the preferred option, to identify gaps in knowledge and accordingly possible new areas of investigation or research. On the other hand, when dredging works are already in progress, a deterministic analysis satisfies the desire for a quick assessment of the risks. Execution methods can in that stage still be changed and mitigation measures might still be implemented. In addition, it might be used to support the development of a monitoring strategy.

### 1.2.3 Scope

The thesis is organized as follows (see Figure 1.1): Chapter 2 explains what a sensitive receiver is and defines the conditions that allow ecological effects to occur. Dose-response curves are introduced. Chapter 3 provides a procedure to formulate source terms and introduces the hydrodynamic and transport model to predict plume dispersion. The conditions resulting from a dredging project are quantified in terms of suspended sediment concentration and exposure duration. In Chapter 4 a risk characterization is carried out, which includes an assessment of uncertainties involved in the entire process. Chapter 5 indicates fields of application for the different risk estimation techniques. Finally, in Chapter 6, the main conclusions are formulated and recommendations are provided.

# Chapter 2

# Effects assessment

The term 'sensitive receiver', or 'receptor of concern', usually means flora or fauna to which ecological risks are posed (Bray, 2008). Examples of sensitive receivers in the aquatic environment include coral reefs, kelp forests, fish, benthos (bottom-dwelling organisms), sea grass beds etc. In this chapter, the effects of an increased suspended sediment concentration on sensitive receivers will be discussed. Effects on populations in aquatic ecosystems will be the focus, but the methods can be extended to include several other receiver types, such as drinking water production facilities or power plant water inlets. It is important to describe the effects in such a way, that it is possible to evaluate the suspended sediment conditions associated with dredging projects. Typically, the effects are expressed in dose-response curves obtained from experimental tests in the laboratory or measurements in the field. In the next paragraphs, the effects are identified and evaluation methods are described.

## 2.1 Aquatic ecosystems

The primary effects of suspended sediment plumes are increased suspended sediment concentration, increased turbidity and increased sedimentation rate. These include effects on seabed communities and juvenile and adult fish and disruption of designated habitats/species. Furthermore, there are effects on estuarine and shallow littoral benthic (bottom-dwelling) communities, effects on fish migration, effects on shell fisheries, effects on sedimentology etc. An increased sediment concentration will lead to a reduced oxygen availability, since anoxic material utilizes oxygen. Increased turbidity results in a reduced light penetration and possibly reduced photosynthesis, when the rate of respiration exceeds the rate of photosynthesis. This typically occurs for water column communities, such as phytoplankton, benthic communities and algae. The deepest point where photosynthesis is still possible (the compensation depth), which is a function of light penetration, might change due to the turbidity level. When the compensation depth is raised from below bottom level to above, problems will arise. Increased sedimentation rate is especially important for corals, which are vulnerable due to a limited ability to survive high rates of settling of suspended particles.

An important consideration in assessing the effects of plumes is the type of biological community that occurs in the environment subject to dredging (John et al., 2000). Communities that typically occur involve opportunistic communities (r-strategists), competitive communities (K-strategists) and intermediate communities (r- and K-strategists). R-strategists exist in dynamic estuarine and littoral habitats, which requires them to be adapted to conditions characterized by rapid change. They do this by means of high genetic variability, which allows a selection of the community to survive extreme events. When a community is destroyed, they colonize new habitats quickly, relying on a large reproductive effort. K-strategists exist in stable environments and therefore have to have a large competitive ability. A larger part of resources is invested in growth and predator avoidance, which leads to a slow recovery after destructive events. R-strategists evolving to K-strategist exist in recovering habitats, where characteristics of both extremes are combined in a weaker form. Depending on the prevailing conditions, effects of plumes can be very different.

### 2.1.1 Natural variation

It is important to understand that 'natural', yearly variation in population size can be significant. To be able to account for this variation, an assessment of existing water quality, biological communities, substratum, fisheries and shell fisheries resources has to be carried out. Effects due to storms, fishing and shipping operation increase this variation, which leads to complex assessment and which makes it difficult to give reliable predictions. In addition, the effects due to dredging operation affect the variation, leading to an even more complex situation. To be able to do an effects assessment however, background variation has to be determined as accurately as possible.

The most significant effect on aquatic ecosystems due to dredging is the direct local removal of substratum and associated species, communities and habitats (Van Moorsel and Waardenburg, 1990). Other effects, e.g. due to suspended sediment plumes, are somewhat less obvious. Concern especially increases where plumes occur in waters that are normally relatively clear, where species require light penetration at depth or relatively sediment-free water in order to filter feed efficiently (John et al., 2000). This assumption is confirmed by field data from the Bristol Channel, where a high background turbidity is present and dredging induced turbidity had a limited effect (Gibb Wales, 1997).

### 2.1.2 Indirect effects and time dependence

For a proper determination of ecological effects, indirect effects have to be assessed as well. Newell et al. (1998) describe the loss of key species in certain communities, such as *Sabellaria spp.*, which can lead to the collapse of the entire biologically-accommodated community. Likelihood and significance of these effects are very important since there are many possible ways in which such interactions might occur. Time can have a large influence on ecological response as well. An important aspect in this respect is the ability of a sensitive receiver to recover from damage that has been incurred during exposure. The earlier made distinction between r-strategists and K-strategists gives an indication whether or not a species has the ability to recover from exposure to a hazard and how fast it can do so. To describe time dependence, certain statistical processes can be used, such as Markov processes or Poisson processes (CUR, 1997). This thesis will include the analysis of neither indirect effects nor the effects as a function of time. It is however possible to develop multiple dose-response relationships and therefore to make a distinction between species and their respective recovery characteristics.

### 2.1.3 Ecotoxicology

Ecotoxicology is the field that studies the effects of toxic chemicals on populations, communities and terrestrial, freshwater and marine ecosystems. Even though suspended sediment does not at all qualify as a toxic chemical, a lot of similarities can be found. The most important similarity is that suspended sediment has the ability to damage a sensitive receiver when the exposure is severe enough. In spite of the fact that relatively few studies have been carried out in an ecotoxicological way, i.e. field experimentation on the whole ecosystem, the response of biological systems to subtle perturbations is increasingly understood by scientists (Villeneuve and Garcia-Reyero, 2011). Ecological risk assessment can benefit greatly from the increased capacity of biological research to analyze, integrate and model complex data.

## 2.2 Dose-response relationships

A 'toxicant' is defined as "an agent that can produce a significant adverse response (effect) in a biological system, causing damage to its structure and function or, in extreme cases, death" (Connel et al., 1999). In general, the dose with which a receiver is exposed to a toxicant is assumed to be related to the biological effect. To make an assessment of the toxicity of a material for a sensitive receiver, clearly defined and measurable effects, or *endpoints*, must be formulated. An endpoint is the directly measured whole-organism outcome of exposure, generally death, reproductive failure or developmental dysfunction. Mortality, or survival, is an example of such an effect and is easy to interpret. Tests to determine the effects of exposure have to be carried out in a systematical way. For tests on organisms, usually a group is exposed to several doses of the relevant material for a fixed period of time, after which the number of dead organisms is determined. A cumulative dose-response curve can be fitted manually as a result (see Figure 2.1). The $LC_{50}$ is defined as the concentration at which there is 50% mortality of the organisms. It is possible to estimate this value by reading it off the graph, but it is more useful to mathematically describe the dose-response curve.

As mentioned in Subsection 1.2.2, biological response does not only depend on suspended sediment concentration or turbidity level, but also on exposure duration. Also, additional response categories have to be defined, which include endpoints such as reproductive failure, developmental dysfunction and nil effect. The dose-response relationship should properly represent these notions.

### 2.2.1 Probit and logit models

A method that is commonly used in toxicology to describe dose-response relationships is the *probit model*, which has been described in detail by Finney (1971). Others however, such as Berkson (1951), prefer the *logit model*. The basis of these methods is the assumption that the response, plotted against dose, has the shape of a cumulative normal or logistic distribution respectively. The similarity between these models is that they both describe variables with a restricted domain of possible outcomes. When only two outcomes are possible, the dependent variable is called 'binary'. The Bernoulli distribution describes a binary variable, where $\Pr(y = 1) = \pi$ (note: not the number $\pi = 3.14$) and $\Pr(y = 0) = 1 - \pi$. The probability $\pi$ however can differ among individual situations, which requires another probability model. The probit and logit models are very suitable due to the binomial response of receivers

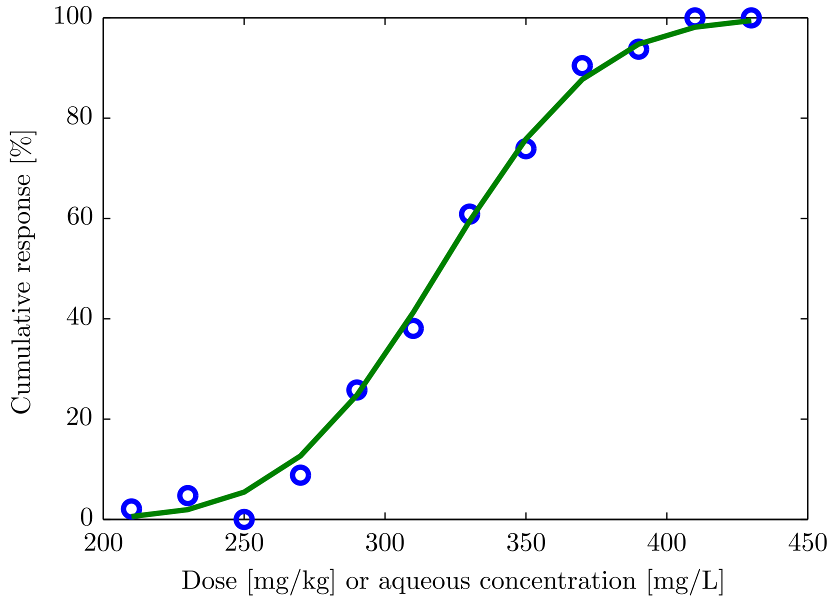


Figure 2.1: Manually fitted cumulative dose-response curve, which is the result of a lethality experiment. Data points are indicated as circles. The curve can be interpreted as the empirical distribution function of the resistance of the sensitive receiver.

(survival/mortality) and the sigmoidal shape of the dose-response curve. The methods are discussed in more detail together with their respective advantages and disadvantages.

In a linear probability model, the binary dependent variable is described as follows:

$$y_i = x_i'\beta + \varepsilon_i = \beta_1 + \sum_{j=2}^{k} \beta_j x_{ji} + \varepsilon_i, \quad \mathrm{E}(\varepsilon_i) = 0, \tag{2.1}$$

where the $k \times 1$ vector $x_i$ represents the explanatory variables for individual $i$. Since $y_i$ can only take on the values 1 or 0, this means that $x_i'\beta = \mathrm{E}(y_i) = 0 \cdot \Pr(y_i = 0) + 1 \cdot \Pr(y_i = 1)$. As a result,

$$\pi_i = \mathrm{E}(y_i) = x_i'\beta, \tag{2.2}$$

where $\pi_i \equiv \Pr(y_i) \equiv \Pr(y_i = 1) \equiv \Pr(y_i = 1 \mid x_i)$. In case of a binomial dose-response relationship, the response $y_i$ is either survival ($y_i = 0$) or mortality ($y_i = 1$), where $x_i$ is the dose or concentration. The linear probability model is not applicable due to several shortcomings. It is not constrained to the unit interval and the error terms $\varepsilon_i$ are not normally distributed. A cumulative distribution function (CDF) can be applied to do the necessary translation from the linear predictor $x_i'\beta$ to a more suitable one:

$$\pi_i = F(x_i'\beta), \tag{2.3}$$

where $F$ is the selected CDF and $\beta$ is the parameter vector to be estimated. If $F$ is strictly non-decreasing, this can be rewritten into:

$$F^{-1}(\pi_i) = x_i'\beta, \tag{2.4}$$

where $F^{-1}$ is the inverse of the CDF $F$. For the model in Equation 2.3, often the standard normal density function:

$$f(t) = \phi(t) = \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}t^2} \tag{2.5}$$

or the standard logistic density function:

$$f(t) = \lambda(t) = \frac{e^t}{(1+e^t)^2} \tag{2.6}$$

are chosen. The former leads to the linear probit model, the latter to the linear logit model. The CDF of the normal distribution nor its inverse are available in closed form, so approximations for the integral:

$$\Phi(t) = \int_{-\infty}^{t} \phi(s)\mathrm{d}s = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{t} e^{-\frac{1}{2}s^2}\mathrm{d}s \tag{2.7}$$

are necessary. An advantage of the logit model is that the CDF can be computed explicitly:

$$\Lambda(t) = \int_{-\infty}^{t} \lambda(s)\mathrm{d}s = \frac{e^t}{1+e^t} = \frac{1}{1+e^{-t}}. \tag{2.8}$$

It is often informative to define the relative preference of option 1 as compared to option 0, which is called the 'odds ratio':

$$\frac{\Pr(y_i = 1)}{\Pr(y_i = 0)} = \frac{F(x_i'\beta)}{1 - F(x_i'\beta)}. \tag{2.9}$$

Another advantage of the logit model is that the natural logarithm of the odds ratio, the 'log-odds', is a linear function of the explanatory variables:

$$\log\left(\frac{\Lambda(x_i'\beta)}{1-\Lambda(x_i'\beta)}\right) = x_i'\beta, \tag{2.10}$$

because $\Lambda(t) = e^t/(1+e^t)$ and $1 - \Lambda(t) = 1/(1+e^t)$, so that $\Lambda(t)/(1-\Lambda(t)) = e^t$.

The parameters of the non-linear probit and logit models can be estimated by Maximum Likelihood (Heij et al., 2004). Variable $y_i$ follows a Bernoulli distribution with the probability on outcome $y_i = 1$ as specified in Equation 2.3 and $1 - \pi_i$ on outcome $y_i = 0$, or $\pi(y_i) = \pi_i^{y_i}(1-\pi_i)^{1-y_i}$, $y_i = 0,\ 1$. As a result, the log-likelihood is given by:

$$\begin{aligned}
\log(L(\beta)) &= \sum_{i=1}^{n} y_i \log(\pi_i) + \sum_{i=1}^{n} (1-y_i)\log(1-\pi_i) \\
&= \sum_{i=1}^{n} y_i \log(F(x_i'\beta)) + \sum_{i=1}^{n} (1-y_i)\log(1-F(x_i'\beta)) \\
&= \sum_{\{i;\ y_i=1\}} \log(F(x_i'\beta)) + \sum_{\{i;\ y_i=1\}} \log(1-F(x_i'\beta)). \qquad (2.11)
\end{aligned}$$

The parameter estimation is done by maximization of the log-likelihood, i.e. solving the first order conditions, where $f(t)$ is the derivative of the CDF $F(t)$:

$$g(\beta) = \frac{\partial \log(L)}{\partial \beta} = \sum_{i=1}^{n} \frac{y_i}{\pi_i} \frac{\partial \pi_i}{\partial \beta} + \sum_{i=1}^{n} \frac{(1-y_i)}{1-\pi_i} \frac{\partial (1-\pi_i)}{\partial \beta}$$
$$= \sum_{i=1}^{n} \frac{y_i}{\pi_i} f_i x_i - \sum_{i=1}^{n} \frac{(1-y_i)}{1-\pi_i} f_i x_i = \sum_{i=1}^{n} \frac{(y_i - \pi_i)}{\pi_i(1-\pi_i)} f_i x_i = 0, \quad (2.12)$$

where $f_i = f(x_i'\beta)$, corresponding to the CDF $F$. The non-linear equations $g(\beta) = 0$ have to be solved numerically to estimate $\beta$. For the logit model, where $F = \Lambda$, the expression for the gradient (see Equation 2.12) simplifies, because:

$$\lambda_i = \frac{e^{x_i'\beta}}{(1+e^{x_i'\beta})^2} = \frac{e^{x_i'\beta}}{1+e^{x_i'\beta}} \left(1 - \frac{e^{x_i'\beta}}{1+e^{x_i'\beta}}\right) = \Lambda_i(1-\Lambda_i), \quad (2.13)$$

so that $f_i = \pi_i(1-\pi_i)$. The logit parameters are then estimated with:

$$g(\beta) = \sum_{i=1}^{n} (y_i - \pi_i) x_i = \sum_{i=1}^{n} \left(y_i - \frac{1}{1+e^{-x_i'\beta}}\right) x_i = 0. \quad (2.14)$$

To obtain a measure for the goodness of fit, the model can be tested by the $LR$-test on the null hypothesis that all coefficients (except the constant term) are zero. This test can be used for the probit model as well as for the logit model. The test follows asymptotically a $\chi^2(k-1)$ distribution, where $k$ is the length of $\beta$.

### 2.2.2 Ordered response models

Previously, the dependent variable had two possible outcomes: survival or mortality. When it is more suitable to define a finite number of possible outcomes larger than two, the data are called 'multinomial'. Biological effects of suspended sediment or turbidity may already be significant before the first organism dies. It would be useful to also be able to include a reduced growth rate, reduced organism density or habitat damage in the ERA. Newcombe and Jensen (1996) have studied 80 published reports on fish responses to suspended sediment in streams and estuaries. Data triplets were collected consisting of suspended sediment concentration, duration of exposure and severity of ill effect (SEV) for fishes. The SEV was scored along a semi-quantitative ranking scale, as shown in Table 2.1. Between 1 and 15, or no effect and 100% mortality, the SEV represents proportional differences in true effects. The data set which has been presented in their study will serve as an example in the remainder of this chapter.

