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The contribution of mud to the net yearly sedimentation volume in the Dutch Wadden Sea

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a review based on literature

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Title

The contribution of mud to the net yearly sedimentation volume in the Dutch Wadden Sea

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Summary

This literature study describes the present knowledge on mud import, -concentration and mud deposition in the Dutch Wadden Sea. It also discusses a method to convert between mud weight percentages and mud volume percentages. Knowledge on the mud contribution to the net annual sedimentation volume in the Wadden Sea is essential for future sustainable coastal management. An extensive summary of the main findings and their contribution to answering the research questions of sub-project 'Systeemkennis Zeegaten' of Kustgenese 2.0 is presented in the report.

The main conclusions are:

- Various authors give estimates of recent mud deposition in the Wadden Sea between 1.2 and 3 $*10^9$ kg/year.
- Only a small percentage of the gross mud transports is net deposited.
- Mud only contributes to the sediment volume for mud weight percentages above 15%, because at that moment sand grain contacts start to be broken up.
- The average mud deposition is estimated to be between 0.7 and $4,1*10^9$ kg/year in mass and between 0.7 and $3.4*10^6$ m^3/year in volume or between 8 and 37% of the total annual sedimentation volume.

References

Plan van Aanpak Kustgenese 2.0 versie januari 2017. Bijlage B bij 1220993-001-ZKS-0005-vdef-r-Offerte Kustgenese 2.0 Deltares, 27 januari 2017.

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Achtergrond

Het Nederlandse kustbeleid streeft naar een structureel veilige, economisch sterke en aantrekkelijke kust. Dit wordt bereikt door het onderhouden van het gedeelte van de kust dat deze functies mogelijk maakt; het Kustfundament. Dit gebeurt door middel van zandsuppleties; het suppletievolume is ongeveer 12 miljoen m^3/jaar sinds 2001.

In 2020 neemt het Ministerie van Infrastructuur en Waterstaat een beslissing over een eventuele aanpassing van het suppletievolume. Het Kustgenese 2.0 programma heeft als doel hiervoor de kennis en onderbouwing te leveren. Deltares richt zich in opdracht van Rijkswaterstaat binnen het project Kustgenese 2.0 op de volgende hoofdvragen:

1 Is er een andere zeewaartse begrenzing mogelijk voor het kustfundament?
2 Wat is het benodigde suppletievolume om het kustfundament te laten meegroeien met zeespiegelstijging?

Deze twee vragen beslaan het grootste gedeelte van het onderzoek binnen het project. Een derde belangrijk onderwerp wat daarbij ook behandeld zal worden is:

3 Wat zijn de mogelijkheden voor de toepassing van suppleties rond zeegaten?

Deze literatuurstudie maakt deel uit van het deelproject ‘Systeemkennis Zeegaten’. Het vergroten van onze kennis over zeegatsystemen is belangrijk om vragen te kunnen beantwoorden over de zandvraag van de getijbekkens van de Waddenzee. Deze zandvraag kan gezien worden als een belangrijke verliespost voor zand uit het kustfundament, en is daarom een belangrijke parameter om het benodigde suppletievolume te berekenen wat nodig is voor het onderhoud van het kustfundament. Daarnaast is systeemkennis van getijbekkens ook nodig om vragen te beantwoorden over de mogelijkheden van ingrepen rondom zeegaten.

Het deelproject ‘Systeemkennis Zeegaten’ draagt dus bij aan het beantwoorden van de tweede en de derde hoofdvraag van het project Kustgenese 2.0. Dit gebeurt door een combinatie van literatuurstudies, analyse van (veld)data en modelstudies en –ontwikkeling. De hoofdvragen van Kustgenese 2.0 zijn vertaald in meerdere onderzoeksvragen. De onderzoeksvragen waar het deelproject ‘Systeemkennis Zeegaten’ zich op richt zijn hieronder gegeven. Deze literatuurstudie richt zich alleen op onderzoekvraag SVOL-10.

