“Slibvaren”

ADJUSTMENT OF THE HARBOUR ADMITTANCE POLICY BY REDUCTION OF THE MINIMAL REQUIRED UNDER KEEL CLEARANCE (UKC)

Master thesis
Geert Roukens
Delft, 25 November 2016

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ADJUSTMENT OF THE HARBOUR ADMITTANCE POLICY BY REDUCTION OF THE MINIMAL REQUIRED UNDER KEEL CLEARANCE (UKC)

by

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Abstract

All harbours require frequent dredging to cope with sedimentation. In certain cases the deposited sediment/silt forms a weak soil layer referred to as fluid mud. The top layer is often used as nautical bottom, while its presence is not necessarily harmful to the vessel. This could lead to the conclusion that the safety margin underneath a vessel (i.e., Under Keel Clearance (UKC)) is too large/safe and can be reduced. Research indicates that the UKC can be decreased to smaller ($<10\%$) or negative (0 to -10%) values. Reducing the UKC leads to less dredging and allowance of higher draught vessels. This can create economic benefits for the port authority and, depending on the chosen strategy, shipping company. Less dredging is also likely to reduce the amount of sediment that is re-suspended and could thus assist the system in reducing turbidity. Altered vessel behaviour by a smaller UKC and the possible resulting safety impairments create application challenges. These effects are caused by undulations in the water-mud interface (when sailing close to the fluid mud) or a too strong mud layer (when sailing through the mud).

A discussion is instigated as the result of different end-user objectives: navigational safety versus optimal port profit. Extensive knowledge from various scientific fields is required to make a sound consideration between safety and benefits. Within this thesis, the alignment between end-users and required scientific topics is studied using a Decision Support Model (DSM). The DSM is based on a Frame of Reference approach by van Koningsveld [2003] which is meant to improve communication and aid decision making. For conceiving the DSM, various objectives from end-users are categorized into three management context: economy, ecology and safety. In reducing the UKC the benefits (economy and ecology) are opposed by the potential downsides (safety). Knowledge from literature led to relevant topics in each management context. Three strategies where used for quantification: draught increase, dredging decrease or draught increase with maintaining the current UKC requirement.

The general DSM was applied to the case of Delfzijl where fluid mud and UKC reduction are topics of discussion. Weighing the strategies results in a dredging reduction being optimal. Relative small visiting vessels and high turbidity in the area cause this outcome. Difficulties in quantifying sub-elements are the result of knowledge gaps which might be resolved by further research. After addressing the topics of research, a sound decision on application can be made.

The complete DSM and the outcomes where presented to port authority, harbour masters and pilot at Delfzijl. Based on the DSM, these end-users where able to point out topics of concern

and provide additional feedback. These topics, mainly regarding safety, where subsequently assessed with a probabilistic tidal window model as proposed by Bouw [2005]. The model copes with the request for extra safety and can be easily extended when new knowledge on survey error and vessel velocity is obtained.

From this thesis it was apparent that the main challenge for an UKC reduction is the absence of a means to designate the strength based nautical bottom. Port authorities have no means of assessing the strength of the bottom and corresponding effects on vessel behaviour. This affects the decision whether to start experimentally reducing the UKC for visiting vessels. Resulting in no possibilities to gain experience in the concept. In addition, the port authority is not able to determine the depth contour change induced by an envisioned dredging reduction.

Samenvatting

Alle havens lijden onder sedimentatie waardoor frequent baggeren nodig is. In sommige gevallen zorgt deze sedimentatie voor afzetting van een vloeibare bodemlaag, ook wel 'fluid mud genoemd. De bovenkant van deze laag wordt vaak gezien als de nautische bodem dit terwijl hij geen sterkte heeft. Aangezien deze laag bij scheepsberoering geen directe schade veroorzaakt, zou men kunnen concluderen dat de huidige gehanteerde veiligheidsmarge (10 % van de diepgang) onnodig groot is. Uit onderzoekt blijkt dat, in geval van aanwezigheid van 'fluid mud, de veiligheidsmarge verkleind (tussen 0 en 10 %) of negatief (tussen 0 en -10 %) kan worden. Het verkleinen van de marge creert mogelijkheden voor het toelaten van schepen met een hogere diepgang of het reduceren van onderhoudsbaggeren. Beide zullen zorgen voor een verhoogde havenomzet. Daarnaast zorgt verminderen van baggeren mogelijk voor een verlaging van de ecologische impact. Het reduceren van de veiligheidsmarge is niet geheel zonder risico. Onderzoek toont aan dat golven kunnen ontstaan in de water-modder overgang. Dit kan zorgen voor een ander scheepsgedrag waarop niet gerekend is. Wanneer de vloeibaarheid van de modder verkeerd wordt ingeschat, dan kan dit leiden tot mogelijke bodem collisie en bijhorende gevaren.

Poging tot het reduceren van de veiligheidsmarge leidt tot een discussie tussen verschillende eindgebruikers. Gebruikers gemoeid met optimalisatie van de omzet zien het economisch voordeel van de reductie. Aan de andere kant twijfelen gebruikers die zich bezighouden met veiligheid over de mogelijke gevolgen van de verlaging. In deze thesis wordt met behulp van een besluitvormingsmodel getracht de twijfels die leiden tot de discussie bloot te leggen. Het model is gebaseerd op de 'Frame-of-Reference aanpak van van Koningsveld [2003]. Voor opstellen van het besluitvormingsmodel worden verschillende doelen van eindgebruikers gecategoriseerd in de contexten: veiligheid, economie, ecologie. Door vermindering van de veiligheidsmarge zullen de economische en ecologische voordelen tegenover de nadelen omtrent veiligheid staan. Op basis van drie strategien wordt een probleemafbakening bereikt en is kwantificeren van de voordelen per strategie mogelijk.

Het opgezette besluitvormingsmodel wordt getoetst op de case van Delfzijl. Daar is een reductie van de veiligheidsmarge al enige tijd punt van discussie. Kwantificering en daaropvolgende afweging van de strategien geeft aan dat een reductie van baggerinspanning optimaal is voor Delfzijl. Dit komt doordat relatief kleine schepen de haven aandoen. Daarnaast gaat het aanliggende Ems-Dollard gebukt onder een hoge sediment concentratie in het water. Tijdens de kwantificering van de strategien wordt gestuit op onbekende relaties. Deze moeili-

jkheden komen voort uit kennishiaten die overbrugd moeten worden voor verbetering van het besluitvormingsmodel. Overbrugging van deze hiaten zal leiden tot hantering van een kleinere veiligheidsmarge.

Het besluitvormingsmodel, de kwantificering en strategie vergelijking zijn gepresenteerd aan eindgebruikers in Delfzijl. Door de overzichtelijkheid van het besluitvormingsmodel wordt gemerkt dat de eindgebruikers gemakkelijk hun twijfels kunnen uitspreken. Zowel vastgelegde als nieuwe onderwerpen komen hier aan bod. Een deel van deze twijfels, met name omtrent veiligheid, zijn vervolgens geanalyseerd met behulp van een probabilistisch getijpoorten model bedacht door Bouw [2005]. Met het model kan extra veiligheid worden ingebouwd ten opzichte van een op sterkte gebaseerde nautische bodem. Niet alleen kan extra veiligheid ingebouwd worden, eveneens kan het makkelijk uitgebreid worden na verkrijgen van nieuwe kennis over invoerparameters als meetfouten en invloed van scheepsnelheid.

Tijdens deze thesis werd duidelijk dat de grootste uitdaging ligt in de afwezigheid van een passende techniek of methode voor het bepalen van een op sterkte gebaseerde nautische bodem. Hierdoor hebben havenautoriteiten niet de mogelijkheid om de locatie van de bodem te bepalen. Daardoor is de havenautoriteit terughoudend met het experimenteel verminderen van de veiligheidsmarge. Doordat dit niet geprobeerd wordt zal geen ervaring opgedaan worden en wordt niet bewezen dat het concept veilig toepasbaar is. Eveneens kan de havenautoriteit ook niet bepalen hoe het bodemprofiel zich zal ontwikkelen wanneer baggeren wordt verminderd.

Acknowledgement

This thesis was completed under contract at Van Oord Dredging and Marine contractors B.V. and in collaboration with EcoShape. Being involved with these leading firms in marine ingenuity and Building with Nature concepts resulted in gained experience which can not be replaced and which will be valuable for my upcoming years.

Extensive input from involved end-users was required for a comprehensive thesis. As a result multiple people from different companies are interviewed. This created a dynamic environment and caused constant change of work making this thesis a challenging and satisfactory piece. I would like to show my appreciation for all people who reserved time for meeting me. Special gratitude goes out to: Leendert Bourgonjen and Joop van Dijken employed at Groningen Seaports for providing me with local knowledge and data for conducting my case study. Bas Deen registered to the Dutch pilotage for providing his view and believes on the concept as a pilot and Arie Norddijk and Pieter Nordbeck employed at Port of Rotterdam, for showing a different port authority perspective on the matter.

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Nomenclature

$\Delta\rho_{0,max}$	Characteristic density difference $(= \rho_{max} - \rho_{min})/2$
$\Delta\varphi$	Change in phase lag $[rad]$
Δd	Change in thickness of dredged layer $[m^3]$
ΔL	Added load $[ton]$
ΔSSC	Change in suspended sediment concentration $[mg/L]$
ΔSSC_{total}	Suspended sediment concentration by Cronin $[mg/L]$
ΔT	Draught increase $[m]$
ΔT_s	Sedimentation volume per tide $[m^3/tide]$
$\Delta V_{dredged}$	Change in dredged volume $[m^3]$
ΔW	Increase of dredged material $[kg]$
Δz	Bed level increase $[m]$
$\Delta\rho_m$	Maximum salinity induced density difference in the entrance $[m^2]$
$\hat{a}$	Tidal amplitude $[m]$
∇	Water displacement $[m^3]$
∇_m	Weight of displaced salt water $[kg]$
ρ_d	Density of bottom deposit $[kg/m^3]$
ρ_{fm}	Density of fluid mud $[kg/m^3]$
ρ_{max}	Maximal density in the harbour entrance $[kg/m^3]$
ρ_{min}	Minimal density in the harbour entrance $[kg/m^3]$
$\rho_{s,bottom}$	Average bottom density $[kg/m^3]$
ρ_{SSC}	Material density in suspension
ρ_w	Density of water $[kg/m^3]$

φ	Phase lag [rad]
φ_r	change of phase lag ($= \varphi_t$) [deg]
φ_t	Phase lag horizontal tide [deg]
A_c	Conveyance area at the entrance [m^2]
B	Ship width [m]
b_0	Entrance width [m]
C	Circumference [m]
c_0	Concentration outside [kg/m^3]
c_a	Ambient suspended concentration [mg/L]
C_B	Block coefficient [$-$]
c_{es}	Concentration suspended sediment in discharge water [mg/L]
C_{squat}	Squat coefficient [$-$]
d	Thickness of dredged layer [m]
D_{total}	Total dredged weight from Cronin model [kg]
$f_e, f_{t,e}, f_d, f_{t,d}$	Eysink coefficients for exchange flow rates [$-$]
F_s	Sedimentation Rate [kg/s]
fm	Mixing coefficient [$-$]
g	Gravitational constant [m/s^2]
h	Water depth [m]
h_0	Average entrance depth [m]
L_F	Vessel load factor [t/m^3]
L_{pp}	Ship length between perpendiculars [m]
n	Number of tides a year [$-$]
n_s	Number of tides with fresh water discharge per year [$-$]
ND_{fm}	Nautical depth above fluid mud [m]
ND_{sill}	Nautical depth above sill [m]
p	Trapping coefficient [-]
$P(\xi > 0)_{25-year}$	Bottom touch probability over 25 year life span [$-$]
$P(\xi > 0)_{ship}$	Change of bottom touch for one transit [-]
$P(\xi > 0)_{year}$	Yearly bottom touch probability [$-$]

p_z	Sand fraction in the bottom deposit $[-]$
Q	Exchange flow $[m^3/s]$
Q_s	Sediment driven density current averaged over tide $[m^3/s]$
Q_T	Temperature driven density current averaged over tide $[m^3/s]$
Q_d	Density driven flow over tide $[m^3/s]$
Q_{es}	Fresh water discharge averaged over tide $[m^3/s]$
Q_e	Entrainment flow averaged over tide $[m^3/s]$
Q_t	Tidal filling averaged over tide $[m^3/s]$
r	Radius of a circle $[m]$
S	Harbour surface area $[m^2]$
T	Ship draught $[m]$
T_h	Horizontal residence time $[s]$
T_t	Tidal period $[s]$
T_v	Vertical residence time $[s]$
t_{travel}	Travel time $[s]$
u	Average basing flow velocity $[m/s]$
u_0	Peak current in front of the harbour $[m/s]$
u_c	Critical flow velocity $[m/s]$
U_{crit}	Critical vessel speed $[kn.]$
V_s	Ship volume per meter submerged $[m^3/m]$
v_s	Sailing speed $[m/s]$
V_{d0}	Volume of density driven exchange without tidal effects $[m^3/tide]$
$V_{dredged}$	Dredged volume $[m^3]$
V_{es}	Total volume of fresh water during one tide $[m^3/tide]$
V_{ha}	Harbour volume below water level $[m^3]$
$V_{t,total}$	Total exchanged volume over one tide $[m^3/tide]$
V_t	tidal prism $[m^3/tide]$
W_s	Settling velocity$[mm/s]$
WL	Water level with respect to NAP $[m]$
Y_p	Yield point $[Pa]$

Z_v	Maximum squat [m]
z_{fm}	Depth location of fluid mud top [m]
z_{RTZ}	Location of rheological transition zone where 100 Pa is reached [m]
z_{sill}	Depth location of sill top [m]

1

Introduction

The maritime community uses a margin between the keel and channel floor [PIANC, 2014]. With this under keel clearance (UKC) manoeuvrability is unaffected and bottom collisions hardly occur. However, at many ports the bottom consists of a fluid mud layer having weak strength [McAnally et al., 2007a]. Therefore, this layer appears to be more forgiving upon collision. This instigated a discussion whether the current UKC might be unnecessarily large/safe [PIANC, 1983].

Port authorities would like to reduce the required UKC for economical benefits. A smaller UKC creates the opportunity to reduce maintenance costs and/or allow higher draught vessels. However, reduction of the UKC, when fluid mud is present, may create navigation difficulties (Delefortrie [2007]; Vantorre [2001]). Parties responsible for navigational safety (i.e., pilots, captains and harbour masters) are therefore reluctant on reducing the UKC. As a result, there is a disagreement between the involved parties on whether application is justified and safe.

Challenging nature of fluid mud and thereby induced manoeuvrability effects complicates the difference in views. Addressing the safety issues requires detailed knowledge originating from different fields of expertise (i.e. fluid- and soil mechanics, monitoring, measuring, technology, port management and ship manoeuvring). These different scientific fields have their own corresponding challenges and uncertainties. The knowledge from each field must be translated to end-users in order to provide sufficient information on application of a reduced UKC-policy.

Despite the extensive research efforts both drawbacks and benefits are still unclear. This was shown by a questionnaire held among stakeholders in 2012, where the outcomes revealed:

"It is unclear what the expected improvements will be in terms of improved reliability of navigable water depth, other types of contracts, dredging strategies. The impact on frequency of dredging activities, the amount of dredged material and manoeuvrability are still unclear" [Kruiver et al., 2013]

For safely applying a smaller UKC, port authorities, contractors and pilots need knowledge on the principles of fluid mud and ship interaction. With this knowledge port authorities are able to quantify the expected benefits creating an opportunity for decision making on whether or not to allow a decreased UKC. Furthermore, this knowledge is used to create guidelines and establish operational parameters for safe usage of an altered UKC-policy.

Important element is the communication between different end-users on the employed strategy. Although the port authority might seem in charge of making the decision, all the other involved end-users have to support the strategy change. Once shipping companies, international organisations, captains and/or pilots are insufficiently involved in the decision process they may not commit to the strategy adjustment.

1.1 Objective and research questions

Altering the UKC-policy will lead to a change in either maintenance strategy or harbour entrance policy. Safely applying this policy demands for a decision making tool to be used by port authorities, harbour masters and pilots for assessing whether an altered UKC proves a safe procedure and what is gained by implementation of the concept. Besides aiding decision making the tool will also serve as a guide for communication. This can be stated in a main objective for this thesis:

> ***'Aid decision making on practising an altered UKC policy by designating opportunities and risks linking management/end user needs to scientific 'know-how"***

The objective of the thesis is reached by addressing the following research questions:

1. Who are the end-users and what are their objectives/expectations regarding implementation of the concept?
2. What decision issues arise when attempting application of an adjusted UKC policy?
3. What are key indicators for quantification of the benefits & drawbacks originated from application?
4. Which knowledge gaps do we have to fill before UKC policy can be adapted?
5. What hinders the decision making?
6. How to cope with the apparent knowledge gaps?

1.2 Report outlay

This thesis consists of two parts. The first part, comprising chapters 2, 3 and 4 is on theory and derivation/improvement of a general Decision Support Model (DSM). The part starts with chapter 2 providing a theoretical introduction necessary before addressing the decision issues. Based on this theory and method a Decision Support Model (DSM) is derived in chapter 3. Obtained insights and information from DSM application leads to model improvements presented in chapter 4.

The second part, consisting of chapters 5, 6 and 7, is on DSM application to the case study Delfzijl. Case specific details are described in chapter 5. Quantification yields the optimal UKC reduction strategy and missing knowledge gaps. The improvements achieved during quantification are shown in chapter 4. Presenting the improved DSM and quantification at Delfzijl result in feedback as presented in chapter 7 and further investigation of three topics.

2

Theoretical background

Background knowledge is required before focussing on the decision issue. This chapter elaborates on principles of Under Keel Clearance (UKC), nautical depth and fluid mud. Aim of this chapter is not to study the mud nor ship interaction itself but to elaborate on current scientific research. This will provide background knowledge relevant for this thesis.

The chapter begins with an elaboration on vessel navigation and required safety regulations in section 2.1. The next section 2.2 elaborates on the impact of harbour sedimentation and thereby induced maintenance dredging. Section 2.3 explains how the incoming sediment is able to form a fluid mud deposit. Defining the mud layer and how to measure its strength will be discussed. Reducing the UKC when fluid mud is present leads to benefits and difficulties as explained in section 2.4. Elaboration on the Frame of Reference approach is located in section 2.5. This approach is meant to maintain structure and overview while improving end-user communication. The last section 2.6 elaborates on end-user objectives and expectations. They are important since they provide the research topics in this thesis.

2.1 Ship navigation

2.1.1 Nautical bottom & -depth concepts

Vessel navigation requires a minimum depth to be present in a shipping channel. This nautical depth is the difference between the water level and the nautical bottom. The bottom is defined by PIANC [1997] as:

"The level where physical characteristics of the bottom reach a critical limit beyond which contact with a ships keel causes either damage or unacceptable effects on controllability and manoeuvrability."

Over a period of time, accretion induced by siltation, described in 2.2.2, will cause the bed level to exceed the guaranteed depth limit. When a layer with critical characteristics exceeds the guaranteed depth limit, it is designated as hazardous and is removed. Various ports use density criteria as the critical limit, varying in the range of 1,150 to 1,350 kg/m^3, see table 2.1.

Table 2.1: Density criteria for nautical depth [McAnally et al., 2007b]

Country	Port	Critical density (kg/m^3)
The Netherlands	Rotterdam	1,200
Thailand	Bangkok	1,200
Surinam	Paramaribo	1,230
Belgium	Zeebrugge	1,151-1,347
China	Yangtze	1,250
China	Liang Yungang	1,250-1,300
China	Yianjing Xingang	1,200-1,300
UK	Avinmouth	1,200
France	Dunkirk	1,200
France	Bordeaux	1,200
France	Nantes-Saint Nazaire	1,200

The critical density is chosen based on the rheological transition zone (RTZ). This is the level at which viscosity increases quickly over depth indicating soil being of sufficient strength to harm a vessel hull or affect its navigation. Full scale test have shown that when the vessels keel touches this zone, navigation is influenced. Designating a density for which the rheological transition is not reached, leads to a practical application. For definition of this density, various bottom measurements inside the harbour are conducted for linking the transition zone to the density. Definition of an universally applicable critical density is impossible [Vantorre et al., 2006]. A layer with a high fraction of small particles will yield a higher viscosity while having the same density. As a result, difference in bottom composition at each location yields an other density for which rheological transition occurs [Delefortrie and Vantorre, 2016].

Measurement techniques

In other occasion nautical bottom determination is based on density (gradients). These surveys are easy, quick and cheap. A multi-beam technique is often used for density gradient determination [Vantorre et al., 2006]. The surveys are conducted by emitting different frequencies with a submerged sounding probe. High frequencies (210 kHz) are reflected by small density gradients indicating the water-fluid mud interface. The low frequency echoes (33 kHz) are reflected by relatively large density gradients, indicating the fluid mud-soil boundary. Time required for receiving the reflected signal enables depth determination of the specific layer.

A significant higher location of the 210 kHz level with respect to the 33 kHz level, indicates the presence of fluid mud, see figure 2.1 [Granboulan et al., 1989]. Although the sounding probe is able to indicate the thickness of the fluid mud layer, it is inconsistent for property determination. Furthermore, the reflection strength is proportional to the density gradient. Most fluid mud layers are thick with a small density increase over depth. This small density

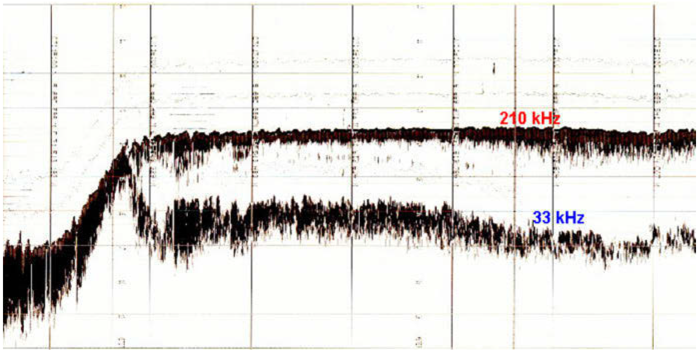


Figure 2.1: Example of a multi-beam echo sounding at the harbour of Zeebrugge [Delefortrie and Vantorre, 2016].

gradient causes a weak reflection. As a result, determination of the firm bottom (33 kHz measurements) is inaccurate with the multi-beam survey technique [McAnally et al., 2007b].

2.1.2 Under Keel Clearance (UKC)

Safe navigation in harbours and channels is guaranteed by maintaining a margin between the vessel keel and the nautical bottom [PIANC, 1985]. The nautical depth at the harbour should be sufficient for the vessel draught and the required margin or Under Keel Clearance (UKC). According to the guidelines for harbour approach channels [PIANC, 2014], the distance between the keel and the bottom must be 10 % of the vessel draught, see figure 2.2.

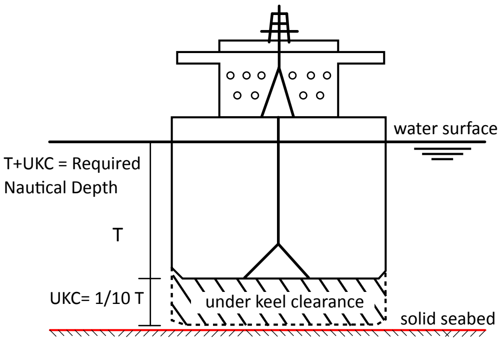


Figure 2.2: Nautical bottom and under keel clearance PIANC [1983]

Squat

Vessel draught is impacted by squat resulting from navigation through a confined water body. The water flowing around the hull has a relative velocity with respect to the vessel. Due to this velocity difference, a water level depression appears around the ship. This sinkage is referred to as squat and impacts the draught. Squat effects are relatively large for confined channels, big ships and high velocities [PIANC, 2014].

Squat determination is difficult and various methods are available (PIANC [2014] and Vantorre et al. [2014]). These methods are based on empirical relations and none of them are able to make an exact calculation. However, the method by Tuck and Taylor [1970] is easily applicable and is relatively accurate. The method as described in PIANC [2014], reads in formula:

$$Z_v = \frac{F_{nh}^2}{\sqrt{1-F_{nh}^2}} \cdot \frac{\nabla}{L_{pp}^2} \cdot C_{squat}, \tag{2.1}$$

in which:

$$F_{nh} = \frac{v_s}{\sqrt{g \cdot h}} \quad \& \quad \nabla = C_B \cdot L_{pp} \cdot B \cdot T, \tag{2.2}$$

where Z_v = maximum squat, v_s = sailing speed, g = gravitational constant, h = height water column, ∇ = water displacement, L_{pp} = ship length between perpendiculars, T = ship draught, B = ship width, C_B = block coefficient and C_{squat} = squat coefficient.

Tidal window

When a minimal UKC can not be maintained with respect to the nautical bottom, a ship waits for a higher water level. This tidal window depends on the location of the nautical bottom, draught and tide. Depending on the tide present at the considered location, a tidal bound vessel will have one or more tidal windows. In this thesis the tidal window is used for comparison purposes. If, in a new situation, the tidal window is altered new topics like waiting time are introduced and the comparison is not valid.

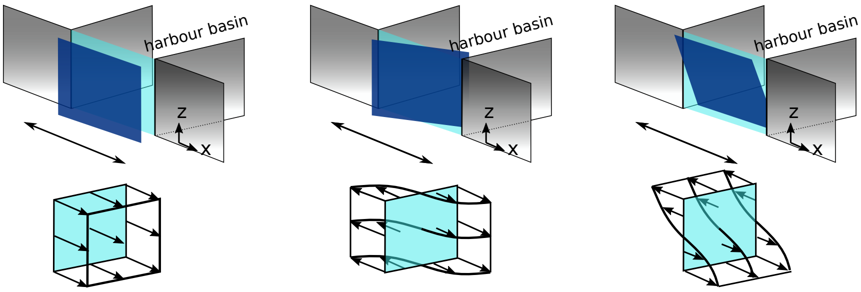
2.2 Harbour siltation

2.2.1 Exchange flow mechanisms

The interaction between harbour basin- and surrounding water is described by the exchange flow rate Q. The exchange flow is governed by three mechanisms. Whether one or multiple flow mechanisms is/are governing depends on the size of the port basin, the depth and width of the ports entrance, the flow velocity in front of the port and the variations in salinity in front of the port basin [de Boer and Winterwerp, 2016]. The three mechanisms are depicted in figure 2.3 and explained below.

Tidal filling

Tidal filling and -emptying occurs over one tidal cycle, see figure 2.3a. Tidal filling imports sediment rich water into the basin where a relative low energy regime is present. After a high water slack period, the tide drops and the basin is emptied till the low water level. Over this period water with relative low concentrations leaves the basin (Winterwerp [2016] and de Boer



(a) Tidal filling and emptying **(b)** Horizontal circulations eddy - flow separation **(c)** Vertical circulations mainly density currents

Figure 2.3: Exchange flow mechanisms (Vanlede and Dujardin [2014];Winterwerp [2016])

and Winterwerp [2016]). This process results in a nett import of sediment over a tidal cycle, leading to a bed level increase. Tidal filling will influence the other two exchange mechanisms.

Horizontal shear flow

At the basin entrance flow separation occurs and a turbulent mixing layer is formed as a result of a passing current, see figure 2.3b. Affected by horizontal shear flow (entrainment), the mixing layer will grow in length. When this mixing layer meets the opposite end of the entrance a stagnation point is formed. As a consequence of continuity, the flow separation line is slightly deflected into the basin. Entrainment and stagnation cause a large horizontal eddy to be formed in the basin which attracts sediment (Winterwerp [2016] and de Boer and Winterwerp [2016]).

Density driven currents

Mainly the presence of a salinity gradient induce a density driven currents. The gradient origins from the salt front pushed in and out over a tidal cycle. This process is intensified by a freshwater discharge in the basin. Density differences induce currents over the water column, see figure 2.3c. Low density water (i.e, fresh water, warm water and/or low concentrations) will flow on top of high density (i.e., salt water, cold water and/or low concentrations). This mechanism impacts the complete basin in absence of other current/stirring forces. This mechanism is therefore more effective than the other two mechanisms [Eysink, 1989]. Density driven currents can also occur due to difference in sediment concentrations. As a result of the concentration, a higher density is obtained. This flow occurs near the bottom where stratification is present. Sediment in the upper part of the water column is often well mixed therefore concentration does not lead to density differences.

2.2.2 Sedimentation rate

The low energy conditions inside the basin enables imported particles to settle, leading to harbour siltation [Te Slaa et al., 2012]. Exchange flow Q, ambient concentration c_a and settling velocity W_s are governing for this process [PIANC, 2008]. A schematic representation of these processes is depicted in figure 2.4. Determination of the earlier explained exchange flows Q is most challenging [Winterwerp, 2016].

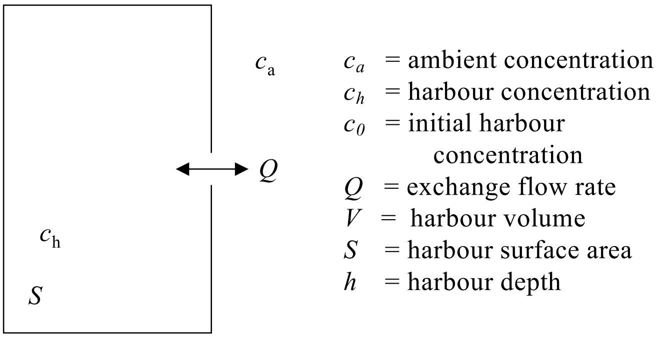


Figure 2.4: Schematic harbour basin [PIANC, 2008]

The mass balance for harbour suspended sediment is [PIANC, 2008]:

$$\frac{dVc_h}{dt} = Qc_a - Qc_h - \alpha S W_s c_h \tag{2.3}$$

Where $F_s = \alpha S W_s c_h$ is the sedimentation rate with αW_s being the effective sediment settling velocity. This is the settling velocity reduced by vertical mixing and/or increased by concentration gradients or flocks. α varies between 0.1 and 10.

Rewriting equation 2.3 according to the steps used in the report by PIANC [2008] results in the sedimentation rate:

$$F_s = \left[\frac{T_v}{T_h + T_v} + \left(\frac{c_0}{c_a} - \frac{T_v}{T_h + T_v}\right) exp\left\{-\left(\frac{1}{T_h} + \frac{1}{T_h}\right)t\right\}\right] \alpha S W_s c_a \tag{2.4}$$

With $T_h = \frac{V_{ha}}{Q}$ and $T_v = \frac{h}{\alpha W_s}$ being the horizontal- and vertical time scale respectively. With W_s = settling velocity, h = water depth and V_{ha} = harbour volume below water level.

2.2.3 Trapping Coefficient

Above described procedure can be shortened to a simple formula for quick determination of effects originated from harbour and/or dredging adjustments [PIANC, 2008]:

$$Sedimentation \quad Rate = F_s = p \cdot Q \cdot c_a, \tag{2.5}$$

where p = basin trapping efficiency, Q = rate of water exchange between the harbour basin and surrounding water and c_a = ambient suspended sediment concentration outside the harbour.

Basin trapping efficiency can be determined from:

$$p = 1 - \exp\left[-\frac{W_s}{h}\left(1 - \frac{u^2}{u_c^2}\right)_{basin} T_h\right], \tag{2.6}$$

where W_s = sediment settling velocity, h = basin water depth, u = average basin velocity, u_c = critical velocity for sedimentation and T_h = horizontal residence time.

The siltation rate can be lowered by applying Keep Sediment Out (KSO) and/or Keep Sediment Moving (KSM) techniques. KSO strives for a reduction of the amount of sediment coming in by altering Q and c_a. KSM attempts to alter the basin properties by influencing the trapping efficiency p.

Interesting to notice that hydrodynamic conditions are not the only parameter for the trapping efficiency. Ship movements and thrusters/screws as well as frequency- and method of dredging are important [de Boer and Winterwerp, 2016].

For most occasions the trapping efficiency is governed by the ratio of horizontal T_h to vertical residence time T$_v$ due to the u/u_c ratio being << 1. T_h can be reduced by an increase in exchange flow or a decrease in harbour volume [PIANC, 2008].

2.2.4 Dredging and turbidity

Above described sedimentation demands frequent dredging in order to keep the port operational. Relocating sediments induces turbidity at the dredging location and at the disposal site (Bray [2008], Winterwerp et al. [2013] and Winterwerp and Wang [2013]). The way at which this turbid cloud disperses dependent on the type of dredging equipment [Pennekamp et al., 1996]. The turbidity, caused predominantly by suspended sediment concentration (SSC), determines sunlight intrusion [Postma, 1961]. Light energy is essential for photosyntheses activity by algae [Colijn, 1982]. Algae provide nourishment for heterotrophic lifeforms like plankton and fish. A decrease of autotroph activity reduces the nutrients availability for the heterotrophic life-forms. This reduces the presence of heterotroph lifeforms. Quantification of SSC can be conducted by sampling water or optical measurement tools. Optical equipment (by a nephelometer measuring Nephelometric Turbidity Units (NTU)) is often used during dredging activities for monitoring purposes. In order to aid the NTU measurement, dispersal models can be used to determine the affected area.

Vessel transits and maintenance dredging cause (re)suspension of material impacting the SSC (Aarninkhof et al. [2008] & Bray [2008]). However, it is not necessarily the reason for a high turbidity in an estuarine system. In most situations channel deepening and widening for accommodating bigger vessels causes an import of sediment. The measures induce tidal amplification which increases the flood- or eb dominance of the system. The sediment transport, having a non-linear relation to the flow velocity, will increase exponentially leading to higher import of suspended material. Channel straightening and reduction of intertidal flats, often coinciding with port development, amplify these effects (van Maren et al. [2015] & Bosboom and Stive [2015])

2.3 Fluid mud properties & -processes

Previous described nett import of sediment results in a bed level increase. When this sediment composition consists sufficient clay and silt fractions fluid mud layer is formed. This layer is soft and has low strength properties. McAnally et al. [2007a] defined fluid mud as:

"A high concentration aqueous suspension of fine grained sediment and flocks, but which has not formed an interconnected matrix of bonds strong enough to eliminate the potential for mobility."