A suitable model to relate the SEV to suspended sediment concentration and exposure duration, is the ordered response model. The severity of ill effect is an 'ordinal' variable, since its outcomes are ordered. The ordered alternatives are ranging from 1 to $m$ (here: $m = 15$), but numerical values have no explicit meaning. The outcome $y_i$ is not used directly, but related to an index function:

$$y_i^* = x_i'\beta + \varepsilon_i, \quad \mathrm{E}(\varepsilon_i) = 0. \quad (2.15)$$

| SEV | Description of effect |
|---|---|
| | **Nil effect** |
| 1 | No behavioral effects |
| | **Behavioral effects** |
| 2 | Alarm reaction |
| 3 | Abandonment of cover |
| 4 | Avoidance response |
| | **Sublethal effects** |
| 5 | Short-term reduction in feeding rates |
| | Short-term reduction in feeding success |
| 6 | Minor physiological stress |
| | Increase in rate of coughing |
| | Increased respiration rate |
| 7 | Moderated physiological stress |
| 8 | Moderate habitat degradation |
| | Impaired homing |
| 9 | Indication of major physiological stress |
| | Long-term reduction in feeding rate |
| | Long-term reduction in feeding success |
| | Poor condition |
| | **Lethal and paralethal effects** |
| 10 | Reduced growth rate |
| | Delayed hatching |
| | Reduced fish density |
| 11 | 0 – 20% mortality |
| | Increased predation |
| | Moderate to severe habitat degradation |
| 12 | > 20 – 40% mortality |
| 13 | > 40 – 60% mortality |
| 14 | > 60 – 80% mortality |
| 15 | > 80 – 100% mortality |

Table 2.1: Scale of the severity of ill effect (SEV) associated with excess suspended sediment (Newcombe and Jensen, 1996)

The outcome $y_i$ is the observed variable and is related to the index function by $(m-1)$ threshold values $\tau_1 < \tau_2 < \cdots < \tau_{m-1}$ in the following way:

$$\begin{aligned} y_i &= 1 \quad \text{if} \quad -\infty < y_i^* \leq \tau_1, \\ y_i &= j \quad \text{if} \quad \tau_{j-1} < y_i^* \leq \tau_j,\ j = 2, \ldots, m-1, \\ y_i &= m \quad \text{if} \quad \tau_{m-1} < y_i^* < \infty. \end{aligned} \tag{2.16}$$

When $F$ is the CDF of $\varepsilon_i$, then:

$$\begin{aligned} \pi_{ij} = \Pr(y_i = j) = \Pr(\tau_{j-1} < y_i^* \leq \tau_j) &= \Pr(y_i^* \leq \tau_j) - \Pr(y_i^* \leq \tau_{j-1}) \\ &= F(\tau_j - x_i'\beta) - F(\tau_{j-1} - x_i'\beta), \quad j = 1, \ldots, m, \end{aligned} \tag{2.17}$$

where, only here, $\tau_0 = -\infty$ and $\tau_m = \infty$. The parameters that have to be estimated are $\beta$ and the $(m-1)$ threshold values. The explanatory variable $x_i$ should not contain a constant term, otherwise the threshold parameters are not identified. Estimation can be done by Maximum Likelihood. The log-likelihood is:

$$\log(L(\beta, \tau_1, \ldots, \tau_{m-1})) = \sum_{i=1}^{n} \sum_{j=1}^{m} y_{ij} \log(\pi_{ij}) = \sum_{i=1}^{n} \log(\pi_{iy_i}), \tag{2.18}$$

where $y_{ij} = 1$ if $y_i = 1$ and $y_{ij} = 0$ if $y_i \neq 1$. For the CDF $F$, again the normal or logistic distribution are often used, yielding the *ordered probit* and *proportional odds* model respectively. Joint significance of explanatory variables can be tested by the $LR$-test with hypothesis $\beta = 0$. Quality of predictions is generally analyzed with a classification table and subsequent hit rate.

## 2.3 Dose-response curves

The development of dose-response curves is explained using a selection of the data from Newcombe and Jensen (1996, pp. 720 – 724). Data of 80 studies, resulting in $n = 171$ data triplets, on the effects of suspended sediment (particle sizes 0.5 – 250 $\mu m$) on juvenile and adult salmonids, specifying severity of ill effect, suspended sediment concentration and exposure duration, are re-fitted with an ordered probit model, as described in Equation 2.15:

$$\text{SEV}_i^* = \beta_1 \log(C_i) + \beta_2 \log(T_i) + \varepsilon_i, \quad i = 1, \ldots, 171, \tag{2.19}$$

where $C_i$ is the suspended sediment concentration in $mg/L$ of sample $i$ and $T_i$ is the exposure duration in $h$ of sample $i$. Instead of the original fifteen, the number of categories is set to three ($m = 3$): behavioral effects, sublethal effects and lethal and paralethal effects. None of the data points showed a nil effect, so this category is discarded. In Subsection 2.3.1, an alternative method to obtain data specifying a nil effect will be presented. A scatter plot of the data on the grouped SEV scale is shown in Figure 2.2. The data are fitted with an ordered probit model using Maximum Likelihood, with regression parameters as depicted in Table 2.2. The cumulative probabilities are shown in Figure 2.3, which are estimated with the following equation:

$$\Pr(\text{SEV} \leq j) = \Phi(\hat{\tau}_j - x'\hat{\beta}), \tag{2.20}$$

| Variable | Coefficient | Std. error | t-statistic | P-value |
|---|---|---|---|---|
| $\hat{\beta}_1$ | 0.2066 | 0.0414 | 4.9878 | 0.0000 |
| $\hat{\beta}_2$ | 0.2495 | 0.0393 | 6.3490 | 0.0000 |
| $\hat{\tau}_1$ | 0.6203 | 0.3066 | NA | NA |
| $\hat{\tau}_2$ | 2.5393 | 0.3791 | NA | NA |

Table 2.2: Fitting parameters for the ordered probit model after Maximum Likelihood Estimation.

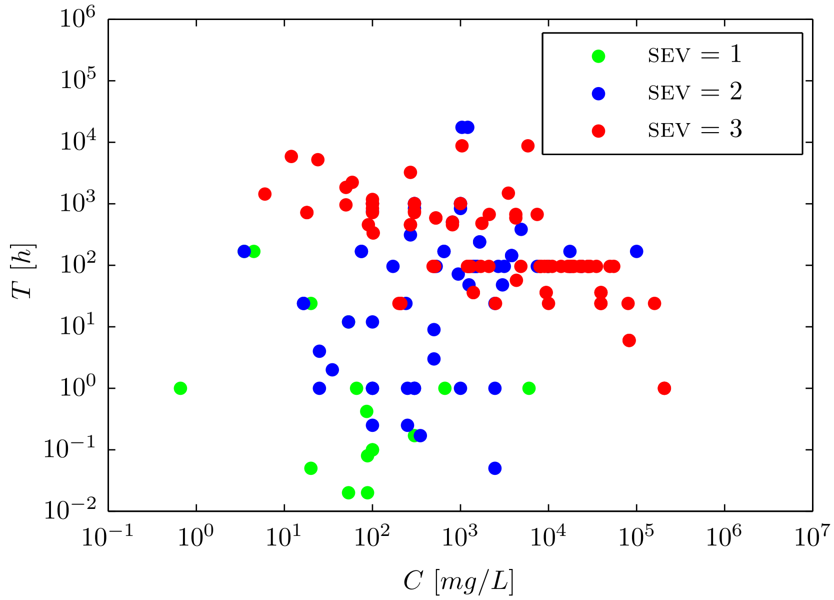


Figure 2.2: Scatter plot on a log-log scale with severity of ill effect (SEV) as a function of suspended sediment concentration $C$ and exposure duration $T$. SEV $= 1$ leads to behavioral effects, SEV $= 2$ to sublethal effects and SEV $= 3$ to lethal and paralethal effects

where $x_1 = \log(C)$, $x_2 = \log(T)$, $\hat{\tau}_j$ is the estimate for the $j$th threshold value and $\hat{\beta}$ is the estimate for the parameter vector $\beta$ in the probit or logit model. A special case arises when $j = m$, since $\Pr(\text{SEV} \leq m) = 1$ for every value of $x'\hat{\beta}$. The critical value of $x'\hat{\beta}$ can be interpreted as the strength and will therefore be referred to as $R = (x'\hat{\beta})_{crit}$.

### 2.3.1 Nil effect

As mentioned in the previous paragraph, the data from Newcombe and Jensen (1996) do not show any 'nil effect', i.e. there is an effect in every situation. To determine a threshold for behavioral effects however, there need to be data showing a nil effect as well. A method to obtain these data is described by McArthur et al. (2002), although the article proposes a completely different approach to formulate dredging guidelines. Measurements of suspended sediment concentration over a period of several months or even years before dredging activities commence give insight in naturally occurring levels, during which the ecosystem attributes

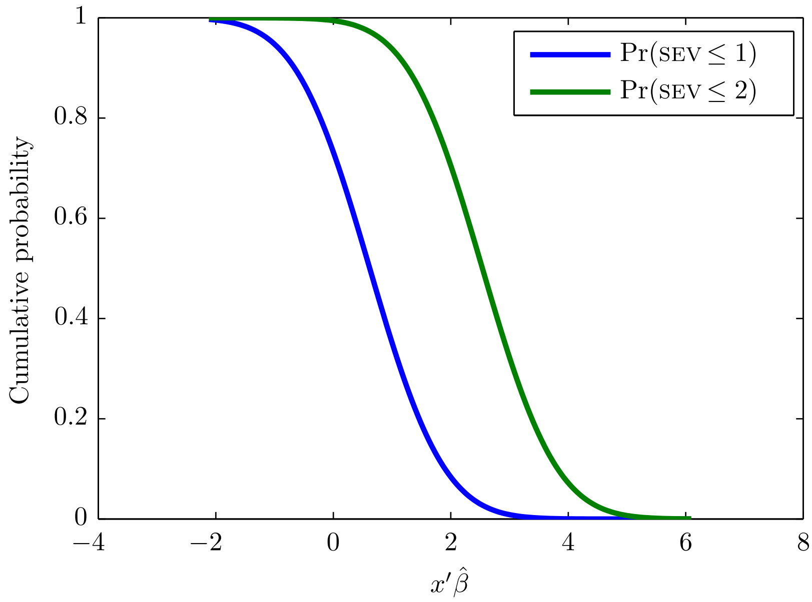


Figure 2.3: Dose-response curves. An ordered probit model is fitted using Maximum Likelihood. The cumulative probabilities $\Pr(\text{SEV} \leq j)$ are plotted as a function of $x'\hat{\beta}$, where $x_1 = \log(C)$, $x_2 = \log(T)$ and $\hat{\beta}$ as specified in Table 2.2. The probability $\Pr(\text{SEV} \leq 3)$ is 1 for every value of $x'\hat{\beta}$

under consideration (in their case coral) are supposed to be able to survive. Occasional high concentration levels, occurring for example during extreme storm events, can be tolerated by species that are adapted to the natural variation. The results from the measurements can be used as a background situation as well as to provide data points for the category 'nil effect'.

### 2.3.2 Haber's rule

In the early 1900s Fritz Haber studied the lethality of war gases by assessing the concentration in the air and the time an animal had to breathe the air before death ensued. He developed the concept that the product of the concentration of a substance and the duration with which it is administered produces a fixed level of effect for a given endpoint. The concept is since then referred to as 'Haber's rule':

$$C \times T = k, \tag{2.21}$$

where $k$ is a constant. When logarithmically transformed, the hyperbolic Equation 2.21 becomes linear. The data in Figure 2.2 allow very well a fit according to Haber's rule. Miller et al. (2000) explain that Haber's rule is a special case in a family of power law curves, which relate concentration and exposure duration to a fixed level of response for a given biological endpoint. An exponent on either $C$ or $T$, depending on the type of response, results in a power function. The relative importance of $C$ and $T$ is examined by raising both to a power, leading to the more general power law:

$$C^{\beta_1}\ T^{\beta_2} = k. \tag{2.22}$$

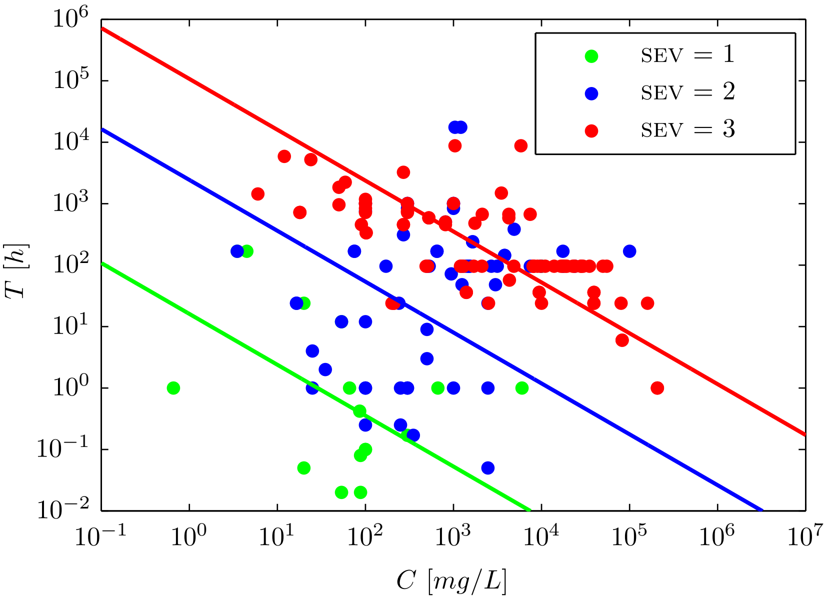


Figure 2.4: Graphical representation of Haber's rule. The regression lines are realizations of a family of power law curves, which relate concentration and exposure duration to a fixed level of response for a given biological endpoint.

The probit model presented in Equation 2.19 is a member of this power law family, when it is rewritten into:

$$e^{\mathrm{SEV}_i^*} = k^* = C_i^{\beta_1}\ T_i^{\beta_2}. \tag{2.23}$$

The result is shown in Figure 2.4. According to Ten Berge et al. (1986), Haber's rule means that regression coefficients $\beta_1$ and $\beta_2$ should be about equal. Table 2.2 shows that this is in fact the case. To illustrate the importance of the ratio of $\beta_1$ to $\beta_2$, they rewrite the probit model into:

$$\mathrm{SEV}_i^* = \beta_2 \log(C_i^n\ T_i), \tag{2.24}$$

where $n = \frac{\beta_1}{\beta_2}$. The term $C_i^n$ can be considered as a 'dose factor' and may be expressed in the following form:

$$\int_0^T [C_i(t)]^n \mathrm{d}t, \tag{2.25}$$

where $C_i(t)$ is the concentration as function of time during exposure. The data from Newcombe and Jensen (1996) apparently obey Haber's rule, which is reflected in the regression coefficients being about equal. In other situations, when the coefficients are not equal, the broader family of power law curves and hence the probit model can still be used effectively.

# Chapter 3

# Exposure assessment

## 3.1 Source term formulation

In Appendix A dredge plumes and their characteristics, the sources of plumes and the dynamics that are involved in the dispersion process are discussed. As can be read in Section A.2, a dredge plume resulting from TSHD overflow has a dynamic and a passive phase. The dynamic phase is difficult to understand due to several complicated and interacting processes (De Wit, 2010). Quantification is particularly difficult. Entrainment of ambient water into the plume, interaction of the plume with the cross flow due to currents and TSHD trailing speed, entrainment of air in the overflow mixture, mixing by propellers of the TSHD and influences resulting from flow around the hull are the most significant processes. These processes compromise a proper understanding of the near-field effects, which makes the determination of the source term a complex problem. The amount of fine sediment entering the environment is therefore hard to predict. Estimates based on field measurements seem to be more promising compared to detailed modeling of all relevant processes. As a result, the most suitable method is to formulate a source term for the passive phase of the plume. The passive plume is less complex, since advection and diffusion are processes that are well understood.

### 3.1.1 Methods

John et al. (2000) determine four ways to represent a dredge plume source term:

1. Sediment concentration increases in the vicinity of the dredging activity ($mg/L$)
2. Rate of release of sediment into the water column per unit of time ($kg/s$)
3. 'S'-factor approach, in which the total mass of sediment put into suspension is expressed relative to the quantity of material that is dredged ($kg/m^3$)
4. Sediment flux method, which describes the sediment loss through the boundaries of a designated area within which the dredger is working

The weakness of method 1 is that it is site specific and therefore not suitable for applications with a universal scope (Van Eekelen, 2007). The second method is more promising, since release rate can be used as a source term (Whiteside et al., 1995). The way in which the term is formulated is still a problem however, because material type and the corresponding near-field behavior have to be included somehow. Method 3 is proposed by Pennekamp et al. (1996), where he refers to the S-parameter. The S-factor depends on soil class, type of dredger and the ambient conditions (and the way in which the dredging technique is used). The S-factor approach has the advantage that (as a first estimate) for similar methods the known factors can be reused. The fourth method has been applied in the Øresund link project, but the method is a measuring method rather than a sediment resuspension description. A very extensive measuring setup is indispensable.

A combination of methods 2 and 3 seems to be the most appropriate for this thesis, although the formulation of the source term will still be complex. Method 2 is often used in plume modeling, but normally the dynamic plume phase is not taken into account. The current practice for a TSHD for example is as follows: samples are taken from the hopper near the overflow spillways. Measured concentrations are then multiplied by the overflow discharge, which is assumed to be equal to the pumping rate. The rapid settling of sediment that occurs during the dynamic plume phase is ignored, which results in higher estimates compared to a situation where measurements of the suspended solids concentration in the surrounding waters are carried out. To account for this problem, assumptions have to be made regarding sediment fractions that remain suspended and form the passive plume. In the next paragraphs the method will be outlined for several types of dredging equipment.

### 3.1.2 Trailing suction hopper dredger

To be able to quantify the dredge plume source term, several parameters need to be determined. The water-sediment mixture that is pumped into the hopper can be described by the mixture discharge, in situ concentration, dry mixture density and sediment grain size distribution. The settling process that subsequently takes place, results in an overflow mixture with different properties than the suction mixture. A certain portion of the fraction of fines, which is the main contributor to turbidity, will be retained inside the hopper. The remaining fines will be released through the overflow arrangement and result in a source term for the dynamic plume. This is a non-stationary source term, since the overflow discharge depends on hopper content. Empirical relations are available to estimate the fraction of fines in the suction mixture that will end up in the overflow mixture. The production rate $P$ of the TSHD, a mass flux, is estimated by the following equations:

$$Q_m = \frac{1}{4}\pi D^2 \cdot V_m \cdot n, \tag{3.1}$$

$$c_{situ} = \frac{\rho_m - \rho_w}{\rho_s - \rho_w}, \tag{3.2}$$

$$P_s = Q_m \cdot c_{situ}, \tag{3.3}$$

$$\rho_{m,dry} = \rho_k \cdot (1 - \frac{\rho_k - \rho_m}{\rho_k - \rho_w}), \tag{3.4}$$

$$P = \rho_{m,dry} \cdot P_s, \tag{3.5}$$

where $Q_m$ is the suction mixture flow rate, $D$ is the diameter of the suction pipe, $V_m$ is the mixture velocity, $n$ is the number of suction pipes, $c_{situ}$ is the in-situ concentration, $P_s$

is the in-situ production rate, $\rho_{m,dry}$ is the dry mixture density, $\rho_m$ is the mixture density, $\rho_w$ is the density of water, which is a function of temperature and salinity (Unesco, 1981), $\rho_s$ is the in-situ density of material and $\rho_k$ is the density of the sediment grains. To determine the dynamic plume source term $B$, this production estimate needs to be multiplied by the fraction of fines, $f_{fines}$, and the fraction discharged through the overflow, $f_{overflow}$. The dynamic plume source term reads:

$$B = P \cdot f_{fines} \cdot f_{overflow}. \tag{3.6}$$

Subsequently, it is necessary to translate this dynamic plume source term into a component of the passive plume source term. This particular component is called $x_1$. This means multiplying it by the the fraction of fine sediment in the overflow discharge, which constitutes the surface plume (see Figure A.1). This factor is referred to as $f_{dyn}$. Spearman et al. (2011) propose an empirical value of 5–15% for hoppers. In addition there are components originating from the draghead plume, erosion of the local bed by propeller jet and re-entrainment of the dynamic bed plume, $x_2$, $x_3$ and $x_4$ respectively. The passive plume source term reads:

$$x_1 = B \cdot f_{dyn}, \tag{3.7}$$

$$X = \sum_{i=1}^{4} x_i. \tag{3.8}$$

## 3.2 Plume modeling

To be able to predict suspended sediment concentrations in the area of interest, a hydrodynamic and transport simulation program is required. The source term, as formulated in the previous paragraph, has to be included in the model. A suitable program for this purpose is the open source hydrodynamic model Delft3D-FLOW. In addition the pre-processing tool DelftDashboard is used, which is related to Delft3D and available within *OpenEarth* (Van Koningsveld et al., 2010). DelftDashboard is a standalone MATLAB based graphical user interface, which facilitates a quick set up of new models. A large number of coupled toolboxes is available, which enable the use of several open source data sets. In particular the Dredge Plume toolbox within DelftDashboard allows a convenient specification of source terms for dredge plumes.