- SVOL-07 Wat zijn de drijvende (dominante) sedimenttransportprocessen en -mechanismen en welke bijdrage leveren ze aan de netto import of export van het bekken?
- SVOL-08 Hoe beïnvloeden de morfologische veranderingen in het bekken en op de buitendelta de processen en mechanismen die het netto transport door een zeegat bepalen? Hoe zetten deze veranderingen door in de toekomst, rekening houdend met verschillende scenario's voor ZSS?
- SVOL-09 Wordt de grootte van de netto import of export beïnvloed door het aanbod van extra sediment in de kustzone of de buitendelta?
- SVOL-10 Wat zijn de afzonderlijke bijdragen van zand en slib aan de sedimentatie in de Waddenzee, als gevolg van de ingrepen en ZSS? En wat betekent dat voor het suppletievolume?
- INGR-01 Hoe beïnvloedden de ontwikkelingen van een buitendelta (inclusief de verandering van omvang) de sedimentuitwisselingen tussen buitendelta, bekken en aangren-

zende kusten en welke consequenties en/of randvoorwaarden levert dat voor een suppletieontwerp?
- INGR-02 Is het, op basis van beschikbare kennis van het morfologisch systeem, zinvol om suppleties op buitendeltas te overwegen?

De bijdrage van slib aan het jaarlijks sedimentatievolume in de Nederlandse Waddenzee
De Waddenzee bestaat uit zowel zandige als slibrijke gebieden. Het is verder bekend dat er op bepaalde plaatsen in het bekken (bijvoorbeeld in verlaten geulen) grote hoeveelheden slib zich in relatief korte tijd kunnen afzetten. Voor het bepalen van het suppletievolume (bestaande uit zand) voor het kustfundament is alleen het zandverlies naar de bekkens relevant. Daarom is het belangrijk om te weten hoeveel van het netto volume wat jaarlijks in de bekkens sedimenteert uit zand, en hoeveel uit slib bestaat. In deze literatuurstudie wordt op basis van bestaande kennis en literatuur een inschatting gegeven van het aandeel van slib aan de sedimentatie in de Waddenzee. Ook geven we in de bijlagen een breed overzicht van de verschillende aspecten en mechanismen achter de verspreiding en het afzetten van slib binnen de gehele Waddenzee als binnen (delen) van een enkel getijbekken.

Uit het overzicht blijkt dat er een overvloed aan slib aanwezig is in de waterkolom. Maar hoe groot de bruto import van slib uit de Noordzee exact is, is onbekend. Een groot deel van het slib beweegt heen en weer in en uit de zeegaten. Door het vergelijken van schattingen van de bruto transporten in de bekkens (in de orde van $100*10^9$ kg/jaar) met schattingen van de lange termijn depositie van slib ($0,7\text{-}4,1*10^9$ kg/jaar), krijgen we het beeld dat slechts een paar procent van het slib voor langere tijd (> 1 jaar) kan neerslaan op de bodem.

De depositie van slib betekent niet automatisch een bijdrage aan het sedimentvolume van de bodem. Voor slibpercentages (in gewichtsprocenten) onder de 15% blijven de slibkorrels ‘verborgen’ in de poriën van het zandskelet in de bodem. Daarnaast hebben sommige depositieplaatsen voor slib nauwelijks een lange termijn invloed op het zand dat nodig is om op peil te blijven met zeespiegelstijging. Dit, omdat ze na verloop van tijd weer opgeruimd worden.

Alleen sedimentatie in gebieden als baaien, verlaten geulen en moddervlakten zal naar verwachting permanent significante volumes slib tot bezinking laten komen. Op basis van korrelgrootte kaarten en relaties voor het soortelijk gewicht van slib is een schatting gedaan van de bijdrage van slibsedimentatie in gewicht en in volume. Geschat wordt dat $0,7\text{-}4,1 *10^9$ kg/jaar wordt afgezet op langere termijn van enkele decennia. Het slib vormt daarbij een volume bijdrage van $0,7\text{-}3,4*10^6$ m^3/jaar of 8-37% van de jaarlijkse afzetting van sediment in de Waddenzee. Wel zij opgemerkt dat de bovenwaarde wellicht een overschatting is, omdat monsters ter bepaling van de korrelgrootte meestal in het zomerseizoen worden genomen. Over het algemeen zijn zomermonsters slibrijker dan monsters genomen in de winter; de precieze omrekeningsfactoren zijn echter niet bekend. Maar zelfs als de percentages wat lager zouden zijn is het duidelijk dat slib in volume significant bijdraagt aan de reductie van de sedimentvraag van de Waddenzee. Om dit nader te kunnen kwantificeren is het nodig om een diepgaandere studie te maken waarbij de hoogteontwikkeling en de korrelgrootte in detail worden berekend over verschillende perioden. Dit valt buiten de scope van deze literatuurstudie.