Fluid mud typically ranges in densities, from very low to clay-like values with densities between 1,080 to 1200 $\mathrm{kg/m^3}$ [McAnally et al., 2007a].

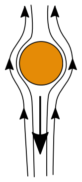
2.3.1 Formation & Loss

Estuarine systems en therein located harbours often experience an abundance in silt and clay particles. Their small grain size require little energy for transportation further downstream to these estuaries [Bosboom and Stive, 2015]. Harbour basins have to low energy regimes leading to settling particles. When settling velocities exceed consolidation rates a weak bottom or fluid mud layer is formed. Settling velocity is the result of the force equilibrium between gravity and drag acting on a particle, see figure 2.5a. The resulting force will lead to a settling particle [Winterwerp and Van Kesteren, 2004].

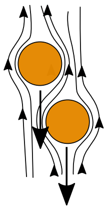
Settling velocity is affected by hindered settling. Hindered settling occurs when particles experience water drag originating from other particles settling in proximity. This water drag is the result of water flowing around a settling particle. Smaller particles will settle closer to each other. Hindered settling and effect on settling velocity is therefore dependent on grain size [Winterwerp, 2002]. Figure 2.5b is a graphical representation of this process.

Fluid mud is a composition of small grains, water and organic material. The small grain sizes induce low settling velocities. Aggregation of small grains due to flocculation creates flocks with higher settling velocities, see figure 2.5c. Flocculation is influenced by cohesion which is related to the grain properties [Winterwerp and Van Kesteren, 2004].

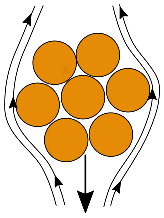
Multiple small particles with a combined volume equal to one large particle, will have a higher total surface area. As a result, there is more room for organic material to attach. This organic material or extracellular polymer substances (EPS or sugar) enhances cohesion. EPS is excreted by algae which is influenced by salinity, sun and temperature, therefore a seasonal variation in fluid mud characteristics can be distinguished [McAnally et al., 2007a].



(a) Settling of a grain



(b) Hindered settling



(c) Flocculation

A soil skeleton formed by the settled flocks, enables the fluid mud layer to effectively trap water, hence the fluid behaviour of the layer. This water will, in absence of a stirring force, gradually flow out of the mixture making fluid mud a transient state. The phase over which water is expelled from the mixture is referred to as consolidation. Time required for the water to leave the mixture is governed by particle size and corresponding pores in between [Winterwerp and Van Kesteren, 2004]. Water expulsion causes viscosity- and density increase, eventually leading to a firm soil layer unsuitable for sailing through.

2.3.2 Rheological properties

The mud must behave like a fluid in order to make way for a navigating vessel. Density (gradient) measurements are unable to define the fluidness, since it is a static parameter defining a dynamic (fluid) process [Wurpts and Torn, 2005]. For strength determination the rheological properties are decisive due to their relation to the dynamic behaviour. Rheology addresses the ability of matter to deform and/or flow [Barnes et al., 1989]. Combination of parameters indicates yield stress and viscosity to be decisive [Meinsma, 2011].

The yield stress is the force per area providing the transition from mud to fluid mud. For navigation purposes, the yield stress must be below 100 Pa. The yield point (Yp) indicates the maximum required stress to provide the transition. Viscosity (η) is related the mud fluidness and shows the resistance against gradual deformation. The maximal viscosity required for creating fluid behaviour should not be lager than 100 Pa·s. Moreover, the mud should show complete fluid behaviour (i.e. $\eta \rightarrow 0$) at an exerted shear stress lower than 500 Pa. If the viscosity is to high, the mud will not react to the excreted forces and is unable to make way for the vessel. Figure 2.6 depicts the above described conditions. Point A represents the maximal viscosity where flow fluid behaviour starts to occur, at point B the mud is completely fluid. The sample depicted in figure 2.6 meets the above described criteria and is suitable for sailing through.

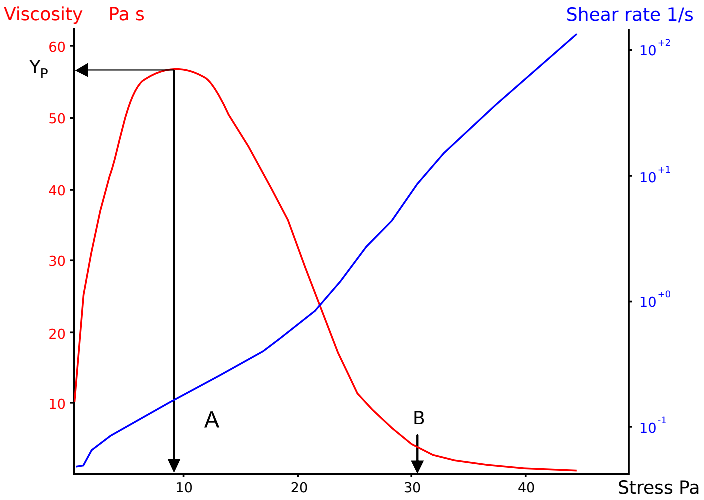


Figure 2.6: Rheology determination of a sediment core taken in Delfzijl. Rheology parameters highlighted [Meinsma, 2011]

2.3.3 Measurement techniques

Two approaches for new nautical bottom surveys are considered Kruiver et al. [2013] and Druyts and Brabers [2016]. The first approach aims at property determination of the fluid mud layer and its suitability for UKC reductions. Main objective is to define one or more parameter(s) corresponding to fluid mud and suitability for navigation. The obtained parameters should be universally applicable as nautical bottom definition. Type of equipment or method needed for determination of these properties is equally important. The second approach states that when a vessel keel touches the rheology transition zone manoeuvrability is affected. Therefore this zone corresponds to the PIANC [1997] definition. Locating this transition zone is sufficient for defining the nautical bottom.

Druyts and Brabers [2016], Kruiver et al. [2013] and McAnally et al. [2007b] elaborate on techniques available for determination of fluid mud characteristics. Various reports and journals reveal the need for equipment capable of establishing the viscosity and yield stress (Wurpts and Torn [2005]; Kruiver et al. [2013]; McAnally et al. [2007b]). In addition, the layer thickness is required in order to determine its reaction to the compressed flow lines. For nautical depth determination, the depth of occurrence is also obliged.

The method of Kruiver et al. [2013] requires four parameters for accurately defining the fluid mud characteristics leading to a nautical bottom and -depth profile determination.

- Viscosity
- Mud layer thickness
- Shear stress
- Water level

Measurement equipment should determine bottom layer viscosity. According to Kruiver et al.

[2013] and Druyts and Brabers [2016] multiple tools are available. Below description is on equipment functioning, later elaboration on the flaws and failures is located in section 6.1.1.

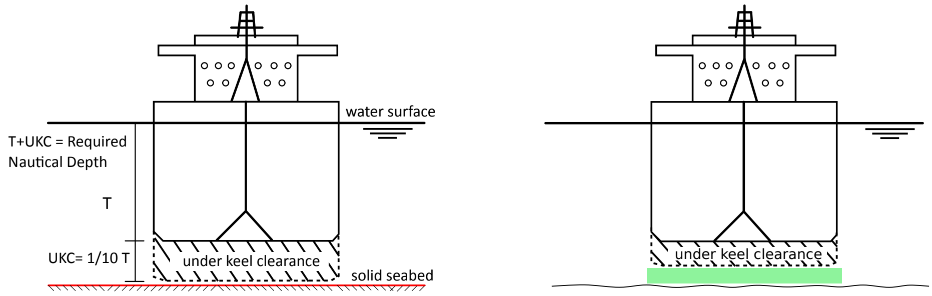
- **Rheometry profiler**
  Uses a small propeller measuring the resistance encountered when lowered. Measures layer depth and thickness, as well as viscosity and shear stress [Van Craenenbroeck et al., 1991].
- **Friction resistance (e.g. GraviProbe and Accceleroprobe)**
  By dropping a free-fall penotrometer, the frictional resistance can be determined. Both the depth and friction is measured with this technique. The measured deceleration and wall friction during impact and travel through enables determination of the undrained shear strength. With empirical relations, the viscosity can be determined. The density is determined with the help of a pressure gauge measuring the pore pressure. This instrument can be used to determine the interface between fluid- and consolidated mud [Geirnaert et al., 2013].
- **Tuning fork (e.g. RheoTune and DensiTune)**
  Density can be measured by the vibration generated with a tuning fork which is applied in-situ. After placement in the material one of the prongs is vibrated. Depending on the material, the other prong will react at a specific response vibration. The response will depend on the shear strength of the material at which the fork is present. After calibration at site, the tuning fork can be used for viscosity determination. The relation between shear strength and material however is empirical. The instrument is lowered vertically through the water and fluid mud yielding a vertical depth profile of the density. The tuning fork is a point measurement utility (Fontein and van der Wal [2006];McAnally et al. [2007b]).
- **Towing a cable (e.g. Rheocable)**
  An object of specific density is towed behind a vessel. Sailing with a certain (predefined) speed will keep the object from sinking in the stronger mud. This results in the object “floating” at the interface between weak (fluid) and strong mud . The object, having a pressure gauge, is able to determine the depth [Druyts and Brabers, 2012].
- **Marsh funnel**
  A laboratory test with a marsh funnel. This is a simple device for measuring viscosity by observing the time it takes for a known volume of liquid to flow from a cone through a short tube. It is standardized for use by mud engineers to check the quality of drilling mud [Balhoff et al., 2011].
- **Rotovisco test**
  A laboratory test with a rotating vane or cylinder. During the test, the dynamic viscosity is measured at a defined shear rate or shear stress. It determines the yield point with controlled stress as a function of density. It is a standard method for characterizing sludges [Talmon, 2015].
- **Capillary viscometer**
  A laboratory test measuring time taken by the fluid to flow in a capillary tube between two marks. This time is proportional to the kinematic viscosity [Viswanath et al., 2007].

Although a transition to another more reliable parameter must be made, determination of the density is still valuable for dredging preparations. The maintenance efficiency depends on the density of the material. Beforehand assessment of location and density for specific layers enables timely adjustment during dredging operations. Furthermore, with a known volume and density, the required hopper volume can be calculated, revealing the number of hopper trips required [Geirnaert et al., 2014].

2.4 Effects of lowering the UKC

2.4.1 Benefits

Presence of a fluid mud layer instigates the discussion whether the current required UKC is needlessly large. Reduction of the UKC (shown in figures 2.7a and 2.7b) decreases the required nautical depth. The green space indicates available room for bed level or draught increase. A higher draught will increase economic revenue for port authorities and shipping agencies. A higher located bed level will reduce dredging and therefore costs of a port authority. In addition, less maintenance dredging reduces the burden for ecology.



(a) Nautical bottom and under keel clearance, source: PIANC [1983]

(b) Diminished UKC due to presence of a soft bottom layer

Figure 2.7: Alter the UKC with reference to soft bottom layer

2.4.2 Difficulties

Navigating with a smaller UKC above a fluid mud layer causes two modes to occur. Each of this states affects the vessel and its navigation in a different way [Vantorre, 2001]:

- **Low UKC (between 10 % to 0 %)**
  The presence of a two layer system (i.e. an air-water and a water-mud interface) will result in undulations at the water-mud interface.
- **Negative UKC (between 0 % to -10 %)**
  If the mud is not fluid enough, sailing through is impossible.

The above mentioned UKC values are with respect to current location of the nautical bottom. Determination of the nautical bottom based on different criteria will result in UKC values of 10 % or higher.

The vessel- fluid mud behaviour is a two way interaction with a highly dynamic character. After a vessel passage, the mud and its conditions will be altered. However, in this thesis the impact of the vessel on the fluid mud is left out.

Low UKC (between 10 and 0 %)

Water in a channel is pushed aside by a navigating vessel, resulting in return current at the sides and underneath the vessel. Keel clearance reduction causes compressed streamlines under the vessel, see figure 2.8. Flow line compression causes rudder instabilities and increased engine power demands. Compressed flow lines in combination with possible bottom collisions reveal the need for a minimum UKC, as described in section 2.1.2.

In the presence of fluid mud, the compressed flow lines induce undulations in de water-mud interface. Subsequently, the streamlines can be impacted by the undulations resulting in an amplification see figure 2.9. Growth of these undulations where observed by Vantorre [2001]. Observations from simulation runs showed the amplitude and impact of these undulations to be dependent the vessel speed:

- At very low speed, the water-mud interface remains undisturbed (1$^{\text{st}}$ speed range)
- At intermediate speed an interface sinkage is observed under the ship's bow, which at a certain section changes into an elevation. This internal hydraulic jump is perpendicular to the ship's longitudinal axis and moves towards the stern when speed is increased (2$^{\text{nd}}$ speed range)
- At higher speed, the jump occurs behind the stern (3$^{\text{rd}}$ speed range)

Problems arise in the transition from the 2$^{\text{nd}}$ to the 3$^{\text{rd}}$ speed range. This problems are caused by the obstruction of flow under the vessel (shown in figure: 2.9). In addition, increasing the speed cause occurrence of these undulations at the stern. Occurrence at the vessel's rudder and screw will lead to controllability issues. The unpredictable nature of the undulations induced by the 2$^{\text{nd}}$ speed range and a low UKC (i.e., 13 to 3 %) is more dangerous than navigating with a negative UKC (i.e., 0 to -10 %) [Vantorre, 2001]. Figure 2.10 depicts the undulations corresponding to the speed. The transition from 2th to 3rd speed range is depicted in figure 2.11 and is described with the formula [Vantorre, 2001]:

$$U_{crit} = \left[0.296gh\left(1 - \frac{\rho_w}{\rho_{fm}}\right)\right] \tag{2.7}$$

where U_{crit} = critical vessel speed, h = water depth, ρ_w = density water and ρ_{fm} = density fluid mud. The transition boundary is shown in figure 2.11.

Influence on rudder control and stopping distance is correlated to; fluid mud characteristics, layer thickness and UKC [Delefortrie, 2007].

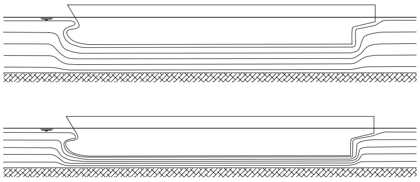


Figure 2.8: Influence of the under keel clearance on the flow lines [Delefortrie, 2007]

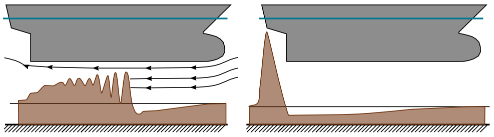


Figure 2.9: Water-mud interface motions, (a) 2^{nd} speed range; (b) 3^{rd} speed range [Vantorre, 2001]

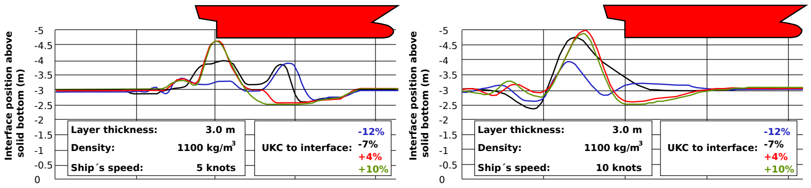


Figure 2.10: Mud-undulation/speed relation [Lataire, 2014]

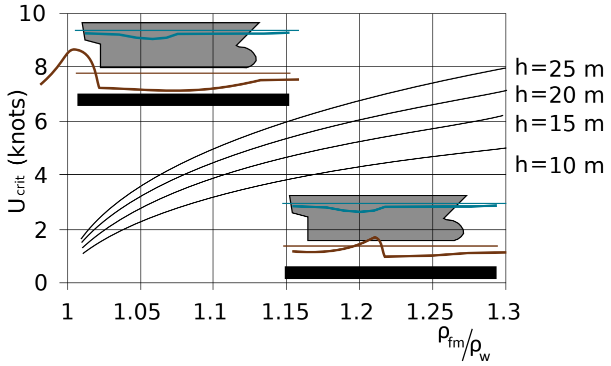


Figure 2.11: Critical speed separating the 2^{nd} and the 3^{rd} speed range [Vantorre, 2001]

Negative UKC (0 and -10 %)

When the ship sails trough the fluid mud, rheological properties become governing. Sailing through the mud requires the vessel to overcome the yield stress and viscosity of the fluid mud, as described in section 2.3.2. When the ship touches the rheological transition zone where the yield stress exceeds 100 Pa, sailing through the mud becomes dangerous. Real life test by Vantorre [1990] showed that problems occur when touching this zone. During field test, the SS Lepton was not able to slow down on its own, even though the slow navigation speed [Vantorre et al., 2006].

2.5 Frame of Reference

Deciding when and how to decrease the UKC instigates multiple uncertainties and difficulties. In order to objectify and match these uncertainties to required research, a structured approach is used. This structure is obtained by application of a Frame of Reference approach [van Koningsveld, 2003]. This approach is developed as a tool for matching end user needs to specialist knowledge originated from different scientific fields (van Koningsveld and Mulder [2004]; van Koningsveld et al. [2003]; van Koningsveld [2003]; Garel et al. [2014]). Aside from providing a state of the art and indication of knowledge gaps, the FoR is used for establishing indicators helpful for the implementation of a certain procedure or concept. As stated in the introduction, chapter 1, an UKC reduction requires knowledge originated from various scientific fields which was elaborated in this chapter. The FoR approach gives an indication of different facets involved with their needed corresponding background knowledge while showing problems/difficulties for reaching specified goals.

FoR is used to obtain indicators for management measures in the use of a new UKC policy. These indicators serve several functions making them important for monitoring:

- Simplification
- Quantification
- Standardisation
- Communication

By application of indicators the manageability of a problem is simplified and the possible interventions can be evaluated in an objective way.

The framework consists of linked elements creating a flowchart, as depicted in figure: 2.12. This frame aids the iteration process due to the feedback connection in the evaluation state. After stating an strategic- and operational objective, the frame of reference splits into 4 main elements:

- the Quantitative State Concept (QSC),
- the Benchmarking procedure,
- the Intervention procedure, &
- the Evaluation procedure.

Strategic objective

The strategic objective is the first step in the FoR approach. This step states the main goal or long term vision of a project. It proves vital to state an all-including objective since the other steps depend on this element.

Operational objective

The main goal of the project entails multiples sub elements each with their own goal or objective. The manner in which this objective is stated determines what is seen as the desired state, how this is benchmarked, the way to intervene and what the evaluation of these interventions on the operational as well as the strategic objective is.

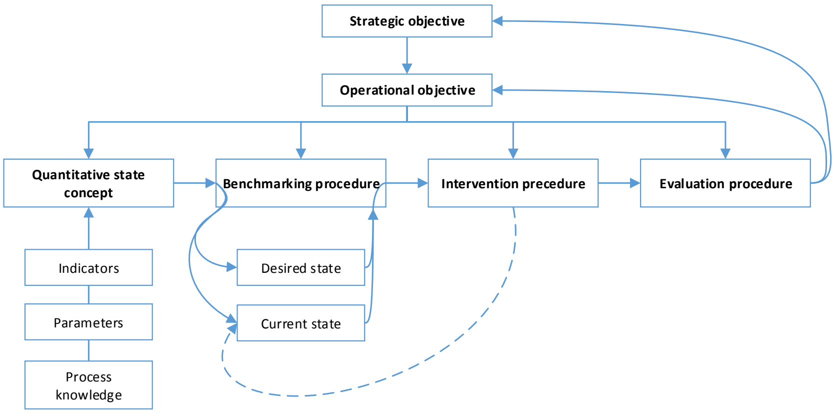


Figure 2.12: Frame of Reference [van Koningsveld and Mulder, 2004]

Quantitative State Concept (QSC)

In the Quantitative State Concept decision on the parameters to be measured in order to quantify the objective. What parameter is seen as representative for the problem.

Benchmarking procedure

During the benchmark procedure, the current state is compared to the desired state. This procedure involves how to measure the different states. The step is important since it reveals when to intervene in a system.

Intervention procedure

The intervention procedure describes the action to be taken to change the current situation into a desired situation. Ideally this is done by one intervention, however if the originally proposed action is ineffective, a second additional or substitute intervention can be adopted during the consecutive iterations.

Evaluation procedure

The last step is the evaluation procedure where the effectiveness of the intervention is estimated. This evaluation is conducted in terms of effectiveness in reference to the operational objective and the strategic objective.

2.6 End-Users

The Frame of Reference is filled with knowledge on theory (explained previously) and questions/hesitations from involved end-users. These end-users have different opinions on the topic originating from their field of expertise and/or different professions. The considered end-users with corresponding intentions are:

- **Port Authority**
  Interested in a minimal risk and a fully and optimal functioning port.
- **The International Maritime Organization**
  Standard-setting authority for the safety, security and environmental performance of international shipping.
- **Pilot**
  In charge of safely guiding ships in and out of the harbour.
- **Harbour master**
  Official acting on behalf of the port authority to enforce regulations an ensure navigational safety and port operations.
- **Captain**
  At all times responsible for the vessel and its load.
- **Shipping company**
  Interested in a safe and operational berth for loading and unloading goods.
- **Marine contractor**
  Interested in optimal dredging efficiency for cost reductions.
- **Non-governmental environmental organisation (NGEO)**
  Interested in improvement and expansion of ecological environment
- **Research institutes**
  Interested in knowledge on fluid mud and ship reactions

2.6.1 Views and expectations

In preparation of this thesis work, discussion was held with multiple end-users. Ascertained expectations where:

- **Port Authority**
  Port authorities expect that the adjustment of the keel clearance policy leads to a maintenance cost reduction and/or an increase in revenue by accommodating deeper draught vessels. Goal of each port authority is different depending on their vision for port usage and development. Port location, type of goods transshipped, possibility of growth, maintenance effort and ecological impact highly influence the application of the procedure (Bourgonjen [2016]; Nordbeck [2016]).
- **Pilots**
  Expectations of the pilots is that vessel behaviour and navigation will change by an UKC reduction. Fear is that this diminishes the navigational safety by impacting turning radius and stopping distance. Both of them are a necessity for safe arrival and departure of vessels. The Dutch pilotage supports research on the alternation of altering the UKC. Pilots in the Netherlands are self employed therefore an opinion of one pilot does necessarily represent the complete pilotage [Deen, 2016].
- **Dredging company**
  Expectation at Van Oord is a reduction of dredging operations from application of a smaller UKC. This results in two different attitudes towards the concept; on the one

hand income from dredging operations is the main profit for a dredging company. Reduction could lead to a revenue decrease. On the other hand adaptation of the UKC policy will most likely coincide with development/deployment of new dredging methods/equipment [van den Heuvel, 2016]. As a result new opportunities arise for the company. Furthermore, dredging companies strive for ecological improvement since their core activity is often seen as harmful for nature. New dredging methods/equipment could decrease the ecological impact of dredging and improve company status.

- **Research institutes (Deltares & Delft University of Technology)**
  Researchers are looking for the most relevant parameter(s) that define the nautical bottom at every location. Furthermore there is a need to develop a tool to measure this parameter continuously. Ideas for both the parameter and the tool exist, however practical has to be investigated.

3

Conceiving a Decision Support Model

The previous chapter described a theoretical background on vessel navigation, fluid mud and FoR-method (chapter 2). The FoR method (section 2.5) described a structured approach for capturing problems/hesitations from end-users on application of a new policy.

This chapter elaborated on the derivation of the Decision Support Model (DSM). Conceiving the DSM based on the Frame of Reference approach, encapsulates the different views and opinions in multiple frameworks. With the DSM the link between knowledge and practice is improved. In addition the DSM can be used to direct required research efforts. Ultimately the DSM serves as a tool for both specialists and end-users to refer to in their communication and decision process.

The first section, 3.1, elaborates on three managements contexts. Important are the issues involved in each context and how they are captured within the framework. The section afterwards describes how, with the help of three strategies, the management contexts are integrated in a comprehensive Decision Support Model shown in section 3.2.

3.1 Management contexts

Positive effects on port profit and ecology and safety hazards (described in section 2.4.1) can be subdivided in three different management contexts: ecology, economy and safety. Each of these contexts are discussed separately in this section for defining involved issues. These issues are subsequently captured and described in the Frame of Reference, as explained in section 2.5.

3.1.1 Safety

Reduction of UKC results in effects for manoeuvrability, as explained in section 2.4.2 [Delefortrie and Vantorre, 2006]. Interviews have indicated the stopping distance and rudder control as important points of concern [Kruiver et al., 2013]. To what extend and when these effects cause unsafe/unexpected events is important. At the same time, determination of a nautical bottom based on strength properties is more difficult in comparison to a multi-beam technique, as explained in section 2.3.2. This results in a higher uncertainty and survey error.

Above described issues are linked to safety at the time of arrival and departure. These issues correspond to one strategic objective: ‘Maintain navigational safety in the harbour’.

Each issue is formulated with an operational objective:

- Improved reliability of navigable depth by improving measurement accuracy.
- Secure sufficient rudder control
- Secure stopping manoeuvre within design guideline

Measurement equipment

A density gradient is inadequate to assess the dynamic character of fluid mud, as elaborated in section 2.1.1. A new technique/method for nautical bottom survey is therefore required. Various pieces of equipment are available to determine the strength of a fluid mud layer, see section 2.3.3. Assessment of the soil layer requires a dynamic measurement and is preferably taken in-situ. Not conducting lab test yields quicker results an cause no stirring effects to the sample. New survey equipment should be accepted by all parties as reliable and effective. Function and application of the equipment should be scientifically based for acceptance. The new equipment should be accurate for determination of the parameters described in section 2.3.3.

Current state is where nautical bottom is determined based on a density gradient. Improvement is obtained by employing a different measurement method/equipment. Adapting to other methods is therefore the intervention. Difference between present day- and improved accuracy induces the evaluation of the operational objective. Additionally, the time frame of deployment and accompanying costs of the equipment/method are equally important. Evaluation for the strategic objective is the overall safety. Measurements introduce errors, therefore, knowledge on the accuracy is essential.

Figure 3.1 stated the complete framework.

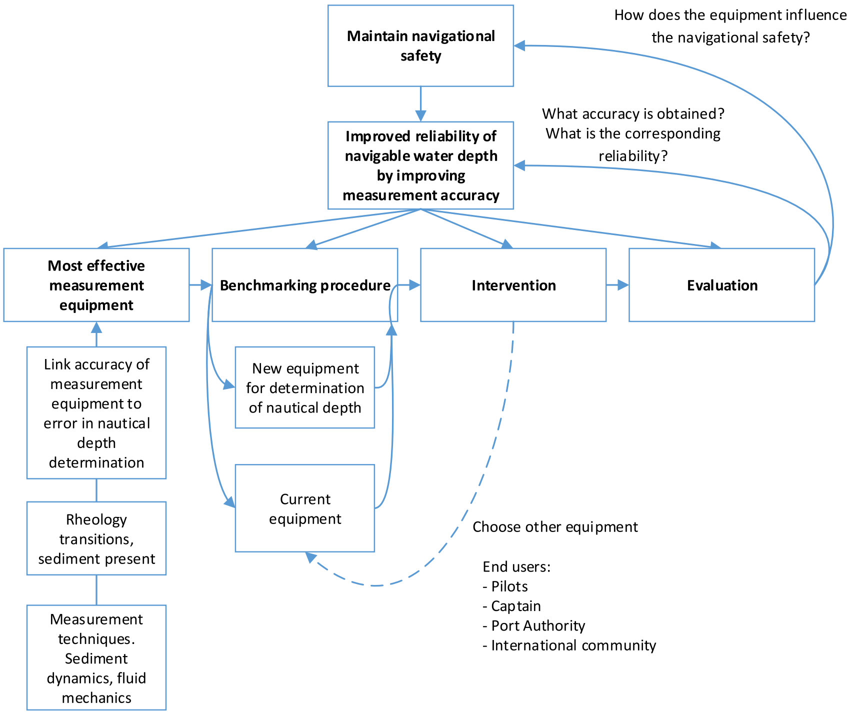


Figure 3.1: Management context element - Safety measurement accuracy

Sufficient rudder control

Limited rudder control, as described in section 2.4.2, will not cause safety issues when rudder angles are adjusted properly. Knowledge on how and to what extend the rudder control is affected by the UKC enables timely and appropriate angle adjustments [Meinsma, 2012]. Sufficient steering capabilities are therefore tested within the QSE condition; ship reaction to rudder angle in reference to UKC.

Required rudder control depends on the harbour lay-out and type of vessel. Complex harbours with multiple turning basins and fairways demand additional rudder adjustments and tug assistance. Other harbours require a limited amount of rudder adjustments making the approach relatively easy.

In order to evaluate the QSE-state, reduction of the UKC is the first intervention. Current state in the port corresponds to the desired state since safety regulations are met. The intervention should be conducted to such extend that hazardous situations will not occur. This is contrary to earlier described purpose of an intervention, in section 2.5. A hazard can occur when a ship is not able to make a required turn within the available room (due to a low UKC). If this is known beforehand, tugs can be deployed as an additional intervention to maintain vessel controllability [Delefortrie, 2007].

Resulting framework is stated in figure 3.2

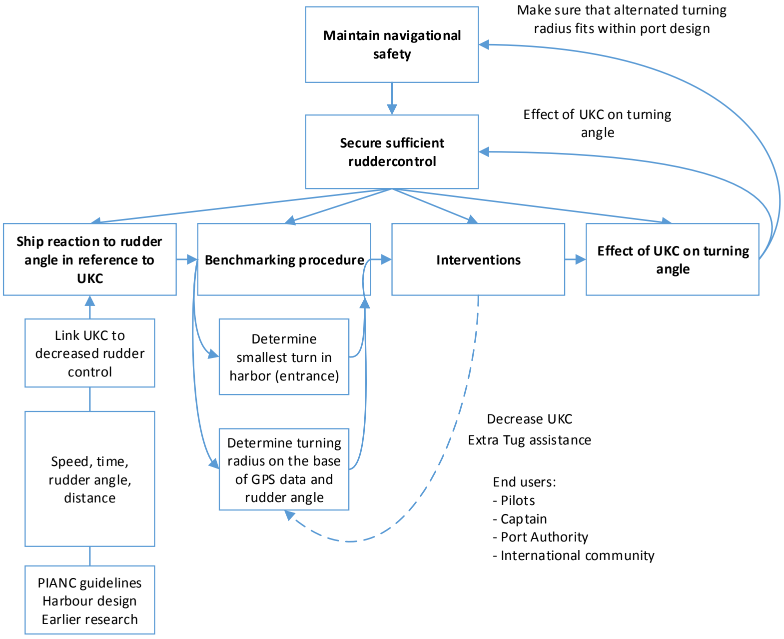


Figure 3.2: Management context element - Safety rudder control

Stopping distance

Idea for application of a new UKC-policy is the deployment of tugs to safeguard vessel manoeuvres. Tugs have the ability to stop and steer a vessel when thrust is lost [Delefortrie, 2007]. Tug-tie up is performed over the stopping distance inside a harbour [PIANC, 2014], during of which a vessel must maintain an unassisted course. For tie-up, the vessel speed is reduced to 4 knots over distance L_1. After reducing speed, tug tie up takes place over length L_2 [Ligteringen and Velsink, 2012]. A velocity of 4 knots is within the critical speed zone depicted in figure 2.11 in section 2.4.2. Knowledge to what extend a specific ship will be affected by the present UKC and mud layer, enables assessment whether problems can occur and what actions are required. Elaboration on the risk impact of lowering the UKC and quantification of corresponding increase in stopping distance is valuable. This ratio is therefore seen as the QSE and should be obtained during the simulation runs and/or real life tests.

The original accounted for stopping distance is seen as the desired situation. The intervention will change the current (desired) state. Again the intervention should take place till the new situation is to hazardous. Research on the relation between UKC and stopping length yields knowledge on ship behaviour. If the vessel can not safely enter or leave the harbour, more favourable conditions should be waited for. A second intervention is therefore wait for a more favourable UKC. Considering knowledge form section 2.4.2, this could either be a lower UKC ($< 3\,\%$) or bigger UKC ($>13\,\%$).

Resulting framework is stated in figure 3.3

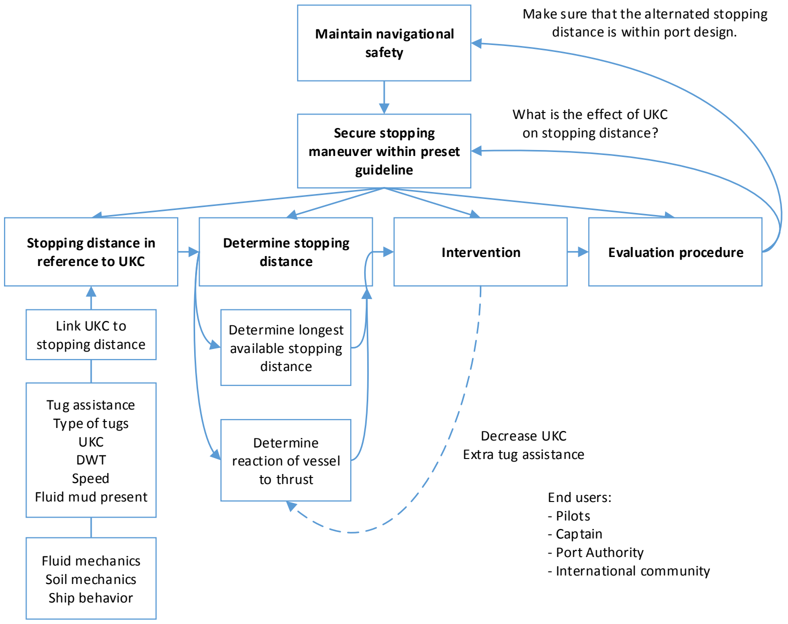


Figure 3.3: Management context element - Safety stopping distance

3.1.2 Economy

A smaller UKC reduces the required nautical depth for navigation, as explained in section 2.4.1. The extra space can be used for higher draught vessels or a maintenance cost reduction. Both of them serve the same strategic objective: “Increase the port profit by application of an adjusted UKC”.