Delft3D-FLOW is a model which calculates non-steady flow and transport phenomena that result from tidal and meteorological forcing. The numerical hydrodynamic modeling system solves the unsteady shallow water equations in two (depth-averaged) or three dimensions. The system of equations consists of the horizontal equations of motion, the continuity equation and the transport equations for conservative constituents. The flow is forced by tide at the open boundaries, wind stress at the free surface, pressure gradients due to free surface gradients (barotropic) or density gradients (baroclinic). A conceptual description of Delft3D-FLOW can be found in the User Manual (Deltares, 2009). In Appendix B, some aspects are discussed in more detail. It involves the governing equations, boundary conditions, grid and numerical scheme.

### 3.2.1 Flow modeling

The 2DV (depth-averaged) non-linear shallow water equations are derived from the three dimensional Navier Stokes equations for incompressible free surface flow. Several assumptions and approximations are used, the main three being the Boussinesq approximation, the eddy viscosity concept and the assumption of shallow water. The set of partial differential equations in combination with an appropriate set of initial and boundary conditions is solved on a finite difference grid.

#### Continuity equation

The depth-averaged continuity equation is given by:

$$\frac{\partial \zeta}{\partial t} + \frac{\partial HU}{\partial x} + \frac{\partial HV}{\partial y} = 0, \tag{3.9}$$

where $H = \zeta + d$, with $\zeta$ the water level and $d$ the depth and $U$ and $V$ are depth-averaged velocities in $x$- and $y$-direction respectively.

#### Momentum equations in horizontal direction

The depth-averaged momentum equations in $x$- and $y$-direction are given by:

$$\frac{\partial U}{\partial t} + U\frac{\partial U}{\partial x} + V\frac{\partial U}{\partial y} = fV - g\frac{\partial \zeta}{\partial x} - \frac{1}{\rho_0}P_x + \frac{1}{\rho_0 H}(\tau_{sx} - \tau_{bx}) - \nu_H \nabla^2 U, \tag{3.10}$$

and

$$\frac{\partial V}{\partial t} + U\frac{\partial V}{\partial x} + V\frac{\partial V}{\partial y} = -fU - g\frac{\partial \zeta}{\partial y} - \frac{1}{\rho_0}P_y + \frac{1}{\rho_0 H}(\tau_{sy} - \tau_{by}) - \nu_H \nabla^2 V, \tag{3.11}$$

where $f$ is the Coriolis parameter, $g$ is the acceleration due to gravity, $\rho_0$ is the reference density of water, $P_x$ and $P_y$ represent the pressure gradients, $\tau_{sx}$ and $\tau_{sy}$ are the surface wind stress in the $x$- and $y$-direction, $\tau_{bx}$ and $\tau_{by}$ are bottom frictional stress in the $x$- and $y$-direction and $\nu_H$ is the horizontal eddy viscosity coefficient. The Laplace operator is defined as $\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}$. Equation 3.9, Equation 3.10 and Equation 3.11 constitute the 2D depth-averaged shallow water equations.

#### Bed boundary condition

For 2D depth-averaged flow the shear-stress at the bed induced by a turbulent flow is assumed to be given by a quadratic friction law:

$$\vec{\tau}_b = \frac{\rho_0 g \vec{U}|\vec{U}|}{C_{2D}^2}, \tag{3.12}$$

where $|\vec{U}|$ is the magnitude of the depth-averaged horizontal velocity and $C_{2D}$ is the 2D-Chézy coefficient.

**Free surface boundary condition**

At the free surface, the boundary conditions for the momentum equations require a formulation for the surface stress. Without wind, the stress is zero. The magnitude of the wind shear-stress is determined by:

$$|\vec{\tau}_s| = \rho_a C_d U_{10}^2, \tag{3.13}$$

where $\rho_a$ is the density of air, $U_{10}$ is the wind speed 10 meter above the free surface (time and space dependent) and $C_d$ is the wind drag coefficient, dependent on $U_{10}$. At the open water boundaries, data needed for the boundary conditions can be obtained from measurements, tide tables or from a larger model, which encloses the model at hand (nesting).

**DelftDashboard**

DelftDashboard supports the development of a rectilinear, boundary fitted grid and supplies databases to obtain a bathymetry, boundary conditions and initial conditions. The Domain Decomposition toolbox within DelftDashboard allows the model to be divided into several smaller model domains. Grid refinement in one domain results in a finer grid, compared to a course grid in another domain. This is useful when the resolution requirements for simulated physical processes are different. The interfaces between the domains are called DD-boundaries. These boundaries enable communication during computations, so that parallel computing is possible. This reduces the simulation time significantly.

### 3.2.2 Sediment transport modeling

Sediment transport and morphology are supported in Delft3D-FLOW; bed-load and suspended load transport of non-cohesive sediments and suspended load of cohesive sediments can be modeled. The advection-diffusion (mass-balance) equation that has to be solved for 2D, depth-averaged transport of suspended sediment is given by:

$$\frac{\partial HC^{(\ell)}}{\partial t} + \frac{\partial HUC^{(\ell)}}{\partial x} + \frac{\partial HVC^{(\ell)}}{\partial y} - \frac{\partial}{\partial x}\left(\varepsilon_{s,x}^{(\ell)} \frac{\partial HC^{(\ell)}}{\partial x}\right) - \frac{\partial}{\partial y}\left(\varepsilon_{s,y}^{(\ell)} \frac{\partial HC^{(\ell)}}{\partial y}\right) - (D^{(\ell)} - E^{(\ell)}) = 0, \tag{3.14}$$

where $H = \zeta + d$, with $\zeta$ the water level and $d$ the depth, $C^{(\ell)}$ is the depth-averaged mass concentration of sediment fraction $(\ell)$, $U$ and $V$ are depth-averaged flow velocity components, $\varepsilon_{s,x}^{(\ell)}$ and $\varepsilon_{s,y}^{(\ell)}$ are eddy diffusivities and $D^{(\ell)}$ and $E^{(\ell)}$ are the rates of sediment deposition and erosion respectively.

Sediment is different from ordinary constituents, such as salinity and heat, since it is exchanged between the bed and the flow and it settles due to the action of gravity. The settling velocity, deposition and erosion are processes that are sediment-type specific. The exchange of suspended sediment is determined by the flux from the bed to the bottom layer and vice versa. In every cell a source and sink term are then applied and the bed level is updated.

### Erosion and deposition

To calculate the exchange between water phase and bed, the Partheniades-Krone formulations are used (Partheniades, 1965):

$$E^{(\ell)} = M^{(\ell)} S(\tau_{cw}, \tau_{cr,e}^{(\ell)}), \tag{3.15}$$

$$D^{(\ell)} = w_s^{(\ell)} C^{(\ell)} S(\tau_{cw}, \tau_{cr,d}^{(\ell)}), \tag{3.16}$$

where $M^{(\ell)}$ is the erosion parameter, $S(\tau_{cw}, \tau_{cr,e}^{(\ell)})$ is an erosion step function, $w_s^{(\ell)}$ is the (hindered) sediment settling velocity of sediment fraction $(\ell)$, $S(\tau_{cw}, \tau_{cr,d}^{(\ell)})$ is a deposition step function, $\tau_{cw}$ is the maximum bed shear stress, $\tau_{cr,e}^{(\ell)}$ is the critical erosion shear stress and $\tau_{cr,d}^{(\ell)}$ is the critical deposition shear stress.

### Settling velocity

Cohesive sediment tends to form flocs when it is suspended in salt water. These flocs are larger than the particles they consist of and have a higher settling velocity. For single mud flocs with a fractal structure in still water, a formula for the settling velocity can be obtained from a balance between gravitational and drag force. For spherical, Euclidean particles in the Stokes' regime, where $Re_f \ll 1$, the Stokes' formula for a stationary settling particle reads (Van Rijn, 1984; Winterwerp and van Kesteren, 2004):

$$w_{s,r} = \frac{(\rho_s - \rho_w) g D_f^2}{18\mu}, \tag{3.17}$$

where $D_f$ is the representative mud floc diameter and $\mu$ is the dynamic viscosity. To take into account flocculation effects and hindered settling, Van Rijn (2007) proposes the following equation for the sediment settling velocity:

$$w_s = \phi_{floc} \phi_{hs} w_{s,r}, \tag{3.18}$$

where $\phi_{floc}$ is the flocculation factor and $\phi_{hs}$ is the hindered settling factor. For a salinity $Sa \geq 5ppt$ and particles finer than $D_{sand} = 63\ \mu m$, the flocculation factor is given by:

$$\phi_{floc} = [4 + \log_{10}(2c/c_{gel})]^{\alpha}, \quad \text{with a minimum value of 1 and a maximum value of 10,} \tag{3.19}$$

where $\alpha = (D_{sand}/D_{50}) - 1$, with $\alpha_{min} = 0$ and $\alpha_{max} = 3$; $c$ is the mass concentration $(= \rho_s c_{volume})$ and $c_{gel}$ is the gelling mass concentration (between 130 and 1722 $kg/m^3$). Hindered settling is negligible due to the low suspended sediment concentrations in dredge plumes (i.e. $\phi_{hs} = 1$).

| Symbol | Description |
|---|---|
| $x^i_j$ | $x$ co-ordinate of waypoint $j$ of dredge track $i$ |
| $y^i_j$ | $y$ co-ordinate of waypoint $j$ of dredge track $i$ |
| $t^i_{start}$ | Start time of dredge track $i$ |
| $t^i_{stop}$ | Stop time of dredge track $i$ |
| $Q^i_{start}$ | Discharge at $t^i_{start}$ for dredge track $i$ |
| $Q^i_{stop}$ | Discharge at $t^i_{stop}$ for dredge track $i$ |
| $c^i_{start}$ | Concentration at $t^i_{start}$ for dredge track $i$ |
| $c^i_{stop}$ | Concentration at $t^i_{stop}$ for dredge track $i$ |
| $t^n_{c;start}$ | Start time of dredge cycle $n$ |
| $d^n_c$ | Duration of dredge cycle $n$ |
| $N_c$ | Amount of simulated dredge cycles |

Table 3.1: Parameters that are applied in the Dredge Plume toolbox

### 3.2.3 Dredge Plume toolbox

The representation of the source term in Delft3D-FLOW can be done conveniently by using the pre-processing tool DelftDashboard. The Dredge Plume toolbox consist of a series of MATLAB routines which translate a user defined dredge track into a series of discharge locations ($m$, $n$) and corresponding start and stop times. The source term is represented by a discharge $Q$ and a concentration $c$. The input parameters are depicted in Table 3.1. The values in between $Q_{start}$ and $Q_{stop}$, and $c_{start}$ and $c_{stop}$ are obtained by linear interpolation. This allows for a non-steady source term, representing the hopper loading curve (e.g. Miedema and Vlasblom, 1995).

### 3.2.4 Model restrictions

- For reasons of computational efficiency a two dimensional (2D, depth-averaged) grid is imposed. To be able to do this, the fluid has to be vertically homogeneous. For far-field suspended sediment plume simulation, the flow regime is assumed to be vertically well-mixed, which makes this simplification a logical choice.

- One of the features of DelftDashboard to enable a quick model setup is the possibility to generate a rectilinear grid. However, the boundaries of a river, an estuary or a coastal sea are in general curved and are not smoothly represented on a rectangular grid. The boundary becomes irregular and may introduce significant discretization errors.

- Small negative sediment concentrations ($-1\ mg/L$) can be found in a computation. These negative concentrations can be suppressed by applying a horizontal Forester filter (Deltares, 2009). However, this can result in a substantially larger computing time. It is suggested to accept small negative concentrations and to apply a Forester filter only when the negative concentrations become unacceptably large. For this thesis, a Forester filter has not been applied.

- Hindered settling has not been modeled. This simplification can be made, since hindered settling is important for high concentrations in particular, which are not expected in far-field suspended sediment plumes. Flocculation on the other hand might have a significant effect on particle fall velocity and is included in the calculation of $w_s$. Interaction between different sediment types, which might for instance lead to unexpected flocculation dynamics, is not modeled.

- Wave action is not taken into account. In some cases however, wave orbital motion can result in additional diffusion near the free surface. For this thesis, the plume dispersion process is assumed to be driven by tide and wind only.

- Processes occurring during the first few minutes of the plume generation are responsible for the loss to the bed of a considerable proportion of the fine sediment initially released into the water column. However, considering the complexity of the processes in the near-field, accurately modeling concentrations would require very detailed data and an expensive 3D model including a jet model, such as CORMIX. These detailed data are not available and on top of that 3D modeling would decrease computational efficiency, which would render the model not practically applicable. Instead a 2DH model in which the dredge plume source term already includes the near-field processes is applied. This requires the formulation of a translation factor $f_{dyn}$, as discussed in Subsection 3.1.2.

## 3.3 Load curve

The hydrodynamic and sediment transport modeling results in suspended sediment concentrations for every grid cell at every time step. An example contour plot of a suspended sediment plume is shown in Figure 3.1. The grid cells of interest are those in which sensitive receivers are located. For those locations, observation stations can be added to the model to obtain detailed ouput for various parameters. The time series of suspended sediment concentrations for sensitive receiver *SR2* is shown in Figure 3.2. The graph depicts one and a half day of simulation output, starting on August 4th at noon. The simulation started 12 hours earlier, allowing for spin-up of the hydrodynamic model. When the graph is assumed to represent the total exposure, the time series has to be converted to a series of values for concentration and exposure duration. A possible method to obtain these values is to divide the maximum concentration level into a number of equal parts, which enables the determination of exceedance durations. This procedure is represented by the purple lines in Figure 3.2. The result is a series of combinations of concentration and exposure duration. When these points are connected in a graph with concentration and duration on the axes, a curve arises. This translation of a time series into a 'load curve' is done in Figure 3.3.

It is possible to plot the load curve in Figure 2.2 to obtain a first impression of the expected effect, see Figure 3.4. The different points on the curve lead to different effects, one more severe than the other. One point will result in the most severe effect for that particular simulation. This point can be interpreted as the load and will therefore be referred to as $S$. The mathematical definition of the load $S$ will be developed in Chapter 4.

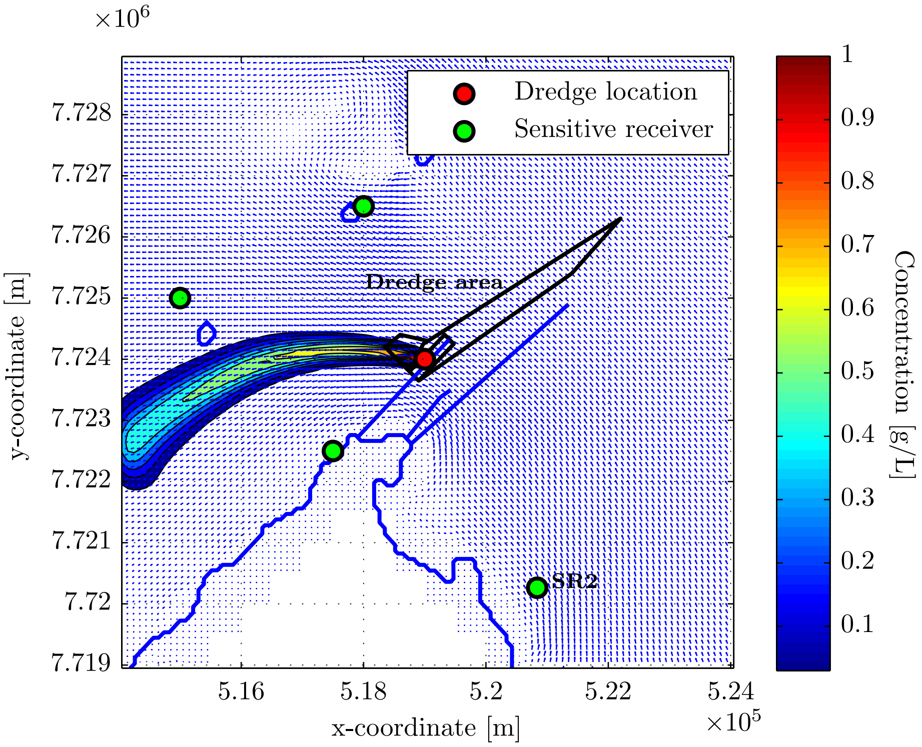


Figure 3.1: Plume dispersion after one hour of dredging. The sensitive receiver *SR2* is located South-East of the dredging project.

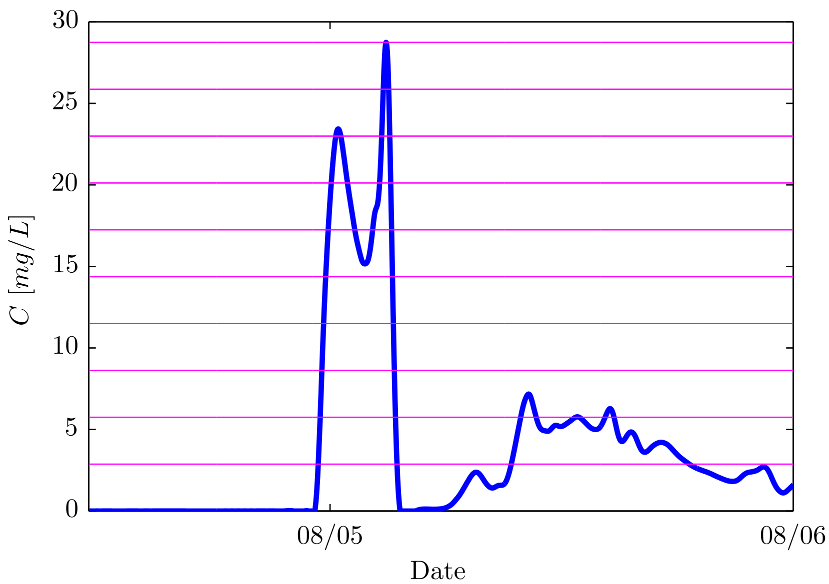


Figure 3.2: Time series of suspended sediment concentration $C$ for sensitive receiver *SR2*, located as specified in Figure 3.1. The maximum level is divided into 10 equal parts, which enables determination of exceedance durations.