Samenvattend zijn de belangrijkste conclusies van dit rapport:

- Verschillende auteurs komen tot een totale slibdepositie in de Waddenzee tussen de 1,2 en 3 $*10^9$ kg/jaar.
- Pas met slibpercentages vanaf 15% wordt het zandkorrelcontact verbroken en draagt slib bij aan het sedimentatievolume, verder neemt de volumebijdrage van sliblagen in de tijd afnemen als gevolg van consolidatie.
- Afgeschat wordt dat de volumebijdrage van slib aan het totale sedimentatievolume in de Waddenzee tussen de 0,7 en 3,4 miljoen m^3/jaar ligt en tussen 0,7 en $4{,}1*10^9$ kg/jaar in gewicht. Hierbij is ervan uitgegaan dat 5.7 miljoen m^3/jaar van het totale sedimentatievolume van 9.3 miljoen m^3/jaar sedimenteert in gebieden met slibpercentages boven de 15%. De aanname is dat in de rest van het Waddengebied gemiddeld de zeespiegelstijging wordt gevolgd en dat daar 3.6 miljoen m^3/jaar wordt afgezet.

Een vertaling van de inzichten naar de onderzoeksvragen van Kustgenese 2.0
Een rechtstreekse en volledige beantwoording van onderzoeksvraag SVOL 10 (Tablel1.1) is met deze literatuurstudie helaas niet mogelijk gebleken. Toch is er wel al veel inzicht in de mogelijke volumebijdrage van slib aan het totaal sedimentatievolume in de Waddenzee verkregen.
[SVOL-10] De volumebijdrage van slib aan het totale sedimentatievolume in de Waddenzee wordt geschat te liggen tussen de 0,7 en 3,4 miljoen m^3/jaar, of 8 tot 37%.

Vervolgstappen Kustgenese 2.0
Op basis van de geschatte en relatief grote bijdrage van slib aan het sedimentatievolume en de mogelijke implicaties voor het benodigde suppletievolume lijkt aanvullend onderzoek gerechtvaardigd. Binnen Kustgenese 2.0 is er evenwel geen vervolgonderzoek gepland naar de bijdrage van slib aan het totaal sedimentatievolume. Binnen de KPP onderzoeken (Kennis voor Primaire Processen) “Beheer en onderhoud kust 2018” en “Morfologie Wadden 2018” zijn er mogelijkheden om zand en slibbalans van de Westelijke Waddenzee uit te werken.

Tablel1.1 Overzicht onderzoeksvragen Kustgenese 2.0

Code	Onderzoeksvraag	Bijdrage
SVOL-07	Wat zijn de drijvende (dominante) sedimenttransportprocessen en -mechanismen en welke bijdrage leveren ze aan de netto import of export van het bekken?	NEE
SVOL-08	Hoe beïnvloeden de morfologische veranderingen in het bekken en op de buitendelta de processen en mechanismen die het netto transport door een zeegat bepalen?	NEE
	Hoe zetten deze veranderingen door in de toekomst, rekening houdend met verschillende scenario's voor ZSS?	NEE
SVOL-09	Wordt de grootte van de netto import of export beïnvloed door het aanbod van extra sediment in de kustzone of de buitendelta?	NEE
SVOL-10	Wat zijn de afzonderlijke bijdragen van zand en slib aan de sedimentatie in de Waddenzee, als gevolg van de ingrepen en ZSS? En wat betekent dat voor het suppletievolume?	JA
INGR-01	Hoe beïnvloedden de ontwikkelingen van een buitendelta (inclusief de verandering van omvang) de sedimentuitwisselingen tussen buitendelta, bekken en aangrenzende kusten en welke consequenties en/of randvoorwaarden levert dat voor een suppletieontwerp?	NEE
INGR-02	Is het, op basis van beschikbare kennis van het morfologisch systeem, zinvol om grootschalige suppleties op buitendeltas te overwegen?	NEE

1 Introduction

1.1 Kustgenese 2.0

The Dutch coastal policy aims for a safe, economically strong and attractive coast (Deltaprogramma, 2015). This is achieved by maintaining the part of the coast that supports these functions; the coastal foundation. The coastal foundation is maintained by means of sand nourishments. The total nourishment volume is approximately 12 million m^3/year since 2000.