Five operational objectives can be perceived, two of which already explained above. The operational objectives are:

- Reduce maintenance dredging cost
- Allow a higher draught resulting in higher shiploads
- Decrease time lost due to hindrance caused by dredging equipment
- Decrease waiting time by letting ships enter with a lower UKC
- Attract higher shipping classes by using increased navigational depth

For Delfzijl, the later discussed case, waiting time and hindrance are a non existing. The last objective “attraction of high draught vessels” requires accommodation of bigger vessels by expansion of berths and channels. In most ports this demands far reaching port developments which are often not feasible. Furthermore, the bigger vessels should be attracted to the port before a revenue increase can be noticed. Since this is seen as out of the problem scope it is neglected for this thesis. Therefore, the first two objectives are considered in this thesis.

Reduce maintenance cost

Estimation the dredging benefit is conducted by determining dredged volume eventually linked to a price per cubic metre. QSE is the cost of maintenance dredging for a specific port. Current state is the cost for maintenance dredging conducted in the harbour. A lower UKC (i.e. the intervention) supposedly reduces these costs to a desired state. Quantifying this last state is complicated, a small cost-saving is an improvement and thus desirable. However, if the effectiveness of reducing the maintenance cost is low and great effort or safety impairments are involved, reaching the desired state (i.e. a small improvement) is not sufficient. This is to be checked during the evaluation state on operational and strategical level. “Exactly how much is gained by using a smaller UKC to reduce maintenance dredging?” is an important assessment. Checking the gain in reference to other measures (i.e. allowing additional load) is important to check for the effectiveness on a strategic level.

Resulting framework is stated in figure 3.4

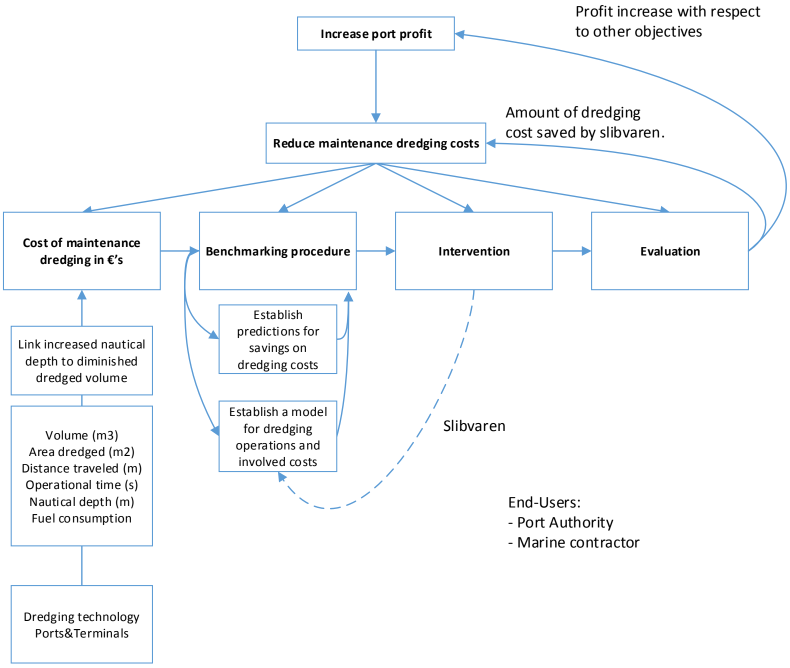


Figure 3.4: Management context element - Economy; dredging

Allow higher draught

Added load originating from a higher draught enables quantification on the increased revenue for the port authority. The increase depends on the wages paid per transshipped volume/quantity.

Current situation is the present draught and corresponding load providing port dues as income. Improved situation, reached by the intervention, is an enhanced income by allowance of a higher draught (i.e., load). An incremental revenue increase is already designated as desirable. Indication of the effectiveness corresponding to an increased load is essential. Evaluation on strategic level comprehends the check of effectiveness with reference to other strategies/benefits.

Resulting framework is stated in figure 3.5

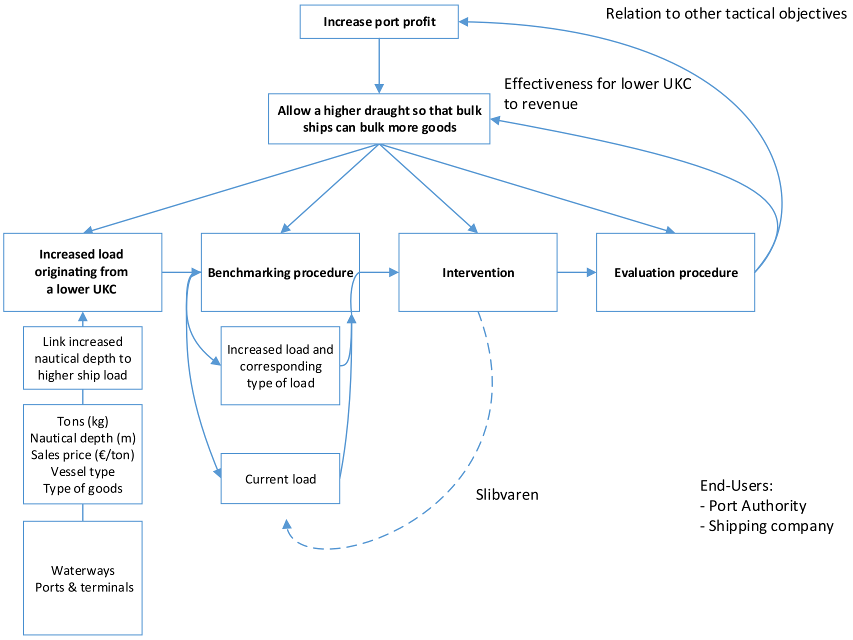


Figure 3.5: Management context element - Economy; increased draught

3.1.3 Ecology

Reduction of maintenance dredging decreases the burden for nature due less disposal of (fine) sediment and use of environmental unfriendly equipment, see section 2.2.4. Strategic objective corresponding to the procedure is therefore “the increase of opportunities for nature.”

Common knowledge and simple reasoning yields four main benefits to comply with the strategic objective:

- Reduce turbidity at disposal site caused by relocating sediment.
- Reduce bottom coverage caused by relocation of material
- Less dredging movements in the harbour result in lower turbidity in the harbour
- Increase recovering period for benthos in harbour

Discussion with port authorities and employees at Deltares and Van Oord reveal turbidity levels and benthos lifeforms inside the harbour indecisive. Little to no literature is discovered on ports being suitable for lifeforms and habits. In addition, vessel movements already cause higher SSC levels with respect to dredging equipment inside harbours [Aarninkhof et al., 2008].

Bottom coverage by disposed material in the Ems-Dollard is not covered in literature. Possible reason is the dynamic character of the Ems-Dollard estuary inducing an ever changing bathymetry. Furthermore, relocated sediment contains high fractions of fines creating an higher impact on SSC levels in reference to bottom coverage.

Turbidity

A higher bed level originates from a decreased UKC which is seen as the intervention. The current state is the Suspended Sediment Concentration (SSC) in the estuary, preferably measured at different locations. The current primary production is equally important, checking the SSC with respect to autotroph activity indicates how SSC reduction influences photosynthesis.

Evaluation for the strategic objective monitors the improved opportunities for nature corresponding to the turbidity decrease. Satisfied condition is where turbidity levels are diminished with reference to present SSC levels. This reduction coincides with an increase in primary production. Important in this evaluation is the effect of decreased SSC on the increase of light intrusion. Second step evaluation for the strategic objective is whether the diminished SSC will ultimately provide more primary production and thus create a better opportunity for nature.

Reduction of SSC during dredging operations can also be obtained by implementing alternative disposal methods. Goal of this thesis is the impact of a reduced UKC policy, therefore other available disposal measures are disregarded.

Resulting framework is stated in figure 3.6

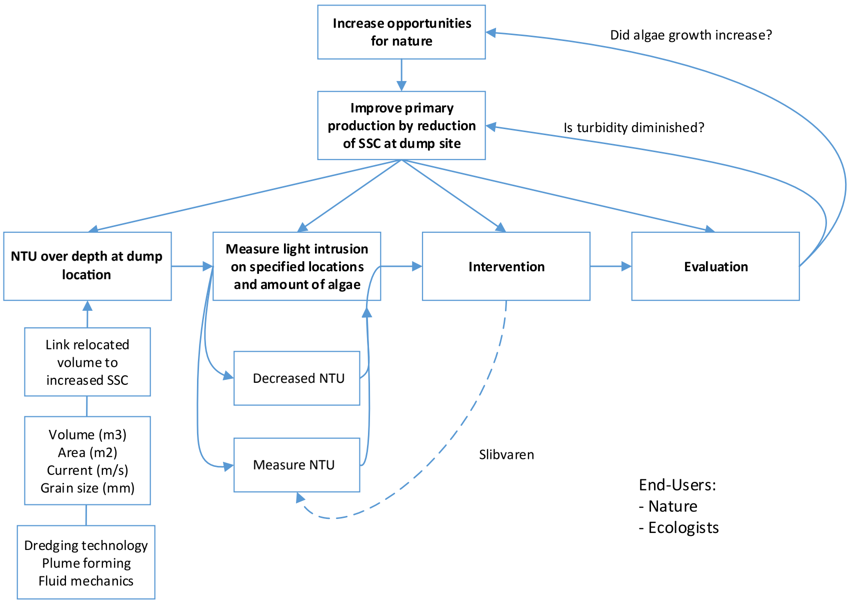


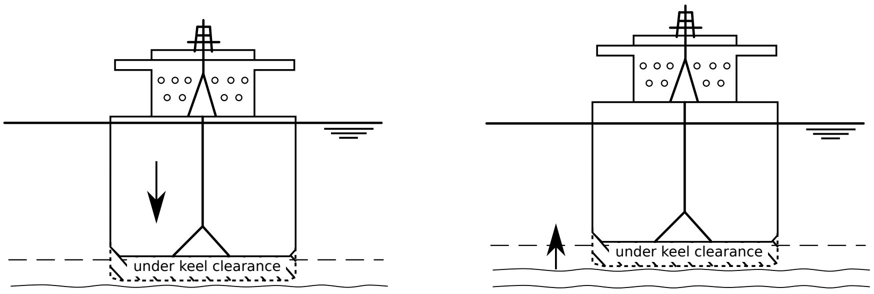
Figure 3.6: Management context element - Ecology

3.2 Decision Support Model

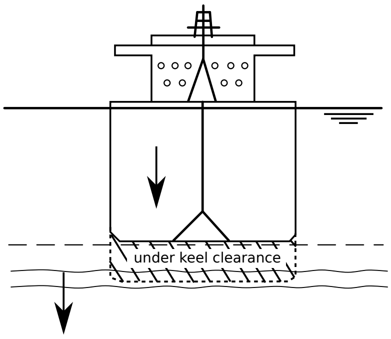
Integrating the described management contexts into one complete DSM is conducted by deploying three strategies. Strategy 1 and 2 each represent one of the two operational objectives (draught increase and dredging decrease) in the economic management context, figures 3.7a and 3.7b respectively. This creates a bound subset of challenges present for each strategy. Strategy comparison indicates the optimal strategy and what knowledge gaps should be bridge. A third strategy is used to check what measures are required in order to fulfil strategy 1 without adjusting the UKC policy. The strategy is depicted in figure 3.7c. Table 3.1 indicates the impact of each strategy on the different management contexts.

Table 3.1: Qualitative impact of strategies

	Safety	Ecology	Economy
Strategy 1	-	0	+
Strategy 2	–	+	++
Strategy 3	0	–	+/-



(a) Higher draught and higher load **(b)** Higher bed level and less dredging



(c) Higher draught without UKC reduction

Figure 3.7: Three different strategies

Combination of strategies and management context elements leads to the complete Decision Support Model. Figure 3.8 depicts the complete overview, revealing the relations between the different strategies and frameworks. The frameworks are indicated with a red upper left corner.

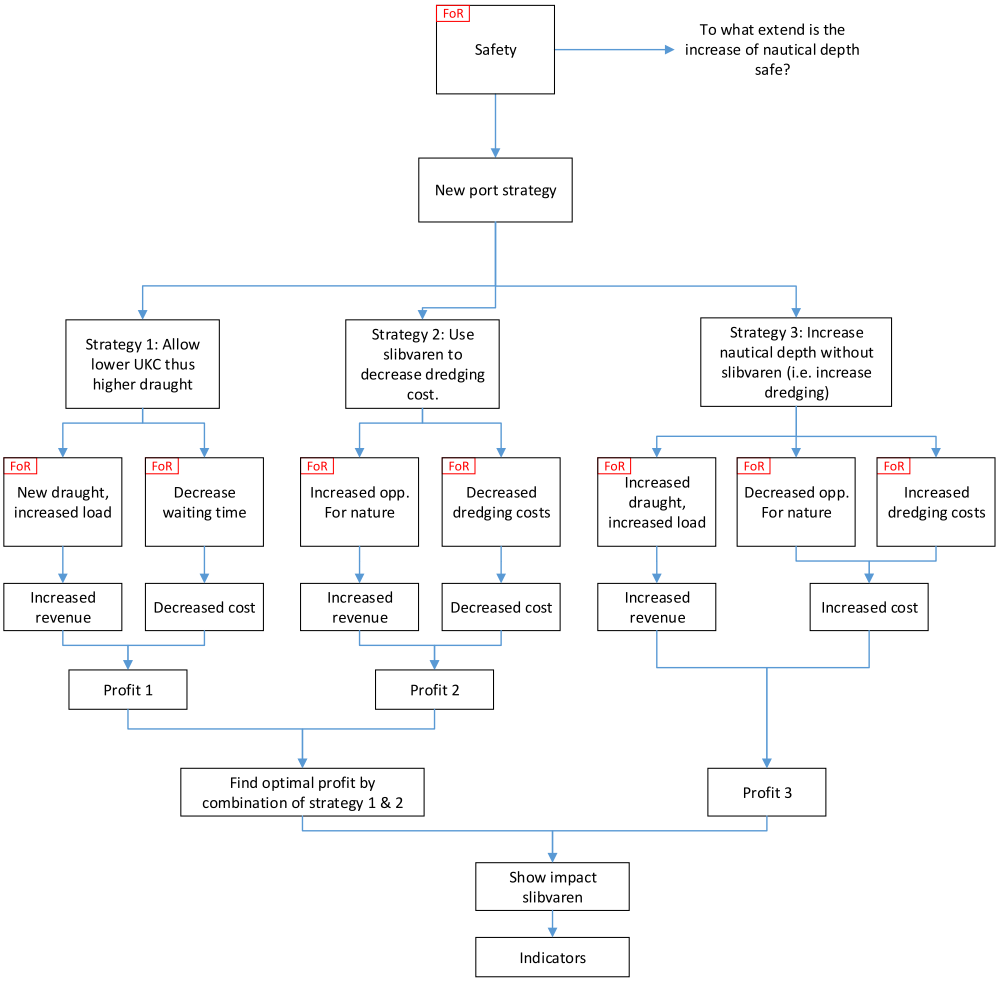


Figure 3.8: Decision support model

4

Decision Support Model improvement

Previous chapter introduced a Decision Support Model, conceived for helping decision making and indicating missing knowledge. The initial DSM was discussed with involved end-users for designating optimization of several states. The adjustments where instigated from new theoretical knowledge and insights during the thesis progress. Discussions with end-users on the case of Delfzijl (later explained) also revealed improvements. For overview purpose the improvement is not stated after the case since the it comprises the general part of the thesis.

This chapter describes the improvements for each management context.

4.1 Safety

This section elaborates on the changes in the management context ‘safety’. The complete overview of the adjusted management context is stated in table 4.1. The asterisks define adjusted/reformulated states. The numbers are used to substantiate the improvement.

In reference to the earlier stated management context elements in section 3.1.1, the following changes where made:

1. In the previous version the operational objective described an improvement. In light of difficulties of measuring rheology (described in 2.3.3), an improvement of reliability is far-fetched. Therefore striving for unaltered error, deployment time and time between survey and result is sufficient over the first period.
2. After discussion with researchers at TU Delft and port authorities, the effectiveness of the equipment was defined by: measurement error, time to conduct a complete survey and interval between survey and result. These elements are therefore implemented as the quantitative state.
3. The desired state depends on the current characteristics from equipment used for the nautical bottom survey. The parameters are case specific, for Delfzijl they are located in section 5.2.1

4. Only possibility of checking new in-situ measurement technique is by lab testing soil samples. These soil samples should be taken at the survey location at the same time the equipment is used.
5. For tug-assistance to be possible, the vessel should maintain an unsupported course for a specific length after passing the breakwater. The required length is described by theory by Ligteringen and Velsink [2012].
6. Initially, the UKC reduction was the first intervention. Tug assistance was stated as second intervention when manoeuvrability was dangerously low. However, this element should describe the situation previous to tug tie-up. As a result, tug assistance can is not a valuable intervention. New knowledge on specific UKC affects, explained in 2.4.2 showed an UKC between 13 % and 3 % pose the most difficult conditions. Waiting for water levels where these clearance is outside these values is preferred.
7. The initial stated "ship reaction" is better described by vessel rate of turn. This was also used by other researchers.
8. Each port requires one or multiple turns. Every turn must be taken within accommodated space. Defining the maximum of every turn is therefore crucial.

Table 4.1: Management context: Safety

Management issue	Measurements	Stopping length	Rudder control
Strategic objective	Maintain navigational safety while adjusting the UKC.	Maintain navigational safety while adjusting the UKC.	Maintain navigational safety while adjusting the UKC.
Operational objective	Designate the new $*^1$ nautical bottom with present accuracy and equipment deployment time	Secure stopping manoeuvre for arriving vessels	Secure sufficient rudder control for departing vessels
Quantitative state concept	Establish error in m, $*^2$ deployment time and time to result in hours	Stopping distance in meters in reference to UKC	Rudder angle in $*^7$ comparison to rate of turn and turn radius
Benchmarking desired state	Error, time required $**^3$ for complete survey and time needed for result with current eq.	Slow down distance L_1 $**^5$ and tie-up distance L_2	Max. available $**^8$ Turn radius at the port
Benchmarking current state	Cross-check $*^4$ measurements with soil samples	Establish current ** state by acquiring stopping length of vessel	Establish current state by acquiring turning rate and rudder angle data
Intervention procedure	Utilize an extra or different piece of equipment	Wait for a favourable $*^6$ UKC	1.Tug-assistance 2.Decrease UKC
Evaluation procedure	**Operational:** Assess * whether equipment meets current accuracy and employment time	**Operational:** What is the effect of UKC on the stopping distance	**Operational:** What is the effect of UKC on the turn radius and rudder angle
	Strategic: Assess * the wheter safety is affected by new measurement error	**Strategic:** Assess whether the present safety is maintained after application of the altered UKC	**Strategic:** Assess whether the present turn radius is met

* *reformulated to fit new goal/parameter*
** *requires case-specific information*

4.2 Ecology

This section elaborates on the changes in the management context ‘ecology’. The complete overview of the adjusted management context is stated in table 4.2. The asterisks define adjusted/reformulated states. The numbers are used to substantiate the improvement.

Table 4.2: Management context: Ecology

Management issue	**Turbidity**
Strategic objective	Increase opportunities for nature
Operational objective	Reduce turbidity (NTU) by decreasing the SSC $**^1$ as originated from relocated material, by implementing a new dredging strategy
Quantitative state concept	SSC, NTU and chlorophyll-a production over water column $*^2$
Benchmarking desired state	Target SSC in the area $*^3$
Benchmarking current state	Measure SSC and turbidity over the water column *** by sampling and NTU measurements.
Intervention procedure	Decrease the minimum allowed UKC
Evaluation procedure	**Operational:** Determine the amount of reduced *** relocated material. **Strategic:** Assess if reduced SSC leads to a lower *** NTU and higher Chlorophyl-a

*	*reformulated to fit new goal/parameter*
**	*filled with specific values*
***	*adjusted for corresponding to reformulated states*

1. Original objective focussed on reduction of NTU over depth. This does not create a link between turbidity and SSC. Knowledge on the relation to SSC and NTU should be obtained, therefore both should be measured. Hence the objective is reformulated covering NTU and SSC over the water column.
2. Parameters are SSC and NTU over water depth. Later quantification in section **??** shows the difficulties in linking SSC to NTU and NTU to Chlorophyll-a production. In order

to get more insight all three should be measured.

3. The desired condition depends on the ecological condition of the area. For Delfzijl this is discussed in 5.1.2.

4.3 Economy

Table 4.3 shows the complete overview of the economy management context. The asterisks define adjusted/reformulated states. The numbers are used to substantiate the improvement.

1. Original objective from section 3.1.2 stated the reduction of dredging cost, but did not describe how this reduction was obtained. Specifically stating the change in bed-level which will lead to an smaller harbour volume, should be used for quantification in section 6.2.2.
2. The old quantitative state described the benefit in monetary units without describing the dependency of trapping coefficient.
3. For equal comparison of benefits and drawbacks the tidal windows, as explained in section 5.2.2, should be unaltered. This is therefore implemented as the desired state.
4. Quantification in section 6.2.2 used the equilibrium between UKC decrease and nautical bottom level increase. This is implemented in the benchmark state.
5. Measured parameter should be the increase of draught in stead of the load.
6. For equal comparison of benefits and drawbacks the tidal windows, as explained in section 5.2.2, should be unaltered. This therefore implemented as the desired state.
7. Quantification in section 6.2.2 used the equilibrium between UKC decrease and nautical bottom level increase. This is implemented in the benchmark state.

Table 4.3: Management context: Economy

Management issue	Reduce maintenance	Higher draught
Strategic objective	Increase port profit	Increase port profit
Operational objective	Maintain a higher bed level *[1] by reduction of UKC, resulting in a lower trapping coefficient and reduced maintenance cost.	Allow a higher draught by reduction of the UKC, resulting in a higher revenue.
Quantitative state concept	Dredged quantity **[2] originating from a smaller harbour volume originating from a new nautical bottom	Draught increase in **[5] meter
Benchmarking desired state	Unaltered tidal window **[3] when a low UKC is used and bed level is increased	Unaltered tidal window **[6] when the concept is applied.
Benchmarking current state	Determine TW while **[4] decreasing nautical depth and decreasing UKC	Determine TW while **[7] increasing draught and decreasing UKC
Intervention procedure	Decrease UKC	Decrease UKC
Evaluation procedure	**Operational:** Reduced *** dredged quantity expressed in monetary units	**Operational:** Assess the *** extra load per vessel corresponding to the amount of draught increase
	Strategic: Assess the increased port profit originating from the new UKC policy	**Strategic:** Profit by increasing the draught

*	*reformulated to fit new goal/parameter*
**	*filled with specific values*
***	*adjusted for corresponding to reformulated states*

5

Case description; Delfzijl

The previous two chapters elaborated on DSM derivation and later improvements. The DSM consisted of management elements conceived from an end-user perspective with knowledge on fluid mud theory and UKC adjustments. In order to check if practical application coincides with the established DSM, a case study is conducted.

This chapter elaborates on the chosen case study: Delfzijl. This case is interesting due to previous research on application of new UKC policy (Meinsma [2011]; Meinsma [2012]; Meinsma [2013]; Barth et al. [2016]). Furthermore, next research phase is on the actual application of the new policy. Since the DSM will streamline decision making, it will be a contribution for applying a new UKC policy.

The chapter starts with an elaboration on the situation in and around the port of Delfzijl is described in section 5.1. In section 5.2 vessel information, entrance policy, maintenance and determination of the nautical bottom is explained. In this section the general theoretical knowledge from chapter 2 is applied to the port of Delfzijl. The next section 5.3 clarifies on the current maintenance policy. Interesting in this section is a detailed calculation of the sedimentation processes in the harbour. The chapter concludes with section 5.4 where an elaboration is given on the previous conducted research at Delfzijl.

5.1 Delfzijl

5.1.1 Location & Lay-out

The port of Delfzijl is located in the north-east of the Netherlands situated near the entrance of the Ems-Dollard estuary. The port consists of an outer- and inner harbour separated by a lock. Maximum allowed draught of the inner harbour is 5 metres. In the outer harbour vessel draughts up to 9 m can be accommodated [Groningen Seaports, 2016a].

The harbour entrance at Delfzijl is located parallel to the Ems-Dollard estuary. The entrance width at the bottom is 208 metres with a nautical depth of 9.5 to 10.0 metres (depending on maintenance). In each section of the channel the navigable width is 100 metres [Groningen Seaports, 2016a]. Figure 5.1 shows the lay-out and location of the port of Delfzijl.

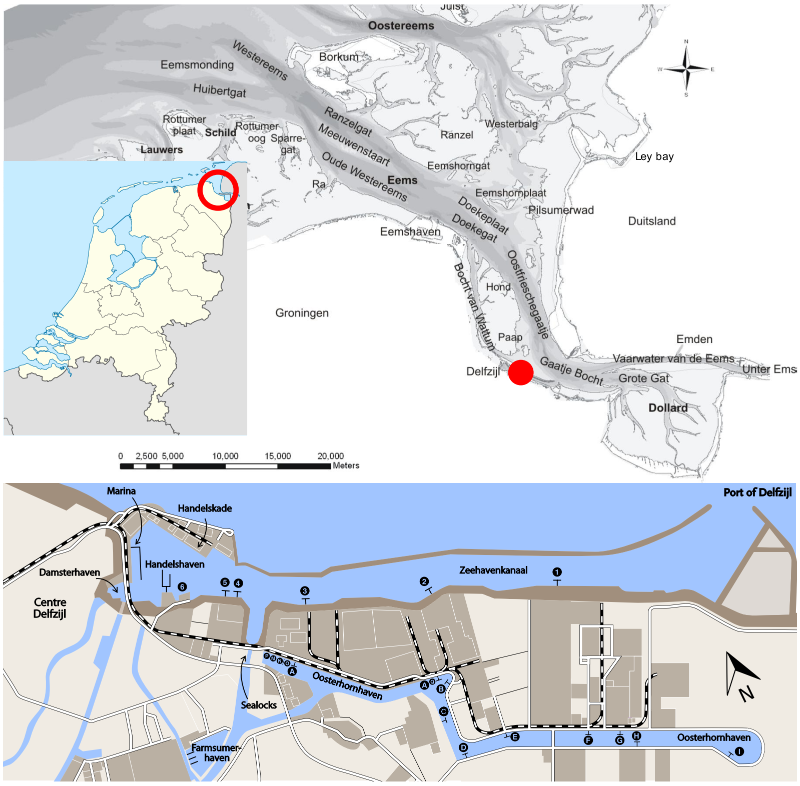


Figure 5.1: Location and lay-out port of Delfzijl [Cleveringa [2008], Groningen Seaports [2016a]]

like the rest of the Dutch coastal area's, Delfzijl experiences a semi-diurnal tide. Averages are depicted in table 5.1.

Table 5.1: Vertical tides Delfzijl in reference to NAP [Groningen Seaports, 2016a]

	HW [m]	LW [m]	Mean range [m]
Mean spring tide	+ 1.44	- 1.82	3.26
Mean tide	+ 1.31	- 1.68	2.99
Mean neap tide	+ 1.12	- 1.47	2.59

Vessel and wages

Normative vessel for the port of Delfzijl is the MS Tornes [Meinsma, 2011], details are shown in table 5.2. The draught is implemented in this thesis.

Per quantity of transshipped goods port dues must be paid at to the port authority, see table 5.3. These result in a revenue for the port authority depending on cargo type and -quantity. In this situation the average price of all cargo with destination and/or origin of the "Zeehavenkanaal" is used, see table 5.3 . Average of the cargo in the "Zeehavenkanaal" is € 0.768.

Table 5.2: MS Tornes characteristics Meinsma [2011]

MS Tornes	
Length	113 m
Width	20 m
Max. draught	7.5 m
Dead weight	8.721 ton

Table 5.3: Cargo tariffs for freight originated or destined for berths at "Zeehavenkanaal" [Groningen Seaports, 2016a].

Cargo	price [€/ton]
Alumina	0.783
Glycerine	0.994
Salt	0.651
Vegetable oil	0.666
MDI	0.827
Methanol	0.684
Average	**0.768**

5.1.2 Ems-Dollard Estuary

The Ems-Dollard estuary changed over time due to natural development and human interventions (Herrling and Niemeyer [2007], Raad voor de Wadden [2010] & Spiteri et al. [2011]). Interventions like channel deepening for navigation purposes, construction of three big ports and a cruise ship dockyard. A brief overview of interventions is stated in table 5.4, for a full overview the reader is referred to Herrling and Niemeyer [2008].

Table 5.4: Summary of human interventions in and around the Ems-Dollard Estuary [van Maren et al., 2016]

Period			Description
±1000	-	1509	Lowering of the peat-lands bed level due to drainage resulting in regular floods and development of Dollard Bay
1509	-	1924	Reclamation of large parts of Dollard Bay
1800	-	present	Degeneration of an ebb channel (the Bocht van Watum) probably in response to the reduction of the size of Dollard Bay
1950	-	present	Construction of ports and deepening of tidal channels
1960	-	1994	Extraction of fine sediment from the port of Emden and its approach channel
1990	-	present	Extraction of fine sediment from the lower Ems River

As explained in section 2.2.4 channel widening and -deepening are the main origin of the high SSCs in a estuary. These interventions cause flood dominance to occur, increasing the import of sediment to the system. However, the first SSC increase due to the shipping channel expansions appeared less severe because sediment could sink at the edges of the estuary. Over period of time these areas where reclaimed for agricultural purposes. However, an increase in suspended concentration was hardly noticed due to sand-mining in the estuary. When sand mining stopped in the 90s, problems resulting from expanded channels became apparent. Further expansion of harbours and shipping activities intensified the problem, tipping the system out of its natural state (Lenselink et al. [2015] & van Maren et al. [2016]).

As a result of the interventions the estuary is developing from a multi- to a single (deep) channel system [Spiteri et al., 2011]. With decreasing sediment sink areas and increasing flood dominance of the system. Figure 5.2 shows the change in bathymetry over time.

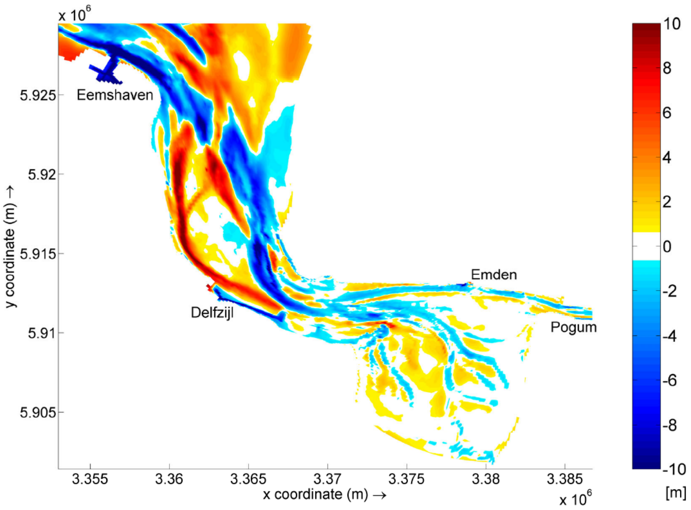


Figure 5.2: Bathymetry development between 1937 and 2005 (Blue=erosion, Red=accretion) of the Ems-Dollard estuary [Herrling and Niemeyer, 2008]

Turbidity

The man induced SSC causes issues in the estuary. Majority of the light extinction in the Ems-Dollard estuary is caused by suspended sediment concentration (SSC) [Stolte et al., 2015]. These create high turbidity resulting in attenuation coefficients of up to $10\,\mathrm{m}^{-1}$. The suspended matter ranges from 100 to 300 mg/l and is highly influenced by fresh water input with a relatively high nutrient content (Colijn [1983]; de Jonge et al. [2012]). The Ems-Dollard is relatively shallow with large areas of 1 meter below NAP, causing complete areas to run dry at low water. In some parts of the estuary, silt content (i.e., grain sizes $< 63\ \mu m$) up to $100\,\%$ is reached [Riegman et al., 2014].