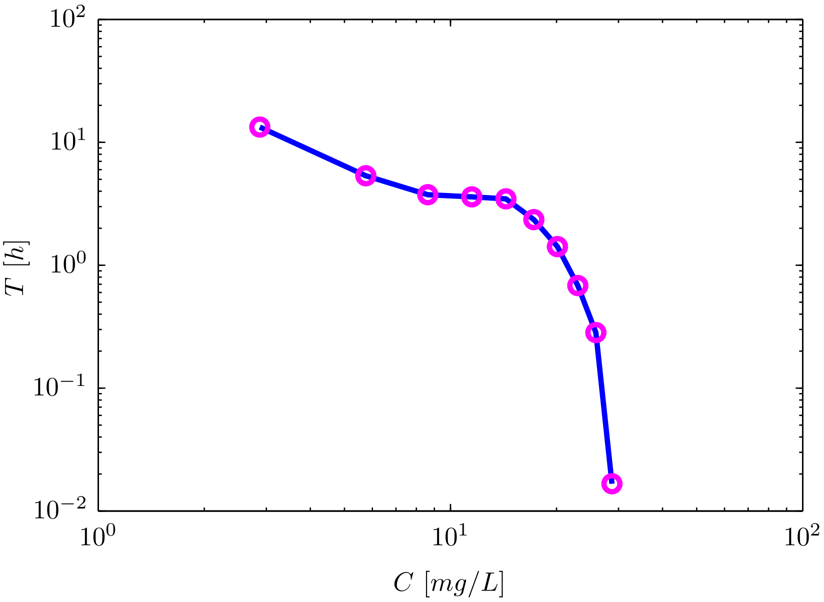


Figure 3.3: Load curve for sensitive receiver *SR2* on a log-log scale, as derived from Figure 3.2. The curve is the result of one simulation. It depicts the suspended sediment concentration $C$ (on the x-axis) and the exposure duration $T$ (on the y-axis) for which it is exceeded.

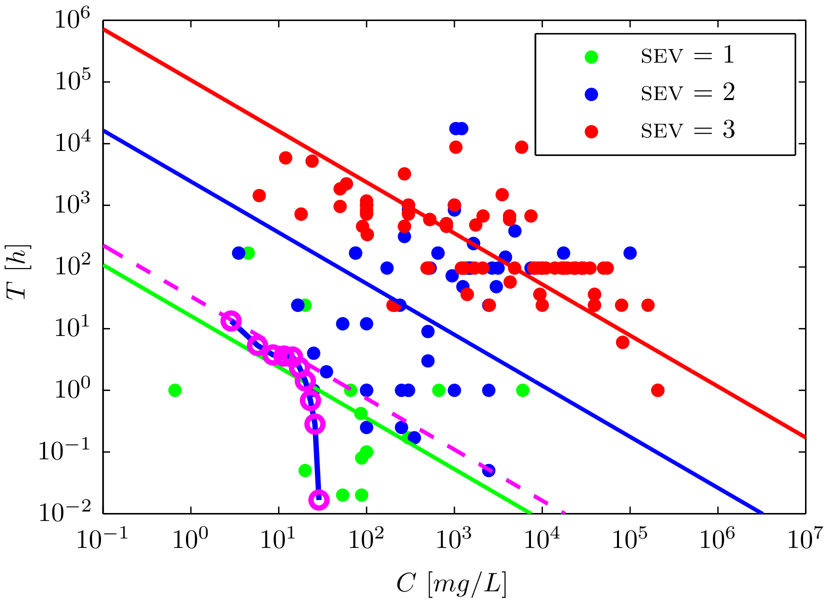


Figure 3.4: The load curve is plotted in Figure 2.2 to obtain a first impression of the expected effect. The community of fish will likely be showing behavioral effects and possibly sublethal effects. The proportions for which these effects occur (i.e., probability for an individual fish) will be analyzed in Chapter 4. The dashed line depicts the critical value of $k^*$, as in Equation 2.23, or the load $S$.

# Chapter 4

# Risk characterization

## 4.1 Uncertainty

Uncertainty plays an important role in the modeling of cause-effect chains (Van Kruchten and de Vries, 2010). Some are related to the response of sensitive receivers, such as natural variations in population size independent of any load at all. Others are related to inherently uncertain weather dynamics or lack of knowledge about plume dispersion. Van Gelder (2000) made a suitable distinction into two basic categories: uncertainties stemming from variability in known populations and uncertainties resulting from a lack of knowledge of fundamental phenomena, inherent and epistemic uncertainty respectively. Epistemic uncertainty can be divided into statistical uncertainty and model uncertainty. Statistical uncertainty includes uncertainty about distribution type and variation in parameters, whereas model uncertainty takes into account lack of knowledge about physical processes and modeling simplifications. Consequently, the results of the modeling exercise are uncertain as well. In this thesis, several sources of uncertainty can be identified:

- Instead of a 3D model, a 2DH model is applied. This simplification is justified due to the intrinsically uncertain behavior and lack of full understanding of near-field plume dynamics, where 3D processes play a significant role (model uncertainty).
- The parameters that determine the shear stresses on the water body, the 2D-Chézy coefficient, $C_{2D}$, wind speed $U_{10}$ and wind direction, are uncertain in space as well as in time (inherent uncertainty).
- The dredge track and related parameters, as depicted in Table 3.1, are unpredictable in nature, as they depend on weather, soil properties, project execution and many other factors (inherent uncertainty).
- The response of a sensitive receiver is modeled by an ordered response model. Fitting parameters are determined based on a limited number of data and are therefore random variables (parameter uncertainty).

## 4.2 Reliability function

Given the uncertainties as described in the previous paragraph, it is recommendable to determine the degree in which it is likely that a certain object functions as it should (CUR, 1997). If it does not, the object is said to 'fail', with corresponding 'failure probability'. The state just before failure occurs is defined as the limit state and reliability is the probability that this state is not exceeded. The reliability is described by a reliability function, with the general form:

$$Z = R - S_D - S_0, \tag{4.1}$$

where $Z$ is the reliability function ($Z \leq 0$ equals failure), $R$ is the strength of the sensitive receiver, $S_D$ is the load due to dredging and $S_0$ represents all other loads. The probability $\mathrm{Pr}_f = \mathrm{Pr}(Z \leq 0)$ is the probability of failure. To be able to provide an estimate for this probability, the hydrodynamic modeling results have to be linked with the ordered response model.

The strength of a sensitive receiver depends on the definition of 'failure'. Values of $x'\hat{\beta}$ do not have a meaningful interpretation and are therefore not suitable to be used in a failure definition. There has to be a variable which has a clear interpretation and is directly related to $x'\hat{\beta}$. The ordered response model provides this interpretation. It is possible to estimate probabilities of any observed outcome $\textsc{sev} = j$ given $x$ for a certain individual with the following equation:

$$\Pr(\textsc{sev} = j \mid x) = F(\hat{\tau}_j - x'\hat{\beta}) - F(\hat{\tau}_{j-1} - x'\hat{\beta}), \tag{4.2}$$

which results in the following for the ordered probit model:

$$\begin{aligned} &\Pr(\textsc{sev} = 1 \mid x) = \Phi(\hat{\tau}_1 - x'\hat{\beta}), \\ &\Pr(\textsc{sev} = j \mid x) = \Phi(\hat{\tau}_j - x'\hat{\beta}) - \Phi(\hat{\tau}_{j-1} - x'\hat{\beta}), \\ &\Pr(\textsc{sev} = m \mid x) = 1 - \Phi(\hat{\tau}_{m-1} - x'\hat{\beta}). \end{aligned} \tag{4.3}$$

These probabilities are very suitable in a failure definition. They can be interpreted as the proportion of the community that will end up in the category under consideration. For every response category, maximum allowable proportions can be defined. These can then be related to a value for $x'\hat{\beta}$. An example of a dose-response relationship is shown in Figure 2.3. The critical value for $x'\hat{\beta}$, i.e. the lowest value, that results from the failure definition is defined as the strength:

$$R = (x'\hat{\beta})_{crit}. \tag{4.4}$$

The hydrodynamic modeling results, which are used to determine the load parameter, are described by $n$ combinations of $k$ explanatory variables. The combinations are denoted by a $k \times 1$ vector $s_i$, $i = 1, \ldots, n$. In this thesis $k = 2$, with one variable representing the natural logarithm of suspended sediment concentration $C$ and one representing the natural logarithm of exposure duration $T$, and $n = 10$. An example of hydrodynamic modeling results is shown in Figure 3.3. The largest load will result from the maximum value of $s_i'\hat{\beta}$, since in the ordered response model, for increasing $x'\beta$, the index $y^*$ increases, which leads to a larger outcome of $y$. This means that the estimated value for $\beta$, which is a strength parameter, will be used in the load part of the reliability function. It is not strictly necessary to separate strength and load factors, as long as the element fails when $Z \leq 0$ (Schiereck, 2000). The maximum value of $s_i'\hat{\beta}$ is defined as the load:

$$S_D + S_0 = \max_i(s_i'\hat{\beta}), \tag{4.5}$$

or in fact $S_D$ when only exposure due to dredging is modeled. The reliability function now has the following form:

$$Z = (x'\hat{\beta})_{crit} - \max_i(s_i'\hat{\beta}). \tag{4.6}$$

Several approaches exist to yield an estimate of risk, where every approach treats uncertainties in a different way. Two well-known methods are the probabilistic and deterministic approach, which will be discussed in the following paragraphs.

## 4.3 Probabilistic approach

A probabilistic approach incorporates variability in exposure and effects estimates. This allows to predict the likelihood of certain effects to occur for different exposure situations. Variability in effects might be due to two sources of uncertainty: the inherent uncertainty about variability in known populations and the epistemic uncertainty due to lack of sufficient data and knowledge. For each individual, a sharp threshold exists for a certain effect to occur. So for an individual at a given site, where the threshold is known, there is no randomness in the response. The dose-response curve in this sense represents the fraction of a community where a given exposure results in a certain effect. Therefore response frequency is a more appropriate measure of effects than response probability. But besides this variation within populations, there is epistemic uncertainty leading to additional variability. Data on response characteristics of sensitive receivers is very limited, let alone of entire ecosystems. As a result, mean thresholds and their deviations are uncertain and add to the variability which was already part of the system itself. Variability in exposure is the result of many sources of uncertainty, as described in previous paragraphs. Exposure is composed of several aspects, including the activities of the stressor, surrounding system characteristics and the modeling of the pathway, which itself depends on stressor and surrounding system. Processes such as tide, wind and dredging operation are neither stationary nor spatially homogeneous and introduce inherent uncertainty in the system. Modeling the dispersion adds epistemic uncertainty. As a result, the model output is not indicated by a single outcome, but rather by a probability distribution of possible outcomes.

Statistical sampling techniques are required to obtain the variability in effects and exposure estimates. Monte Carlo analysis is a method that uses statistical sampling techniques to derive the probabilities of the occurrence of certain effects. The way in which this is done is to specify a probability distribution for every variable that plays a role in the processes leading to the effect. The selection of these variables is an arbitrary process and its success (or failure) depends on the quality of the expert judgement. A large number of random drawings from the respective distributions is carried out. Effects and exposure estimates are then generated by means of the in Chapter 2 and Chapter 3 described methods. Subsequently, Equation 4.6 has to be solved, leading to a value of $Z < 0$, i.e. failure, or $Z > 0$. The failure probability is estimated by:

$$\mathrm{P}_f \approx \frac{n_f}{n}, \tag{4.7}$$

where $n$ is the total number of simulations and $n_f$ is the number of simulations for which $Z < 0$. Another definition of failure, equivalent to $Z < 0$, is the situation for which $S > R$ holds. After a large number of calculations the results for effects and exposure, or strength

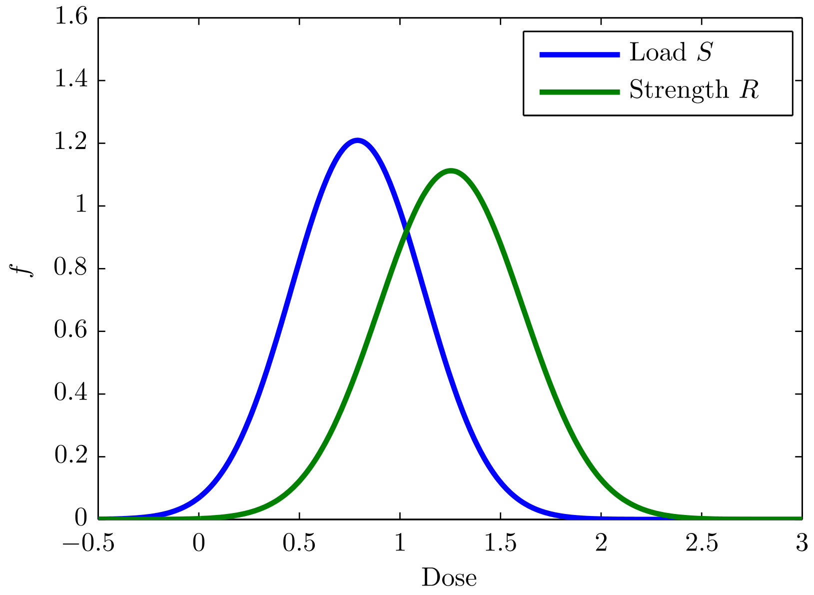


Figure 4.1: Probability density function of the load $S$ and the strength $R$ after a Monte Carlo simulation with sample size a thousand. The development of these particular curves will be explained in Chapter 5

and load, are supposed to approach the distribution of the data generating process, given the specified input parameters. A graphical representation of this outcome is shown in Figure 4.1, where the fitted probability density functions of load and strength are depicted. The data, parameter values and distribution types that were used to obtain these curves will be introduced in Chapter 5.

## 4.4 Deterministic approach

The deterministic approach is based on an estimate of one representative value for exposure, consisting of a linear combination of concentration and duration, which is compared with one representative dose-response curve obtained from field data or laboratory experiments. The effects are assessed as has been set out in Chapter 2, which results in a dose-response curve for each given endpoint. Exposure is modeled with all input parameters taking on a characteristic value and subsequently translated into a load curve as explained in Chapter 3. To obtain representative values for strength and load, partial safety factors might be useful:

$$\begin{aligned} R_{rep} &= \mu_R + k_R \cdot \sigma_R, \\ S_{rep} &= \mu_S + k_S \cdot \sigma_S, \end{aligned} \tag{4.8}$$

where $R_{rep}$ and $S_{rep}$ are representative values for strength and load respectively, $\mu$ is the mean, $\sigma$ is the standard deviation and $k$ is a safety factor for which generally holds that $k_R$ is negative and $k_S$ is positive. The response frequency approach, as discussed in Section 4.3, cannot be applied in this set-up. The safety factor implicitly assumes a certain fraction of the community to show an effect. The uncertainty in the exposure assessment can only

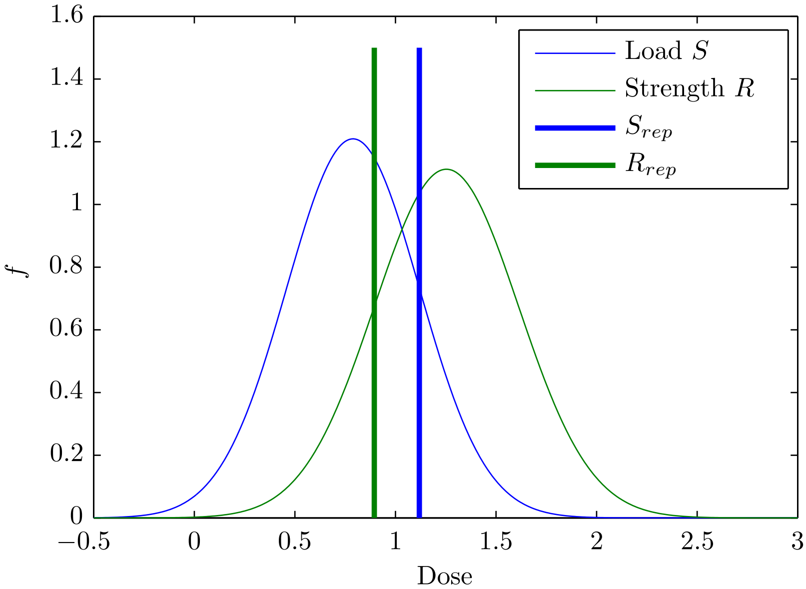


Figure 4.2: Figure 4.1 is expanded with deterministic values for strength $R_{rep}$ and load $S_{rep}$. The values are located at a distance of one standard deviation from their respective means, which would lead to failure

partly be treated by testing a number of scenarios and apply a safety factor based on expert judgement. The precautionary principle dictates selection of parameter values in such a way that a 'worst case scenario' is simulated. This results in representative values for $S$ and $R$, which will practically always lead to $Z$ being smaller than zero, which is equivalent to failure. The relevant parameter values however have to be chosen based on the increased knowledge thanks to gained on-site experience. This leads to more realistic risk estimates.

The deterministic case is in fact a subset of the probabilistic case. The difficulty is that the probability distribution and statistical parameters are unknown in advance. It is therefore impossible to estimate a failure probability. Ideally, parameters are chosen at a certain distance from the mean, expressed in standard deviations. This method is shown in Figure 4.2, an extension of Figure 4.1. In the figure, the values are one standard deviation away from their means. If these values were to be chosen as representative values, the result would be failure.

As a result of the lack of information on distribution of strength and load, it is very complicated to determine safety factors that guarantee both economic feasibility and reliability regarding dredging activity and ecosystem. The uncertainty is reduced when more information is available during the course of the project execution. Factors such as wind and wave climate, soil properties, dredging equipment operation methods and at a certain stage even weather, are becoming less uncertain. Scenarios might provide additional information on risk, by choosing several combinations of conditions and operation practices. It is less time consuming and more computationally cheap compared to a Monte Carlo simulation. It relies however again on expert judgement to guarantee selection of both likely and extreme situations and interpret the results in a correct way.

# Chapter 5

# Application

An ERA is part of a risk management strategy or program. Certain standards and criteria must be met or measures have to be determined to reduce risk. In the end, the results of the ERA are evaluated and lead to a decision whether or not to accept the risk (CUR, 1997). Different risk management programs, which depend on the field of application, require different risk characterization methods and do not have the same compliance criteria and possibilities to mitigate effects or reduce risk. In this chapter, two typical phases in a dredging project are considered: the planning and design phase in Section 5.1 and the execution phase in Section 5.2. To show how the methods presented in the previous chapters are applied in practice, an arbitrary dredging project is used as a case study. The results from the subsequent steps of the ERA are interpreted according to their respective risk management strategies.

## 5.1 Planning and design

### 5.1.1 Introduction

In the planning and design phase of a project, it is possible to explicitly incorporate variability in exposure and effects estimates. A probabilistic approach is assumed to enable better risk assessment, which should therefore be the preferred method in this stage. Insight in uncertainties provides the risk agent with an opportunity to point to gaps in knowledge and gives a quantitative estimate about the importance of the different factors leading to the adverse effect. This can in turn be used to indicate fields of further investigation and the selection of precautionary action and, if appropriate, mitigating measures.