In 2020, the Dutch Ministry of Infrastructure and Environment will make a decision about the nourishment volume. The Kustgenese 2.0 (KG2) program is aimed to deliver knowledge to enable this decision making. The largest part of the scope of the project, commissioned by Rijkswaterstaat to Deltares, is determined by the following main (policy) questions:

1 *What are possibilities for an alternative offshore boundary of the coastal foundation?*
2 *How much sediment is required for the coastal foundation to keep up with sea level rise?*

These two questions take up the largest part of the research within the project. Another, third, important topic that will have to be addressed is:

3 *What are the possibilities (and effects) of applying nourishments around tidal inlets?*

1.2 Research questions

This literature study is part of the sub-project ‘Systeemkennis Zeegaten’ (‘system knowledge tidal inlets’). Expanding our knowledge of tidal inlet systems is paramount for answering questions about the sand demand of the tidal basins of the Wadden Sea. The sand demand can be seen as an important ‘sediment sink’ for the coastal foundation, and is therefore also an important parameter to determine the required nourishment volume to maintain the coastal foundation. Additionally, knowledge of tidal inlet systems is also needed to answer questions about the morphological response to large-scale nourishments around the inlets.

The sub-project ‘Systeemkennis Zeegaten’ therefore contributes to the second and third of the main questions within the project. It will do so by a combination of literature research, analysis of field data and model computations and –development. The main questions have been translated into multiple research questions. The research question that we will address in this report fully reads:

> *SVOL-10: “What are the separate contributions of sand and mud to the sedimentation in the Wadden Sea, as a consequence of human interventions and sea level rise? And how does this affect the required nourishment volume for the coastal foundation?”*

The Wadden Sea is known to consist of both sandy and muddy areas. It is also known that in some areas (e.g. abandoned channels) large quantities of mud can accumulate in a relatively short time. To determine the required nourishment volume for the coastal foundation, only the loss of sand volume to the tidal basins is of relevance. It is therefore important to know how much of the net annually deposited volume consists of sand, and how much of mud.

In this literature study we provide a first estimate of the contribution of mud to the net yearly sedimentation volume in the Dutch Wadden Sea. In the appendices a broad description on different aspects and mechanisms in mud distribution and deposition on various spatial scales is provided.

1.3 Definition of mud

In general, mud includes both the clay fraction (<2 microns) and the silt fraction (2-63 microns). It depends on the function of the mud on which is concentrated how mud is defined. For instance, if one is interested in the function for organisms mud might include organic content. If one is only interested in the long-term sedimentation organic matter should be excluded, but calcareous particles should be included. If one is interested in the sedimentary behavior only the siliciclastic content should be regarded. Here we define mud as all sediment particles <63 microns including organic matter. Clay and silt particles are mixed during the flocculation process and the ratio between the two is rather constant over larger areas (Flemming & Delafontaine, 2000). This is important, because it makes generalizations on mud characteristics over Dutch Wadden Sea possible.

1.4 Approach

Mud which is deposited in the Wadden Sea originates from the North Sea. Thus, the approach will be to look at the path mud follows step by step. We will start at the transport from the North Sea all the way up to permanent deposition and consolidation in the Wadden Sea.

We will show that there is an abundance of mud present in the water column of the Wadden Sea. Whether this can settle and remains deposited, and to what extent the mud contributes to the sediment volume in the backbarrier basin, depends mainly on the hydrodynamic conditions. These conditions are determined by the natural dynamics of the area and by human induced changes, both acting on various spatial and temporal scales. Due to this, mud deposition also varies in time and space.

It is important to recognize that only a part of the suspended mud which is provided by the North Sea waters is deposited in the Wadden Sea and will remain settled longer than a year. Subsequently, of this long-term mud sedimentation only a part contributes to the sediment volume of the Wadden Sea, since a part of the mud volume can be stored within the pores between the sand grains in the bed. This is illustrated in Figure 1.1.

Upon burial the sediment is compacted and density increases. In literature mud transport and deposition is often discussed in terms of weight. This is partly due to the huge variations in dry weight density of mud. Where wet mud may have a dry matter density of about 450 kg/m^3, strongly consolidated muds may go to 1600 kg/m^3. For that reason we stick to quantifying mud as much as possible in weight. Only for the volumetric contribution mud will be quantified in m^3. In this report we will also address the compaction of mud.