The suspended sediment concentration (SSC) is shown in figures 5.3 and 5.4. Data in figure 5.3 was measured by the Dutch government under the “Monitoring Waterstaatkundige Toestand des Lands” (MWTL) program. Data previous to 1990 is also available, however Vroom et al. [2012] & van Maren et al. [2015] debate on the reliability of these measurements. The

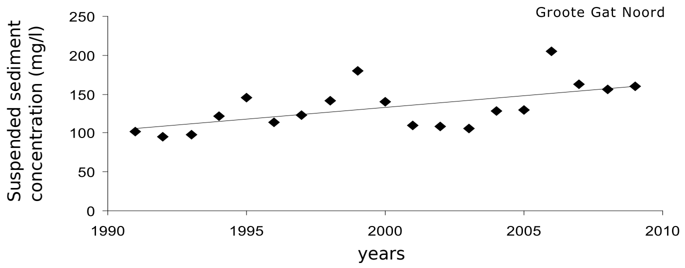
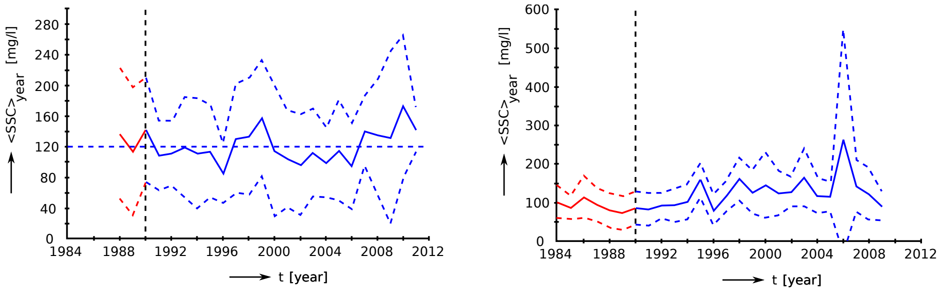


Figure 5.4: Suspended matter in mg/l [Raad voor de Wadden, 2010]

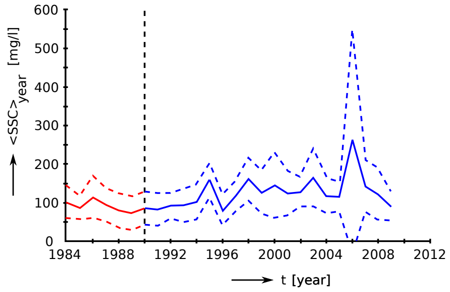
discussion originates from the small number of gauging locations over the area of interest, changes between measurement method, procedures and the sampling frequency before 1990.

Vroom et al. [2012] used the measurements showed in figure 5.3 for a trend analysis. The analysis showed a significant trend increase for "Groote Gat Noord", affirming the correctness of figure 5.4



(a) Bocht van Watum

(b) Bocht van Watum Noord



(c) Groote Gat Noord

Figure 5.3: Plot of SSC yearly means (plus and minus spread) at locations near Delfzijl [Vroom et al., 2012].

5.1.3 Ecosystem

Biodiversity in the Ems-Dollard is relative small in comparison to the Wadden sea, due to the harsh environment. The surrounding water is brackish and predation by birds is high due to exposure on tidal flats. This creates an system with less biodiversity and high percentage of deposit feeders, see figures 5.5 & 5.6.

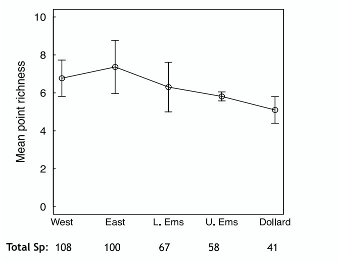


Figure 5.5: Species richness in the Dollard region [Compton, 2015]

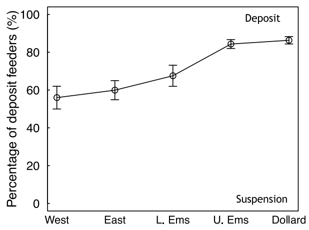


Figure 5.6: Percentage of deposit feeders [Compton, 2015]

Primary production

Average primary production found in 2012 and 2013 are 120 and 125 $gCm^{-2}y^{-1}$ respectively [Riegman et al., 2014]. Colijn [1983] found a yearly average of 165 $gCm^{-2}y^{-1}$.

5.2 Navigation policy

5.2.1 Nautical bottom and -depth

At Delfzijl nautical bottom surveys are performed with the multi-beam equipment, a technique explained in section 2.3.3. In the "Zeehavenkanaal" two depth profiles can be distinguished with this technique, shown in figure 5.7. Measurements are taken every first week of each month or when certain situations require additional deployment. Depth measurements are conducted by the port authority (Groningen Seaports). The pilotage and harbour master use the 210 kHz level as the nautical bottom (Bourgonjen [2016] and Meinsma [2011]). All UKC values in this thesis are with respect to the 210 kHz level survey as performed by Groningen Seaports.

Two locations within the channel are normative: an entrance sill and a fluid mud peak in the channel. The sill is located at NAP-9.5 m at the entrance of the harbour and a fluid mud layer is located at NAP-8.7 m. Both of them are depicted in figure 5.7. The location and height of the sill is constant due to the maintenance strategy. The fluid mud body is dynamic of nature with a varying location between consecutive measurements, see figure 5.8.

Depths described above, mean LW levels (table 5.1) and vessel draughts in the inner harbour, result in an unrestricted inner harbour. Only vessels originating or destined for berths in the outer harbour (i.e. "Zeehavenkanaal" and "Handelshaven") are therefore considered.

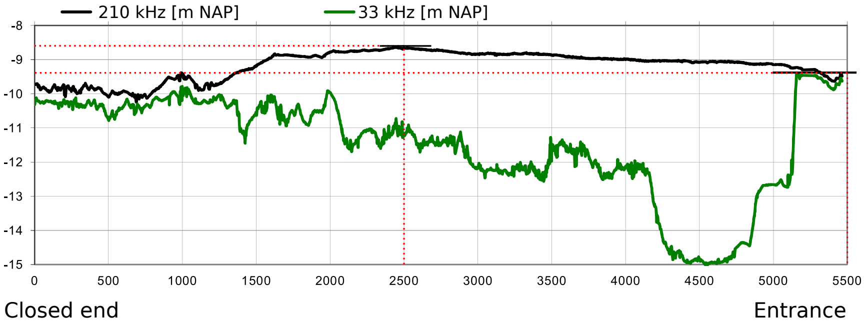


Figure 5.7: Longitudinal profile Zeehavenkanaal, measured on 2^{nd} of May 2015 [Barth, 2016]

In a first approach the top of the fluid mud is assumed as static in time, located at a depth of -8,7 m NAP with a distance of 3000 m from the entrance, depicted in figure 5.7. Average travel time between top sill and top fluid mud is 30 minutes [Meinsma, 2012].

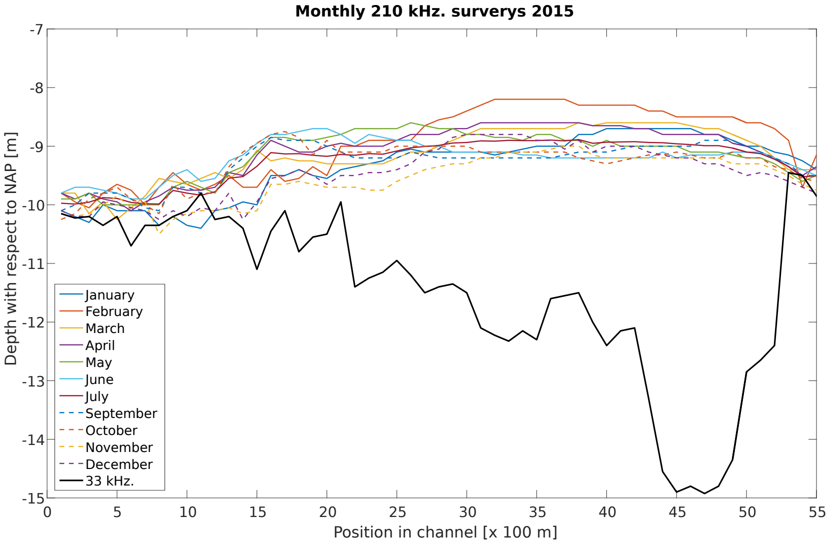


Figure 5.8: Bottom profile development over 2015. Elaboration on used charts is located in appendix A.

5.2.2 Tidal window

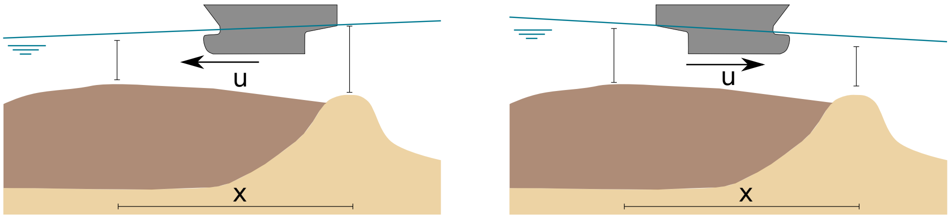
As described in section 2.1.2 an inability to maintain a 10 % UKC causes a tidal closure. The tidal window as the result of vertical water motion is influenced by a current or horizontal tide. To overcome this cross-current, the vessel must have a high travel velocity. A relative small turn in the entrance leads to an unsafe situation when the vessel travels at high velocity.

Therefore, deep draught vessels are advised to enter around high water slack when horizontal tide is lowest. These vessels will enter 30 minutes before and 30 minutes after HW. Departing vessels are not affected by the crosscurrent since navigation at maximum velocity overcomes drift effects [Meinsma, 2011]. All vessels arrive and depart without mandatory tug assistance. Although not obliged, tugs are always available within power ranges of 5.8 to 56 ton bollard pull [Groningen Seaports, 2016a].

The tidal window is influenced by the location and composition of the nautical bottom. As the result of deviations in bathymetry and geometry different situations are present at each harbour. The bottom profile at Delfzijl, shown in figure 5.7, indicates a fluid mud hotspot and a sill in the entrance. The local hotspot in Delfzijl occurs due to a focus in sediment deposit as the result of the exchange flow mechanisms, as explained in section 2.2.1. As a consequence, the UKC can be reduced above the fluid mud deposit while a 10 % UKC must be maintained at the entrance. When determining the tidal window for Delfzijl four manoeuvres can be distinguished:

- **At dropping tide:**
  1. **Vessel arrival**, see figure 5.9a
     Vessel will cross the entrance sill before arriving at the shallow part in the channel. The dropping tide causes the lowest part in the harbour to be decisive for determination of the tidal window.
  2. **Vessel departure**, see figure 5.9b
     Vessel will pass the entrance sill at the end of its transit. The dropping tide causes the sill to be decisive.
- **At rising tide:**
  3. **Vessel arrival**, see figure 5.10a
     The lowest part is decisive for arrival. Once the lowest part is cleared more room for error is present due to the rising tide.
  4. **Vessel departure**, see figure 5.10b
     Water depth above top sill is smallest. Once the vessel clears the lowest part, unhampered navigation is guaranteed.

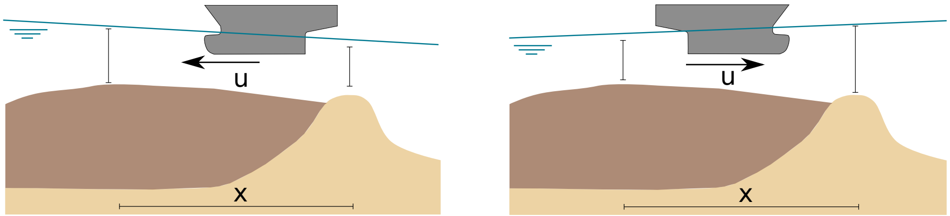
These situations depend on the tidal cycles at the location, see figure 5.11. The design vessel with a draught of 7.5 m is used for tidal window determination, see table 5.2. Depicting the height of the sill and shallow part results in two sinusoidal lines showing the available nautical depth. The horizontal line in the figure corresponds to the required nautical depth (i.e., vessel draught including 10 % UKC). Passage of either one of the locations is only possible if the water level is sufficient (i.e. above the horizontal line). In the current situation a ship maintains a 10 % UKC when navigating above the sill and shallow part, depicted in figure 5.11. In this tidal situation, the shallow part governs the tidal window for all circumstances. If the shallow part consists of fluid mud, adjustment of the allowed UKC is possible.



(a) Situation 1: Vessel arrival

(b) Situation 2: Vessel departure

Figure 5.9: At dropping tide



(a) Situation 3: Vessel arrival

(b) Situation 4: Vessel departure

Figure 5.10: At rising tide

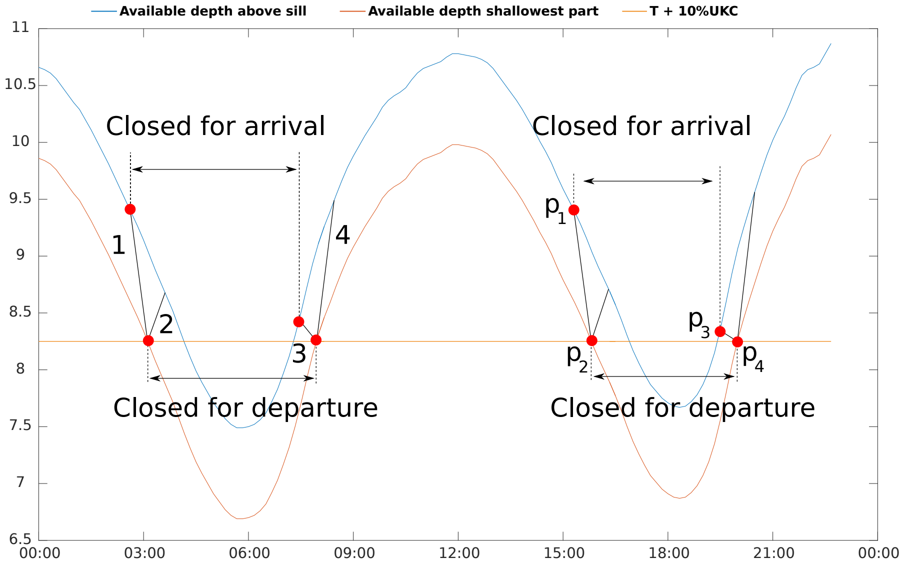


Figure 5.11: Tidal window for the current situation (i.e. T + 10 % UKC). Vessel draught = 7.5 meter, tide of 1^{st} of January 2010 [Rijkswaterstaat, 2016]

Determination of the tidal window based on data of one day can be performed by hand-calculation. However, extensive tidal data is available, requiring a tool to determine tidal window based on yearly data. Elaboration on the functioning of the TW-tool is located in appendix C.1.2. The tool is later used for quantification.

5.3 Maintenance

Sedimentation theory, explained in section 2.2, requires frequent dredging at Delfzijl. This maintenance is conducted by dredging company 'De Boer'. The contractor is responsible for maintenance in the "Zeehavenkanaal" and approach channel "Paapsand Süd". Different dredging area's with guaranteed depths are designated in the "Zeehavenkanaal", see the map in figure A.01 in appendix A. The contractor is responsible for maintaining the specified depths and is free to determine type of equipment and frequency of deployment (i.e. a performance based contract).

A water-air injection dredger (WAID) or Airset is used at Delfzijl. The Airset is deployed in section A (front end) of the "Zeehavenkanaal", see table 5.5. Deployment in part B (mid section) is also permitted. However, due to low flow velocities in the section a Trailer Suction Hopper Dredger (TSHD) is more efficient. A TSHD is therefore deployed in sections B and C. Part of the removed material by TSHD is relocated to the silt-trap, the rest is disposed at permitted locations in the Ems-Dollard estuary. Sediment deposited at the silt-trap, near the channel entrance, is later removed by the Airset. Total relocated volume amounts to approximately 1.6 million m^3 each year, see figure 5.12. Current performance based 8 year contract with a value of € 1.8 million/year, expires in 2016 [Kamphuis, 2013].

Table 5.5: Dredge sections Delfzijl. Table belonging to figure A.01 in appendix A

Dredge section	area's
A	1, 2 & 12
B	3,4,5 & 6
C	7, 8, 9, 10 &11

For maintenance purposes, the 2/3th depth is used in dredge areas 1 to 4. This is the 2/3th difference between the 33 kHz and 210 kHz measurements. The remaining area's are maintained based on the 210 kHz depth [Meinsma, 2011].

Above described maintenance approach resulted in deployment of the Airset between 40 and 45 times a year with a total of 2575 hours in 2015. The Airset was supported by a TSHD, deployed 10 to 15 times a year with an operation time of 800 hours in 2015 [van Dijken, 2016b].

Changes in dredged volume depicted in figure 5.12 are the result of multiple harbour adjustments. After construction of the harbour with a total area of 75 hectare, the resulting yearly maintenance was 0.6 million m^3/year. The sudden increase in 1976 is caused by relocation of the entrance from west to east with a corresponding basin expansion of 250 ha. At the same

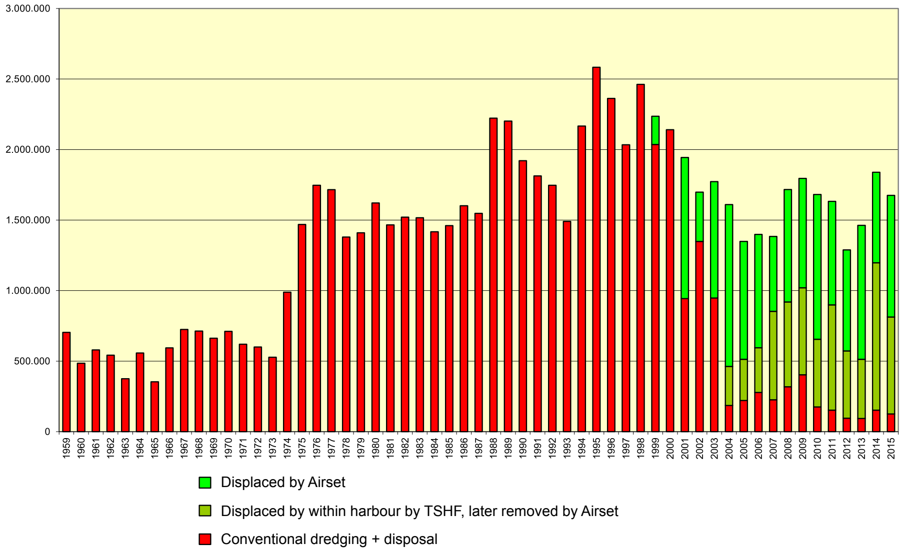


Figure 5.12: Maintenance dredging quantities in Delfzijl [m^3] (Paapsand Süd excluded)[van Dijken, 2016a]

time a silt trap of 15.5 ha was constructed at the harbour entrance. These measures led to an average dredged volume of 1.7 million m^3/year. The reduction after 1989 is caused by a silt trap increase of 5.5 ha and a harbour area decrease of 27 ha [Meinsma, 2011].

Decrease after 2000 might be the result of a decreased trapping coefficient. This would have been the result of Airset deployment which resembles a KSM technique, see section 2.2.3. However, the decrease from 2.2 million m^3/year to 1.6 million m^3/year is large. With Eq. 2.5 the difference in trapping coefficient p can be determined between 2000 and 2015. With the original trapping coefficient of 0.33 [Eysink, 1999], p between 0.2 to 0.25 is obtained for 2015. Often trapping coefficient reductions are small by KSM procedures [PIANC, 2008]. Most likely the reduction originates from a combination of a smaller trapping coefficient and difficulty in dredging production determination. This difficulty origins from the fact that sediment is not brought to the surface during Airset deployment. As a result, production determination can only be conducted by bottom surveys. Measurement errors and inaccuracy lead to a less accurate dredging production (Wilson [2007] & MarCom Working Group [2013]). In addition, the Airset is mostly deployed in 2 or 3 consecutive days whether bottom surveys take place in between each day or after 2 days is unclear. If the latter is the case, than dredged material from the first day might have settled at the dredge site and is therefore dredged the second day as well.

One could question the relevance of dredging production determination for an Airset technique. Conventional dredging methods pick up the sediment and relocate it by transport. Number of vessel trips, time and fuel consumption directly depends on the amount of material being relocated. With Airset deployment the guaranteed depth and time needed to maintain this depth, determines the cost of the dredging contract.

Extensive elaboration on the governing exchange flow for the annual dredged volume is located in section 5.3.1. Since the reduction of dredged volume between 2000 and 2015 can not be clarified, a detailed sedimentation rate is calculated. This calculation is located in section 5.3.1.

Airset

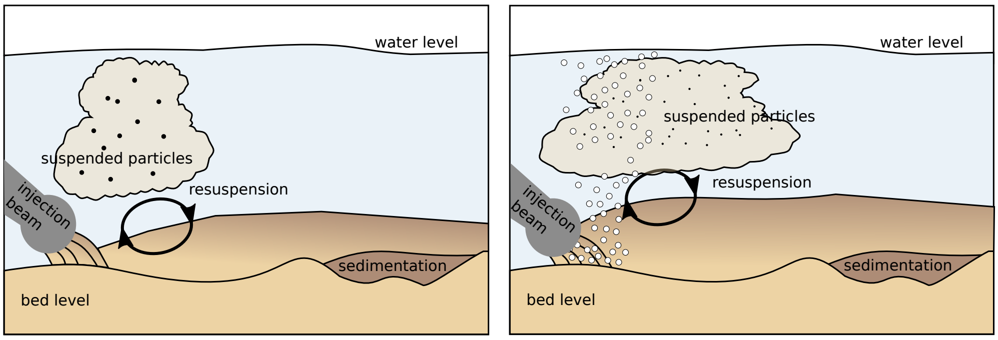
Airset dredging resembles water injection dredging (WID), see figure 5.13. Difference between the techniques is adding adding air to the injected mixture. The rising bubbles induce extra turbulence at the bottom, transporting particles to higher levels in the water column [Bourgonjen, 2016]. When the particles are brought into suspension during dropping (outgoing) tide they will be transported out of the harbour. As a result of the short travel distance and higher current velocities at the entrance, the Airset is more effective at the front end of the harbour. Whether loosening capabilities improve by injecting an air-water mixture is unclear. No literature is present on the functioning of the Airset and no other harbours are maintained with a similar technique.

Considering jets, the air might decrease jet efficiency as a result of bubbles leaving the mixture shortly after exiting the jet nozzle. In addition, rising bubbles will break down to an equilibrium size of 4 mm. This leads to low capabilities of transporting grains [van Rhee, 2016]. Origin of applying an air-water mixture probably has to do with patents on conventional WID techniques. Considering the filing date of the WID-patent by van Weezenbeek, the technique was not publicly available until 2007 [van Weezenbeek, 1987].

Airset induced turbidity

The turbulence induced by the Airset will re-introduce settled particles into the water column, creating turbidity. This turbidity can be harmful for an ecosystem as discussed in section 2.2.4. In order to check the Airset induced turbidity Wiertsema & Partners conducted NTU measurements with the help of an YSI-sensor during Airset deployment [Meinsma, 2011]. They concluded that the water column was slightly better mixed over the vertical but no significant increase op SSC was noticed. This conclusion corresponds to the above statement that the Airset is not very efficient in agitation of bed material. Side note by Meinsma [2011] was made that the measurements where conducted during Airset deployment, for a bottom flow velocity of almost zero. Therefore the loosened material had not fully entrained the water column. Measuring at a time interval after deployment could lead to other values.

It is not clear what the impact of the Airset is for ecology. According to van Maren [2016] an Airset/WID procedure is better for the system despite of the re-suspension of material. In a healthy system, dredging operation will slightly influence the SSC. Whether relocation by TSHD or WID/Airset is performed, the sediment will remain in the system and the average turbidity is only influenced on a small scale. However, benefit of injection dredging is the turbidity cloud only being transported in vicinity of the harbour. When relocating the sediment to other parts of the system (TSHD) a bigger area will be influenced by the activity. Reduction of dredging always helps but a more influential matter would be the extraction of sediment from the system. From where the sediment is extracted determines to great extend the resulting effects [van Maren et al., 2015].



(a) Water injection dredging [MarCom Working Group, 2013]

(b) Probable functioning Water-air injection dredging

Figure 5.13: Two dredging methods compared

5.3.1 Sedimentation process at Delfzijl

Main drive for research on the nautical bottom in Delfzijl is caused by implementation of a new dredging strategy in 2001 [Bourgonjen, 2016]. Re-suspension of bottom material with the Airset caused deviations between the 33 kHz and 210 kHz echo-soundings. The 210 kHz soundings depicted the bottom layer at lower depths then before, as described in section 2.3.3. Reaction of pilots on the apparent diminished navigational depth resulted in awareness for the problem and led to research on whether or not this layer would be harmful for the vessel and its navigation [Bourgonjen, 2016]. Figure 5.14 indeed shows a higher 210 kHz level when comparing April 1999 to April 2015 surveys.

A shallower depth will decrease the residence time due to a smaller harbour volume below average water level, see section 2.2.2 Eq. 2.6. Reduction of the residence time decreases the trapping coefficient, see Eq. 2.6 in section 2.2.3. If the higher bed level was undesirable, then dredging quantity should have been increased. This is in contradiction with the depicted dredging reduction shown in figure 5.12. Therefore, this section elaborates on exchange flows and sedimentation process at Delfzijl.

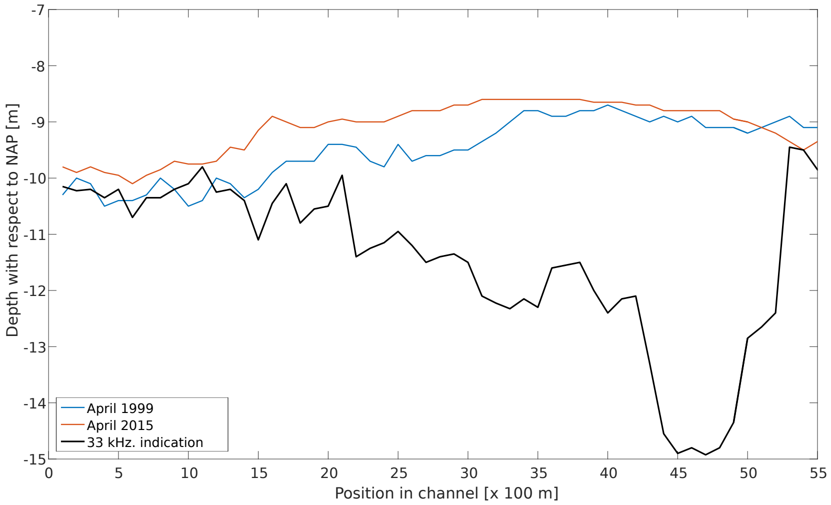


Figure 5.14: Comparison 210 kHz measurement between 1999 (conventional dredging) and 2015 (Airset dredging). Elaboration on used charts is located in appendix A

Annual siltation

All three exchange flow mechanisms, described in section 2.2.1, are present in the harbour entrance of Delfzijl. A current of 0.7 and 1.2 m/s [van Rijn, 2016] and a maximum of 1.5 m/s [Meinsma, 2011] is present flowing perpendicular to the entrance. The mixing layer, caused by flow separation, is pushed into the harbour during tidal filling as depicted in figure 5.15. This results in an eddy formation inside the harbour basin during rising tide. Suspended material is attracted to the centre of the eddy.

A density gradient is present due to a changing density front and a fresh water discharge of 400 $\cdot 10^6$ $m^3/year$ with a sediment concentration of 0.005 kg/m^3 originating from a lock and weir [van Rijn, 2016]. This drives a density exchange flow in the harbour entrance. Affected by the tide a two layer system is formed as depicted in figures 5.16b and 5.16c. During tidal filling, high density water will enter the basin in the lower half of the water column. At the same time low density clear water will flow out of the basin at the upper half. During dropping tide, the low density water will flow out in the upper half op the water column while at the lower part water will still run into the harbour. The already turbid water will pick-up more sediment when flowing across the bottom. Therefore, this mechanism constantly imports water with high SSC while, relatively clear water flows out.

Density currents induced by difference in sediment concentrations are neglected. The bottom sill divides the dense sediment layers at the bottom, as shown in figure 5.17

In order to determine the annual siltation, calculation of the governing mechanisms is conducted. Determination of the flow mechanisms is done with the help of the Eysink model as

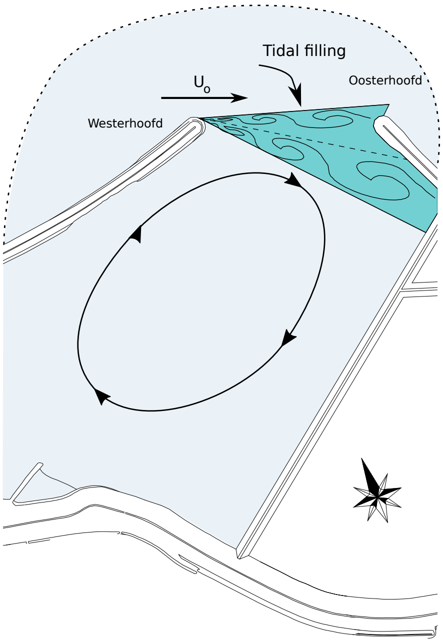
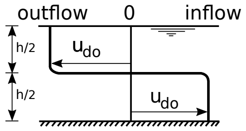
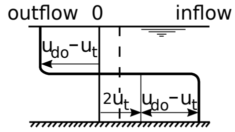


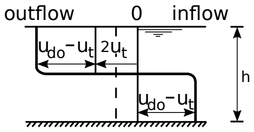
Figure 5.15: Entrainment flow and tidal filling.



(a) no tide



(b) with tidal filling



(c) with tidal emptying

Figure 5.16: Tide effect on density driven flow [Eysink, 1989].

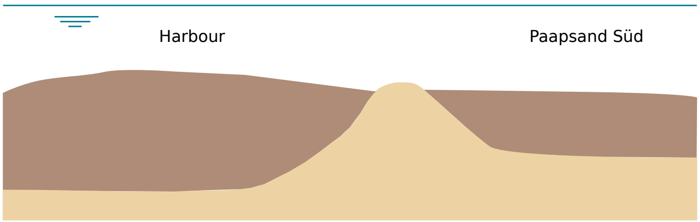


Figure 5.17: Separation of different suspended concentrations by presence of a sill.

described in section B.1.

Equation 2.5 from section 2.2.3, is used to determine the current siltation rate in the basin with a trapping coefficient (p) of 0.33 [Eysink, 1999]. The exchange flow is calculated with the formulas B.1, B.2, B.3 & B.4 from section B.1.

The following values are used for calculation.

Table 5.6: Important parameters for the Delfzijl harbour basin

Parameter		Value	Reference
Harbour surface	S	2.2 x10^6 m^2	Eysink [1999]
Avg. entrance depth	h_0	9.3 - 9.7	Meinsma [2013]
Entrance width	b_0	200 m	Groningen Seaports [2016a]
Tidal range	$2\hat{a}$	3.0-3.5 m	Groningen Seaports [2016a]
Tidal period	T_t	12h25m	Bosboom and Stive [2015]
Peak current outside	u_0	0.7 - 1.2 m/s	Meinsma [2011]
Concentration outside	c_0	0.15 - 0.3 kg/m^3	Vroom et al. [2012]
Settling velocity	W_s	0.1 mm/s	Eysink [1999]
Max. density	ρ_{max}	1015 - 1018 kg/m^3	Eysink [1999]
Min. density	ρ_{min}	1005 - 1011 kg/m^3	Eysink [1999]

The fresh water is discharged during the flood phase, leading to less inflow of water in the entrance [Eysink, 1999]. The fresh water has a specific concentration and leads to a density gradient in the mixture.

The total exchanged volume during one tide $V_{t,total}$ is [Eysink, 1999]:

$$V_{t,total} = [\langle Q_t \rangle + \langle Q_e \rangle + \langle Q_d \rangle] \cdot T_t + V_{es} \frac{n_s}{n} \tag{5.1}$$

where V_{es} = volume fresh water discharge, fm = mixing coefficient, n_s = number of tides with fresh water discharge, Q_t = tidal filling averaged over tide, Q_e = entrainment flow averaged over tide, Q_d = density driven flow over tide and n = number of tides a year (= 705). Equations for Q_t, Q_e and Q_d can be found in appendix B.1.

The fresh water discharge is obtained by:

$$V_{es} = Q_{es} \cdot T_t \tag{5.2}$$

The average fresh water discharge (Q_{es}) is 21.25 m^3/s over 438.4 tides and the mixing coefficient on average is 3 [Eysink, 1999].

Table 5.7: values of Eysink coefficients

f_e	0.02	Eysink [1999]
$f_{t,e}$	0.2	Eysink [1999]
f_d	0.1248	see appendix B.2
$f_{t,d}$	0.5613	see appendix B.2

Exchange flow is recalculated to sedimentation volume per tide ΔT_s by [Eysink, 1999]:

$$\Delta T_s = \frac{p(c_a \cdot V_{t,total} + c_{es} \cdot V_{es} \cdot \frac{n_s}{n})}{\rho_d} \tag{5.3}$$

Trapping coefficient amounts to 0.33 for Delfzijl as calculated with Eq. 2.6. For values u = 0.18 m/s, u_c = 0.3 m/s and T_h = 16 hours [Eysink, 1999].

The density of the bottom deposit ρ_d is then calculated with:

$$\rho_d = 1250 \cdot p_z^2 + 350 \quad kg/m^3 \tag{5.4}$$

The sand fraction in the deposit p_z is typically 0 - 0.05 for Delfzijl [Eysink, 1999].

Values obtained with this method are:

Table 5.8: Sedimentation Delfzijl

Q_d	52.5 m$^3/s$
Q_e	-18.6 m$^3/s$
Q_t	147.7 m$^3/s$
Q_{es}	21.25 m$^3/s$
$V_{t,total}$	9.1 $\cdot$ 10^6 m^3/tide
ΔT_s	1.70 million m^3/year

The total yearly sedimentation rate corresponds to the average annual dredging volume shown in figure 5.12.

Trapping coefficient

Previous sedimentation rate calculation, in section 5.3.1, was performed with a p-value of 0.33. However, begin of this section stated a noticed bed level increase by application of a new dredging technique. In order to asses if the change in dredging strategy was noticed in the trapping coefficient, p calculations are performed in this section. For this purpose only the shipping channel is considered. Volumes originated from rest area's are calculated first. Channel volume is obtained by average width, length and depth of a transect, see section 5.1. In formula:

$$V_{channel} = \sum_{n=1}^{55} h_n \cdot W \cdot L \tag{5.5}$$

Using the total harbour volume of 1999, as described in section 5.3.1, enables assessment of the rest volume in the harbour:

$$V_{rest} = V_{ha1999} - V_{channel1999} \tag{5.6}$$

Where h_n = depth in transect n, W = width of the transect (=100m), L = length of the transect (=100m), $V_{channel1999}$ = channel volume corresponding to 1999 bottom profile, V_{ha1999} = harbour volume below avg. water level (=$13.75 \cdot 10^6$ m^3) and V_{rest} = harbour volume in rest area.