As part of the plume modeling exercise, a baseline simulation of suspended sediment levels is developed against which effects of dredging are measured. To be able to obtain a reliable baseline, the study should include reference sites, all potential activities carried out by third parties and natural occurrences. Natural variability should be included as accurately as possible to simulate a certain level of uncertainty already present in the existing situation. In case of storms, unexpected seabed mobility or benthic activity however, this is difficult to achieve. The consequences of the dredging activity, including an increase in suspended sediment concentration, have to be modeled to assess the marginal adverse effect on the environment. To account for possible large scale variability, such as seasonal effects, two or more simulations are necessary. This is different for every set of circumstances and should be approached accordingly.

When the risk estimates are obtained, there are two possibilities: the situation is either acceptable or not acceptable. In the latter case, measures should be implemented to change the system in such a way that the situation becomes acceptable. To be able to do this, risk of adverse effects has to be reduced. This can be done by means of precautionary action or mitigating measures. There are several options to reduce suspended sediment and turbidity generation. They can be categorized into four groups (Bray, 2008):

1. Use of different equipment
   (a) Environmental disc bottom cutter
   (b) Sweep dredger or low turbidity dredger, which are useful for environmentally sensitive projects
   (c) Auger dredger, which is especially suitable for clean up
   (d) Environmental grab
   (e) Anti Turbidity Valve (ATV)
2. Change in way of operation
   (a) Speed of the vessel
   (b) Pump speed
   (c) Navigation
   (d) Overflow discharge
   (e) Hoisting speed
3. Environmental windows

   Temporal constraints can be placed upon a dredging operation in order to protect a habitat (Clarke, 2004). A window represents the time period during which the operation is allowed. Seasonal restrictions prohibit dredging operation during a specific season, which is suitable if suspended sediment conditions show seasonal variation. Tidal restrictions on the other hand prohibit dredging operation for a certain duration within a tidal cycle, depending on the direction of the tidal current.
4. Physical barriers
   (a) Cooking pot
   (b) Silt screen
   (c) Bubble screen

### 5.1.2 Case study

#### System description and hazard identification

To be able to carry out a case study, an arbitrary location is selected to stage a dredging project. As described in Chapter 1, the system description is the first step in the ERA. The area of interest is schematized according to the methods described in Section 3.2. The global model grid and refinements at the dredge area, together with the dredge tracks and the

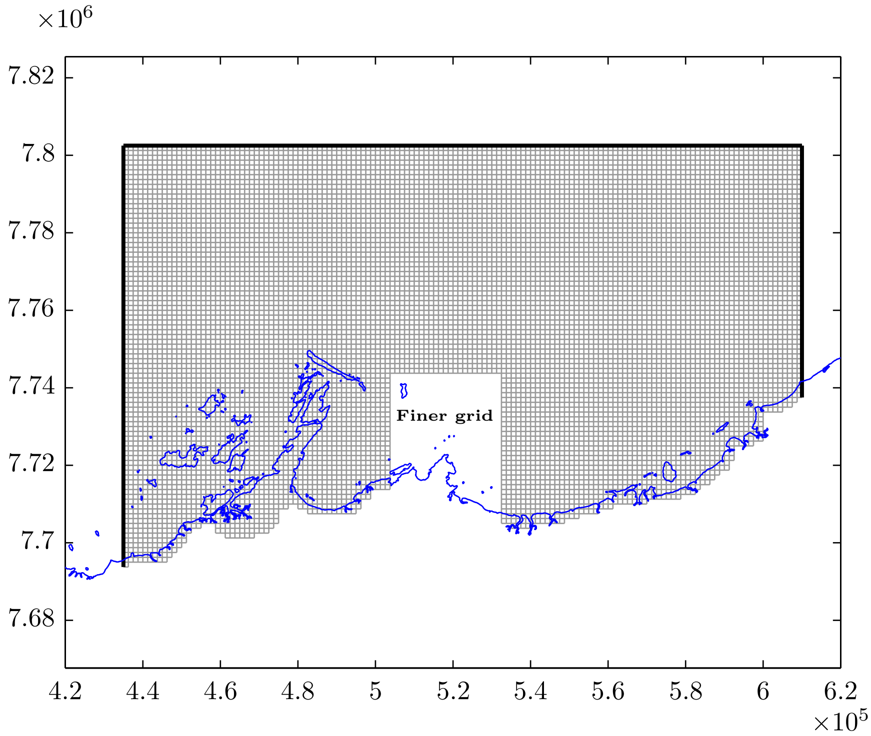


Figure 5.1: The region of interest with rectilinear grid. The grid sizes are 1250 $m$ by 1250 $m$. The dredging area and the area around it are covered with a finer grid. The Domain Decomposition toolbox within DelftDashboard allows for this grid refinement.

location of the sensitive receiver of interest $SR2$, are depicted in Figure 5.1 and Figure 5.2. The dredge area consists of an approach channel, two berth pockets and a turning basin. A large TSHD will be the dredging vessel that is simulated in this case study. The hazard is identified to be the suspended sediment plume generated by overflow of the hopper. An increased suspended sediment level might have an effect on the earlier indicated sensitive receiver $SR2$.

### Effects and exposure assessment

The data that were introduced in Chapter 2 are assumed to be representative for the sensitive receiver $SR2$ considered in this case study. The dose response curve that results from the data set is given by the ordered response model in Equation 2.20. For three response categories and two explanatory variables, there are four parameters to be estimated. The results as specified in Table 2.2 will be used in this case study. The standard errors of the regression parameters are assumed to represent the uncertainty in effect estimates. These are used in the Monte Carlo simulation as standard deviation of the strength variables. The strength variables consist solely of the regression parameters of the ordered response model. The variables that are applied in the probabilistic analysis are listed in Table 5.1. The load is calculated as described in Chapter 3, with many factors influencing the results. The variables that are considered most important, are listed in Table 5.1 as well. It is important that the stochastic variables are independent, since otherwise they cannot be used in a probabilistic

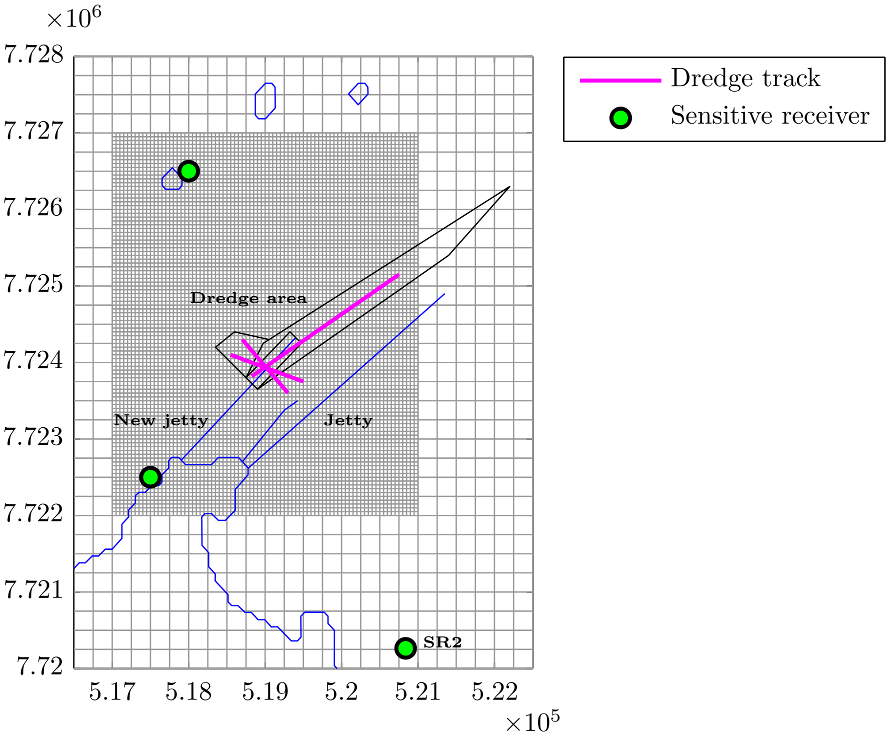


Figure 5.2: The dredging area with coarse grid (250 $m$ by 250 $m$) and fine grid (50 $m$ by 50 $m$). The dredge tracks cover approach channel, turning basin and berth pockets. The sensitive receiver $SR2$, which will be investigated, is located South-East of the dredging project.

| | Variable | Description | Distribution | Parameters | |
|---|---|---|---|---|---|
| **Strength** | $\hat{\beta}_1$ | – | Normal | $\mu = 0.2066$ | $\frac{\sigma}{\sqrt{n}} = 0.0414$ |
| | $\hat{\beta}_2$ | – | Normal | $\mu = 0.2495$ | $\frac{\sigma}{\sqrt{n}} = 0.0393$ |
| | $\hat{\tau}_1$ | – | Normal | $\mu = 0.6203$ | $\frac{\sigma}{\sqrt{n}} = 0.3066$ |
| | $\hat{\tau}_2$ | – | Normal | $\mu = 2.5393$ | $\frac{\sigma}{\sqrt{n}} = 0.3791$ |
| **Load** | $\hat{\beta}_1$ | – | Normal | $\mu = 0.2066$ | $\sigma = 0.0414$ |
| | $\hat{\beta}_2$ | – | Normal | $\mu = 0.2495$ | $\sigma = 0.0393$ |
| | $C_{2D}$ | Chézy parameter | Normal | $\mu = 55$ | $\sigma = 5$ |
| | $w_s$ | Settling velocity | Lognormal | $\mu = -9.91$ | $\sigma = 0.472$ |
| | $Q$ | Source discharge | Lognormal | $\mu = 2.31$ | $\sigma = 0.472$ |
| | $c$ | Source concentration | Lognormal | $\mu = 2.59$ | $\sigma = 0.472$ |
| | $U_{10}$ | Wind velocity | Weibull | $\lambda = 7.896$ | $k = 2$ |
| | $Dir_{wind}$ | Wind direction | Uniform | $a = 0$ | $b = 360$ |

Table 5.1: Stochastic variables that are applied in the Monte Carlo simulation, to satisfy a probabilistic approach. The strength variables are the regression parameters of the ordered response model. Load variables are modeling parameters and source term components.

calculation.

The modeling of the plume dispersion is a relatively expensive calculation. Depending on practical circumstances, such as computer power and model efficiency, the computation time will vary. For the 2DH Delft3D-FLOW model that has been used in this thesis, with domain size and grid spacing as indicated in Figure 5.1 and Figure 5.2 and time step $\Delta t = 1\ s$, a day in real time is simulated in roughly four minutes. As a result, the simulation of one day of dredging implies a modeling time of several days for a Monte Carlo simulation with a sample size of one thousand. In addition, half a day in the model is reserved for spin-up of the hydrodynamics, after which the dredging source is implemented. Another half a day of modeling allows the suspended sediment concentration to increase to represent previous dredging works. The second day in the model is assumed to be a 'representative day' of the dredging project. The exposure duration within this day is then extrapolated to obtain the exposure as a result of the entire project.

### Risk characterization

The definition of 'failure' determines the mean value for the critical dose, or strength. This value has to be calculated to be able to solve the reliability function. In this case study, the critical conditions are defined as follows: the sensitive receiver $SR2$ fails if 10% of the individuals in the community or more demonstrate lethal or paralethal effects (category 3) or if 90% of the individuals in the community or more demonstrate at least sublethal effects (category 2). This translates into the probabilities $\Pr(\text{SEV} = 3) \geq 10\%$ and $\Pr(\text{SEV} \geq 2) \geq 90\%$ respectively. In this case the equation for $(x'\hat{\beta})_{crit}$ reads:

$$(x'\hat{\beta})_{crit} = \min(x'\hat{\beta} \mid \Pr(\text{SEV} = 3) = 10\%,\ x'\hat{\beta} \mid \Pr(\text{SEV} \geq 2) = 90\%). \qquad (5.1)$$

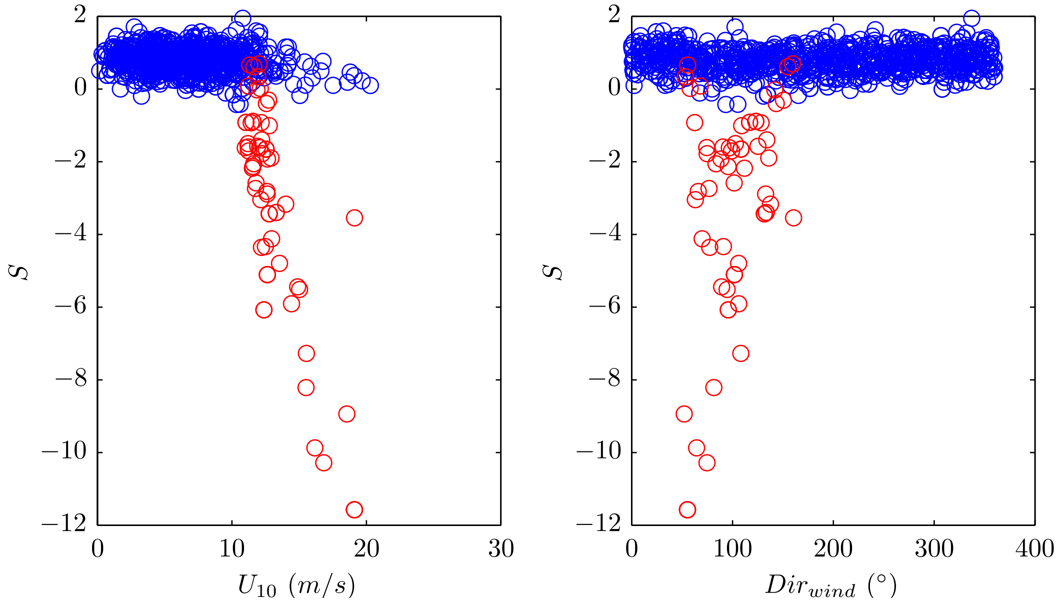


Figure 5.3: Scatter plot with load $S = (x'\hat{\beta})_{crit}$ as a function of wind velocity $U_{10}$ (left) and wind direction $Dir_{wind}$ (right) for sensitive receiver $SR2$. The red circles meet the criteria $U_{10} > 10.95\ m/s$ and $50° < Dir_{wind} < 161°$ and are excluded from further analysis. However, they remain important simulation results.

The value for $(x'\hat{\beta})_{crit}$ can be obtained using the model described in Equation 4.3. The following two equations have to be solved:

$$\begin{aligned} &\Pr(\textsc{sev} \geq 2) = 1 - \Phi(\hat{\tau}_1 - x'\hat{\beta}) = 90\%, \quad \text{and} \\ &\Pr(\textsc{sev} = 3) = 1 - \Phi(\hat{\tau}_2 - x'\hat{\beta}) = 10\%. \end{aligned} \tag{5.2}$$

With the definition of failure in place, the Monte Carlo simulation can be carried out. One thousand samples have been drawn from the a-priori specified distributions, every one yielding a value for $R$, $S$ and $Z = R - S$ for every sensitive receiver in the model. Sensitive receiver $SR2$, as indicated in Figure 5.2, will be subject to analysis.

Before the assessment continues, an important observation has to be mentioned. At $SR2$, wind velocity and direction have a noticeable effect on load $S$, especially certain combinations of the two. This can be observed in Figure 5.3. Values for wind velocity $U_{10} > 10.95\ m/s$ in combination with wind directions ranging from 50° to 161° lead to very small values for the load $S = (x'\hat{\beta})_{crit}$. Apparently, for those weather conditions the dredge plume leaves the area where the sensitive receivers are located. These 64 simulation results are excluded from further analysis, but remain important when decisions need to be made.

The simulation results for $SR2$ are shown in Figure 5.4, where the histograms seem to indicate that both strength $R$ and load $S$ are normally distributed. For the load $S$, 64 simulation results which lead to extremely low $S$-values are excluded. The hypothesis of normality can be tested with the Kolmogorov-Smirnov goodness-of-fit hypothesis test. For the strength $R$ the null hypothesis of normality cannot be rejected, with a $P$-value of 0.90. The same holds for the load $S$, where the null hypothesis again cannot be rejected, with a $P$-value of 0.80. This result allows a regression of the load $S$ on a number of explanatory variables, since a normal distribution is implicitly assumed for all variables in a linear regression model. The resulting thousand $Z$-values for $SR2$ are shown in Figure 5.5. The number of failures is 152, which leads to a probability of failure of $\Pr_f = 15\%$. The number of included observations was 936, so the histogram indicates $936 - 152 = 784$ successes. Together with the 64 excluded simulation results the amount of successes is $784 + 64 = 848$, since every excluded result indicated a success.

**Evaluation**

The 936 exposure results will be analyzed in more detail. It is expected that the value of the load $S = (x'\hat{\beta})_{crit}$ is a function of all explanatory variables, but their relative influences might differ substantially. There are six explanatory variables: the Chézy coefficient $C_{2D}$, settling velocity $w_s$, source term components $Q$ and $c$ and wind velocity and direction $U_{10}$ and $Dir_{wind}$. Other variables, such as dredging duration and location, cannot be included, since deterministic values were assigned to them. The variables are assumed to be independent, since they were drawn from an a-priori specified distribution, so indirect effects do not have to be examined. To estimate the influence of respective explanatory variables, a simple regression analysis is carried out, according to the following model:

$$S_i = \gamma_1 + \gamma_2 \cdot x_i + \varepsilon_i \quad (i = 1, \ldots, 936), \tag{5.3}$$

where $x$ is one of the six explanatory variables listed above. The results of the regressions are shown in Table 5.2. The $P$-values of the Chézy parameter $C_{2D}$, the settling velocity $w_s$ and the wind direction $Dir_{wind}$ are all larger than 5%, which indicates that their coefficients do not significantly differ from zero. These three variables can therefore be removed from analysis, which means that deterministic values can be applied. Alternatively, the load $S$ can be explained in terms of all six variables to determine the significance of the entire regression. In addition to a constant term, the two ordered response model regression parameters $\hat{\beta}_1$ and $\hat{\beta}_2$ are included as well, but are not of physical interest. The model is now given by:

$$\begin{aligned} S_i = {} & \gamma_1 + \gamma_2 \cdot C_{2D;i} + \gamma_3 \cdot \log(w_{s;i}) + \gamma_4 \cdot \log(Q_i) + \gamma_5 \cdot \log(c_i) + \\ & \gamma_6 \cdot U_{10;i} + \gamma_7 \cdot Dir_{wind;i} + \gamma_8 \cdot \hat{\beta}_{1;i} + \gamma_9 \cdot \hat{\beta}_{2;i} + \varepsilon_i \quad (i = 1, \ldots, 936). \end{aligned} \tag{5.4}$$

Variables that are not significant, based on their t-statistic, can be excluded from the regression. This exercise can be repeated until all variables are significantly different from zero. The results are presented in Table 5.3. The parameter estimates are obtained using the method of ordinary least squares. The column '$P$-value' contains the $P$-values for the null hypothesis that the corresponding parameter is zero against the two-sided alternative that it is non-zero. The results of Table 5.3 show that all coefficients are different from zero at the 5 percent level of significance. The Chézy coefficient and wind direction however appear to have a very small influence. The influence of settling velocity is relatively minor as well.