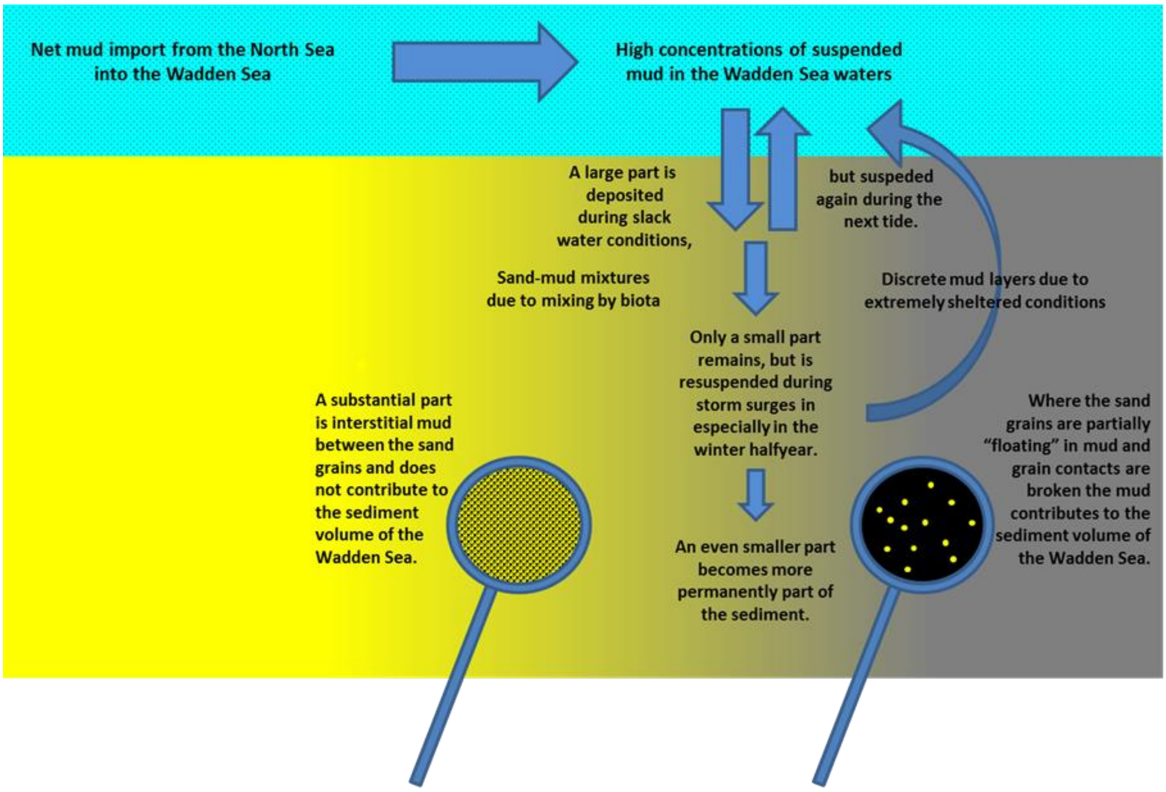

Figure 1.1 Conceptual sketch of the pathways of contribution of mud to the sediment volume in the backbarrier area.

1.5 Outline

In this first Chapter an introduction to Kustgenese 2.0 and the research questions is presented, together with the objective of this study. Next, in Chapter 2, Mud import, mud weight and mud volume percentages in the Dutch Wadden Sea are discussed. In Chapter 3, Discussion, Results and Recommendations are presented. In Appendix A regional trends and patterns of mud deposition in the Dutch Wadden Sea are discussed, while Appendix B and C focus on mud distribution within (parts of) a tidal basin.

2 Mud import, -weight and –volume percentage

2.1 Annual mud import

To understand the contribution of deposited mud to the volume changes of the backbarrier, it is necessary to understand how mud is transported from the North Sea and deposited in the Wadden Sea (See Figure 1.1). The following chain of steps is identified: from suspension in the North Sea, via import through the inlet, via suspension in the Wadden Sea via settling on the bottom, to a contribution to the net long-term (>1 year) deposition. However, this does not answer our question since only part of the long-term deposition really contributes to the volume of sediment in the backbarrier area and even that volume will be compacted over time, leaving a smaller volume. In the following sections these steps are discussed in a general way for the Dutch Wadden Sea. It will be shown that there are several open questions, nevertheless the annual contribution of mud to the total sedimentation volume is estimated based on available data and studies.