The calculated exchange flow rates and the adjusted harbour volume lead to the values shown in table 5.8. The new harbour volume results in residence time increase somewhere between 18 to 19 hours.

The flow velocity u might be affected by the channel depth change between 1999 and 2015. However, recent research indicated unaltered flow velocities in the “Zeehavenkanaal” (i.e., 0.18 m/s) [Meinsma, 2013].

With the above calculations, the siltation rate corresponding to each bottom profile, depicted in figure 5.8, can be assessed. Values are shown in table 5.9.

Values in table 5.9 show no trapping coefficient and sedimentation rate difference between 1999 and 2015. Above described relation between an higher bottom level resulting from Airset dredging is therefore questionable. The similarity between the parameters might origin from additional dredging in order to maintain the nautical bottom level at the same location. However, yearly dredging production (shown in figure 5.12) contradicts this by indicating a reduction of dredged volume over the years.

Other interesting aspect is the residence time between 18 and 19 hours. This is in contradiction with report by Eysink [1999] where a 16 hours residence time is implemented. As a consequence, siltation rates do not correspond to figure 5.12 in section 5.3. Either Airset production rates are not accurate or the sedimentation rate predictions of the Eysink model are poor. The latter can be related to the density driven exchange flow rate. This is the density difference caused by a salt front pushed into the channel during rising tide. Density differences caused by fresh water discharge are not implemented in the model. For the situation in Harlingen, showing similar conditions as Delfzijl, the relative contribution of the fresh water discharge on the sedimentation is assessed on 25 to 50 % [de Boer and Winterwerp, 2016]. Using 25% yields a deposited volume of approximately 1.5 million m^3/year, which is a bit closer to the depicted yearly dredged quantity in figure 5.12.

Table 5.9: Channel volumes, basin volumes and residence times

Month	$V_{channel}$ [x10^6 m^3]	V_{ha} [x10^6 m^3]	T_h [h]	p	F_s [x10^6 m^3/yr]
1999					
April	5.32	13.75	18.8	0.367	1.93
2015					
January	5.24	13.68	18.7	0.365	1.93
February	5.03	13.46	18.4	0.361	1.90
March	5.13	13.56	18.6	0.363	1.91
April	5.10	13.54	18.5	0.362	1.91
May	5.14	13.57	18.6	0.363	1.91
June	5.16	13.60	18.6	0.363	1.92
July	5.18	13.62	18.7	0.364	1.92
August	5.17	13.61	18.6	0.364	1.92
September	5.20	13.63	18.7	0.364	1.92
October	5.21	13.65	18.7	0.365	1.92
November	5.36	13.79	18.9	0.368	1.94
December	5.36	13.79	18.9	0.368	1.94
Avg. 2015	5.19	13.63	18.7	0.364	1.92

Entrance sill functioning

Apart from separating the density layers at the bottom, the sill reduces import of sediment while keeping the fluid mud layer inside. The height of the sill does not influence the amount of water exchanged by tidal filling. A shallower entrance will increase flow velocity at the location. This effects the horizontal- and vertical mixing layers. As a result, less material will accumulate in the harbour. Opposite effects occur for deepening the entrance. The above described Eysink model can be used for showing the effect of the entrance depth for the port of Delfzijl. Figure 5.18 shows the effect of adjusting the harbour entrance while keeping all other parameters unaltered.

Ambient concentration effects

Adjusting the ambient concentration outside the harbour leads to a significant reduction of dredged material. Since Delfzijl contributes to the SSC outside the harbour by relocation of bottom material, reduction will decrease the ambient concentration in term leading to a positive feedback. Figure 5.19 shows the effect of ambient concentration on the annual siltation.

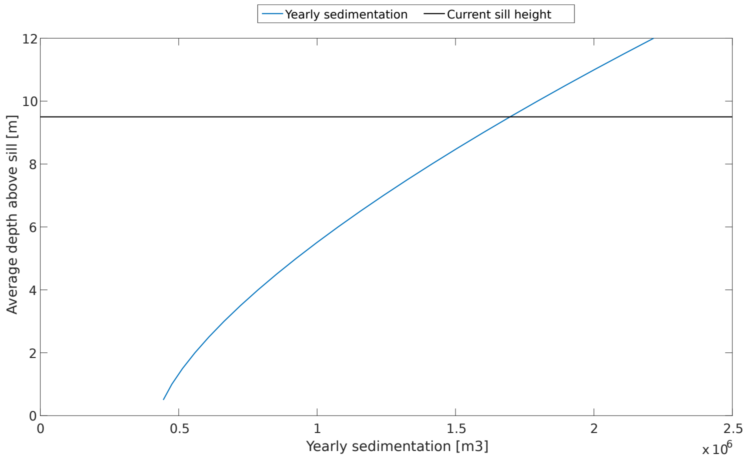


Figure 5.18: Annual siltation as a function of entrance depth

From the figure it is clear that a significant gain can be obtained by reducing the SSC in the system.

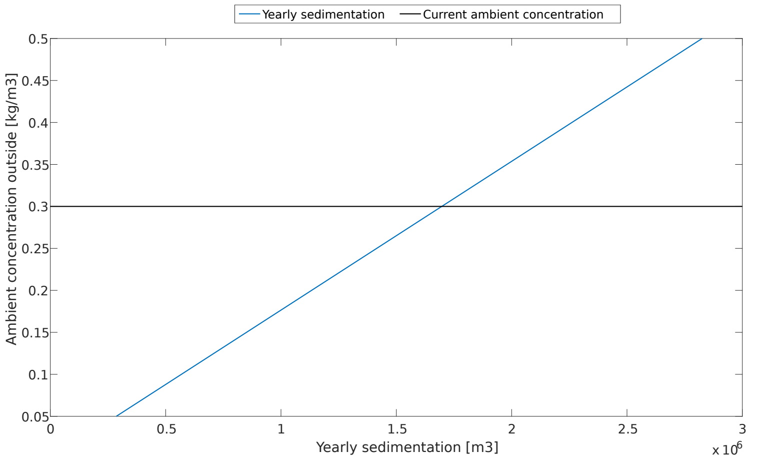


Figure 5.19: Annual siltation as a function ambient concentration

5.4 Previous UKC research at Delfzijl

As already stated, various researches are conducted on the fluid mud conditions and adapting the UKC at Delfzijl. Research started with an exploration to the possibilities in Delfzijl [Meinsma, 2011]. Afterwards, simulation studies were conducted [Meinsma, 2012]. In the simulations viscosity values of artificial fluid mud layers where added. Pilots where asked to steer the vessel through the artificial mud layers. Minor influence on navigability by the added layers was noticed. In later stages samples from the "Zeehavenkanaal" where taken to check if viscosity values resembled the artificial layers added during simulations [Meinsma, 2013]. Results showed the artificial layer deviated from the samples, see table 5.10. However, being in the same order of magnitude it was concluded that the mud was suitable for navigating with small or low UKC. In the next phase full scale tests where conducted, leading to confirmation of the conclusion [Barth, 2016].

Table 5.10: Dynamic viscosity comparison between model test conducted in phase 2 [Meinsma, 2012] and full scale field tests in phase 3 [Barth, 2016]

Density	Model tests	Average	After stirring	2 days after stirring
1108 kg/m^3	0.03 Pa.s	0.09 Pa.s	0.09 Pa.s	0.08 Pa.s
1149 kg/m^3	0.06 Pa.s	0.12 Pa.s	0.12 Pa.s	0.14 Pa.s
1179 kg/m^3	0.10 Pa.s	0.18 Pa.s	0.15 Pa.s	0.21 Pa.s
1207 kg/m^3	0.19 Pa.s	0.28 Pa.s	0.19 Pa.s	0.29 Pa.s

During the full scale tests different samples were taken by means of a sludge sampler. More information on the application of the sludge sampler is found in the report by Barth [2016].

Dredging effort and mud conditions

Report by Meinsma [2013] shows the Airset trajectories monitored from 5 September till 2 December 2011. Within this period the Airset was in operation for nearly 500 hours. The trajectories can be used to make and estimation on the hours spend at the specified measurement locations used in the report, see table 5.11. The same reports holds density measurements over depth. The table indicates the critical 1200 kg/m^3 location, see section 2.1.1 for explanation on the critical density. Table 5.11 gives an indication of time spend and where the resulting critical density is located.

Table 5.11: Hours spend between 05-09-2011 and 2-12-2011 for maintaining specified measurement locations by Wiertsema & Partners [Meinsma, 2011]. * max. measurement depth, 1.2 density not layer not located

Measurement	Location [m]	Time spend [hh:mm:ss]	1.2 ton/m^3 level [m]	95% confidence 1.2 ton/m^3 [m]
B07	2000	N/A	N/A	N/A
B08	2300	N/A	N/A	N/A
B09	2640	N/A	N/A	N/A
B10	2940	1:11:36	-11.26	-10.74
B11	3170	1:11:36	-11.14	-10.35
B12	3500	1:11:36	-11.30	-10.36
B13	3750	1:44:17	-11.23*	-10.81*
B14	4020	6:15:13	-11.14*	-10.86*
B15	4290	14:10:26	-11.10*	-11.10*
B16	4590	14:10:26	-11.15*	-11.15*
B17	4840	77:13:27	-11.17*	-11.17
B18	5180	78:06:15	-11.20*	-11.20*
B19	5300	73:59:27	-11.18*	-10.02
B20	5500	79:11:52	-10.60*	-9.62
B21	N/A	72:54:22	-9.65	-10.20
B22	N/A	73:17:50	N/A	N/A
Cumulative		494:38:23		

Airset deployment fluidizes the layer by injecting water, resetting the consolidation process. Some time after deployment, the strength in the layer is regained. Time required for this process determines the dredging frequency. Figures 5.21, 5.22 and 5.23 show test results from Wiersema & Partners at measurement locations shown in figure 5.20. The figures indicates a difference in strength regain from begin (B12 and B16) to end (B6 and B9) of the harbour. B12 and B16 are currently maintained by Airset deployment, the layer is therefore weaker. B6 and B9 where stirred for this test only, therefore having no history of conditioning.

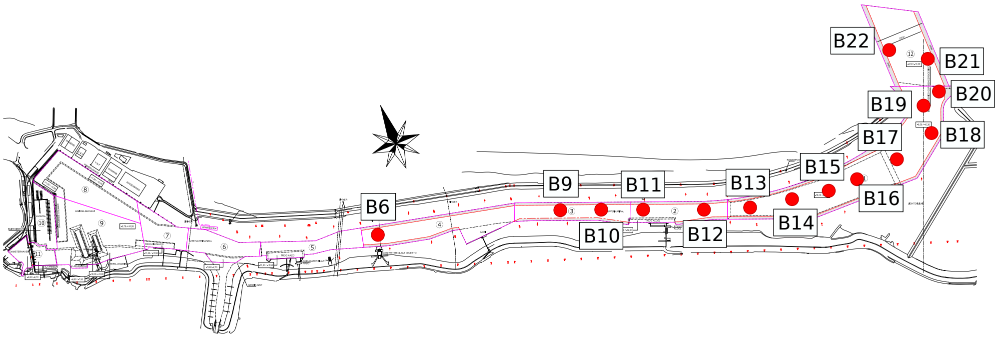


Figure 5.20: Measurement locations Meinsma [2013]

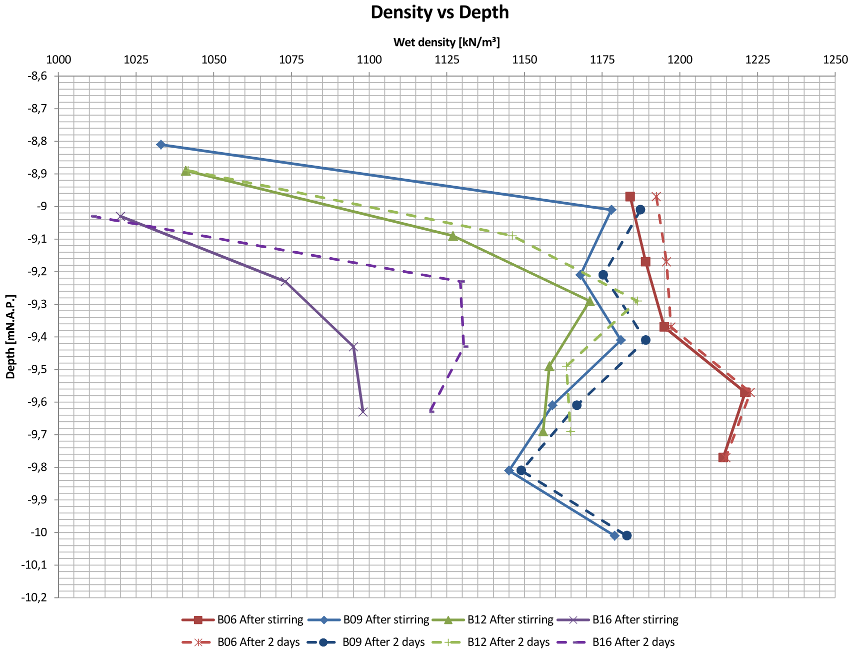


Figure 5.21: Influence of stirring samples on density over depth [Barth, 2016]

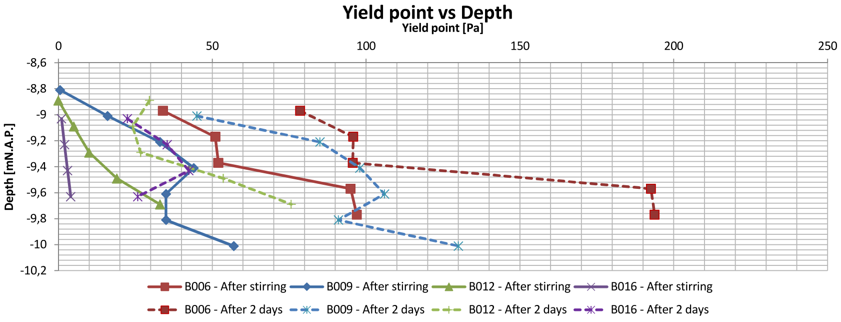


Figure 5.22: Influence of stirring samples on flow point over depth [Barth, 2016]

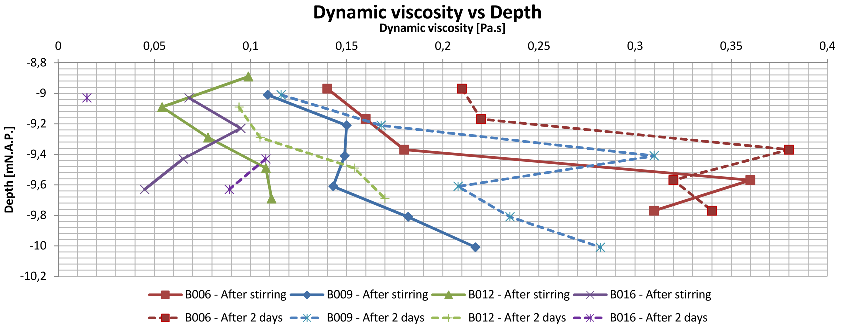


Figure 5.23: Influence of stirring samples on dynamic viscosity over depth [Barth, 2016]

6

First run decision support model: Delfzijl

The previous chapter introduced the Delfzijl case. This long stretched port basin with a thick fluid mud deposit proved suitable for reducing the UKC. The chapter described current conditions and earlier research. Further information on tides and vessels where also stated. This information is essential for assessment of the Decision Support Model (DSM).

The DSM from chapter 3 and case description of Delfzijl in chapter 5 are combined in this chapter. Checking whether decisive parameters/values can be designated at Delfzijl to fill the DSM indicates where knowledge is required. It also results in an improved framework which stated in chapter 4. Quantification of the different states within the management context elements, enables assessment on the chosen parameters. At the same time the quantification will designate miss formulations and knowledge lacks.

The safety context, section 6.1, determines to what extend the UKC requirement can be decreased. The section will elaborate on missing links/relations and research. The next section 6.2 designates the relations for the economical context. The required ecological relations and parameters are designated in section 6.3. The chapter concludes with a comparison of the strategies in section 6.4.

6.1 Safety

6.1.1 Measurement equipment

Current nautical bottom surveys are based on the 210 kHz. frequency. This frequency roughly indicates the top of the fluid mud layer having a density of 1,050 kg/m^3 [Meinsma, 2013]. Error by application of the multi-beam is assessed on 0.5 ft. (15cm) for a water depth of 35 ft. (10.7 meters) [U.S. Army Corps of Engineers, 1991]. Surveys are conducted in 1 to 2 days, see table A.01 in appendix A.

Dynamic measurements are required for determining fluid mud properties. Section 2.3.3 introduced available techniques applicable for determination of the defined parameters. Selection of one decisive tool is problematic since each tool poses problems for: accuracy, applicability and practicability. Below stated list reveals the difficulties originating from each equipment.

- **Rheometry profiler**
  A labour-intensive procedure due to point measurements. Hard objects (i.e. rocks or branches) at the measurement site cause problems. The instrument disturbs the layer when used.
- **Friction resistance (e.g. GraviProbe and Acccceleroprobe)**
  Determination of viscosity and shear stress is based on empirical relations and requires calibration tests at each harbour. Furthermore, the measurements are point measurements leading to a low practicability. The probe is intrusive, influencing the fluid mud properties.
- **Tuning fork (e.g. RheoTune and DensiTune)**
  Based on point measurements with a low practicability. The measurement utility is intrusive affecting the properties of the layer. Determination of shear strength and density is possible. However for non-Newtonian fluids (e.g., fluid mud) accuracy is low. Viscous matter will dampen the prong vibration too much. Tuning before measurements requires separate calibration at each measurement location.
- **Towing a cable (e.g. Rheocable)**
  A line with a length of at least three times the channel depth is used. These line surveys are more practical, however, most port authorities ban cables in the water due to possible inflicting danger for screws and/or rudder.
- **Marsh funnel**
  This lab test requires multiple soil samples for funnel testing. A large sample size and number is required for accurate results. Considering the difficulty of taking one uninfluenced fluid mud sample, this method is highly impracticable for continuous measurements.
- **Rotovisco test**
  The test yields accurate determination of viscosity and yield stress based on soil samples. Taking unperturbed samples is difficult and will disturb the fluid mud itself.
- **Capillary viscometer**
  Yields a direct measurement of viscosity based on soil samples. However, other parameters are not defined and samples are required.

Locating the rheological transition zone, one of the proposed methods in section 2.3.3, can be conducted with the Rheocable [Druyts and Brabers, 2012]. The technique is relatively easy to apply wiht line measurements as result. However, the technique will not define the thickness of the fluid mud layer. Strength definition is not conducted, creating the inability to assess whether mud undulations will appear and what the effect on the vessel and its navigation will be. In addition, the technique is intrusive causing the layer to be disturbed by the measurement. Whether this disturbance results in a positive or negative effect is unclear.

Defining the fluid mud properties, the other proposed method in section 2.3.3, might be able with the GraviProbe [Geirnaert et al., 2013]. Measuring frictional resistance is promising when considering one specific harbour. Due to calibration, the equipment can not used with the same settings at other harbours. Dependency on point measurements makes this technique relatively slow. Furthermore, most of the GraviProbe research is conducted by the producing company (DotOcean). Reliability is therefore unknown.

6.1.2 Turning radius

As a first step, the present state in Delfzijl is quantified. This step is seen as the desired state since a vessel must be able to make the turn. A bend in the entrance channel requires a change of heading from 150 to 280 degrees for incoming vessels. The turn in the bend has a radius of approximately 900 meters. The turn requires a turn rate which depends on the vessel speed. An incoming vessel will make the 130 degree heading change of $\frac{1}{5}^{th}$ of the turn circle (=1130m), see figure 6.1. Combination of these numbers with the vessel velocity yields the values in table 6.1. When a vessel can make this turn, the desired state is met. Simulation runs by Verwilligen et al. [2012] reveal these required turn rates possible to achieve when sailing with low or negative UKC. Increased time frame and a lower rate of turn are obtained by decreasing travel velocity. If velocity adjustments prove insufficient, tugs assistance can be used. Tug make fast must be done prior to the manoeuvre.

The circumference C of the circle is given by:

$$C = 2 \cdot \pi \cdot r \tag{6.1}$$

where r = radius of the circle.

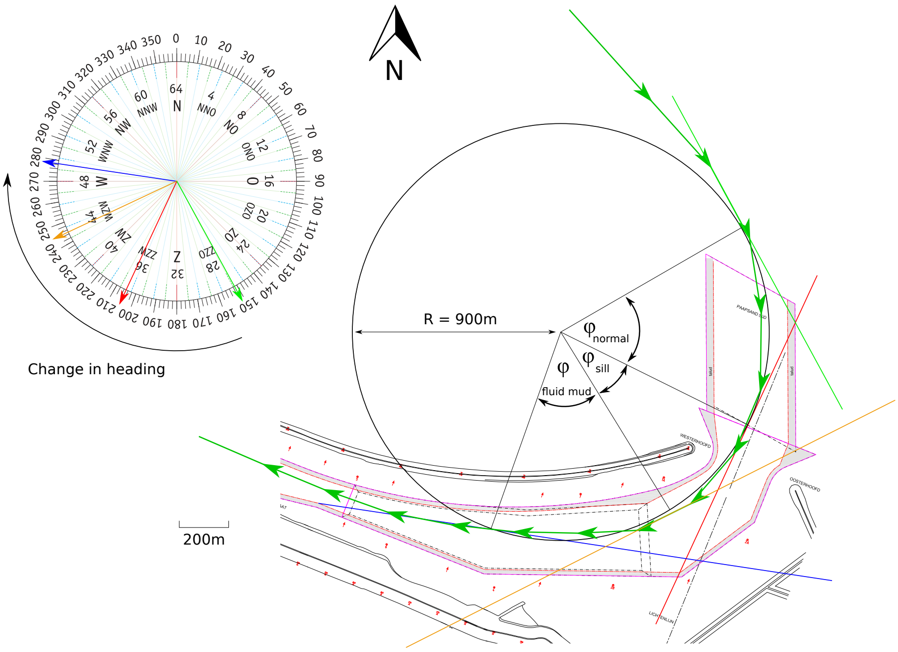


Figure 6.1: Navigational route (in green) and course change of vessel 'Juist' (IMO 9506112) arriving at Delfzijl on 5th of June 2016. Route obtained from MarineTraffic [2016]

For checking the current state, the impact of UKC and fluid mud conditions on the turn ability of the vessel must be determined. A smaller UKC results in a higher turning radius, see

Table 6.1: Heading change over incoming vessel 'Juist' T = 7.1m

Location	Heading in [°]	Heading out [°]	Distance travelled [m]	Vessel speed [kn]	Required turn rate [°/min]
φ_{normal}	151	205	840	10	19.0
φ_{sill}	205	245	630	7	13.5
$\varphi_{fluid\,mud}$	245	278	530	5	9.5

figure 6.2. To what extend the radius is affected depends on the rheological properties of the fluid mud. Research on UKC and fluid mud strength was conducted by Lataire [2014] showed in figure 6.2. As explained in section 2.4.2, the picture clearly indicates better steering capabilities with negative UKC. Determination whether a positive or negative UKC will be present is therefore important. Also the thickness and strength of the layer is of influence.

As stated a turn with a tactical diameter of 1800 m should be made by a design vessel of 120 m at Delfzijl. In order to make the turn Tactical/L must be 15 or lower. The image indicates several mud conditions for when the turn would be possible with UKC's ranging from 0.9 tot 1.1. However, it is important to notice the difference in vessel size between the tests and the case of Delfzijl. 6000 TEU vessels average in length between 290 to 310 meter while 120 m is already a long vessel for Delfzijl. Therefore it is unclear whether the turning cycle experiment by Lataire [2014] represents the situation at Delfzijl.

Table 6.2: Flanders Hydraulic Research (FHR) tested mud conditions on prototype scale [Delefortrie et al., 2007]

Mud	Density [kg/m^3]	Viscosity [Pa.s]
B	1180	0.10
C	1150	0.06
D	1100	0.03
E	1260	0.29
F	1200	0.11
G	1250	0.33
H	1210	0.19

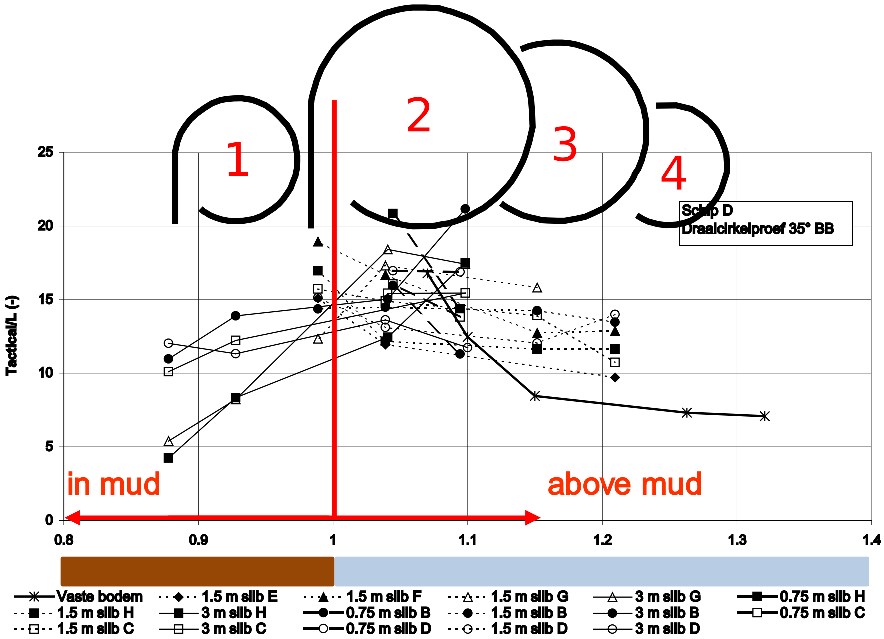


Figure 6.2: Turning circle tests (full to port) with a 6000 TEU container vessel: tactical of UKC with respect to mud layers from table 6.2. [Lataire, 2014]

6.1.3 Stopping distance

Maintaining course after passing breakwaters for tug tie-up is not applicable for Delfzijl. The calm conditions on the river enables tug tie-up outside the breakwaters. Maintaining course over this period will therefore not take place above the fluid mud in the harbour.

For other ports where stopping distance is a limiting factor, required length can be determined with the approach explained by Ligteringen and Velsink [2012].

6.2 Economy

Before defining the economical benefit, the 'over-depth' obtained by reducing the UKC, must be determined. The draught or bed level increase depends on the extra room originating from an UKC reduction. Earlier research in Delfzijl indicates possibilities of a reduction to -10 % UKC. Therefore a reduction form current state (10 %) to the possible UKC is investigated. The Tidal Window (TW) tool is used for quantification. Elaboration on the functioning of the TW-tool is located in appendix C.1.2. With the tool, the impact originating from an UKC reduction can be assessed. Table 6.3 shows UKC effect on reducing the tidal closure. Restriction by the horizontal tide affects the tidal window for arrival, as was elaborated in section 5.2.2. This leads to a significant impact on the TW tool. Adjustment of the TW tool is therefore required in order designate the time and date of 1 hour around HW. As a result the nautical depth is indecisive for an arriving design vessel.

Table 6.3: Close time in percentage based on available nautical depth

	Closed for:	1 Jan 2010	2010	2001 - 2015
T + 10% UKC	arrival	95.8	92.0	92.0
	departure	38.8	35.9	34.7
T + 5% UKC	arrival	95.8	92.0	92.0
	departure	36.1	32.5	31.3
T + 0% UKC	arrival	95.8	92.0	92.0
	departure	36.1	31.4	30.1
T - 5% UKC	arrival	95.8	92.0	92.0
	departure	36.1	31.4	30.0
T -10% UKC	arrival	95.8	92.0	92.0
	departure	36.1	31.4	30.0

Matching the UKC from table 6.3 to an increased draught or -bed level results in an equilibrium situation. A situation where a small UKC matches a higher draught/bed level with an unaltered TW. The draught/bed level increase is conducted with the help of the Matlab-tool described in section C.1.2 and are shown in the conclusion (section 6.4). The Matlab tool is applied on tidal data from 2001 to 2015 for a fixed bottom profile as shown in figure 5.7 in section 5.2.1.

6.2.1 Increased load

Filling the available space by increasing the draught is the operational objective. At the Port of Rotterdam first assessment of added load is done by application of a load factor $L_F = 150\,\text{ton/cm}$ [Nordbeck, 2016]. Application of this load factor for Delfzijl leads to an overestimation due to difference in ship sizes between the harbours. Therefore a approximation of the load factor is performed by:

$$L_F = \rho_w \cdot g \cdot V_s, \tag{6.2}$$

where: ρ_w = water density, g = gravitational constant and V_s = ship volume per meter submerged.

Simplification of the MS Tornes to a cube shape with dimensions shown in table 5.2, results in a volume of 2300 $\text{m}^3/\text{m}_{submerged}$. With the assumption of salt water ($\rho_w = 1025$) a load factor of 23 ton/cm is obtained. This load factor does not account for the shape of the hull. For accurate quantification, the type of vessel arriving at port should be known.

With the load factor the added load ΔL per increase in draught ΔT is:

$$\Delta L = L_F \cdot \Delta T \tag{6.3}$$

The load factor, draught increase and average cargo wages (from section 5.1.1) combined yields a net revenue. Table 6.4 in the last section states the revenue when a design vessel like the MS Tornes is allowed to maintain a higher draught. In reality, the MS Tornes maximal draught is 7.5 m and can therefore not be increased. The increased draught can only be used when employing an higher draught vessel.

6.2.2 Maintenance dredging reduction

Filling the extra space by increasing the bed level reduces the maintenance dredging. A relation is used to assess the yearly bed level increase caused by the sedimentation rate. First step is determination of the bed level increase by the incoming sediment. Reducing this bed level increase with the value of the bed level increase leads to a reduced dredging amount.

Current volume dredged in Delfzijl over 2015 amounts to 1,600,000 m^3. This amount accumulates in the front end of the channel. Assuming the front end of the harbour is between 1000 en 5000 meters, measured from the closed end of the basin.

With the assumption of a horizontal bed level increase due to sedimentation. The bed level increase Δz is calculated by:

$$\Delta z = \frac{V_{dredged}}{S}, \tag{6.4}$$

where $V_{dredged}$ = dredged volume and S = dredged area (=harbour surface). In this, S is the dredged area calculated by the length and width of the approach channel. The total length amounts to 4000 m, see figure 5.7 shown in section 5.2.1, the width of channel is roughly 150 m, measured from the dredging atlas by Groningen Seaports [van Dijken, 2012]. The thickness of this dredged layer d equals Δz and is calculated by:

$$d = \frac{V_{dredged}}{S} \tag{6.5}$$

The bed level is maintained at a higher position due by maintaining a smaller UKC. Resulting decreased dredged volume,$\Delta V_{dredged}$ is expressed by:

$$\Delta V_{dredged} = S \cdot \Delta d \tag{6.6}$$

in which Δd = difference between the current depth and the new allowed depth. The depth decrease (Δd) is determined by the reduction of the UKC and tidal window.

Maintenance contract cost as explained in section 5.3 leads to € 1.8 million a year. With a total dredged amount of: 11,355,000 m^3, this results in 1.11 €/m^3. Using this value results in an approximated cost reduction shown in table 6.5.

6.3 Ecology

Desired state for increasing the opportunities for nature is a higher light intrusion as the result of less SSC. Ecological conditions shown in figures 5.3 and 5.4 indicate 100 mg/l as the original state while 150 mg/l is present.

Determination of ecological value from reducing the dredged amount requires relations 1 to 5 shown in figure 6.3. As will be discussed below, relation 6 is required as the result of inaccurate relations 4 and 5. The relations are elaborated below.

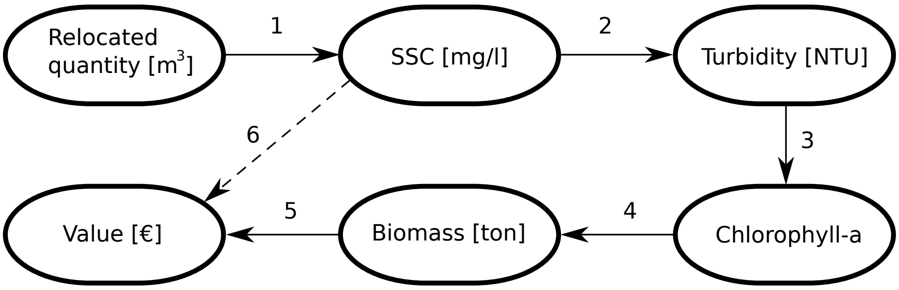


Figure 6.3: Required parameters and relations

1: The Cronin et al. [2015] model

The Cronin et al. [2015] indicated the reduced estuarine SSC concentrations when dredged volume would be relocated to land, numbers shown in figure D.12 and corresponding table D.11 in appendix D.1. Alternative 2 indicates the SSC effects when all dredged sediment from Delfzijl (i.e., 1.6 million m^3/year) would be disposed on land. By relating a small dredging decrease in relocation of all material to land yields a SSC decrease indication.

Determining weight from the dredged volume is performed by application of the average bottom density, $\rho_{s,bottom} = 500$ kg/m^3 [van Maren, 2016]. The increase of dredged material ΔW is estimated by:

$$\Delta W = \frac{\Delta V_{dredged}}{\rho_{s,bottom}} \tag{6.7}$$

From the Cronin model a linearisation is acquired. Total amount of disposed material on land divided by decreased SSC at each location gives a ratio for calculation of the diminished SSC corresponding to the decreased dredging quantity, yielding:

$$\Delta SSC = \frac{D_{total}}{\Delta SSC_{total}} \cdot \Delta W, \tag{6.8}$$

where ΔSSC = difference in SSC, D_{total} = total dredged weight from Cronin model and ΔSSC_{total} = Suspended sediment concentration by Cronin. Above equations are used to compose tables D.22 to D.25 in appendix D.2. From these tables an average in reduced SSC can be obtained as shown in table 6.6. These tables show the decrease of SSC following from dredged volume reduction.