## 5.2 Execution

### 5.2.1 Introduction

When the execution of a dredging project is already in progress, short term predictions of ecological risks are necessary. A deterministic analysis satisfies the desire for a quick

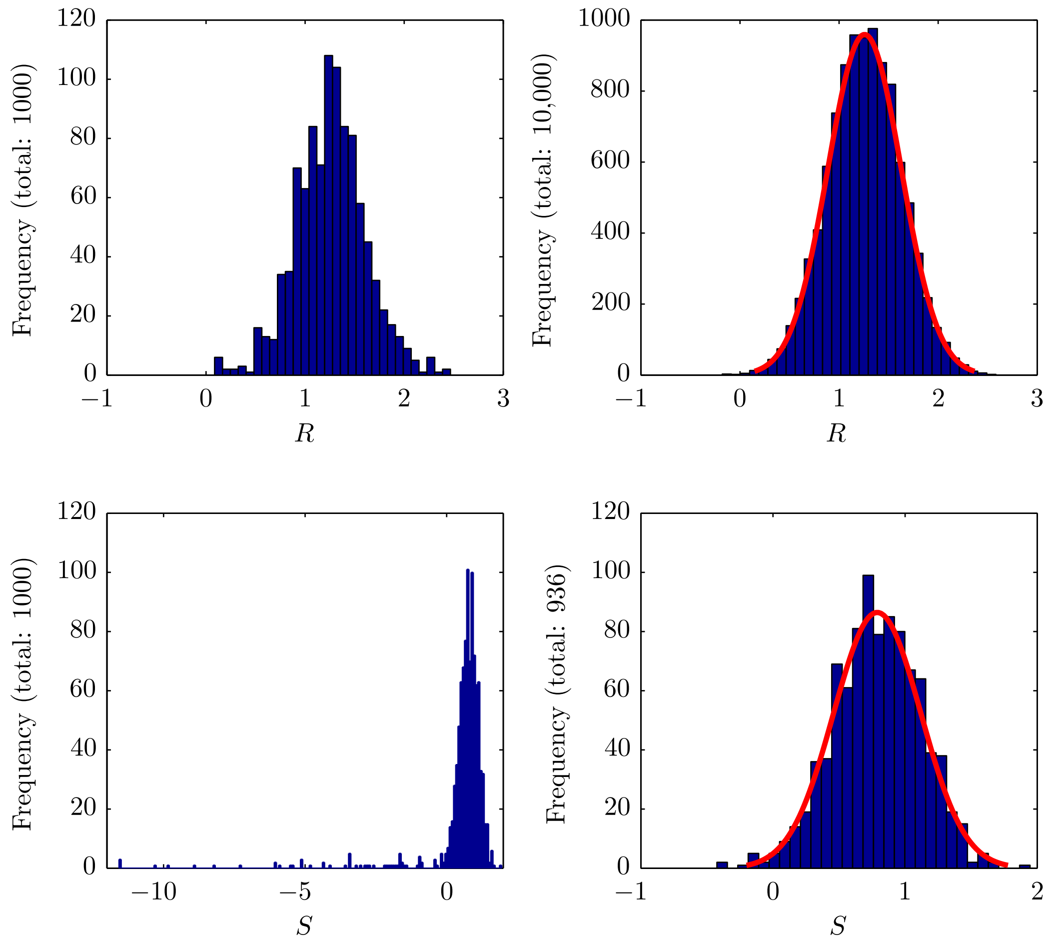


Figure 5.4: Histogram of values for strength $R$ (top) and load $S$ (bottom) after a Monte Carlo simulation. The number of strength realizations is increased to 10000 (top right) to confirm a normal population distribution. The simulation results that meet the criteria $U_{10} > 10.95\ m/s$ and $50° < Dir_{wind} < 161°$ are included (bottom left) or excluded (bottom right) to allow a normal distribution fit.

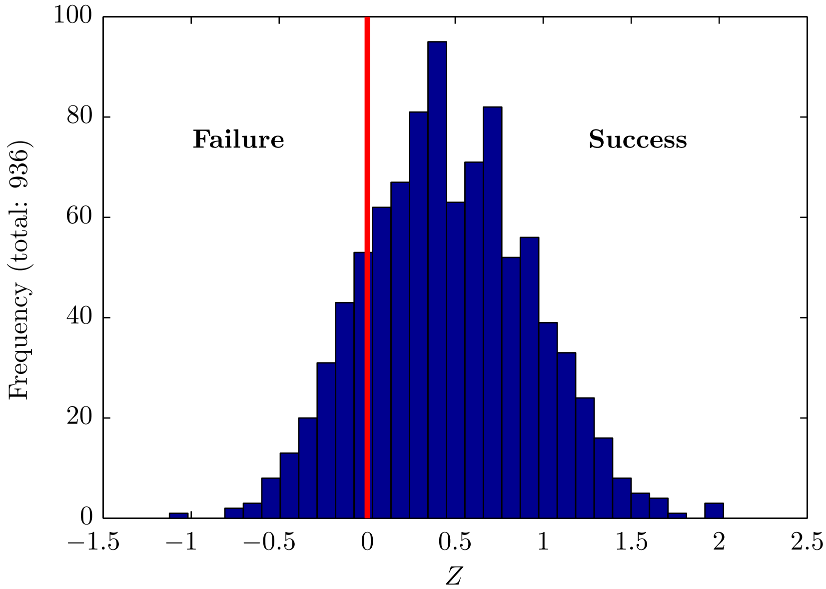


Figure 5.5: Histogram of $Z$-values after a Monte Carlo simulation. $Z < 0$ equals failure, according to Equation 4.6. The result of the simulation is $784 + 64 = 848$ successes and 152 failures, which leads to the conclusion that the failure probability $\Pr_f = 15\%$.

Dependent variable: $S$
Method: least squares
Sample: 1000
Included simulation results: 936

| $x$-variable | $R^2$ | $SSR$ | F-statistic | $P$-value |
|---|---|---|---|---|
| $C_{2D}$ | $7.9 \cdot 10^{-4}$ | 101.7 | 0.735 | 0.392 |
| $\log(w_s)$ | 0.0036 | 101.4 | 3.42 | 0.0647 |
| $\log(Q)$ | 0.098 | 91.81 | 101 | $1.16 \cdot 10^{-22}$ |
| $\log(c)$ | 0.10 | 91.14 | 109 | $3.77 \cdot 10^{-24}$ |
| $U_{10}$ | 0.023 | 99.43 | 21.8 | $3.46 \cdot 10^{-6}$ |
| $Dir_{wind}$ | $1.1 \cdot 10^{-6}$ | 101.8 | 0.00100 | 0.974 |

Table 5.2: Result of regressions shown in Equation 5.3. The column '$x$-variable' indicates which variable is included in the model together with a constant term. The significance of explanatory variables can be tested by $F$-tests using the $SSR$ (sum of squared residuals), or the $R^2$ (coefficient of determination) of the regressions.

| | | | | |
|---|---|---|---|---|
| Dependent variable: $S$ | | | | |
| Method: least squares | | | | |
| Sample: 1000 | | | | |
| Included simulation results: 936 | | | | |
| Variable | Coefficient | Std. error | t-statistic | $P$-value |
| 1 | $-1.3593$ | 0.1005 | $-13.5228$ | 0.0000 |
| $C_{2D}$ | $-0.0021$ | 0.0008 | $-2.7362$ | 0.0063 |
| $\log(w_s)$ | $-0.0626$ | 0.0080 | $-7.8046$ | 0.0000 |
| $\log(Q)$ | 0.2025 | 0.0081 | 25.0998 | 0.0000 |
| $\log(c)$ | 0.2088 | 0.0083 | 25.3021 | 0.0000 |
| $U_{10}$ | $-0.0189$ | 0.0012 | $-16.2241$ | 0.0000 |
| $Dir_{wind}$ | 0.0001 | 0.0000 | 2.1299 | 0.0334 |
| $\hat{\beta}_1$ | $-3.4824$ | 0.0955 | $-36.4757$ | 0.0000 |
| $\hat{\beta}_2$ | 5.9267 | 0.1000 | 59.2812 | 0.0000 |
| $R^2$ | 0.8781 | Mean dependent var. | | 0.7890 |
| Adjusted $R^2$ | 0.8770 | S.D. dependent var. | | 0.3299 |
| S.E. of regression | 0.1098 | F-statistic | | 834.50 |
| Sum squared residuals | 12.4063 | $P$-value (F-statistic) | | 0.0000 |

Table 5.3: Result of regression shown in Equation 5.4. The first variable '1' represents the constant term. The column '$P$-value' contains the $P$-values for the null hypothesis that the corresponding parameter is zero against the two-sided alternative that it is non-zero.

assessment and will allow the responsible agent to decide which measures have to be taken. It might even be possible to change some features of the execution method and several mitigation measures can be applied on short notice. Some of the options to reduce suspended sediment generation, as discussed in Subsection 5.1.1, can be applied when the execution has already commenced. In addition, the ERA might be used to adapt the monitoring strategy and intensify measurements in areas with high risk.

### 5.2.2 Case study

The case study continues when the execution phase commences. The procedure regarding the ERA is the same as for the planning and design phase. The way in which effects and exposure are compared and how the risk is characterized is different. The majority of practical aspects that were mentioned in Subsection 5.1.2 are still applicable. The failure definition for example remains based on the proportion of a community that is allowed to show a certain effect. It is repeated here for clarity: the sensitive receiver $SR2$ fails if 10% of the individuals in a community or more demonstrate lethal or paralethal effects (category 3) or if 90% of the individuals in a community or more demonstrate at least sublethal effects (category 2).

As mentioned in Chapter 4, the deterministic approach is based on an estimate of one representative value for exposure and one representative dose-response curve. The dose-response curve is in this case obtained from the data set by Newcombe and Jensen (1996), as elaborated in Chapter 2. Safety factors, according to Equation 4.8, may be applied to the parameters of the ordered response model, when appropriate. The exposure is again a linear combination of concentration and duration, resulting from dredging production data and hydrodynamic and transport modeling, as explained in Chapter 3. Exposure is modeled with all input parameters taking on a characteristic value.

The average value of the strength is obtained after solving Equation 5.2 for the average values of the regression parameters, as shown in Table 2.2. The result is that the first condition is the most restrictive, which leads to a value for $R = (x'\hat{\beta})_{crit} = 1.2577$. In Figure 5.4, the top right figure, the fitted normal distribution of strength $R$ is shown. The parameters are $\mu = 1.2575$ and $\sigma = 0.3700$. The mean value is nearly the same as the earlier calculated value of $R = 1.2577$. To obtain a value for the load $S$, several scenarios can be simulated. The first one is a 'worst case scenario', which has a low probability of occurrence. This scenario can be interpreted as risk averse. Furthermore there are a likely scenario with dominant wind conditions and a likely scenario with unfavorable wind conditions. The latter may occur not as often as the former, but is likely ot occur at least for a number of days during the project execution.

#### "Worst case scenario"

In a worst case scenario, all variables will be estimated in a conservative manner. Strength $R$ will be determined using Equation 4.8, with a value for $k_R = -1$. This results in a representative value for the strength $R_{rep} = \mu_R + k_R \cdot \sigma_R = 1.2575 - 0.3700 = 0.8875$. The simulation has been carried out with the parameters as specified in Table 5.4, which resulted in a value for the representative load $S_{rep} = 1.5127$. A quick calculation of $Z_{rep} = 0.8875 - 1.5127 = -0.6252$ leads to the conclusion that the ecosystem attribute under consideration, $SR2$, will fail, according to the failure definition stated above. It depends on the risk management program what kind of effort is necessary to increase the $Z$-value to safer territory, i.e. above zero.

When it is of paramount importance that failure, as defined above, never occurs (tail events excluded), mitigating measures or other risk reducing techniques have to be applied.

### Likely scenario

Another possibility is a scenario that has the highest probability of occurrence. All variables take on their expected value and no safety factors are applied. The representative value for the strength will be calculated with average values for all ordered response model regression parameters, which leads to $R_{rep} = 1.2577$. The simulation has been carried out with the parameters as specified in Table 5.4, which resulted in a value for the representative load $S_{rep} = 0.8172$ and $Z_{rep} = 0.4405$. In the most likely situation, failure will probably not occur. However, the value of $Z_{rep} = 0.4405$ is not high compared to the results from the simulation in a 'worst case scenario'. This implies a necessity for careful monitoring and possibly certain preventive measures.

### Likely scenario with unfavorable wind conditions

Average production figures with unfavorable wind conditions is a scenario with a high probability of occurrence as well. All variables take on their expected value and no safety factors are applied. The representative value for the strength will be calculated with average values for all ordered response model regression parameters, which leads to $R_{rep} = 1.2577$. The simulation has been carried out with the parameters as specified in Table 5.4, which resulted in a value for the representative load $S_{rep} = 0.9070$ and $Z_{rep} = 0.3507$. In this very likely situation, failure will probably not occur. However, the value of $Z_{rep}$ is just high enough to avoid failure. This implies a great necessity for careful monitoring and preventive measures.

| Variable | Unit | Value | Comments |
|---|---|---|---|
| Panel 1: ‘Worst case scenario’ | | | |
| $R_{rep}$ | – | 0.8875 | $\mu_R - 1 \cdot \sigma_R$ |
| $C_{2D}$ | $\sqrt{m}/s$ | 55 | Average value |
| $w_s$ | $m/s$ | $1 \cdot 10^{-5}$ | Extremely low value |
| $Q$ | $m^3/s$ | 25 | High production |
| $c$ | $kg/m^3$ | 100 | Many fines in mixture |
| $U_{10}$ | $m/s$ | 2.5 | Low value leads to little dispersion |
| $Dir_{wind}$ | $^\circ$ | 0 | Directed towards sensitive receiver |
| Panel 2: Likely scenario | | | |
| $R_{rep}$ | – | 1.2577 | $\mu_R$ |
| $C_{2D}$ | $\sqrt{m}/s$ | 55 | Average value |
| $w_s$ | $m/s$ | $5.5 \cdot 10^{-5}$ | Average value |
| $Q$ | $m^3/s$ | 11.3 | Average value |
| $c$ | $kg/m^3$ | 15.0 | Average value |
| $U_{10}$ | $m/s$ | 7.0 | Average value |
| $Dir_{wind}$ | $^\circ$ | 90 | Dominant direction |
| Panel 3: Likely scenario with unfavorable wind conditions | | | |
| $R_{rep}$ | – | 1.2577 | $\mu_R$ |
| $C_{2D}$ | $\sqrt{m}/s$ | 55 | Average value |
| $w_s$ | $m/s$ | $5.5 \cdot 10^{-5}$ | Average value |
| $Q$ | $m^3/s$ | 11.3 | Average value |
| $c$ | $kg/m^3$ | 15.0 | Average value |
| $U_{10}$ | $m/s$ | 2.5 | Low value leads to little dispersion |
| $Dir_{wind}$ | $^\circ$ | 0 | Directed towards sensitive receiver |

Table 5.4: In Panel 1 the estimates for relevant variables in a ‘worst case scenario’. The descriptions of the variables are equal to those in Table 5.1. In Panel 2 the estimates for relevant variables in a likely scenario, with dominant wind conditions. Finally, in Panel 3 the estimates for relevant variables in a likely scenario, with unfavorable wind conditions.

# Chapter 6

# Conclusion

## 6.1 Conclusions

The objective of this thesis has been to develop a risk-based approach to assess the effect of dredge plumes on sensitive receivers. In Chapter 1, the Ecological Risk Assessment (ERA) was proposed to act as a framework, which provided a clear approach with a number of discernible steps. Research questions were formulated to be able to reach the objective in an effective way and develop the methods necessary to do a proper risk assessment. Based on the obtained results, conclusions can be formulated. This will be done by revisiting the research questions one by one:

**I How can receiver sensitivity to stresses be quantified?**

The assessment of the vulnerability of natural habitats of a wide range of flora and fauna is not a simple task. Natural variation in distribution and abundance among several species indicates that many complex processes are at work and the addition of exposure to an external stressor will only increase that complexity. Cumulative and indirect effects might occur on top of direct effects, which decreases the reliability of effect estimates. Risk agents should keep in mind this limited reliability. However, methods exist to include variability in dose-response relationships, which provides a way to treat the inherent uncertainty.

Dose-response curves are an effective tool to represent dose-response relationships that occur in aquatic ecosystems. The often encountered sigmoidal shape of the curve enables a normal or logistic distribution function to represent the fraction of a community that shows a certain ecological effect. When a sufficiently large data set is available, curve fitting methods can be applied to obtain a dose-response curve for a certain type of species. Standard errors in parameter estimates resulting from a scatter in the data offers solutions for the problem of uncertainty. It provides information on the degree of uncertainty, which can be used in a later stadium in the risk characterization.

The effect which develops in a receiver does not only depend on the suspended sediment level. Other possibly significant factors include exposure duration and exposure persistence. Whether or not these are in fact important can only be known from field data or laboratory experiments. However, there is a severe lack of data and the data that is available lacks a coherent method of presentation.

Before death ensues in a sensitive receiver which is exposed to a certain suspended sediment concentration, several other effects might occur. Behavior changes, after which sublethal effects and finally lethal and paralethal effects take place. These stages in the severity of effects can be represented by means of an ordered response model, an elaboration of a single dose-response relationship. Multiple categories have to be specified to be able to formulate a suitable definition of failure. The literature is not coherent in that respect, which has lead to a lack of sufficient data.

**II How can stresses be quantified?**

When the overflow plume of a TSHD is analyzed, for example, it appears at first as a negative-buoyant jet. This is referred to as a dynamic plume. Several processes affect the dispersion of the plume, which under the influence of the ambient water flow ultimately results in a passive plume. For other dredging equipment, the processes might be very different. All these notions have to be modeled to obtain a source term for the hydrodynamic and transport model. Subsequently, suspended sediment concentration levels at the location of the sensitive receiver have to be determined.

Delft3D-FLOW, a hydrodynamic and transport model, and DelftDashboard, a pre-processing tool, can be used to carry out the plume modeling. Input has to be specified in terms of a discharge and concentration, taking into account spatial and temporal variation. The result of this modeling exercise is a time series of concentration levels at a sensitive receiver, which has to be related to the earlier derived dose-response curve. This means that at least values for concentration and exposure duration have to be distilled from the modeling output.

**III How can risk be quantified, taking into account the role of uncertainty?**

Ecological effects and the stresses that cause them are not easily quantified. A large number of uncertainties can be indicated, which makes the correct prediction of effects impossible. Variation within ecosystem communities, background conditions and external stresses are inherently uncertain and so are important modeling parameters such as the 2D-Chézy coefficient $C_{2D}$, wind velocity $U_{10}$ and wind direction. Lack of data is causing parameter uncertainty regarding the regression coefficients of the ordered response model. The formulation of the source term, where the dynamic phase of the dredge plume is severely simplified, leads to model uncertainty.

To assess the reliability of a sensitive receiver, effects and exposure estimates have to be compared. This can be done by means of a reliability function $Z = R - S$, where $R$ represents the strength and $S$ represents the load. A value of $Z < 0$ is equal to failure, where failure has to be clearly defined in terms of the effects defined in the dose-response relationship. Two important approaches to characterize risk are the probabilistic and deterministic approach. The former explicitly includes the parameter uncertainty which results from the fitting of an ordered response model, the latter assumes the most likely dose-response curve. In addition, a probabilistic approach requires a large number of exposure simulations where important parameters are represented by stochastic variables, whereas a deterministic approach carries out one representative simulation.

**IV How can a risk-based approach be applied to current dredging practice?**

Earlier concerns regarding a lack of reliable data, several model simplifications, unknown project execution methods, natural variation etc. cast doubt on the reliability and therefore applicability of a quantitative risk assessment. But to quote Nobel laureate Douglas North:

"The price you pay for precision is an inability to deal with real-world issues." It can be of great insight to risk agents and of great value to a dredging firm to estimate effects, exposure and ultimately risk. Risk management strategies are an important aspect of successful project design, planning and execution. Penalties for non-compliance to environmental criteria are severe and unanticipated damage of ecosystems is unwanted. Insight in uncertainties provides the risk agent with an opportunity to point to gaps in knowledge and gives a quantitative estimate about the importance of the different factors leading to the adverse effect. This can in turn be used to indicate fields of further investigation and the selection of precautionary action and, if appropriate, mitigating measures. In addition, the ERA might be used to adapt the monitoring strategy and intensify measurements in areas with high risk.

## 6.2 Recommendations

### 6.2.1 Environmental Impact Assessment

Dredging projects are subject to stringent regulation with respect to environmental compliance. The Environmental Impact Assessment (EIA) is an important aspect of several regulatory frameworks around the globe. The general approach that is currently applied in the dredging industry consists of a prediction of suspended sediment levels, which have to be compared to thresholds as laid out in the EIA. As a result, several conservative assumptions are applied leading to predictions in a worst case scenario. This method guarantees compliance to environmental criteria, but leads to undesirably high cost. In addition, the environmental criteria are rigid, often quite arbitrary and fail to link the dredging activity to ecological effects in an effective way. The effects assessment is carried out in the EIA, whereas the exposure assessment is carried out by the dredging firm. To be able to characterize ecological risk and predict the value of damage to the environment, the ERA has to be carried out by one responsible agent, within the framework of an EIA.

### 6.2.2 Economic analysis

Certain general categories of costs and benefits, applicable to the majority of projects in the vicinity of sensitive receivers, can be discerned. Costs consist of the cost of the dredging project, damage to the environment, the cost of measures that have to be taken to reduce this damage and the cost of measures to obtain positive ecological effects (in addition to unintended effects). Benefits consist of the value of the dredging project and unintended and intended positive ecological effects. Positive ecological effects obtained by the integration of ecosystem services in the value chains of businesses are very beneficial to dredging projects. *Building with Nature*, in which Van Oord Dredging and Marine Contractors B.V. is a partner, is a program which advocates this approach. Assuming a 'Homo Economicus' as decision maker, a cost-benefit analysis will be the basis to decide on the feasibility of dredging projects. A necessary condition to be able to carry out this economic analysis is the possibility to estimate the cost of damage in a quantitative way. It is my recommendation to continue to develop methods to estimate risk of damage in a quantitative way. It is the most transparent and most objective way to assess ecological risk and leads to optimal allocation of resources.

### Valuation of ecosystem services

Table 6.1 shows an example of services an ecosystem provides, in this case an estuary. The valuation of ecosystem services, which enables an estimation of the cost of damage, is a complex and controversial exercise (TEEB, 2010). However, it can inform risk agents and decision makers about costs and benefits of ecosystem conservation. Services have to be identified and subsequently a monetary value has to be determined. In the past decades, the quality of valuation standards has increased, from which the ERA can benefit greatly. If the value of ecosystems is not properly determined, it is hard for dredge firms and authorities to make decisions about the way to deal with them in a responsible manner. The economic value of environmental assets needs to be determined, which can be divided into three parts (Ahmed et al., 2005):

1. Direct uses (products, recreation)
2. Indirect uses (biological support, e.g. a food source; physical protection, e.g. a salt marsh)
3. Non-use values (option and existence values)

Non-use values have had a minor role in the past, but when methods to determine those values will come into existence, they will play an increasingly important role. Environmental valuation in general can and should play an increasingly important role in decision making.

### Valuation of damage to the environment

When the valuation of ecosystem services is carried out, possible damage can be given a monetary value as well. In the past, extensive damage has occurred, but behavior was as though natural forms of capital were valueless (Hawken et al., 1999). Hanemann (1994) has been one of the main proponents of 'contingent valuation' to quantify damage to ecosystems. It is based on people's willingness to pay (WTP) to prevent harm to their environment. Surveys are used to estimate WTP values, after actual damage has occurred. A large-scale contingent valuation study was conducted after the Exxon Valdez oil spill to assess its harm to households within an extensive region of influence (Carson et al., 2003). It is my recommendation to assess the value of ecosystem services in a similar fashion.

| Services | Resources |
| --- | --- |
| • Transportation – provides natural shelter for sea-going vessels and connects the sea with inland waterways<br>• Coastal defense – a buffer area between land and the sea which reduces flood and storm damages<br>• Water cleaning – the filtration process provided by the salt marsh vegetation improves water quality<br>• Disposal areas – in the past more uncontrolled disposal of waste products and dredged material than today<br>• Recreational – supports a variety of recreational activities including tourism<br>• Educational – the diversity found in estuaries attracts scientists and students within biology, geology, chemistry, physics, history and social issues | • Settlement – land claim for industrial, residential and agricultural development<br>• Fisheries – commercially important fishing grounds and, in tropical zones, breeding habitat for shrimp<br>• Raw materials – aggregate removal; in tropical areas mangrove trees are used for timber and fuel<br>• Energy – tidal power plants |

Table 6.1: Functions of estuaries to society (Bray, 2008, p. 363)

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# Appendix A

# Dredge plumes

The primary purpose of dredging is the development and maintenance of navigation infrastructure (PIANC, 2008). Furthermore, dredging can be carried out for e.g. land reclamation, beach nourishments or the removal of contaminated sediment. In order to obtain these goals, material is excavated, transported and relocated elsewhere (Nieuwaal, 2001). This process will result in sudden change of seabed during removal and disposal and the formation of suspended sediment plumes. Examples of sources of dredge plumes are disturbance of the bed by a drag head or erosion of the local bed by a propeller jet. Plumes affect turbidity, suspended sediment concentration and sedimentation rate. Turbidity is an optical measure for cloudiness or haziness and is measured in Nephelometric Turbidity Units ($NTU$). It is defined as the interference with the passage of light rays through water caused by the presence of suspended matter scattering and absorbing light. All three factors may have an effect on sensitive receivers, such as benthic communities or coral reefs. However much more severe, the effects of removal and relocation are usually not the focus of regulation. The effects of plumes can be avoided, reduced or mitigated and are therefore more intensely regulated.

Dredging activities are not the only source of suspended sediment plumes. Natural processes, such as storms, currents and tsunami's and other commercial activities, such as fishing and shipping operation, contribute substantially as well (Aarninkhof, 2008). Suspended sediment concentrations of $15 - 30\ mg/L$ were measured after storm events in Lake Michigan (Pothoven et al., 2007) and river discharges in the Mississippi River (Green et al., 2006). These levels are similar to dredging-induced levels.

## A.1 Plume sources

To carry out a dredging project, several techniques are available (Bray, 2008). These different techniques result in different sources of dredge plumes. The degree of movement during operation is an important factor in the plume generating process. A source is considered a moving source when distance divided by velocity $L/v < 60\ s$, a more or less stationary source when $L/v > 60\ s$ and a stationary source when $L/v = \infty$. Examples of dredging techniques are:

- Trailing suction hopper dredger (TSHD, moving)
- Cutter suction dredger (CSD, more or less stationary)

- Backhoe dredger (BHD, more or less stationary)
- Grab dredger (more or less stationary)
- Bucket ladder dredger (more or less stationary)
- Settlement basin (stationary)
- Stationary suction dredger (stationary)
- Dredging activity during placement of material (stationary)

New innovations in dredging equipment are mainly due to environmental concerns. Modern dredging techniques include the dustpan dredger, dipper dredger and bed-leveler. Environmental aspects of transport and placement might be significant as well and there are several possible types of equipment and techniques, such as e.g. pipelines, hopper barges, roads, conveyor belts or combinations of the above. A selection of equipment will be discussed in more detail, starting with the TSHD.

### A.1.1 Trailing suction hopper dredger

The main causes of sediment release for a TSHD are (see Figure A.1):

- Discharge of overflow water via spillways
- Drag head disturbance at the seabed
- Turbulence caused by the dredger propeller scouring the seabed
- Discharge of screened material (in case of aggregate dredging, only sediment that is necessary is retained, the rest is discharged)
- Light (or Lean) Material over Board (LMOB) discharge
- Disturbance of gas in the sediment may enhance resuspension

The overflow discharge is a major source for the suspended sediment plume. Several aspects, such as trailing velocity and bottom material properties, play an important role in the plume generation phase. The trailing velocity of a TSHD during dredging operation varies from $0.5 - 2\ m/s$. The layer that is removed from the bed has the thickness of $0.1 - 0.3\ m$ in case of a sandy bottom and $0.2 - 0.8\ m$ for a muddy bottom. In case of granular material the way of excavation is shear, erosion and fluidisation. In case of cohesive, plastic bottom material with low strength, high concentrations are most important. Three subsequent phases of the hopper filling process can be discerned:

1. The hopper is being filled up with a sediment-water mixture until the overflow level is reached
2. The hopper overflows into the overflow arrangement, while a large part of the sediment settles (this is probably the course material)

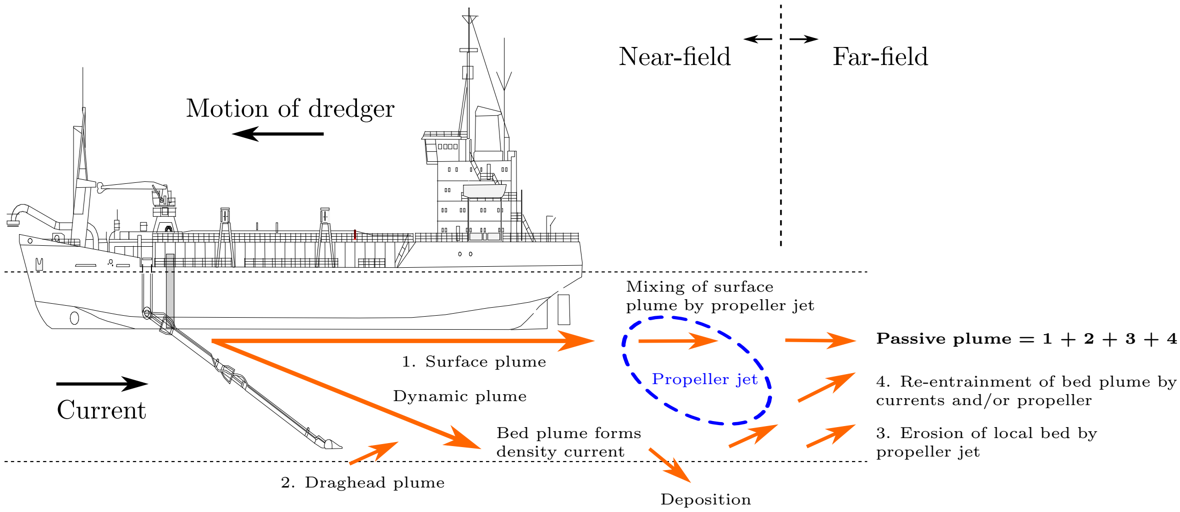


Figure A.1: Sources of a dredge plume near a TSHD (Spearman et al., 2011)

3. The overflow arrangement is adjusted downwards, so the hopper volume decreases up to the maximum hopper content or optimal loading

Phase 2 determines the composition of the water-sediment mixture that is discharged in Phase 3. Van Rhee (2002) developed software to estimate the amount of TSHD overflow, a simple 1DV model and a more extensive 2DV model. To control the sources, some measures are available: optimizing trailing velocity, suction position and pump discharge, reducing water intake/overflowing and the return flow method. Inside the hopper, the settling process has a great influence on the plume formation. Factors that influence the settling process are residence time, concentration of fines and overflow discharge. Several environmental improvements have been developed for the TSHD, such as the green valve system. More types of innovations include:

- Low density trailers with improved settlement
- Controlled overflow
- Outflow close to the keel
- Recirculation of overflow water
- Submerged pumps

### A.1.2 Cutter suction dredger

The main causes of sediment release for a CSD are:

- Rotation of the cutter causes centrifugal forces which 'throw' material out of reach of the suction and adds to turbulence and resuspension
- When excavation production exceeds pumping capacity excess material is released
- The disturbance of gas in the sediment may enhance resuspension

- Rarely the material may be pumped into a barge, in which case there will be losses due to splashing and overflow
- Anchor and wire movement
- Pipeline leakage

To control the sources, some measures are available: optimizing cutter rotating speed, ladder swing velocity and suction discharge, shielding the cutter head or suction head and optimizing the design of the cutter head. The type of cutter head (e.g. for soft soils) can make a big difference for the loose spill layers. This spill layer is easily erodible and will be a long-lasting source for an increased suspended sediment content or turbidity.

### A.1.3 Other equipment

A grab dredger consists of a clamshell grab fixed to a crane; sediment resuspension occurs when the grab impacts with the seabed, during bed disturbance when material is initially removed and by spillage as the grab is hoisted or lowered through the water column. Like grab dredgers, backhoe dredgers re-suspend sediment when the bucket hits the seabed, and spillage occurs when lifted or lowered. A bucket ladder dredger causes a plume by means of bed disturbance by the buckets, spillage from the buckets, leakage from the chutes and spillage during the loading of barges.

## A.2 Plume dynamics

According to Lee and Chu (2003), "plumes are fluid motions that are produced by continuous sources of buoyancy." In the case of overflow discharges of a water-sediment mixture from a TSHD, a negative-buoyant, or dynamic, plume will be formed (Dankers, 2002). The dispersion of the dredging spill depends on hydrodynamic circumstances and sediment properties and has a major influence on its behavior and effects. The plume can be either mixed with the surrounding water to form a passive plume or impinge on the bottom as a result of its momentum and propagate as a density current. The amount of sediment that is discharged, size distribution, disaggregation properties and the amount of energy put into the dredging operation all affect the plume. The finer the sediment, the higher the turbidity for any given concentration will be. Silty mixtures typically produce more noticeable and longer lasting plumes, although this does not necessarily imply a more severe effect.

### A.2.1 Dynamic plume

In a dynamic plume, which propagates under its own volition, the behavior is determined by material concentration and properties. The main causes for a dynamic plume are TSHD overflow, screening during aggregate dredging, pipeline discharge in the aquatic environment and hopper discharge either through bottom opening or pumped discharge. The zone of influence is pancake shaped, after the plume impinges the bottom and subsequently moves radially outward. The radius usually equals $100 - 200\ m$.

### A.2.2 Passive plume

Due to interaction between the dynamic plume and the ambient cross flow, removal of sediment from the dynamic plume can occur, known as stripping (Van Eekelen, 2007). The sediment will then be subject to mixing with the surrounding water, resulting in a passive plume. A division between dynamic and passive phases is convenient, but it should be understood that in reality it is a mixture or transition. Other operations, e.g. the interaction between cutter head and sea bottom when deploying a CSD, may also result in the formation of a passive plume. The dominant processes in a passive plume are advection and diffusion, which are processes in the ambient water. The plume responds to those influences, to the hydrodynamic environment. Other factors that affect the passive plume are the material properties, in particular settling velocity; currents, causing advection and turbulence and finally the additional effects of wind and waves. Due to the rapid mixing of the passive plume with the surrounding water, the released material will be averaged over the water column. The region of influence can go up to several kilometers.

### A.2.3 Classification

For the characterization of plumes in a cross flow, two dimensionless parameters are available: the plume Richardson number $Ri$ and the velocity ratio $\zeta$ (Winterwerp, 2002):

$$Ri = \frac{g\Delta\rho_0/\rho_a D}{W_0^2}, \tag{A.1}$$

$$\zeta = \frac{U}{W_0}, \tag{A.2}$$

where

| | |
|---|---|
| $g$ | acceleration due to gravity |
| $\Delta\rho_0 = \rho_0 - \rho_a$ | difference between initial plume density and ambient density |
| $D$ | initial plume diameter |
| $W_0$ | initial vertical plume velocity |
| $U$ | ambient velocity of the cross flow |

The Richardson number compares buoyancy with kinetic energy and the velocity ratio compares cross flow velocity with vertical plume velocity. Winterwerp (2002) developed a classification diagram, which is depicted in Figure A.2.

Other influences on the plume are ship movements, air in the overflow mixture and the disturbance from ship propellers. Also cohesive sediment properties complicate the matter: sediment concentration, turbulent structure and salinity affect the density and size of flocs, which then affects settling velocity. Whereas settling velocity in the background material is constant in time, in a plume it decreases, since courser sediment settles first.

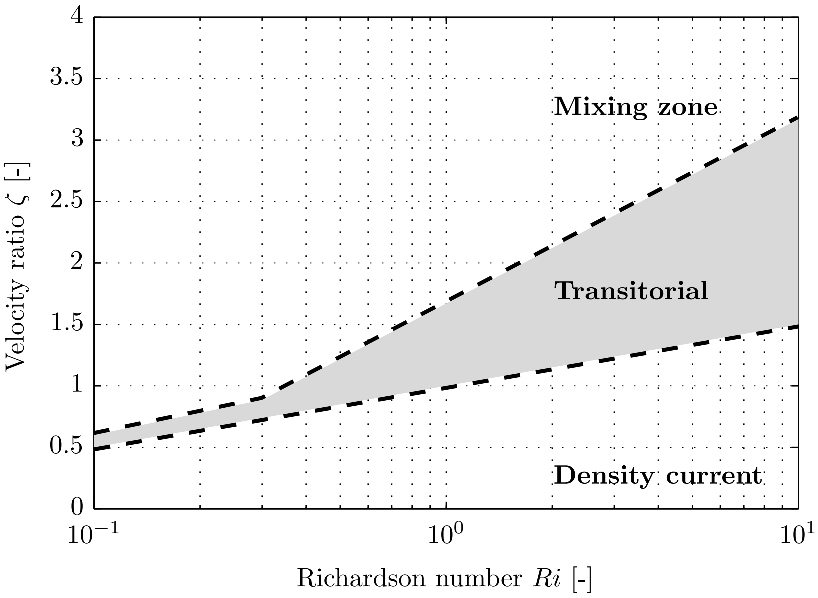


Figure A.2: $Ri$, $\zeta$ diagram with the classification by Winterwerp (2002)

# Appendix B

# Plume modeling

To be able to predict suspended sediment concentrations in the area of interest, a hydrodynamic (and transport) simulation program is required. The source term, as formulated in the previous paragraph, has to be included in the model. A suitable program for this purpose is the open source hydrodynamic model Delft3D-FLOW. In addition the pre-processing tool DelftDashboard is used, which is related to Delft3D and available within *OpenEarth* (Van Koningsveld et al., 2010). DelftDashboard is a standalone Matlab based graphical user interface, which facilitates a quick set up of new models. A large number of coupled toolboxes is available, which enable the use of several open source data sets. In particular the Dredge Plume toolbox within DelftDashboard allows a convenient specification of source terms for turbidity plumes.