Linearisation of the SSC model by Cronin et al. [2015] is a rough assumption since non-linear terms affect the turbidity in an estuary. However, the model is more comprehensive in comparison to other literature and models. The linearisation is therefore seen as the only possible assumption.

2 and 3: From SSC to chlorophyll-a
Next link would be the light attenuation expressed in reference to SSC over the water column, the exact link is however difficult with multiple variations [Babin et al. [2003]; Davies-Colley and Smith [2001]]. In the approach by Stolte et al. [2015] a Delft3D-DELWAQ model is used to approximate the chlorophyll-a production depending on nutrients, temperature and light availability. Although the model is extensive with outcomes near real time measurements, SSC adjustments where not tested. Riegman et al. [2014] implement the DELWAQ model in order to elaborate on the relation between SSC, light attenuation and primary production. They state: “If sufficient nutrients are available computation indicate that 50 % increase in light attenuation coefficient corresponds to 50 % SSC reduction and a 25 % lower primary production in the Dollard. The outermost stations (Huibert Gat and Oude Westereems) designate a 35-40 % reduction of primary production. Nutrient deficiency in late spring is present at the outer located station. These stations indicate different reactions to altering the attenuation coefficient.”

4 and 5: From chlorophyll-a to monetary value
The outcome from Riegman et al. [2014] enables quick assessment on the effect of decreased SSC for increased primary production. Effects on primary production will impact the complete ecosystem. The precise effect is however difficult to ascertain. Even if these effects and the impact on total biomass in the Ems-Dollard would be determined, the complete benefit expressed in monetary units is impossible. One could try to asses the recreational, fishery and other benefits of the area and quantify the income over that. However, the healthiness of the system is experienced far outside the Ems-Dollard itself. For instance, fish caught some where in the north sea could have very well spawned in the Ems-Dollard estuary.

6: “Willingness-to-pay”
Difficulty in links 4 and 5 require a 6^{th} link in which SSC is directly related to monetary value. This relation is obtained by a “willingness-to-pay” principle [Baptist, 2016]. WTP uses required investments for restoring the system as an indicator for the value of the system itself. The investments express the amount, according to society, justified as reasonable.

Newspaper article published by van het Noorden [2015] reveals a needed investment of € 7 million for reduction of the silt problem in the Ems-Dollard. This investment is intended to restore the system to its natural state. Multiple interventions are possible as described in [Lenselink et al., 2015]. Assumption is made that the investment is for restoring the current state (150 mg/l) to the desired state (100 mg/l). In this simplified approach for 1 mg/l diminished SSC, there is a willingness to invest € 140,000. This is a rough assumption since the investment will not necessarily lead to a decrease of 50 mg/l. Furthermore, the investment is based on reaching a certain tipping point in the system. Without achieving the tipping point, an investment is ineffective. Linearly relating a small number of diminished SSC to the investment is therefore not accurate and overestimates the benefits. In absence of a better approach de linearisation is used to give an indication of the healthiness of the system.

Above used intervention is directly related to the Ems-Dollard estuary itself. Based on the taken investment, the benefit of the procedure is assessed differently. While Joustra et al. [2016] justify even higher investments for the complete Wadden Sea area. Numbers between 150-200 millions are stated for improving economy, ecology and recreation in the area.

6.4 Strategy comparison

With the economy and ecology relations, values are obtained enabling quantification of the strategies. First the comparison is made between strategy 1 and 2. Strategy 1 is shown in table 6.4 and strategy 2 is shown in tables 6.5 and 6.6. The obtained draught/bed level increases form the tidal window model shows a limit to what extend the draught or depth can be increased. For draught/bed level increases beyond 19 cm the sill is normative for navigation. Further draught increase results in a smaller tidal window. Sill height reduction could be opted as countermeasure but this will lead to extra siltation as elaborated in section 5.3.1.

Table 6.4: Increased load by altering under keel clearance. Based on tidal data from begin 2001 to end 2015

UKC [%]	ΔT [cm]	Added load [t]	Value [€ /vessel]	Safety
10	0	0	0	o
5	13	300	240	- -
0	14	320	250	-
-5	18	420	320	-
-10	18	420	320	- -

Table 6.5: Saved dredging cost by lowering UKC vessel with T=7.5 meters. Based on tidal data from begin 2001 to end 2015

UKC [%]	Δd [cm]	ΔV [m^3]	Cost saved [€]	Percentage contract costs	Safety
10	0	0	0	0 %	0
5	13	78,000	87,000	4.8 %	- -
0	14	84,000	93,000	5.2 %	-
-5	18	108,000	120,000	6.7 %	-
-10	18	108,000	120,000	6.7 %	- -

Approximately 300 high draught vessels (draught above 5 meters) visit the port of Delfzijl

Table 6.6: Avg. reduced SSC and corresponding net value

UKC [%]	ΔV [m^3]	Avg. SSC reduction [mg/L]	Net. Value [€]
10	0	0	0
5	78,000	1.8	258,000
0	84,000	2.0	278,000
-5	108,000	2.6	358,000
-10	108,000	2.6	358,000

[Groningen Seaports, 2016b]. Only those vessels will benefit from a higher nautical depth in terms of tidal window and load increase. It appears a load increase strategy is less beneficial in reference to adjusting the maintenance strategy.

Strategy 3

When striving for an unaltered UKC policy while increasing the port revenue by employing higher draught vessels table 6.7 is obtained. In the table, the positive values from strategy 1 are present. Intensifying dredging operations provides the increased nautical depth. As a result, dredging costs and the burden for ecology increase. The effect is similar to those of strategy 2, but for strategy 3 the effects are negative.

Summary of al the above mention tables is given in table 6.7

Table 6.7: Net profit strategy 3

UKC [%]	ΔT [cm]	Revenue increase [€/vessel]	Dredging costs [€]	Cost for ecology [€]	Total cost [€]
10	0	0	0	0	0
5	13	240	-87,000	-258,000	-345,000
0	14	250	-93,000	-278,000	-371,000
-5	18	320	-120,000	-358,000	-477,000
-10	18	320	-120,000	-358,000	-477,000

Justifying extra dredging costs implies having 360-400 manoeuvres a year with extra load. Adding burden for ecology demands 1440-1500 manoeuvres. Monitoring vessel manoeuvres in the port of Delfzijl over the past 4 months show approx. 132 manoeuvres susceptible for altering the UKC. On a yearly basis roughly 400 manoeuvres take place in the port. When all vessels will sail with the maximal extra allowed draught, both strategies 1 and 2 will yield the same profit. However, it is highly unlikely that all vessels will in fact use the new nautical depth to full potential. Furthermore, the ecological consequences and corresponding costs indicates strategy 3 as inferior.

6.4.1 Conclusion

Above conditions describe the current condition which should be met. Determining whether and how the turn capabilities of the vessel affected by the UKC is challenging. Simulation runs could designate turn rate versus UKC. However, simulations thus far are conducted with artificial layers and viscosity (Delefortrie [2007], Vantorre [2001] & Meinsma [2012]). Furthermore, no simulation is encountered where UKC could be linked by a (empirical) relation to the turn radius. Therefore no direct link between UKC and turn radius can be made for now.

The above procedure is a rough calculation. In the actual situation, a decreased depth result in a lower volume of the water body in the harbour and therefore the exchange flow rate. This will decrease the siltation rate of the harbour. To what extend the channel volume is impacted will be investigated in the next chapter. Furthermore, less dredging and thus disposal will diminish the ambient suspended sediment concentration (SSC) outside the harbour. Decrease in ambient SSC results in less particles flowing into the harbour and settling.

Improvement obtained by linking a new bottom profile to the trapping coefficient of the basin. This yields a more accurate siltation thus dredged quantity.

7

End-user induced updates

Previous chapter, 6, showed the management context and port strategy quantification. Strategy 2, reduction of dredging, proved the most profitable strategy for Delfzijl. The quantification and thereby acquired knowledge led to adjustments of the initial conceived DSM. These improvements are presented in chapter 4.

During quantification site specific end-user worries became apparent. In order to provide answers for end-users the Tidal Window (TW) tool is extended with a probabilistic module. This module deals with the required UKC with respect to a strength based nautical bottom and the profile development as the result of decreased dredging.

In the first section, 7.1, the end-user feedback obtained from presenting the first quantification and the improved DSM is stated. The probabilistic extension and application is explained in the next section 7.2. The model gives clarification on their doubts and where the uncertainties come from.

7.1 End-user input

Pilots

According to one of the pilots doubt originates from the absence of trials with entrance/departure conditions corresponding to real situations. In specific entrance/departure velocities and hull shapes where not varied. In addition, he questions the effects on long term wear and tear on rudder and screw as the result of felt vibrations. Also the impact of fluid mud on water intakes is not covered. The inlets can be clogged leading to cooling system and/or engine damage.

Above description is from one pilot alone. The pilotage consists of self-employed pilots having their own vision. Earlier description might not represent the vision of all pilots connected to the pilotage.

Port authority

From earlier research and this thesis, three main point of concerns are stated by Groningen Seaports (GSP):

- Meinsma [2013] proposed to use a 15 % UKC in reference to a strength based nautical bottom. For the port authority (GSP), this value was not well substantiated. GSP would like to know where this number originates from and if it is indeed accurate/required.
- The location of the strength based nautical bottom after dredging is reduced. This location should not hamper port operations.
- The dredging reduction and resulting shallower nautical bottom location will induce a new bathymetry at the harbour. GSP fears an unknown/unforeseen development which could affect safety and/or port operations. In addition, the development can not be accurately monitored due to absence of survey equipment.

The experienced absence of theoretical knowledge on Airset dredging was presented to GSP. They state that there is no incentive for conduction research on Airset dredging since the current technique is effective. They acknowledge that if the UKC would be decrease, the focus would shift from ‘removing sediment’ to ‘keeping the sediment fluid’. For that scenario researching whether adding air to the injected mixture is effective, should be conducted.

Harbour Master

Practical problem according to one of the harbour masters, is the replacement of the current nautical depth charts. With monthly chart publications, the authority guarantees an available depth towards shipping agents, pilots, captain and harbour master.. A new parameter, describing a dynamic transition layer, should be translated to an available depth and a specific time frame when this depth is available. GSP and harbour-masters do not have a clear vision how this can be brought into practice and require help to asses the parameters, survey frequency and accompanying costs. How long the measured nautical depth is representative for the actual conditions, is equally important.

Tug-assistance is paid for by shipping agents in the current situation. Application of strategy two implicates no higher draught (thus revenue) while tug-assistance is suddenly required. This should be implemented in a plan for strategy change.

7.2 Probabilistic bottom profile

From the meeting three aspects are assessed based on a probabilistic method:

- If the proposed 15 % UKC by Meinsma [2013] is reasonable,
- Effect of varying speed on the required UKC,
- What would be an optimal strength based nautical bottom location and how does this impact the channel depth contours?

A nautical bottom defined by strength parameters will be less forgiving upon collision. Increasing the UKC to 15 % with respect to that nautical bottom, as proposed by Meinsma

[2013], appears reasonable. However, in the report there is no substantiating evidence for this increase of UKC, leading to hesitations by GSP.

In order to find an explanation for the statement by Meinsma [2013], the location of the strength based nautical bottom should be assessed. Locating the optimal level is done with a probabilistic approach. Trying to relate the optimal level too depth contour changes afterwards, might enable assessment of trapping coefficient variations. Linking this to the trapping coefficient p results in a accurate sedimentation rate. Thesis by Bouw [2005] evaluated multiple methods for a probabilistic determination of a safe tidal window in terms of bottom touch. According to Bouw [2005], the Monte-Carlo approach proved accurate while having the shortest calculation time. Furthermore, the method is easier expanded with physical models without loosing distinction between physical and probabilistic calculations. The same method was later implemented in the software tool “ProTide” by ChartaSoftware [Uil, 2015]. The program determines tidal windows for the port visits at Rotterdam, Amsterdam and Eemshaven based on probabilistic calculations.

Bottom touch probability

Probability of bottom touch per year is based on a channel design life of 25 years. Within that period of time, the chance of a bottom touch must be smaller then 10 % [Bouw, 2005]. Determination of the yearly bottom touch probability $P(\xi > 0)_{year}$ is thereby:

$$\begin{aligned} &P(\xi > 0)_{25-year} = 0.1 = 1 - (1 - p(\xi > 0)_{year})^{25} \rightarrow \\ &\qquad P(\xi > 0)_{year} = 1 - \sqrt[25]{1 - 0.1} = 0.004206 \end{aligned} \tag{7.1}$$

Given the number of vessels, recalculation to bottom touch per transit is possible. Delfzijl is visited by 400 to 450 vessels with a draught > 5 m a year. Since a design vessel with a draught of 7.5 m is used, only vessels with draughts between 7 and 8 meters are considered. Three months of monitoring yielded 14 vessels within the specified draught range, therefore 50 vessels a year [Groningen Seaports, 2016b]. For that situation, chance of a bottom touch for one transit $P(\xi > 0)_{ship}$ must not exceed [Bouw, 2005]:

$$\begin{aligned} &P(\xi > 0)_{year} = 1 - (1 - p(\xi > 0)_{ship})^{50} \rightarrow \\ &\qquad P(\xi > 0)_{ship} = 1 - \sqrt[50]{1 - P(\xi > 0)_{year}} = 8.429 \cdot 10^{-5} \end{aligned} \tag{7.2}$$

A factor 10 can be applied to this number since a bottom touch will not directly lead to damage of the vessel. This yields a probability of touch $8.429 \cdot 10^{-4}$ per transit.

During a transit, the vessel passes all sections in the channel. The complete probability of bottom touch per transit must be smaller than previous stated value. Bouw [2005] applies a small number of transect due to relative constant bottom conditions in the considered approach

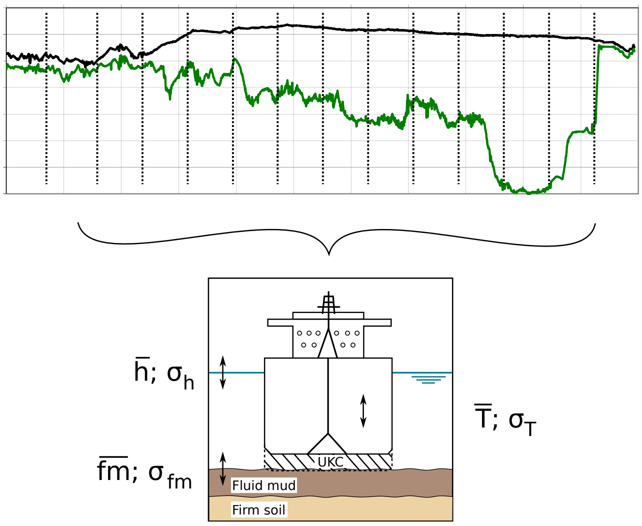


Figure 7.1: Transect approach

channels. However, the dynamic fluid mud character requires a higher number of transects for probability calculation. Therefore, the channel is divided in 55 transects (one every 100 meter). In each of the transects certain (measured) conditions prevail having their own uncertainty and/or errors, see figure 7.1.

The variables and their distribution origin from prevailing conditions and measurement errors, appendix C.1.6 elaborates on the origin of the parameters and their distribution. For the Monte Carlo calculation a script from OpenEarth is used [den Heijer, 2009]. See appendix C.1.5 for further clarification.

Parameters, distribution and deviations are depicted in table 7.1. The values are input for the following Z-function:

$$Z = wl - z_{RTZ} - T - Z_v \tag{7.3}$$

where WL = water level, z_{RTZ} = RTZ with respect to NAP, T = vessel draught and Z_v = vessel squat (see Eq. 2.1 in section 2.1.2)

Model overview

The probabilistic method is implemented in the TW tool. The complete model description is stated in Appendix C. An overview of the model elements and their interaction is shown in figure 7.2.

Table 7.1: Probabilistic parameters. Clarification on the parameters and used errors is located in appendix C.1.6

Parameter	Average value	unit	Distribution	Deviation
Water level	Survey	m	Normal	0.08
Fluid mud	210 survey depth	m	Normal	0.15
Draught	7.5	m	Normal	0.15
L_{pp}	113	m	Normal	1.5
C_s	2.0	-	Deterministic	-
C_b	0.70-0.75	-	Uniform	-
B	20	m	Normal	0.5
v_s	2.5	m/s	Normal	0.5

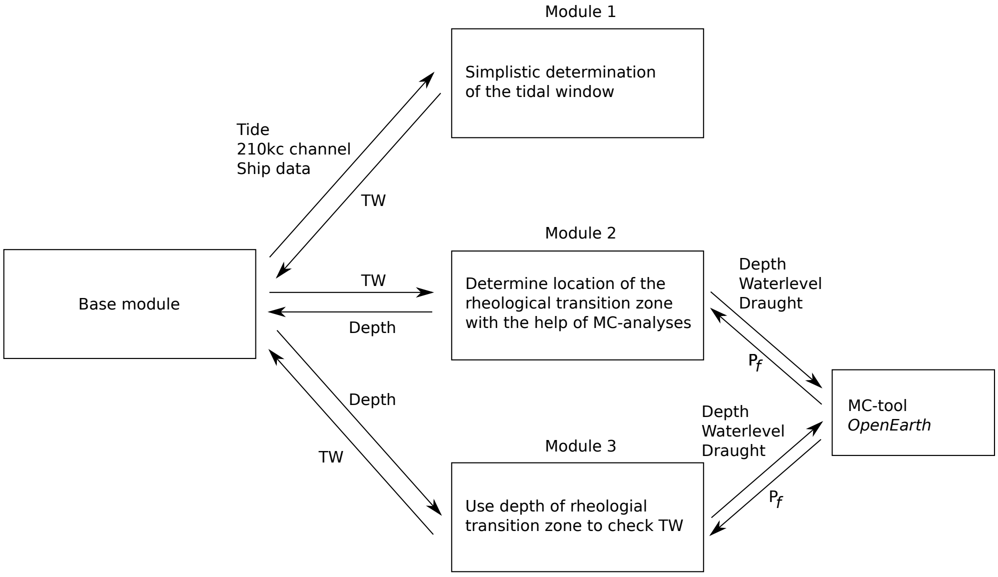
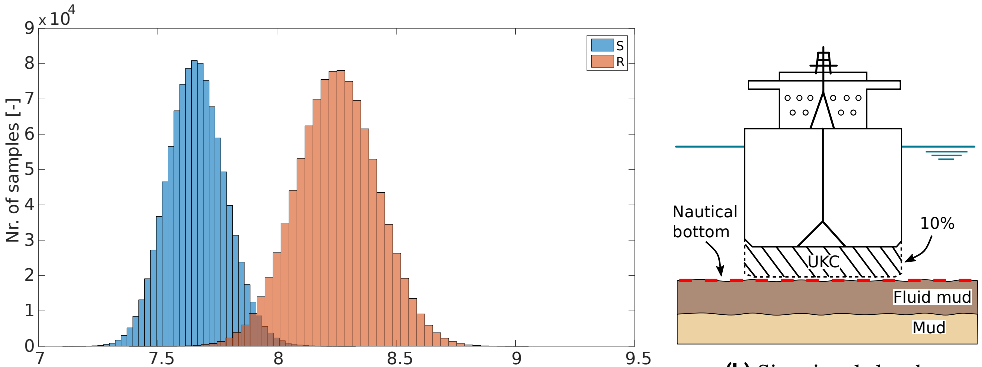


Figure 7.2: Probabilistic nautical bottom determination

7.2.1 New UKC

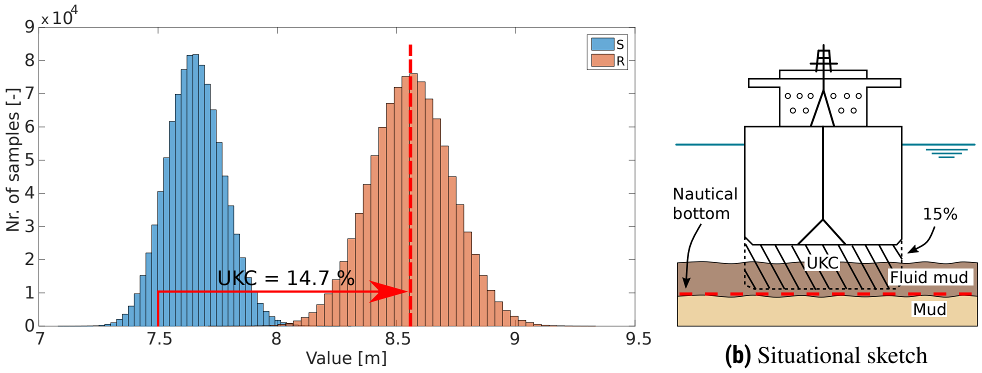
Checking the required UKC in the new situation is conducted for one transect. The resistance R is the nautical depth, taken as draught T plus 10 % UKC. Load S is the vessel draught T. When running the Monte Carlo simulation with the values from table 7.1, figure 7.3a is obtained. The part where S and R overlap ($Z \leq 0$) the keel touches the bottom. In this situation $P_f(Z \leq 0) = 0.003$.



(b) Situational sketch

(a) Resistance (R) versus Load (S) histogram

Figure 7.3: Chance of bottom touch in current situation, $P_f(Z \leq 0) = 0.003$



(b) Situational sketch

(a) Resistance (R) versus Load (S) histogram

Figure 7.4: Chance of bottom touch in new situation, $P_f(Z \leq 0) = 1.2 \cdot 10^{-5}$

Searching for a probability of bottom touch corresponding to the limit by Bouw [2005] with Eq. 7.3, results in figure 7.4a. Difference between figures 7.3a and 7.4a is the increase of the resistance R. This implies that a higher resistance is required in order to comply with the predefined bottom touch probability. When translating this to guidelines, an UKC of 14.7 % is obtained. The accuracy of this value is discussed in section 7.2.4.

7.2.2 Location nautical bottom

Above calculation can be conducted for each of the 55 transect in the channel. This yields a bottom profile over the length of the channel. The calculated depth depends on the input of a current channel. The program calculates a profile with the same tidal window as the current situation. Monthly charts result in 12 optimal locations that can be calculated for 2015. Later comparison is conducted for measurements taken during campaigns in May 2015, therefore only the May channel is presented in figure 7.5.

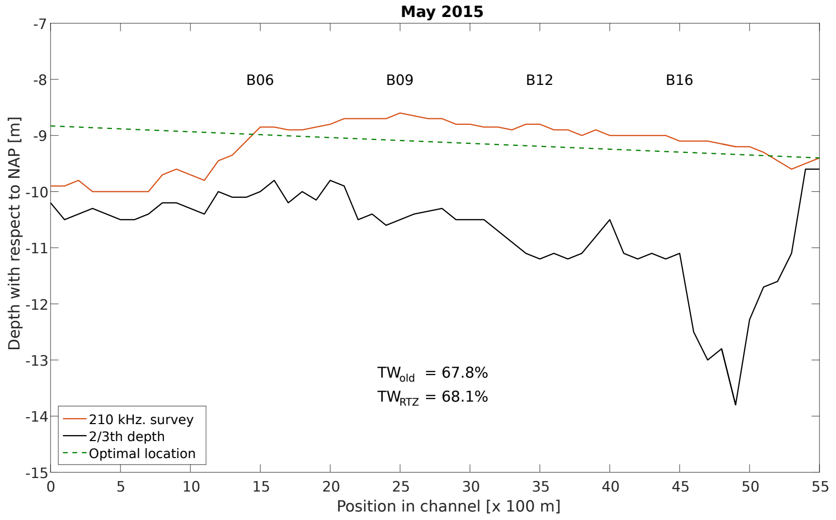


Figure 7.5: Optimal location of the transition zone or critical density location

Rheology based comparison

According to Druyts and Brabers [2016] the nautical bottom coincides with the Rheological Transition Zone (RTZ) where the yield strength Y_p exceeds 100 Pa. Conducted measurements by Barth [2016] tried to locate this level at Delfzijl with the help of a sludge sampler. The measurements where shown in figure 5.22. Their measurements are plotted against the calculated optimal location of the nautical bottom in figure 7.6. However, the measurement campaign by Barth [2016] did not find the RTZ at measurement locations B12 and B16 caused by an insufficient depth. The same holds for measurement B09 directly after stirring [Barth, 2016]. Depth levels depicted at these measurement locations are therefore an indication of the transition zone.

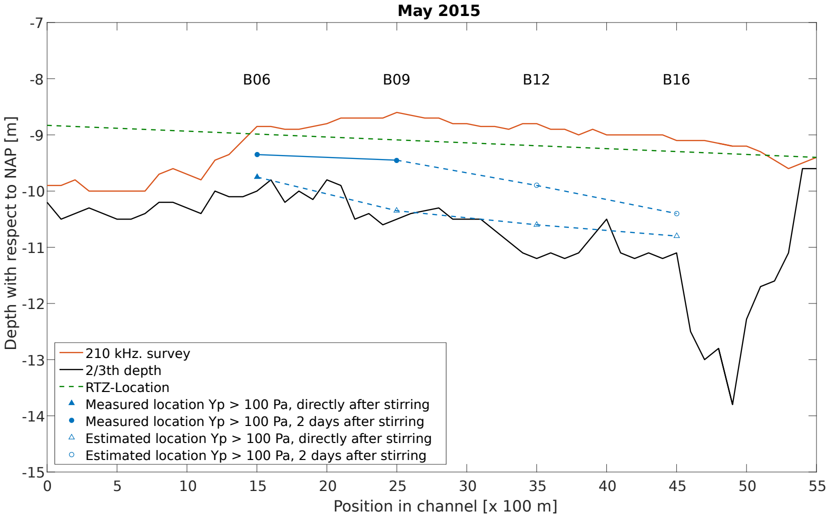


Figure 7.6: Measurement of Rheology Transition Zone, where $Y_P > 100\ Pa$.

Density based

Since the location of the rheological transition zone was inconclusive, the critical density is used for comparison. The same nautical bottom criteria is used in other harbours, as elaborated in section 2.1.1. Barth [2016] stated a density difference between the front and back end of the harbour, 1210 and 1190 kg/m^3 respectively. The critical density in the front end is higher as the result of mud conditioning by the Airset. Since this comparison is used as an indication a critical density of 1200 kg/m^3 is applied over the complete channel length.

Again not al density locations where obtained, however more measurements did gave the location. The measurements are shown in figure 5.21 in section 5.4. Therefore, density measurements from 2011/2012 conducted by Meinsma [2013] are used. The location of the density is stated in table 5.11 and is depicted in figure 7.7. The 1200 kg/m^3 level was not located for measurements at the silt-trap (i.e., B13, B14, B15 and B16). At location B18, the critical density zone was not located as well. Therefore in reality, the depth of this zone is located lower than depicted in figure 7.7.

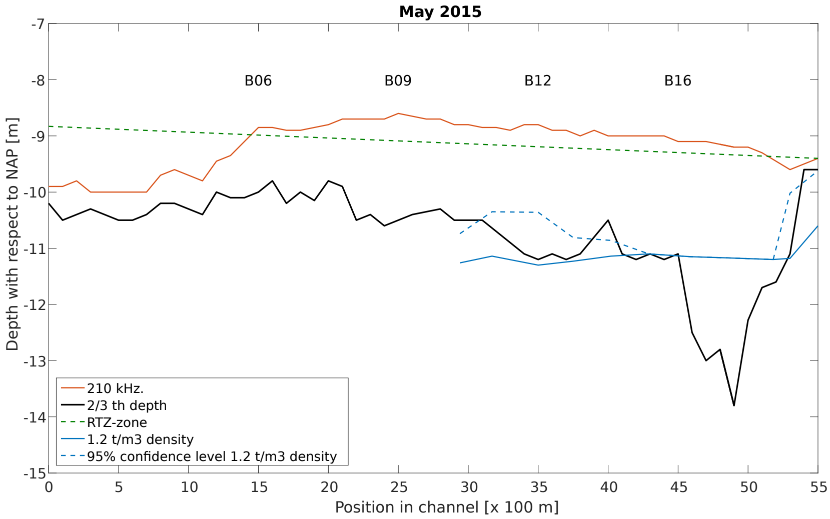


Figure 7.7: Depth level where density exceeds 1200 kg/m^3, values from table 5.11

7.2.3 Profile development

The location of the rheological and critical density as depicted in figures 7.6 and 7.7, is caused by the current dredging effort. The dredging effort is shown in 5.11. Considering the significant difference between density and optimal nautical bottom location, time spend at each location can be reduced. As a consequence, the critical density location will evolve to a shallower depth. Since the level indicates the transition between weak and strong material, a stronger layer will now be present at a shallower depth. This will result in a steeper slope in the water-mud interface. The profile and location of the mud-water interface (210 kHz survey) is hard to estimate as depicted in figure 7.8.

Without knowledge on the development of the mud-water interface, determination of the trapping coefficient can not be conducted. Letting the 1200 kg/m^3 density level transgress its current position causes the mud-water interface to rise. The new position of the mud-water influenced by hydrodynamics, ship movements and dredging operations in a different way.

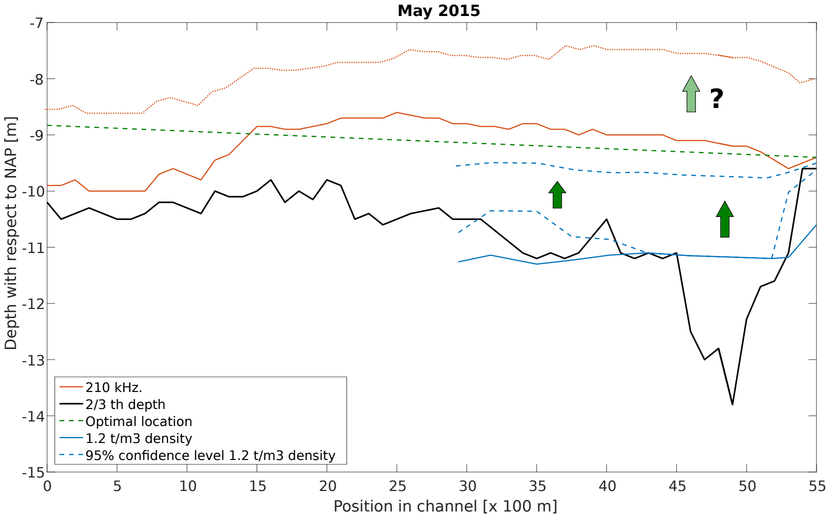


Figure 7.8: Possible channel development as a result of reduced Airset dredging

7.2.4 Governing parameters

Travel velocity

Doubt from the pilot on impact of velocity was examined. Increasing the velocity results in a higher squat and required UKC, see figure 7.9. Squat formulation used in this model is from Tuck and Taylor [1970]. However, multiple different squat formulations are possible each of which containing empirical relations. These relations and dependency of multiple variables and deviations cause a high uncertainty in squat determination as shown in figure 7.10. In addition, the squat formulations account for sailing through an uniform water body. Introducing a second fluid body with a higher density induce unknown squat effects. This should have an positive effect since the buoyancy is increased by the higher density. However, this was not researched therefore a conclusive answer remains.

Measurement error

Figure 7.11 indicates what the effect on an increase measurement error will be on the resistance R. The increase causes a significant spread in the resistance distribution. As a result the average depth must increase to comply with the probability of bottom touch. A higher error is reasonable as the result of new technique application. When quadrupling the error, the required UKC is doubled.

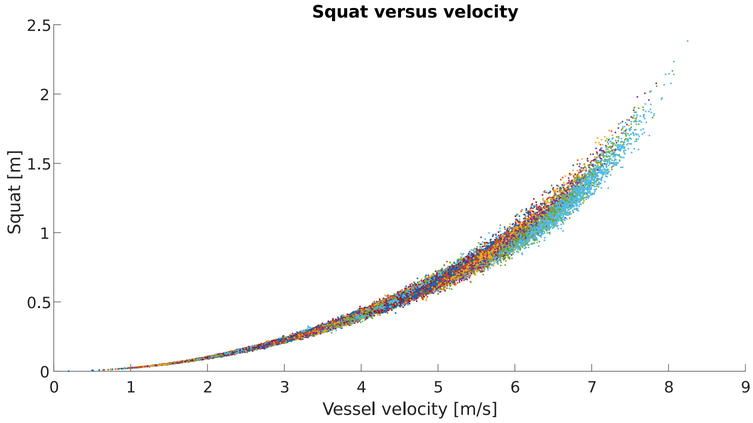


Figure 7.9: Squat increase corresponding to velocity increase

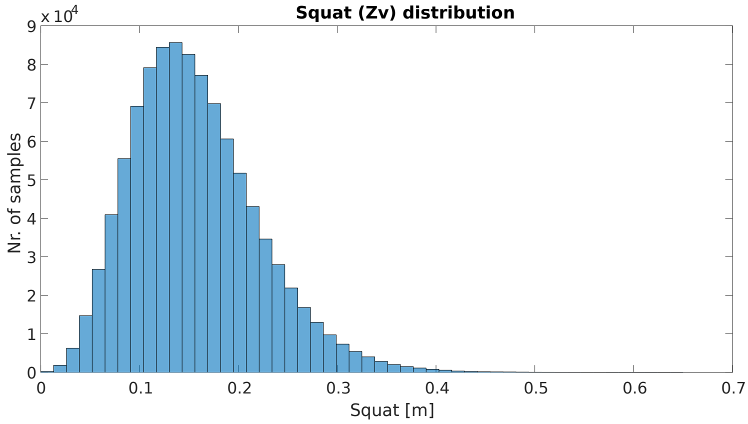


Figure 7.10: Squat histogram, $P_f(Z < 0) = 1.4 \cdot 10^{-5}$

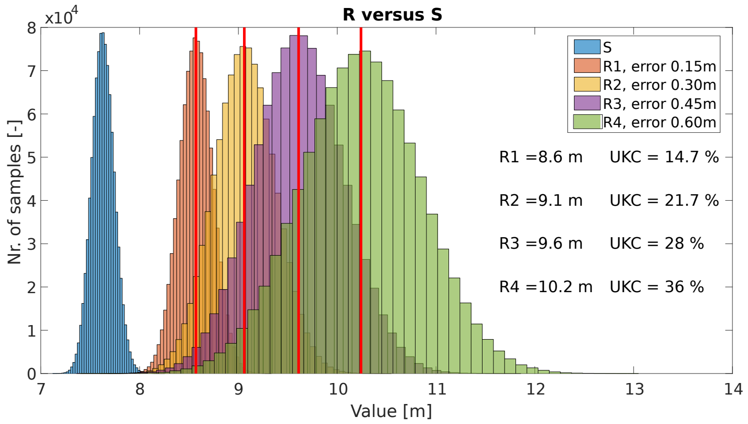


Figure 7.11: R versus S for increasing nautical bottom survey error

8

Discussion

The first Decision Support Model (DSM) shown in chapter 3 was built on theory described in chapter 2. Using the Frame of Reference (FoR) approach as a base for the DSM appeared to be effective. By using the FoR-approach the main issue 'reducing the UKC' was split up into several sub-issues which could be related to three contexts: safety, economy and ecology. Using three strategies enabled consideration of benefits and drawbacks. By this quantification the optimal strategy for Delfzijl was designated, described in chapter 5. Inability to quantify elements could be related to missing knowledge. In addition improvements where conducted in the DSM elements and used parameters as stated in chapter 4.