Delft3D-FLOW is a model which calculates non-steady flow and transport phenomena that result from tidal and meteorological forcing. The numerical hydrodynamic modeling system solves the unsteady shallow water equations in two (depth-averaged) or three dimensions. The system of equations consists of the horizontal equations of motion, the continuity equation and the transport equations for conservative constituents. The flow is forced by tide at the open boundaries, wind stress at the free surface, pressure gradients due to free surface gradients (barotropic) or density gradients (baroclinic).

## B.1 Flow modeling

The 2DV (depth-averaged) or 3D non-linear shallow water equations are derived from the three dimensional Navier Stokes equations for incompressible free surface flow. Several assumptions and approximations are used, e.g. the assumption of shallow water and the Boussinesq approximation. The set of partial differential equations in combination with an appropriate set of initial and boundary conditions is solved on a finite difference grid. In the horizontal direction orthogonal curvilinear co-ordinates are used. Two systems are supported: Cartesian co-ordinates ($\xi$, $\eta$) and spherical co-ordinates ($\lambda$, $\phi$). The frame of reference for the vertical direction is shown in Figure B.1 and for the horizontal direction in Figure B.2. A conceptual description of Delft3D-FLOW can be found in the User Manual (Deltares, 2009). Some important aspects are discussed in more detail.

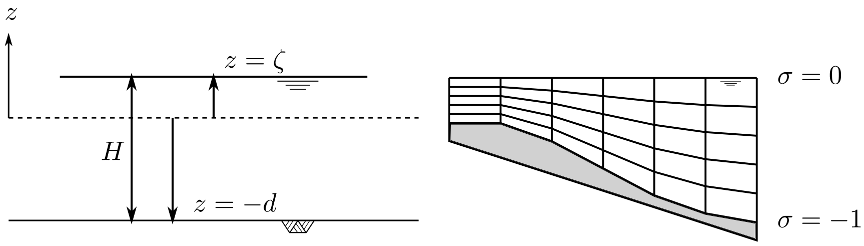


Figure B.1: Frame of reference (left) and $\sigma$-grid (right)

### B.1.1 Continuity equation

The depth-averaged continuity equation is given by:

$$\frac{\partial\zeta}{\partial t}+\frac{1}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial[(d+\zeta)U\sqrt{G_{\eta\eta}}]}{\partial\xi}+\frac{1}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial[(d+\zeta)V\sqrt{G_{\xi\xi}}]}{\partial\eta}=Q, \tag{B.1}$$

where $\zeta$ is the water level and $d$ is the depth, as defined in Figure B.1, $\sqrt{G_{\xi\xi}}$ and $\sqrt{G_{\eta\eta}}$ are coefficients used to transform curvilinear to rectangular co-ordinates, $U$ and $V$ are depth-averaged velocities in $\xi$- and $\eta$-direction respectively, as defined in Figure B.2 and $Q$ is the water discharge or withdrawal per unit area, precipitation and evaporation:

$$Q=H\int_{-1}^{0}(q_{in}-q_{out})\mathrm{d}\sigma+P-E. \tag{B.2}$$

### B.1.2 Momentum equations in horizontal direction

The momentum equations in $\xi$- and $\eta$-direction are given by:

$$\frac{\partial u}{\partial t}+\frac{u}{\sqrt{G_{\xi\xi}}}\frac{\partial u}{\partial\xi}+\frac{v}{\sqrt{G_{\eta\eta}}}\frac{\partial u}{\partial\eta}+\frac{\omega}{d+\zeta}\frac{\partial u}{\partial\sigma}-\frac{v^2}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial\sqrt{G_{\eta\eta}}}{\partial\xi}+$$
$$\frac{uv}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial\sqrt{G_{\xi\xi}}}{\partial\eta}-fv=-\frac{1}{\rho_0\sqrt{G_{\xi\xi}}}P_\xi+F_\xi+\frac{1}{(d+\zeta)^2}\frac{\partial}{\partial\sigma}(\nu_V\frac{\partial u}{\partial\sigma})+M_\xi, \tag{B.3}$$

and

$$\frac{\partial v}{\partial t}+\frac{u}{\sqrt{G_{\xi\xi}}}\frac{\partial v}{\partial\xi}+\frac{v}{\sqrt{G_{\eta\eta}}}\frac{\partial v}{\partial\eta}+\frac{\omega}{d+\zeta}\frac{\partial v}{\partial\sigma}+\frac{uv}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial\sqrt{G_{\eta\eta}}}{\partial\xi}+$$
$$\frac{u^2}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial\sqrt{G_{\xi\xi}}}{\partial\eta}-fu=-\frac{1}{\rho_0\sqrt{G_{\eta\eta}}}P_\eta+F_\eta+\frac{1}{(d+\zeta)^2}\frac{\partial}{\partial\sigma}(\nu_V\frac{\partial v}{\partial\sigma})+M_\eta, \tag{B.4}$$

where $u$, $v$ and $\omega$ are flow velocities in $\xi$-, $\eta$- and $s$-direction, $f$ is the Coriolis parameter, $\rho_0$ is the reference density of water, $P_\xi$ and $P_\eta$ represent the pressure gradients, $F_\xi$ and $F_\eta$ are forces representing the unbalance of horizontal Reynold's stresses, $\nu_V$ is the vertical eddy viscosity coefficient and $M_\xi$ and $M_\eta$ are contributions due to external sources or sinks.

### B.1.3 Bed boundary condition

For 2D depth-averaged flow the shear-stress at the bed induced by a turbulent flow is assumed to be given by a quadratic friction law:

$$\vec{\tau}_b = \frac{\rho_0 g \vec{U}|\vec{U}|}{C_{2D}^2}, \tag{B.5}$$

where $\rho_0$ is the reference density of water, $|\vec{U}|$ is the magnitude of the depth-averaged horizontal velocity and $C_{2D}$ is the 2D-Chézy coefficient.

### B.1.4 Free surface boundary condition

At the free surface, the boundary conditions for the momentum equations require a formulation for the surface stress. Without wind, the stress is zero. The magnitude of the wind shear-stress is determined by:

$$|\vec{\tau}_s| = \rho_a C_d U_{10}^2, \tag{B.6}$$

where $\rho_a$ is the density of air, $U_{10}$ is the wind speed 10 meter above the free surface (time and space dependent) and $C_d$ is the wind drag coefficient, dependent on $U_{10}$. At the open water boundaries, data needed for the boundary conditions can be obtained from measurements, tide tables or from a larger model, which encloses the model at hand (nesting).

### B.1.5 Grid

To solve the partial differential equations the equations have to be transformed to the discrete space. The numerical method of Delft3D-FLOW is based on finite differences. To discretise the 3D shallow water equations in space, the model area is covered by a curvilinear grid. It is assumed that the grid is orthogonal and well-structured. The grid co-ordinates can be defined either in a Cartesian or in a spherical co-ordinate system. In both cases a curvilinear grid, a file with curvilinear grid co-ordinates in the physical space, has to be provided. The numerical grid transformation is implicitly known by the mapping of the co-ordinates of the grid vertices from the physical to the computational space. The geometrical quantities $\sqrt{G_{\xi\xi}}$ and $\sqrt{G_{\eta\eta}}$ introduced in Equation B.1, Equation B.3 and Equation B.4, have to be discretised on the computational grid, see Figure B.2. The primitive variables water level and velocity ($u$, $v$, $w$) describe the flow. To discretise the 3D shallow water equations, the variables are arranged in a special way on the grid, see Figure B.2 and Figure B.3. The pattern is called a staggered grid. This particular arrangement of the variables is called the Arakawa C-grid. The water level points (pressure points) are defined in the centre of a (continuity) cell. The velocity components are perpendicular to the grid cell faces where they are situated.

### B.1.6 Time integration

Due to stability and accuracy, there are time step limitations for the time integration of the shallow water equations in Delft3D-FLOW. When $\Delta x$ and $\Delta y$ are the horizontal grid sizes, there is a number of limitations, as shown in Table B.1.

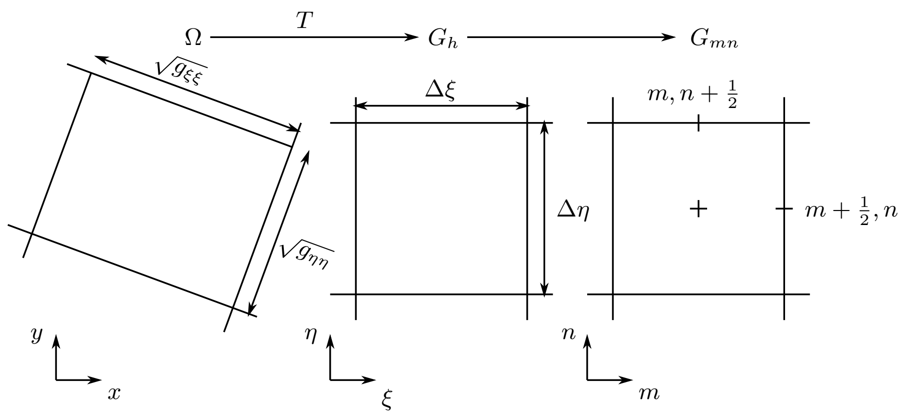


Figure B.2: Mapping of physical space to computational space

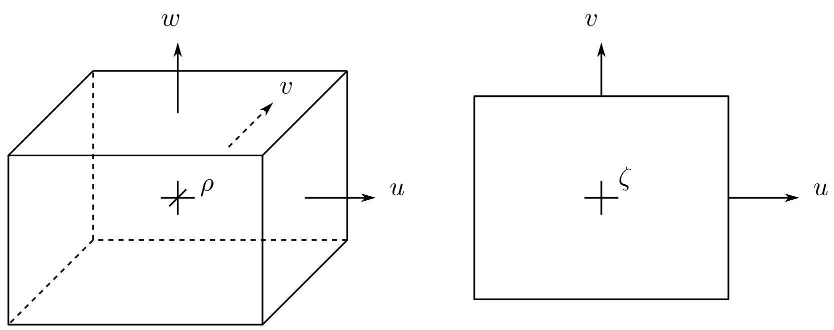


Figure B.3: Grid staggering, 3D view (left) and top view (right)

| | |
|---|---|
| Points per wave period $T$ | $\Delta t \leq \frac{T}{40}$ |
| Accuracy ADI for barotropic mode for complex geometries | $C_f = 2\Delta t\sqrt{gH(\frac{1}{\Delta x^2} + \frac{1}{\Delta y^2})} < 4\sqrt{2}$ |
| Explicit advection scheme "Flooding scheme" and for the $Z$-grid model | $\frac{\Delta t \lvert u \rvert}{\Delta x} < 2$ |
| Stability baroclinic mode internal wave propagation ($Z$-grid model only) | $\Delta t\sqrt{\frac{(\rho_{bottom} - \rho_{top})}{\rho_{top}} g\frac{H}{4}(\frac{1}{\Delta x^2} + \frac{1}{\Delta y^2})} < 1$ |
| Explicit algorithm flooding | $\frac{\Delta t \lvert u \rvert}{\Delta x} < 2$ |
| Stability horizontal viscosity term (HLES, partial slip, no slip) | $2\Delta t\nu_H(\frac{1}{\Delta x^2} + \frac{1}{\Delta y^2}) < 1$ |

Table B.1: Time step limitations

## B.2 Sediment transport modeling

Sediment transport and morphology are supported in Delft3D-FLOW; bed-load and suspended load transport of non-cohesive sediments and suspended load of cohesive sediments can be modelled. The advection-diffusion (mass-balance) equation that has to be solved for 3D transport of suspended sediment is given by:

$$\frac{\partial c^{(\ell)}}{\partial t} + \frac{\partial u c^{(\ell)}}{\partial x} + \frac{\partial v c^{(\ell)}}{\partial y} + \frac{\partial (w - w_s^{(\ell)}) c^{(\ell)}}{\partial z} - \frac{\partial}{\partial x}\left(\varepsilon_{s,x}^{(\ell)} \frac{\partial c^{(\ell)}}{\partial x}\right) - \frac{\partial}{\partial y}\left(\varepsilon_{s,y}^{(\ell)} \frac{\partial c^{(\ell)}}{\partial y}\right) - \frac{\partial}{\partial z}\left(\varepsilon_{s,z}^{(\ell)} \frac{\partial c^{(\ell)}}{\partial z}\right) = 0, \quad \text{(B.7)}$$

where $c^{(\ell)}$ is the mass concentration of sediment fraction $(\ell)$, $u$, $v$ and $w$ are flow velocity components, $\varepsilon_{s,x}^{(\ell)}$, $\varepsilon_{s,y}^{(\ell)}$ and $\varepsilon_{s,z}^{(\ell)}$ are eddy diffusivities of sediment fraction $(\ell)$ and $w_s^{(\ell)}$ is the (hindered) sediment settling velocity of sediment fraction $(\ell)$.

Sediment is different from ordinary constituents, such as salinity and heat, since it is exchanged between the bed and the flow and it settles due to the action of gravity. The settling velocity, deposition and erosion are processes that are sediment-type specific. Equation B.7 needs initial conditions and boundary conditions. The initial conditions can be specified globally or space-varying. The boundary conditions consist of a water surface boundary condition, a bed boundary condition and open inflow and outflow boundary conditions. For the water surface boundary, the diffusive flux is zero:

$$-w_s^{(\ell)} c^{(\ell)} - \varepsilon_{s,z}^{(\ell)} \frac{\partial c^{(\ell)}}{\partial z} = 0, \text{ at } z = \zeta, \quad \text{(B.8)}$$

where $z = \zeta$ is the location of the free surface (see Figure B.1). The exchange of suspended sediment is determined by the flux from the bed to the bottom layer and vice versa. In every cell a source and sink term are then applied and the bed level is updated. The bed boundary condition reads:

$$-w_s^{(\ell)} c^{(\ell)} - \varepsilon_{s,z}^{(\ell)} \frac{\partial c^{(\ell)}}{\partial z} = D^{(\ell)} - E^{(\ell)}, \text{ at } z = z_b, \quad \text{(B.9)}$$

where $D^{(\ell)}$ is the sediment deposition rate of sediment fraction $(\ell)$ and $E^{(\ell)}$ is the sediment erosion rate of sediment fraction $(\ell)$. For the open inflow boundaries, conditions for all conservative constituents need to be specified. A Thatcher-Harleman return time can be specified to simulate re-entry of material that flowed out of the model. Another option allows to specify equilibrium concentration profiles for sediment fractions to be applied to inflow at the open boundaries. At the outflow boundaries, no conditions are applied, which means that only advection is considered.

### B.2.1 Settling velocity

Cohesive sediment tends to form flocs when it is suspended in salt water. These flocs are larger than the particles they consist of and have a higher settling velocity. For single mud flocs with a fractal structure in still water, a formula for the settling velocity can be obtained from a balance between gravitational and drag force. For spherical, Euclidean particles in the

Stokes' regime, where $Re_f \ll 1$, the Stokes' formula for a stationary settling particle reads (Van Rijn, 1984; Winterwerp and van Kesteren, 2004):

$$w_{s,r} = \frac{(\rho_s - \rho_w) g D_f^2}{18\mu}, \tag{B.10}$$

where $D_f$ is the representative mud floc diameter and $\mu$ is the dynamic viscosity. To take into account flocculation effects and hindered settling, Van Rijn (2007) proposes the following equation for the sediment settling velocity:

$$w_s = \phi_{floc} \phi_{hs} w_{s,r}, \tag{B.11}$$

where $\phi_{floc}$ is the flocculation factor and $\phi_{hs}$ is the hindered settling factor. For a salinity $Sa \geq 5ppt$ and particles finer than $D_{sand} = 63\mu m$, the flocculation factor is given by:

$$\phi_{floc} = [4 + \log_{10}(2c/c_{gel})]^{\alpha}, \quad \text{with a minimum value of 1 and a maximum value of 10,} \tag{B.12}$$

where $\alpha = (D_{sand}/D_{50}) - 1$, with $\alpha_{min} = 0$ and $\alpha_{max} = 3$; $c$ is the mass concentration $(= \rho_s c_{volume})$ and $c_{gel}$ is the gelling mass concentration (between 130 and 1722 $kg/m^3$). Hindered settling is negligible due to the low suspended sediment concentrations in turbidity plumes (i.e. $\phi_{hs} = 1$).

### B.2.2 Erosion and deposition

To calculate the exchange between water phase and bed, the Partheniades-Krone formulations are used (Partheniades, 1965):

$$E^{(\ell)} = M^{(\ell)} S(\tau_{cw}, \tau_{cr,e}^{(\ell)}), \tag{B.13}$$

$$D^{(\ell)} = w_s^{(\ell)} c_b^{(\ell)} S(\tau_{cw}, \tau_{cr,d}^{(\ell)}), \tag{B.14}$$

$$c_b^{(\ell)} = c^{(\ell)}(z = \frac{\Delta z_b}{2}, t), \tag{B.15}$$

where $E^{(\ell)}$ is the erosion flux, $M^{(\ell)}$ is the erosion parameter, $S(\tau_{cw}, \tau_{cr,e}^{(\ell)})$ is the erosion step function, given by:

$$S(\tau_{cw}, \tau_{cr,e}^{(\ell)}) = \begin{cases} (\frac{\tau_{cw}}{\tau_{cr,e}^{(\ell)}} - 1), & \text{when } \tau_{cw} > \tau_{cr,e}^{(\ell)}, \\ 0, & \text{when } \tau_{cw} \leq \tau_{cr,e}^{(\ell)}, \end{cases} \tag{B.16}$$

$D^{(\ell)}$ is the deposition flux, $w_s^{(\ell)}$ is the settling velocity, $c_b^{(\ell)}$ is the average sediment concentration in the near bottom computational layer, $S(\tau_{cw}, \tau_{cr,d}^{(\ell)})$ is the deposition step function, given by:

$$S(\tau_{cw}, \tau_{cr,d}^{(\ell)}) = \begin{cases} (1 - \frac{\tau_{cw}}{\tau_{cr,d}^{(\ell)}}), & \text{when } \tau_{cw} < \tau_{cr,d}^{(\ell)}, \\ 0, & \text{when } \tau_{cw} \geq \tau_{cr,d}^{(\ell)}, \end{cases} \tag{B.17}$$

where $\tau_{cw}$ is the maximum bed shear stress, $\tau_{cr,e}^{(\ell)}$ is the critical erosion shear stress and $\tau_{cr,d}^{(\ell)}$ is the critical deposition shear stress.