The model appeared to be helpful during end-user meetings. Via the detailed knowledge of specialists relevant topics could be identified for inclusion in the DSM, whilst at the same time assuring that the meaning and value of the implications of these topics where understandable to the users of specialist knowledge. They where also able to designate were their uncertainties (described in section 7.1) originated from and were/ how it would fit in the DSM. The practical approach of the DSM immediately let to a discussion on problems like the replacement of nautical charts, a new UKC and how to monitor bed-level changes.

Challenge of the DSM is depth and extend of issue inclusion. As elaborated in chapter 3, focus was kept on the Delfzijl case. A general applicable DSM requires encapsulation of challenges at other ports. Encapsulation can be achieved by iteratively adapting the DSM during application at the other locations. Highest effectiveness is reached when DSM improvements are conducted by the end-users themselves. That way new issues can be directly imported into the model and research can be directed to that particular topic. Extensive discussion with Delfzijl end-users led to a DSM comprising all local challenges regarding the UKC reduction.

First quantification showed a significant difference between profits originating from strategy 1 and 2 in comparison to strategy 3 as was shown in section 6.4. This indicates the effectiveness of reducing the UKC at Delfzijl. The quantification from chapter 6 was based on simple relations between parameters. Focus was less on the outcome and more on the presence/absence of the relations. Improving the relations results in a more accurate outcome.

A dredging reduction, as was indicated as optimal for Delfzijl, will affect the depth contour. This led to expressed issues by end-users regarding strength based nautical bottom locations and the UKC with respect to that level. These topics where assessed with a probabilistic tidal window model in chapter 7. The model calculates probability of a bottom touch in order to implement extra safety for the new situation. Running the model in section 7.2.2 based on tidal data resulted in an optimal location of a strength based nautical bottom. However, the model relies on input values to locate a nautical bottom. Unclear measurement errors and squat relations create a model inaccuracy, as was explained in section 7.2.4. Absence of knowledge regarding these topic creates inaccuracy. The model was also meant to assess the impact of a new nautical bottom on the trapping coefficient. Although a depth contour estimate could be made based on model outcomes, the effects from local conditions where not assessed, as was explained in section 7.2.3. As a result relating to the rapping coefficient was not possible.

Incentive for conducting UKC reduction research at Delfzijl was the shallower located 210 kHz depth contour. This higher location was presumed to be the effect from switching to Airset dredging in 2000. Comparison of depth contours and trapping coefficients between 1999 and 2015 could not affirm this assumption. A higher location of the 210 kHz contour would have affected port operations requiring increased dredging. Higher production was not shown from the dredging production graph, figure 5.12 in section 5.3. Inaccurate Airset production estimates could have caused this. An unknown fluid mud interaction with the present exchange flows could also lead to an underestimated production.

Inaccurate Airset production can be related to absent theoretical knowledge regarding Airset functioning. No research is available on Airset functioning nor was the technique used at other locations. Discussions with multiple end-users did not lead to clarity on Airset effectiveness for re-suspending and removing particles. The technique was able to preserve the fluid mud layer in the channel as was indicated by the difference between 210 kHz and 33 kHz surveys. Whether an other technique might be more effective is however unclear.

9

Conclusions & Recommendations

9.1 Conclusions

Goal of this thesis is *'Aid decision making on practising an altered UKC policy by designating opportunities and risks linking management/end user needs to scientific 'know-how"*. Six research questions where proposed to achieve this goal. These formed a step-by-step approach for a valuable input on reduced UKC application. Below the questions are being answered, first in general term (section 9.1.1) followed by application to the case of Delfzijl (section 9.1.2). With the answered questions and the Delfzijl case, conclusion on the DSM functioning is stated in section 9.1.3.

9.1.1 Research questions

1. Who are the end-users and what are their objectives/expectations regarding implementation of the concept?

Based on their objectives/visions end-users can be categorized in three groups:

Economic end-users which comprise port authorities envision optimization of port revenue and -operations. Fulfilment can be achieved by increasing transshipped goods or reducing maintenance and polluting activities. An UKC reduction can effectively accomplish either one of the operational objectives, as was shown by quantification in this thesis.

Safety concerned end-users, pilots and harbour masters rely on their experience in navigation at the harbour. The parties feel closely related to the topic safety and feel highly responsible for it. For them an UKC reduction is a controversial procedure resulting in reluctance amongst the end-users. Their attitude is somewhat changed as the result of trials showing the current policy (10 %) as most difficult. However, some topics, described at question 4, need to be covered before they feel confident with an UKC reduction.

Research end-users are interested in the various scientific topics requiring high specialist knowledge. Although benefits and drawbacks are not affecting them, they feel obliged to help the involved end-users which rely on their specialist knowledge. Expectation is that an

UKC reduction is possible while yielding new intriguing research topics regarding fluid mud behaviour and ship interaction.

End-users involved in multiple harbours, captains and international organisations, where not represented in this thesis. Discussions revealed that involvement of these users will be set in motion when one or multiple ports come up with a suitable application plan.

2. What decision issues arise when attempting application of an adjusted UKC policy?

Deciding on the envisioned goal of the new UKC-policy application is the first issue. Whether application for a draught increase or dredging reduction is chosen depends depends on the port authority's vision. Striving for a revenue increase or reducing polluting activities and maintenance costs determines the goal of application. Other end-user attitudes towards the UKC reduction will depend on the chosen goal. Trying to achieve ecological benefits results in an added incentive for application. At the same time harbour masters wonder how to 'sell' the procedure while tug expenses are required without the ability to transship more goods.

Choice of equipment or method for strength based nautical bottom determination is the next decision. A new technique must have a similar error and deployment time as the current technique, while designating a strength based nautical bottom. With a survey (monitor) technique the decision evolves to experimentally start allowing lower UKC's for some arriving/departing vessels.

Whether to change the dredging technique is the last decision. Current technique at a harbour is effective in achieving its goal 'remove sediment in a cost efficient manner'. Application of a smaller UKC benefits from a fluid bottom layer which shifts the focus to 'keep the sediment moving/fluid'. An injection technique might be more efficient in achieving the new goal.

3. What are key indicators for quantification of the benefits & drawbacks originated from application?

A new equilibrium based on tidal window can be achieved by simultaneous reducing the UKC and increasing the bed level or draught. Using the tidal window as key indicator enabled determination of the obtained space by reducing the UKC.

Strategy dependent key indicators where:

- Vessel size and number of visits for a draught increase strategy. Larger vessels can carry more goods per amount of draught increase.
- Harbour area, current location of strength based nautical bottom and maintenance expenses for a dredging reduction strategy. They determine the required dredging amount for what costs and the possible reduction.
- Turbidity in the system indicated by light intrusion and SSC. The light intrusion relates to the possibility for autotroph activity.
- Turn radius, stopping distance and measurement error for safety related drawbacks. UKC reduction effects on these indicators could not be assessed for the Delfzijl case.

4. Which knowledge gaps do we have to fill before UKC policy can be adapted?

By what means to measure in-situ strength of the soil is the first gap. UKC adjustments require an equipment or parameter relation usable for strength based nautical bottom surveys. In-situ strength determination depends on empirical relations which induce a measurement error. The fluid mud is dynamic because it is influenced by tide, ships and siltation. In-situ point measurements have low repeatability.

Vessel reaction to present UKC regarding to required turn radius and stopping distance is the second gap. For turn radius critical velocity zone (between 2 and 8 knots) for UKC values between 13 and 3 % is most influential. The stopping distance increase when touching the rheological transition zone is required. Not being able to reduce speed within the accommodated space, implies tug tie-up is not possible. For both topics the impact of different hull shapes, velocities and mud characteristics are important.

Valuing the impact of reduced relocated material for ecology is a knowledge gaps. Assessment of ecological impact is not easy. Numerous interrelations between turbidity and autotroph activity cause difficulty in relating them. In addition valuing the increase in nutrients and biomass by better light intrusion is not possible. Scientist have tried for quite some time without achieving a sound solution. Only possibility is a qualitative assessment based on the ecosystem services approach.

Current location of the strength based nautical bottom is a knowledge gap for quantifying economic benefits. The location determines to what extend vessel draughts can be increased. Absence of the current location hinders comparison between current and new strength based nautical bottom. Accuracy of determining dredging reduction depends on this comparison.

Relating a new nautical bottom to trapping coefficient was not possible. This is the result of unknown impact from currents, vessel passages and dredging on the new bathymetry map.

Effects of fluid mud on water intakes and wear & tear are obtained topics. These topics are already clear for research not requiring DSM inclusion.

5. What hinders the decision making?

A measurement equipment or a parameter relation able for in-situ definition of the strength based nautical bottom is required. This not only affects future concept application but also deciding on starting trials with actual arriving/departing vessels. Port authorities have no means of assessing the strength based location and can not assess eventual safety impairments.

Second obstacle is the bathymetry change caused by a dredging reduction. Higher located strength based nautical bottom, originating from a dredging reduction, induces bathymetry changes. With a survey method the depth contour change can be monitored enabling timely interventions.

Experimental application under guidance of tug-assistance is an option after addressing the first two topics. This will create a shift toward new topics governing for the final decision reduced UKC application. Topics which will need attention at that point are: an UKC value with respect to rheological based nautical bottom, effect of UKC on stopping distance and turnability for various vessels/hull shapes and speeds and fluid mud effects on squat.

knowledge gaps in economic and ecology contexts do not form an obstacle for decision making. Current focus is on safety related topics which should be bridged first before focus shifts to the benefits and optimization thereof. Both context do, once quantified, increase the incentive for application and can be used to persuade other parties in joining research efforts. Both of them can therefore be used to aid decision making.

6. How to cope with the apparent knowledge gaps?

Improving communication between specialists and end-users using specialist knowledge enables quicker designation of knowledge gaps. Improved communication is achieved by the FoR based DSM. Acquired knowledge might lead to new gaps. Again researcher will be quicker aware of these gaps leading to faster bridging.

The probabilistic model is able to cope with safety uncertainty. Although accuracy in its current form can not be assessed, the model can be extended with new knowledge and input parameters. In addition the model can be used during port operations determining the tidal window for vessel approach and navigation at the harbour. A similar model is used by ChartaSoftware applied for the ports at Rotterdam, Amsterdam and Eemshaven.

9.1.2 Case-specific

From the first quantification (conducted in chapter 6) we can conclude that the reduction of dredging (i.e., strategy 2) proves optimal for Delfzijl. The small vessel size at the port and the poor ecological condition in the estuary are main incentive for this conclusion. Furthermore, Groningen Seaports strives for growth while in the meantime reducing its ecological footprint. A new, cleaner, dredging strategy contributes to that [Bourgonjen, 2016].

Only local end-users are currently involved with decision making at Delfzijl. End-users involved with multiple harbours or communication between ports is currently absent. When local end-users finalize a conclusive plan on application, this involvement and communication will be triggered.

Although dredging reduction is the optimal strategy, Groningen Seaports is reserved on experimenting with an actual reduction. Depth contour developments caused by a dredging reduction and how the new contour is influenced by local conditions is needed information. This is directly related to absence of equipment/method for in-situ monitoring of the strength based nautical bottom and depth contour developments. Hereby created challenge governs the monthly nautical chart publications. The fluid mud layer is more dynamic, showed in figure 5.8 in section 5.2.1, while the charts are used to guarantee a certain depth over one month.

Presenting the DSM and quantification to the case specific end-users yielded four questioned aspects with their conclusions:

- **Is the 15 % UKC, as was proposed by Meinsma [2013], reasonable?**
  Model runs indicate a 15 % UKC to be valid as a rule of thumb. Input values for velocity,

squat and survey error determine the accuracy of the model. The extra safety required with respect to a new, stronger, nautical bottom can be provided with a probabilistic model as showed in this thesis.

- **What is the effect of varying speed on the required UKC?**
  Squat is influenced by vessel velocity. Extend of influence depends on the chosen squat relation. Accurate squat calculation requires knowledge on squat in the presence of fluid mud.
- **What would be the location of the strength based nautical bottom and how does this impact the bathymetry of the channel?**
  In the new situation the strength based layer will be located at shallower depths, as was shown in figure 7.5 in section 7.2.2. As a result, the fluid-mud interface will also be higher located. This leads to a new force equilibrium and corresponding bottom profile developments. Changes in hydrodynamics, vessel and dredging influence where not taken into account. Therefore prediction on the new bathymetry map could not be made.
- **Change dredging equipment**
  Both rheological and critical density based nautical bottom measurements are located well below the calculated optimum with the probabilistic TW model. Dredging can therefore be reduced. Accurately defining the effects for sedimentation requires the bathymetry change resulting from a dredging reduction. Airset influence on the bathymetry change is unknown due to absent knowledge on the technique other than it being sufficient in Delfzijl.

9.1.3 General objective - Decision Support Model

Based on the questions and case-specific conclusions we can conclude that the DSM was effective. It introduced a new approach resulting in discussions and research topics on general fluid mud and ship interaction.

With the DSM:

- Researchers where able to point out missing topics and users of specialist knowledge could indicate their concerns. This was caused by the DSM being a visualisation of problems concerning the concept.
- End-users more stimulated to bring forward topics which triggered discussion. This input could directly be translated to additional research.
- Better alignment is achieved between end-users and specialists.

9.2 Recommendations

9.2.1 General

The derived DSM should be applied at other ports in collaboration with all local and specialist end-users. This will result in awareness of issues at hand, without spending time on topics less governing for (experimental) application.

Equipment or parameter relation for in-situ determination of the strength based nautical bottom is required. Required link of knowledge between various scientific fields can be obtained by setting up a PIANC work group. The group should focus on Delfzijl and later generalize the research for other ports.

Effects of hydrodynamics, vessel transits and dredging efforts on the new bathymetry should be researched. This will lead to an assessment on required dredging effort. Effect of vessel thrusters on the re-suspension of fluid mud can be done with a numerical based model as is the dredging effort. The new deposit/sedimentation equilibrium can be assessed with a process based model for a site specific case.

Conduct research on squat relations when sailing close to or through fluid mud. Important in the research should be velocity and hull shape impacts on the squat relation and on fluid mud undulations.

Research should be focussed on the effects of undulations on the screw and rudder. Measuring force and vibrations induced by the mud undulations is therein the first step in the research.

Assess common locations of cooling water intakes. Research the effects of fluid mud being sucked into water intakes.

9.2.2 Case-specific

Locating both the rheological transition zone and critical density was inconclusive, indicating the need for an improved measurement campaign. A conclusive method enables monitoring of depth contour changes leading to experimentally reducing dredging operations. In the beginning this will require surveys with a new equipment (or a combination of pieces equipment) that are cross-checked on error by soil sampling and lab-tests.

Formulate an application plan holding vision, guidelines and regulations for (experimental) application. Applying the DSM for assessing issues in the plan stimulates involvement of all end-users and enables designation of uncertainties. Directly focussing research on the concerns will eliminate all uncertainty over time, enabling experimental UKC reduction under guidance of tugs. This yields insight and experience for pilots and captains. With this insights new research topics will arise improving the concept. With new experience and knowledge, the tug assistance might be dispensable after a while.

Apply the probabilistic model at Delfzijl. It is extendible with new squat relations, measurement errors, wave climates and tide conditions leading to a future prove model. With the model, safety can be guaranteed for arriving/departing vessels and their captains. In addition, it gives visual information on available tidal windows.

Research vessel reaction to UKC for local fluid mud conditions and rate of turn requirements. In specific, tests should be conducted for positive UKC (3 - 13 %) for vessels within the critical speed range. These test will reveal whether the turn radius can be met or if tug tie-up is required. If one would know the effect on ship reaction due to an UKC reduction, counter measures can be taken. Previous conducted research in Delfzijl showed that the vessel was easily manoeuvrable and application of the procedure is therefore justified. Effects on the stopping length where not discussed however.

Extended knowledge on possible bathymetry development and accurate prediction of sedimentation rate must be acquired. In order to do so the possibilities for establishing a process based sedimentation model should be investigated.

Conduct more trials or simulation runs specifically for the case in Delfzijl. Trials are the most effective way of showing the vessel reaction when sailing through mud. The trials/simulations should be able to test different vessel velocities, hull shapes and squat predictions. Use the obtained knowledge for determining squat effects impacted by fluid mud. This can be used to expand the probabilistic model so that it accounts for the hull shapes, squat and vessel sizes.

Research the Airset method and functioning. Transport ability of particles to higher levels in the water column and required energy for fluidizing a layer should be topics of research. Comparing Airset dredging to conventional WID should be done to see which technique is more efficient. In addition, explore possibilities of maintaining the complete channel by injection dredging.

Devise an ecology improvement plan for the Ems-Dollard. SSC concentrations are so high that solely an UKC reduction is inadequate. An UKC reduction should be part of that plan.

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Appendix A

Charts of Delfzijl

Channel profiles are obtained from survey charts supplied by Groningen Seaports. Used survey charts are stated in this appendix along with 2 example charts. The Engineering drawing is added as an overview of the harbour basin and sections. Information on the charts is stated in table A.01.

Table A.01: Charts of Delfzijl

Chart name	Author	Survey Date	Publication date
Survey month:			
April 1999	Gert Dekker	8-9 April 1999	15^{th} of April 1999
January 2015	Jakob Meijerhof	4, 5 and 7 January	12^{th} of January 2015
February 2015	Jakob Meijerhof	2 February	5^{th} of February 2015
March 2015	Jakob Meijerhof	2 March	4^{th} of March 2015
April 2015	Jakob Meijerhof	7 and 8 April	9^{th} of April 2015
May 2015	Jakob Meijerhof	4 and 5 May	7^{th} of May 2015
June 2015	Jakob Meijerhof	1 and 3 June	5^{th} of June 2015
July 2015	Jakob Meijerhof	6 July	17^{th} of July 2015
August 2015	Jakob Meijerhof	4 and 5 August	10^{th} of August 2015
September 2015	Jakob Meijerhof	1 September	3^{th} of September 2015
October 2015	Jakob Meijerhof	5 and 7 October	8^{th} of October 2015
November 2015	Jakob Meijerhof	9 November	11^{th} of November 2015
December 2015	Jakob Meijerhof	3 and 4 December	8^{th} of December 2015
Engineering Drawing:			
Nautical depths	Joop van Dijken	-	5^{th} of September 2007

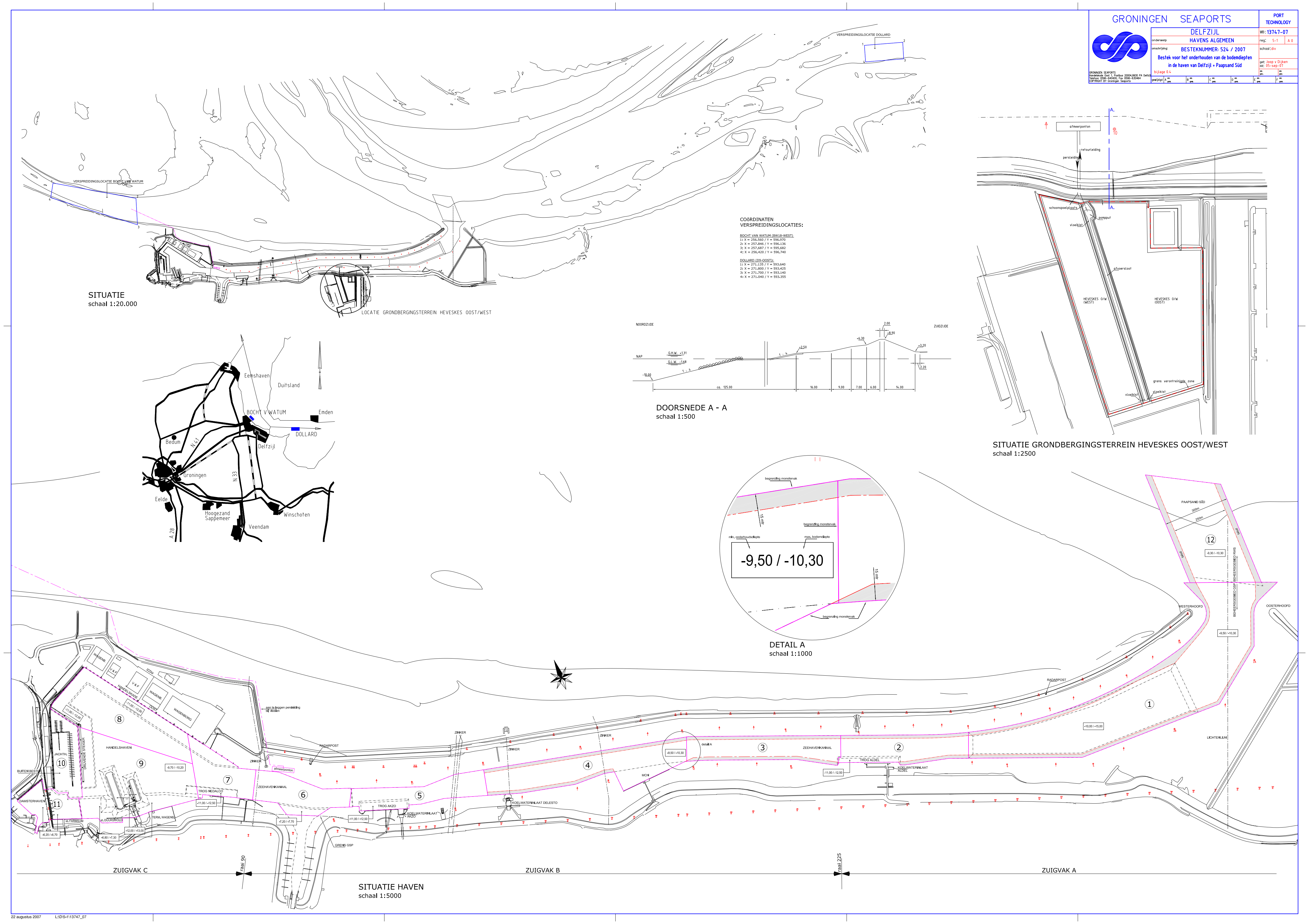


Figure A.01: Dredge sections Delfzijl

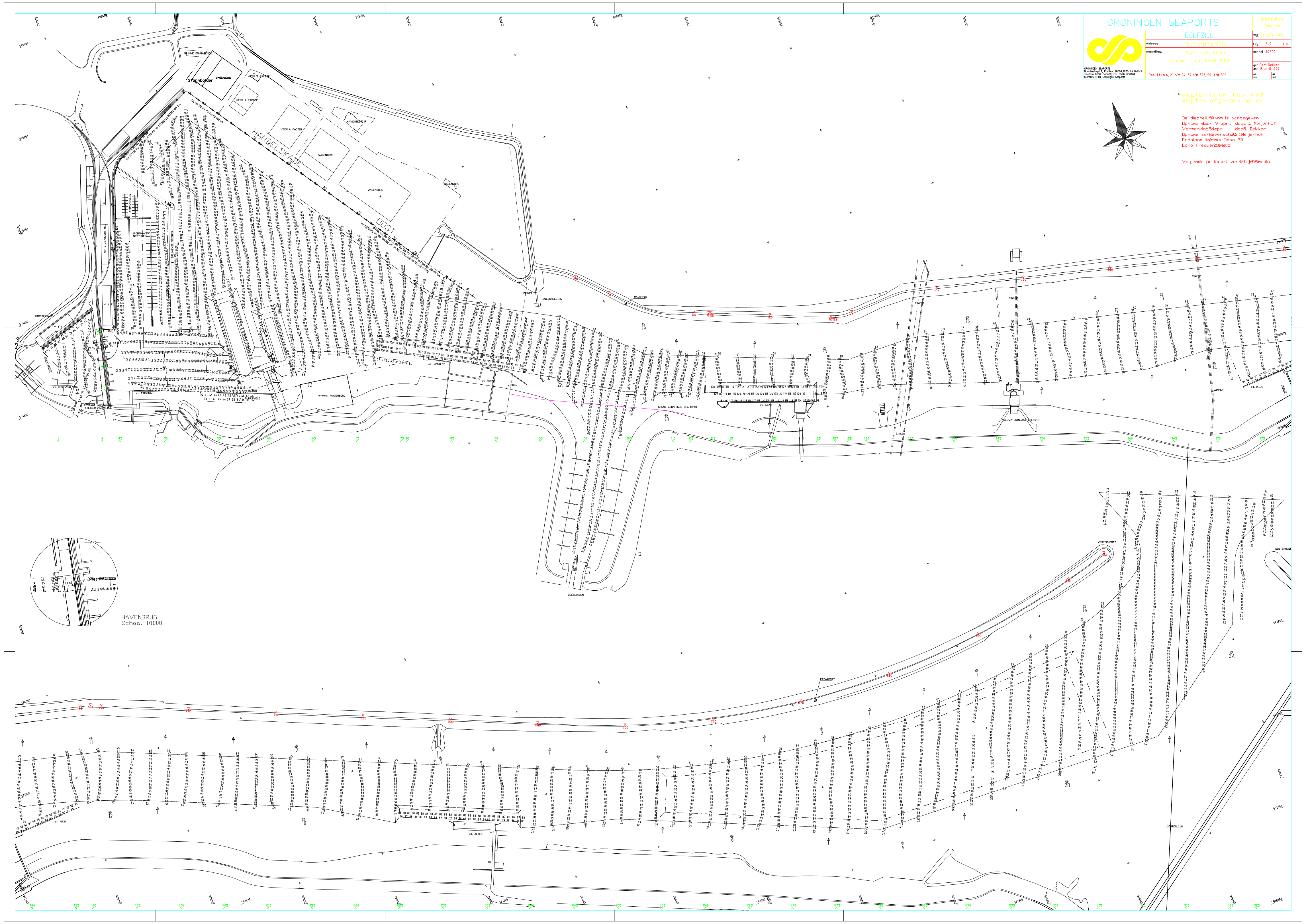


Figure A.02: 210 kHz survey April 1999

Figure A.03: 210 kHz survey April 2015 - sheet 1

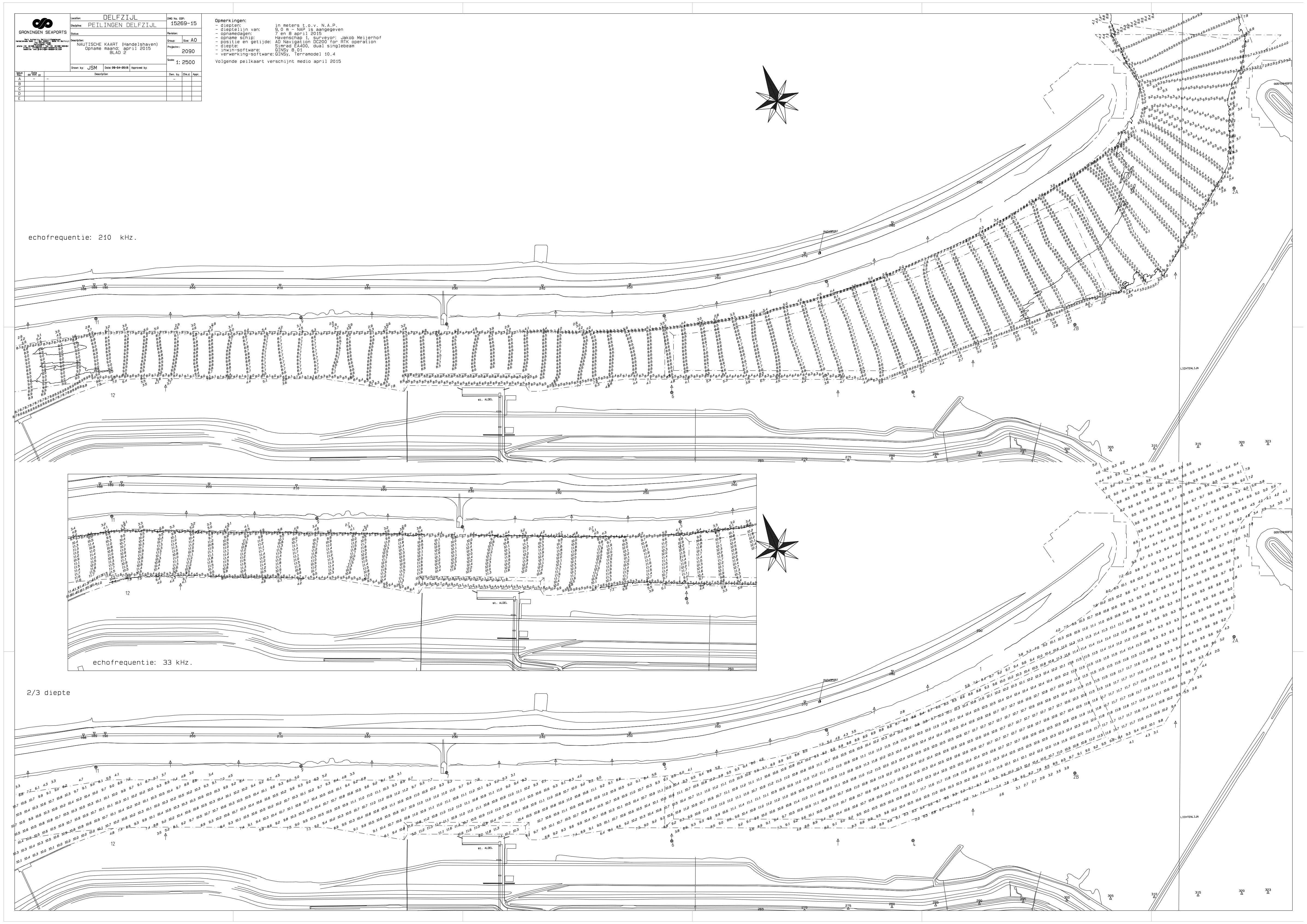


Figure A.04: 210 kHz survey April 2015 - sheet 2

Appendix B

Eysink

B.1 Eysink equations

The exchange mechanisms described in section 2.2 can be approximated by the Eysink model. This model is used during (re)design stages of harbours in order to give a preliminary assessment on sedimentation. In most scenario's subsequent application of process-based models yields more accurate sedimentation numbers.

Eysink [1989] derived the exchange flow rates relationships averaged over the tidal cycle [PIANC, 2008]:

$$\langle Q \rangle = \langle Q_t \rangle + \langle Q_e \rangle + \langle Q_d \rangle + \langle Q_T \rangle + \langle Q_s \rangle \tag{B.1}$$

Where:

$$\langle Q_t \rangle = \frac{2\hat{a}S}{T_t} \tag{B.2}$$

$$\langle Q_e \rangle = f_e A_c \frac{\hat{u}_0}{\pi} - f_{t,e} \frac{\langle Q_t \rangle}{2} \tag{B.3}$$

$$\langle Q_d \rangle = f_d A_c \sqrt{\frac{0.5 \Delta\rho_m g h_0}{\rho}} - f_{t,d} \langle Q_t \rangle \tag{B.4}$$

where: Q_t = tidal filling, Q_e = horizontal entrainment, Q_d = salinity driven density current, Q_T = temperature driven density current, Q_s = sediment driven density current $\hat{u}_0$ = amplitude of the tidal velocity, T_t = tidal period (=44700 s), A_c = conveyance area at the entrance, $\hat{a}$ = tidal amplitude, $\Delta\rho_m$ = maximum salinity-induced density difference, h_0 = mean water depth in harbour entrance, ρ_{SSC} = material density in suspension, $f_e, f_{t,e}, f_d, f_{t,d}$ = coefficients for exchange flow rates, see table B.11 in appendix B.2.

Table B.11: Coefficients for exchange flow rates [PIANC, 2008]

f_e	$f_{t,e}$	$f_{t,d}$	f_d
0.01 - 0.1	0.1 - 0.25	0.1 - 1.0	0.05 - 0.125

B.2 Eysink Coefficients

f_e & $f_{t,e}$ depend on the geometry of the basin and range between 0.01 - 0.03 and 0.1 - 0.25 respectively [Eysink, 1989]. The coefficients are emperical and are determined based on existing knowledge on sedimentation in basins.

f_e is governed by the entrance of the basin, as shown in figure B.21. The angle with respect to the direction of maximum flow determines f_e.

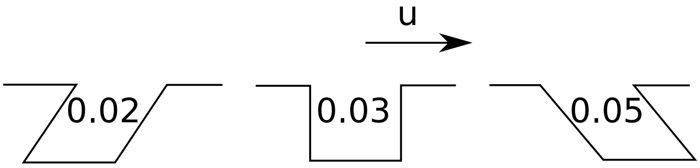


Figure B.21: Values for f$_e$ [Winterwerp, 2016]

f_d depends on V_{d0}/V_{ha} in which V_{ha} is the basin volume below average water level, see figure B.22a.

for $\Delta\varphi > \pi/180$ and $\varphi = \frac{\pi}{2}$ the following equations iteratively executed:

$$f_d = 0.125\sqrt{\sin(\varphi)} \tag{B.5}$$

$$V_{d0} = f_d \cdot h_0 \cdot b_0 \cdot \sqrt{\frac{\Delta\rho_{0,max} \cdot g \cdot h_0}{\rho_w}} \cdot T_t \tag{B.6}$$

$$\Delta\varphi = \varphi - \arctan\left(5.49 \cdot \frac{V_{ha}}{V_{d0}} + 1\right) \tag{B.7}$$

$$\varphi = \varphi - \Delta\varphi \tag{B.8}$$

where $b_0 =$ entrance width, $\Delta\rho_{0,max} =$ characteristic density difference ($= (\rho_{max} - \rho_{min})/2$), $\rho_w =$ density water (=1000 kg/m^3), $\varphi =$ phase lag, $\Delta\varphi =$ change in phase lag, $V_{ha} =$ volume basin below average water level and $V_{d0} =$ volume of density driven exchange without tidal effects.

Iteration from Eq. B.5 to B.8 takes place till $\Delta\varphi$ is no longer larger than $\pi/180$.

$f_{t,d}$ depends on V_{d0}/V_t and the phase lag ϕ_t between u_{d0} and u_t, see figure B.22b.

Above calculated φ is used in the formulas for calculation of $f_{t,d}$. Calculation is conducted with the following formula's:

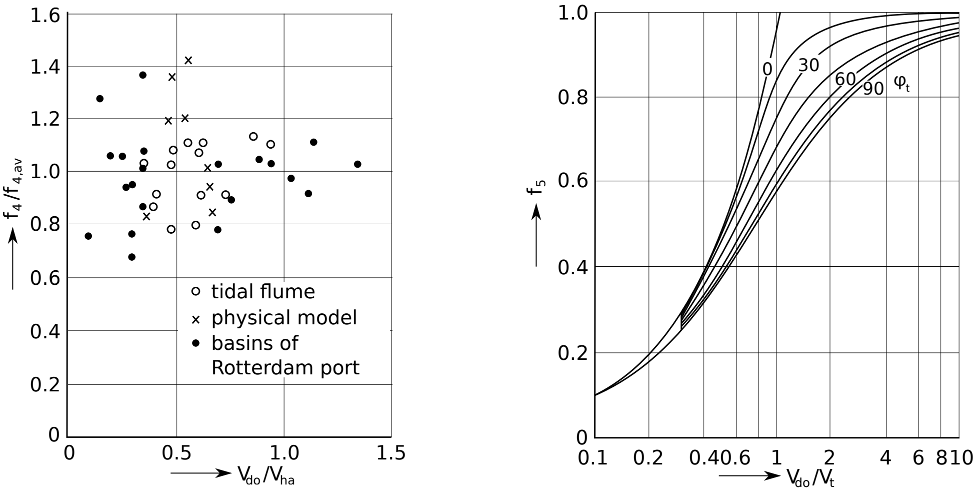
$$\varphi_r = \varphi + \frac{\varphi_t \cdot \pi}{180} \tag{B.9}$$

$$D_1 = \arctan\left(\frac{\frac{V_t}{V_{d0}+1} - \cos(\varphi_r)}{\sin(\varphi_r)}\right) \tag{B.10}$$

$$D_2 = \arctan\left(\frac{\frac{-V_t}{V_{d0}+1} - \cos(\varphi_r)}{\sin(\varphi_r)}\right) + \pi \tag{B.11}$$

$$f_{td} = \frac{V_{d0}}{V_t}\left(1 - \frac{\sin(D_2 - \varphi_r) - \sin(D_1 - \varphi_r)}{2}\right) - \left(\frac{\sin(D_1) + \sin(D_2)}{2}\right) + 1 \tag{B.12}$$

where φ_t = phase lag horizontal tide, φ_r = change of φ_t and V_t = tidal prism



(a) Relative variation in coefficient $f_{4,max}$ determined from model and field data

(b) $f_{t,d}$ coefficient as a function of Q_d/Q_t and phase lag

Figure B.22: Exchange flow rate coefficients [Eysink, 1989]

Appendix C

Matlab model

C.1 Model elements

C.1.1 Base module

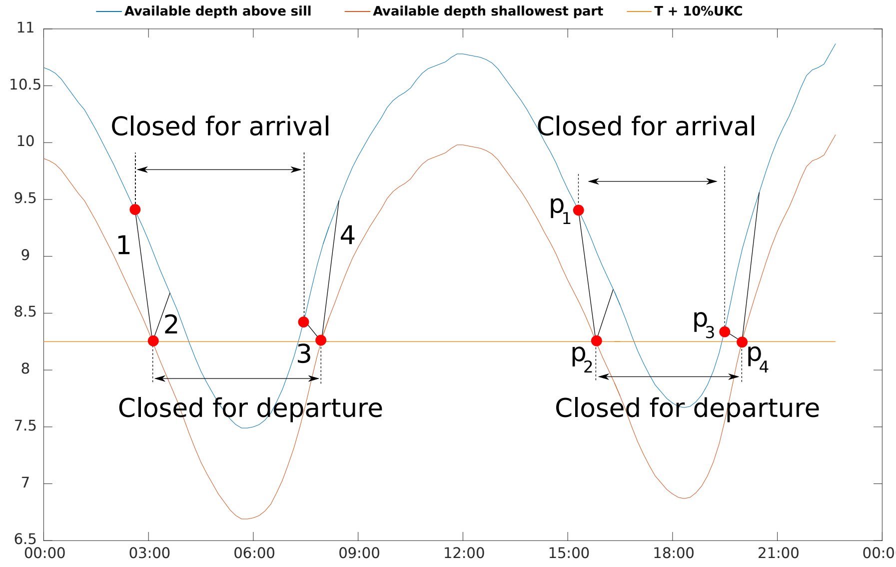
Base module used for reading channel and water level data. Channel data of a month is taken along with corresponding water level conditions in the same month. Furthermore, specific conditions are inserted like design vessel properties and speed. In the base module, the different module are called for calculation.

Requires input of vessel speed, transect length and draught. Reads tidal data from waterbase, storing water level with respect to NAP and date and time of occurrence. Reads table with fluid mud and 2/3th depth location, with values from nautical charts, see appendix A.

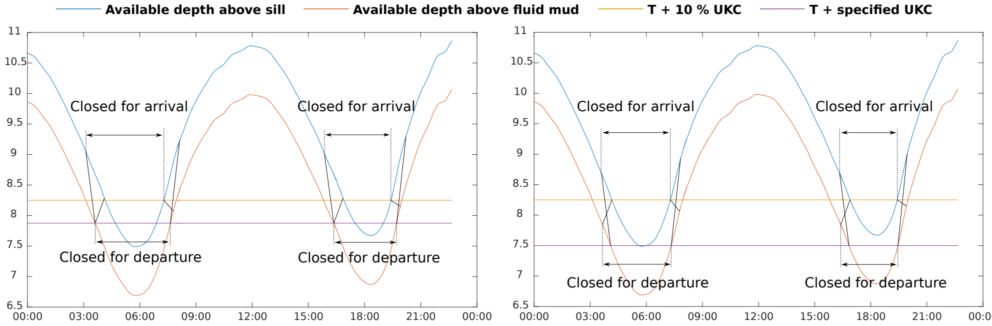
C.1.2 Module 1

Module 1 determines the tidal window based on two bottlenecks in the channel, nautical depth at the entrance and at the highest part of the fluid mud. A vessel should pass both segments with the minimal required UKC. Red dots in figure C.11a represent points of interest. Time between points 1 and 3 determine the closure time for arriving vessels. Points 2 and 4 show the latest time of departure and first time of departure respectively. Points 1 to 4 enable determination of closure times or tidal windows. Module 1 designates the p-values by checking if the vessel is able to pass both bottle-necks during arrival or departure of the port.

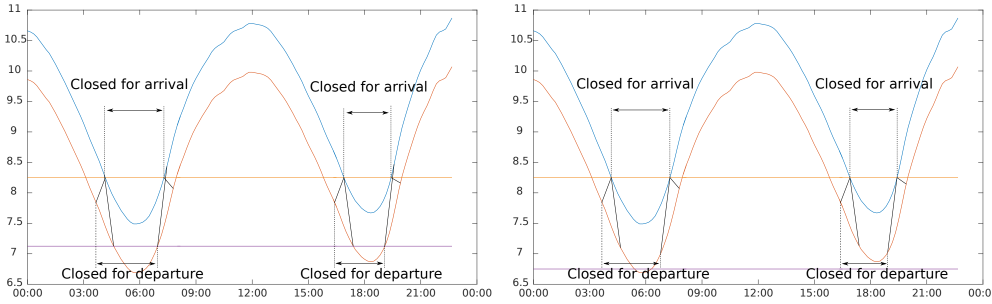
The fluid mud deposit creates the opportunity for reducing the UKC with respect to the mud-water interface. Figures C.11b to C.11e show the altered situation where the adjustment is applied. The UKC alteration is solely justified at the section where fluid mud is present. The entrance, seen as a solid barrier, must be cleared with predefined UKC of 10 %. Module 1 can be used to determine the new tidal window corresponding to this situation.



(a) Current situation (i.e. T + 10 % UKC)



(b) 5 % UKC **(c)** 0 % UKC



(d) -5 % UKC **(e)** -10 % UKC

Figure C.11: Tidal window change induced by an altered under keel clearance. Vessel draught = 7.5 meter, tide of 1^{th} of January 2010 [Rijkswaterstaat, 2016]

From figure C.11, the following remarks can be made:

- altering from +10 % to +5 % results in gain for all four situations.
- adjusting from +5 % to 0 % results in a marginal gain for situations two and three, significant influence on situations one and four
- altering UKC 0 % to -5 % zero gain for situations two and three and a significant gain for situations one and four
- UKC -5 % to -10 % the gain is marginal for all situations.

Only tidal windows for departing vessels are calculated with the module. Each tidal data measurement is used as a start for vessel departure. A travel time is apparent, depending on distance of fluid mud top, entrance sill and velocity. The following conditions must be met for a tidal window:

$$ND_{fm} > T \cdot 1.1 \quad and \quad ND_{sill} > T \cdot 1.1 \tag{C.1}$$

with as parameters:

$$ND_{fm} = WL(t) - z_{fm} \quad and \quad ND_{sill} = WL(t + t_{travel}) - z_{sill} \tag{C.2}$$

Where all values with respect to NAP:

ND_{fm} = nautical depth above fluid mud, ND_{sill} = nautical depth above sill, z_{fm} = depth location of fluid mud top, z_{sill} = depth location of sill top, $WL(t)$ = water level at start-time t, $WL(t + t_{travel})$ = water level after travel time t_{travel}, t_{travel} = travel time ($= \frac{\Delta x}{v_s}$), Δx = distance between top fluid mud x_{fm} and sill x_{sill}, v_s = vessel speed and t = start time t, every 10 minutes.

Water level $WL(t)$ is measured every 10 minutes by Rijkswaterstaat. For a travel time in between two measurements, a linearisation between previous and succeeding data points is used. Determining time t for which either one of the conditions in Eq. C.1 are not met, results in a tidal window.

C.1.3 Module 2

Module 2 calculates the optimal location of the rheological transition zone for each separate transect in a probabilistic way. The module uses the water-level read from the base module and the calculated tidal window from module 1.

$$WL(t) = WL_{n=0} \quad \& \quad WL_n = WL(t + t_{n-travel}) \tag{C.3}$$

where:

$$t_{travel} = \frac{n \cdot l}{V_s} \tag{C.4}$$

in which n = transect number ($0 \leq n \leq 55$), WL_n = water level in transect n, l_n = length of transect (=100m) and $t_{n-travel}$ = travel time to transect n

Equation C.3 results in 4000+ conditions a month in each transect. A percentile of these values is taken based on the tidal window calculated in module 1, becoming decisive water levels.

These water levels are parsed to the Monte Carlo tool, see appendix section C.1.5 for elaboration. The MC tool calculates the probability of bottom touch in each transect. Start depth in the transect is estimated based on the vessel draught and water-level. When the probability of bottom touch exceeds predefined threshold, the depth is increased by a small step. At a certain depth, the probability of failure is below the specified threshold leading to a depth at that transect.

C.1.4 Module 3

Module 3 calculates the probabilistic tidal window corresponding to the channel calculated in module 2. The water level determination in each transect is identical to Eq. C.3. All conditions in each transect are known and parsed to the MC tool. The complete transit, 55 transects as a whole, should not exceeds the total probability of bottom touch. If this conditions is met, the start time t (corresponding to that transit) is marked as within the tidal window.

C.1.5 MC OpenEarth tool

In a probabilistic approach the strength (R) versus the load (S) is investigated. When the load exceeds the strength (i.e., z < 0) the structure fails. Bouw [2005] applied this method for ship navigation. In that approach, the strength depends on the available nautical depth, governed by the location of the nautical bottom and the present water level. Vessel motion and draught are seen as the loading. Both Bouw and ProTide implement the vessel motions caused by the waves. However, vessels are only affected by long (swell) waves which are not present in a sheltered area, therefore only squat is taken into account. In general form, the z function reads [Jonkman et al., 2015]:

$$Z = R - S \tag{C.5}$$

Multiple load/strength relations take place during one ship transit. Investigating these multiple possible loads (draughts and squats) versus different strengths (water levels and nautical bottom locations) results in a probability of failure. In general form, this is written as:

$$P_f = P(Z \leq 0) = P(S \geq R) \tag{C.6}$$

The reliability function of the transit is written as:

$$P(Z > 0) = 1 - P_f \tag{C.7}$$

To simulate multiple possible conditions in a transect, the Monte Carlo method is applied. In the method, random values are drawn from a subset of variables having a certain distribution.

Repetition by applying a number of samples to be drawn for calculation, results in a probability for z. Probability of failure is then described by:

$$P_f = \frac{N_f}{N} \tag{C.8}$$

Solved equations in de module are Eqs. 2.1 and 2.2.

C.1.6 Probabilistic parameters clarification

Values without known distribution are deterministic, others have a normal of uniform distribution. For more information on distribution, see Dekking et al. [2005]. Below section elaborates on the parameters involved and their distribution.

Water level

Water level measurements are obtained from Rijkswaterstaat from waterbase [Rijkswaterstaat, 2016]. In the optimization section, measurements of 2015 are used. According to Data-ICT-Dienst [2009] water level measurements in harbours and shipping lane should follow Dutch standard order A. Therefore deviation can only be 0.10 meters.

Fluid mud layer

Location of the fluid mud layer is based on the 210 kHz surveys from Groningen Seaports, see Appendix A for elaboration. Error of these measurements are in the range of 6 cm (0.2 ft.) in depths of 1.5 to 6 m (5 to 20 ft.) and 15 cm (0.5 ft.) water depths of 10 meter (35 ft.) [U.S. Army Corps of Engineers, 1991]. Depths in Delfzijl range from 8 to 11/,m, therefore 15 cm error is used.

Vessel dimensions

Length between perpendiculars

Length of the MS Tornes is 113 meters (table 5.2 in section 5.1.1), and will depend on the draught of a vessel. Length will increase for higher draughts. The relation between draught and length depends on the hull shape as depicted in figure C.12. Since no information is known on type of vessels and their corresponding hull shapes, a standard deviations is used of 1.5 m.

C.12

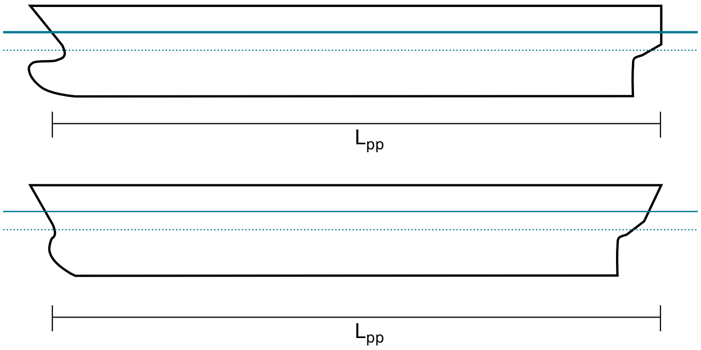


Figure C.12: Hull shape and effect on L_{pp}

Width

Width of the MS Tornes is 20 meters (table 5.2 in section 5.1.1), but will depend on the draught of a vessel. Width will increase for higher draughts. The relation between draught and width depends on the shape of the hull as depicted in figure C.13. Since no information is known on type of vessels and their corresponding hull shapes, a standard deviations is used of 0.5m.

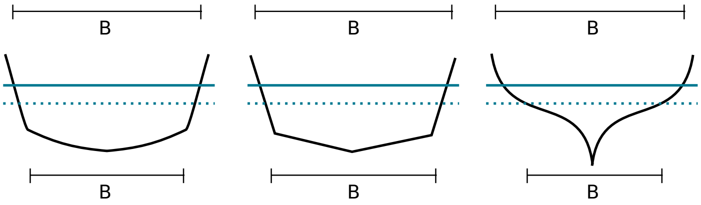


Figure C.13: Schematic representation of width differences for typical hull shapes

Draught

Average max. draught of the MS Tornes is 7.5 meters (table 5.2 in section 5.1.1). Static draught depends on the load and buoyancy of a vessel. Buoyancy is related to the width, length and shape of the hull. In absence of hull shape information, the draught deviation is taken a 0.10 meter. The same deviations is used by Bouw [2005].

Block coefficient

Calculation of block coefficient is done with the formula [PIANC, 2014]:

$$C_B = \frac{\nabla_m}{\rho_w \cdot L_{pp} \cdot B \cdot T}, \tag{C.9}$$

where ∇_m $=$ weight of displaced salt water, L_{pp} $=$ length between perpendiculars, B $=$ vessel width and T $=$ vessel draught.

Table from PIANC [2014] is used in absence of knowledge on mass of displaced water volume. Vessel dimensions from table 5.2 in section 5.1.1 yield C_B values between 0.70 (cargo vessel) and 0.75 (bulk vessel). Therefore a uniform distribution with an upper and lower limit is used.

Squat coefficient

Squat coefficient depends on the block coefficient [PIANC, 2014]. C_S =

- 1.7 for $C_B < 0.7$
- 2.0 for $0.70 \leq C_B < 0.8$
- 2.4 for $C_B \geq 0.80$

Block coefficients between 0.7 and 0.75 are used in the model. Therefore the squat coefficient is 2.0 without distribution.

Squat prediction is in al scenario's empirical. The approach by Hooft is used therefore, a squat coefficient is used of 2.0. A distribution of the squat coefficient is left out.

Sailing speed

Sailing speed is taken as 2.5 m/s (5 kn.) with a deviation of 0.5 m/s [Bouw, 2005].

Appendix D

Suspended Sediment Concentration

D.1 Deltares SSC model

Figure D.11 shows the areas used for the SSC-model by Cronin et al. [2015]. Figure D.12 and table D.11 show results form the Cronin et al. model.

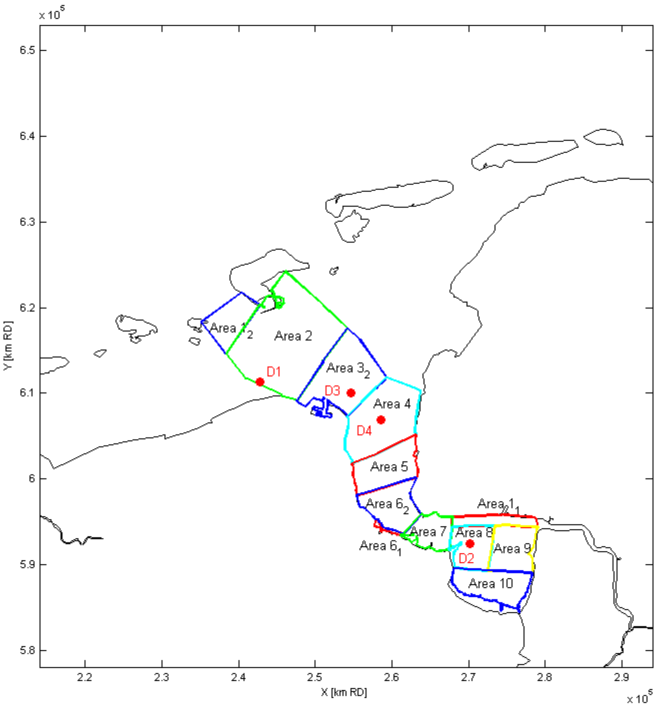
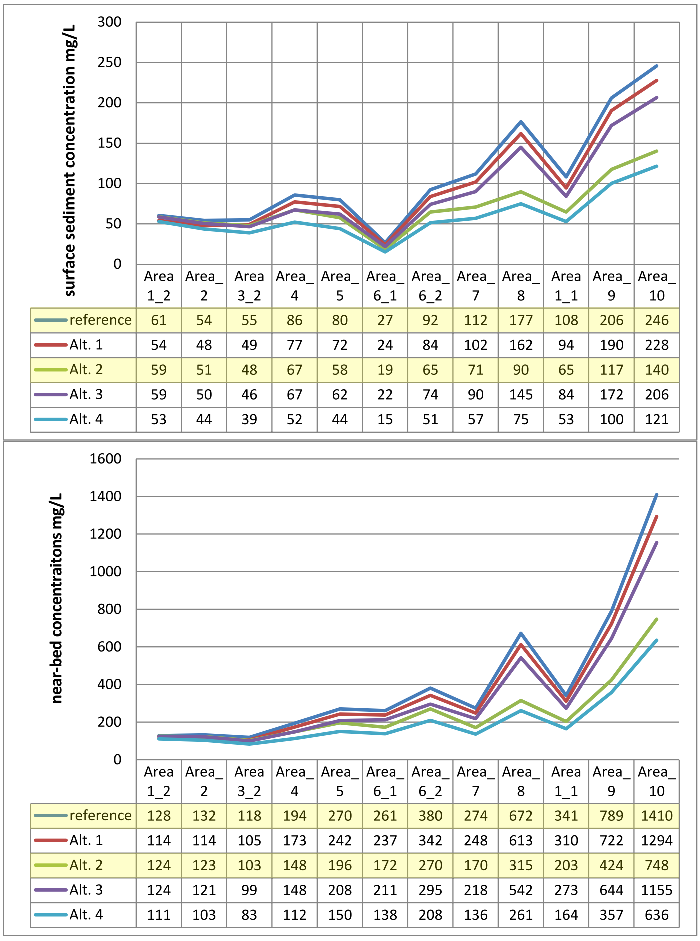


Figure D.11: Definition of area's used in Cronin et al. [2015]



	Area 1_2	Area_ 2	Area 3_2	Area_ 4	Area_ 5	Area_ 6_1	Area_ 6_2	Area_ 7	Area_ 8	Area 1_1	Area_ 9	Area_ 10
reference	61	54	55	86	80	27	92	112	177	108	206	246
Alt. 1	54	48	49	77	72	24	84	102	162	94	190	228
Alt. 2	59	51	48	67	58	19	65	71	90	65	117	140
Alt. 3	59	50	46	67	62	22	74	90	145	84	172	206
Alt. 4	53	44	39	52	44	15	51	57	75	53	100	121

	Area 1_2	Area_ 2	Area 3_2	Area_ 4	Area_ 5	Area_ 6_1	Area_ 6_2	Area_ 7	Area_ 8	Area 1_1	Area_ 9	Area_ 10
reference	128	132	118	194	270	261	380	274	672	341	789	1410
Alt. 1	114	114	105	173	242	237	342	248	613	310	722	1294
Alt. 2	124	123	103	148	196	172	270	170	315	203	424	748
Alt. 3	124	121	99	148	208	211	295	218	542	273	644	1155
Alt. 4	111	103	83	112	150	138	208	136	261	164	357	636

Figure D.12: Surface- and bottom SSC for disposal on land. Alt. 2 represents the situation where dredged material originated from Delfzijl is disposed on land. Data of interest marked yellow. source: [Cronin et al., 2015]

Table D.11: Change of surface and near-bed SSC by disposing 0,8 million ton/year on land. Numbers from figure D.12

Surface SSC	1_2	2	3_2	4	5	6_1	6_2	7	8	1_1	9	10
Current	61	54	55	86	80	27	92	112	177	108	206	246
After extraction	59	51	48	67	58	19	65	71	90	65	117	140
decrease	2	3	7	19	22	8	27	41	87	43	89	106
relative	3.28%	5.56%	12.73%	22.09%	27.50%	29.63%	29.35%	36.61%	49.15%	39.81%	43.20%	43.09%
Near-bed SSC	1_2	2	3_2	4	5	6_1	6_2	7	8	1_1	9	10
Current	128	132	118	194	270	261	380	274	672	341	789	1410
After extraction	124	123	103	148	196	172	270	170	315	203	424	748
decrease	4	9	15	46	74	89	110	104	357	138	365	662
relative	3.13%	6.82%	12.71%	23.71%	27.41%	34.10%	28.95%	37.96%	53.13%	40.47%	46.26%	46.95%

D.2 SSC increase

Table D.22: UKC 5% - Decreased dredging 39,000 ton/year

Surface SSC	1_2	2	3_2	4	5	6_1	6_2	7	8	1_1	9	10
Decreased SSC	0.1	0.1	0.3	0.9	1.1	0.4	1.3	2.0	4.2	2.1	4.3	5.2
New SSC	60.9	53.9	54.7	85.1	78.9	26.6	90.7	110.0	172.8	105.9	201.7	240.8
relative	0.16%	0.27%	0.62%	1.08%	1.34%	1.44%	1.43%	1.78%	2.40%	1.94%	2.11%	2.10%
Near-Bed SSC	1_2	2	3_2	4	5	6_1	6_2	7	8	1_1	9	10
Decreased SSC	0.2	0.4	0.7	2.2	3.6	4.3	5.4	5.1	17.4	6.7	17.8	32.3
New SSC	127.8	131.6	117.3	191.8	266.4	256.7	374.6	268.9	654.6	334.3	771.2	1377.7
Relative	0.32%	0.81%	1.33%	2.61%	4.51%	16.07%	5.83%	4.53%	9.83%	6.23%	8.64%	13.12%

Table D.23: UKC 0% - Decreased dredging 42,000 ton/year

Surface SSC	1_2	2	3_2	4	5	6_1	6_2	7	8	1_1	9	10
Decreased SSC	0.1	0.2	0.4	1.0	1.2	0.4	1.4	2.2	4.6	2.3	4.7	5.6
New SSC	60.9	53.8	54.6	85.0	78.8	26.6	90.6	109.8	172.4	105.7	201.3	240.4
relative	0.17%	0.29%	0.67%	1.16%	1.44%	1.56%	1.54%	1.92%	2.58%	2.09%	2.27%	2.26%
Near-Bed SSC	1_2	2	3_2	4	5	6_1	6_2	7	8	1_1	9	10
Decreased SSC	0.2	0.5	0.8	2.4	3.9	4.7	5.8	5.5	18.7	7.2	19.2	34.8
New SSC	127.8	131.5	117.2	191.6	266.1	256.3	374.2	268.5	653.3	333.8	769.8	1375.2
Relative	0.16%	0.36%	0.67%	1.24%	1.44%	1.79%	1.52%	1.99%	2.79%	2.12%	2.43%	2.46%

Table D.24: UKC -5% - Decreased dredging 54,000 ton/year

Surface SSC	1_2	2	3_2	4	5	6_1	6_2	7	8	1_1	9	10
Decreased SSC	0.1	0.2	0.5	1.3	1.5	0.5	1.8	2.8	5.9	2.9	6.0	7.2
New SSC	60.9	53.8	54.5	84.7	78.5	26.5	90.2	109.2	171.1	105.1	200.0	238.8
relative	0.22%	0.38%	0.86%	1.49%	1.86%	2.00%	1.98%	2.47%	3.32%	2.69%	2.92%	2.91%
Near-Bed SSC	1_2	2	3_2	4	5	6_1	6_2	7	8	1_1	9	10
Decreased SSC	0.3	0.6	1.0	3.1	5.0	6.0	7.4	7.0	24.1	9.3	24.6	44.7
New SSC	127.7	131.4	117.0	190.9	265.0	255.0	372.6	267.0	647.9	331.7	764.4	1365.3
Relative	0.21%	0.46%	0.86%	1.60%	1.85%	2.30%	1.95%	2.56%	3.59%	2.73%	3.12%	3.17%

Table D.25: UKC -10% - Decreased dredging 54,000 ton/year

Surface SSC	1_2	2	3_2	4	5	6_1	6_2	7	8	1_1	9	10
Decreased SSC	0.1	0.2	0.5	1.3	1.5	0.5	1.8	2.8	5.9	2.9	6.0	7.2
New SSC	60.9	53.8	54.5	84.7	78.5	26.5	90.2	109.2	171.1	105.1	200.0	238.8
relative	0.22%	0.38%	0.86%	1.49%	1.86%	2.00%	1.98%	2.47%	3.32%	2.69%	2.92%	2.91%
Near-Bed SSC	1_2	2	3_2	4	5	6_1	6_2	7	8	1_1	9	10
Decreased SSC	0.3	0.6	1.0	3.1	5.0	6.0	7.4	7.0	24.1	9.3	24.6	44.7
New SSC	127.7	131.4	117.0	190.9	265.0	255.0	372.6	267.0	647.9	331.7	764.4	1365.3
Relative	0.21%	0.46%	0.86%	1.60%	1.85%	2.30%	1.95%	2.56%	3.59%	2.73%	3.12%	3.17%

Table D.26: Increased dredging ΔT = 0.13m ΔV = 78,000 ΔW = 39000 ton/year

Surface SSC	1_2	2	3_2	4	5	6_1	6_2	7	8	1_1	9	10
Increased SSC	0.1	0.1	0.3	0.9	1.1	0.4	1.3	2.0	4.2	2.1	4.3	5.2
New SSC	61.1	54.1	55.3	86.9	81.1	27.4	93.3	114.0	181.2	110.1	210.3	251.2
relative	0.16%	0.27%	0.62%	1.08%	1.34%	1.44%	1.43%	1.78%	2.40%	1.94%	2.11%	2.10%
Near-Bed SSC	1_2	2	3_2	4	5	6_1	6_2	7	8	1_1	9	10
Increased SSC	0.2	0.4	0.7	2.2	3.6	4.3	5.4	5.1	17.4	6.7	17.8	32.3
New SSC	128.2	132.4	118.7	196.2	273.6	265.3	385.4	279.1	689.4	347.7	806.8	1442.3
relative	0.15%	0.33%	0.62%	1.16%	1.34%	1.66%	1.41%	1.85%	2.59%	1.97%	2.26%	2.29%

Table D.27: Increased dredging $\Delta T = 0.14\text{m}$ $\Delta V = 84{,}000$ $\Delta W = 42$ ton/year

Surface SSC	1_2	2	3_2	4	5	6_1	6_2	7	8	1_1	9	10
Increased SSC	0.1	0.2	0.4	1.0	1.2	0.4	1.4	2.2	4.6	2.3	4.7	5.6
New SSC	61.1	54.2	55.4	87.0	81.2	27.4	93.4	114.2	181.6	110.3	210.7	251.6
relative	0.17%	0.29%	0.67%	1.16%	1.44%	1.56%	1.54%	1.92%	2.58%	2.09%	2.27%	2.26%
Near-Bed SSC	1_2	2	3_2	4	5	6_1	6_2	7	8	1_1	9	10
Increased SSC	0.2	0.5	0.8	2.4	3.9	4.7	5.8	5.5	18.7	7.2	19.2	34.8
New SSC	128.2	132.5	118.8	196.4	273.9	265.7	385.8	279.5	690.7	348.2	808.2	1444.8
relative	0.16%	0.36%	0.67%	1.24%	1.44%	1.79%	1.52%	1.99%	2.79%	2.12%	2.43%	2.46%

Table D.28: Increased dredging $\Delta T = 0.18\text{m}$ $\Delta V = 108{,}000$ $\Delta W = 54$ ton/year

Surface SSC	1_2	2	3_2	4	5	6_1	6_2	7	8	1_1	9	10
Increased SSC	0.1	0.2	0.5	1.3	1.5	0.5	1.8	2.8	5.9	2.9	6.0	7.2
New SSC	61.1	54.2	55.5	87.3	81.5	27.5	93.8	114.8	182.9	110.9	212.0	253.2
relative	0.22%	0.38%	0.86%	1.49%	1.86%	2.00%	1.98%	2.47%	3.32%	2.69%	2.92%	2.91%
Near-Bed SSC	1_2	2	3_2	4	5	6_1	6_2	7	8	1_1	9	10
Increased SSC	0.3	0.6	1.0	3.1	5.0	6.0	7.4	7.0	24.1	9.3	24.6	44.7
New SSC	128.3	132.6	119.0	197.1	275.0	267.0	387.4	281.0	696.1	350.3	813.6	1454.7
relative	0.21%	0.46%	0.86%	1.60%	1.85%	2.30%	1.95%	2.56%	3.59%	2.73%	3.12%	3.17%