If all suspended mud that enters through the inlets of the Dutch Wadden Sea (including the Ems) would deposit, this would result in very high annual mud deposition (Oost, 1995). However, it assumes that all water flowing into the Wadden Sea is “new” North Sea water with “new” mud. Observations and computations for the Vlie Inlet, however, indicate that a large part of the mud entering the tidal inlets during a flood is the same mud which flowed out of it during the previous ebb (Gerkema et al., 2017). Based on this observation it is likely that the net flow of mud into the Dutch Wadden Sea will be much lower. How much lower is difficult to assess, since accurate measurements are largely missing. In general it can be stated that the gross mud transports into the Wadden Sea are an order of magnitude larger than the net result. An impression of it is given by Van Kessel (2015) who modelled an annual mud balance over the period 1/1 – 1/5/2009 which was calibrated to suspended sediment concentration measurements over that period (Table 2.1). It is assumed that only some $2*10^9$ kg/year of the $8.2*10^9$ kg/year is deposited below MHW; the rest is deposited on the tidal marshes.

Table 2.1 Modelled annual mud budget Wadden Sea based on measurements over the period 1/1-1/5/2009 including tidal marsh deposition (in 10^9 kg/year; Van Kessel, 2015)

	Gross In	**Gross out**	**Net result**
Marsdiep	*37.0*	*-34.3*	*2.7*
Eierlandse gat	*10.7*	*-10.6*	*0.1*
Vliestroom	*47.2*	*-44.6*	*2.6*
Borndiep	*44.1*	*-42.9*	*1.2*
Friesche Zeegat	*42.4*	*-39.8*	*2.6*
Watershed Schier	*7.1*	*-8.5*	*-1.4*
Sluices Afsluitdijk	*0.4*	*0.0*	*0.4*
Total	188,9	-180,7	*8.2*

From Table 2.1 it becomes clear that the gross mud fluxes are of the order of $40*10^9$ kg/year per inlet. This is attributed to the increase of mud concentrations in the North Sea water close to the coast in an eastward direction.

2.2 Suspended mud and long-term gross deposition

The uncertainties in the annual mud budget from the North Sea can at the moment be considered as irrelevant, because there is a surplus of mud available in the water column (i.e. there is much less mud deposited than available in the water column; Van Maren et al., 2016). Within the Dutch Wadden Sea, the waters contain on average some $0.4*10^9$ kg suspended sediment during high tide (Oost, 1995). Concentrations increase towards the mainland coast which is controlled by the North Sea mud concentrations, settling velocity and the probability that deposition occurs (Van Kessel, 2015). To get an idea of the potential volume which is gross deposited: if it is assumed that all suspended sediment present in the Wadden Sea water would settle during the each slack high water on the bottom, $280*10^9$ kg would annually be gross deposited[1]; the number illustrating the potential for mud deposition.

The high potential for mud deposition is also illustrated by the massive sedimentation of mud in embayments, such as the former Lauwerszee, the current Mokbaai and the Eems-Dollard. The same can be concluded from the thick mud layers in abandoned channels in which currents have diminished and from the mud sedimentation on salt marshes (see Appendix C). That there must be an abundance of mud, can also be observed on an even bigger scale: Van Maren et al. (2016) concluded that in the Ems estuary alone some $2\text{-}3*10^9$ kg/year dry weight were deposited from the end of the 16th century up to the beginning of the 20th century, being comparable to the total amount estimated to settle nowadays in the whole Dutch Wadden Sea area. Due to on-going shrinking of the Dollard embayment area net long-term sedimentation became increasingly difficult and nowadays mud sedimentation is only some $1*10^9$ kg/year dry weight. Van Maren et al. (2016) argue that the potential for mud deposition is several times higher than what is being realized. It also implies that both the natural dynamics of the Wadden area and human interventions may change the share of mud sedimentation.

The mud which settles will partially be resuspended during the next tidal flow. This can be concluded from sedimentological observations of the thickening and thinning of slack-tide clay layers in sediments deposited over a neap-spring cycle (cf. Visser, 1980; De Boer et al., 1989). Even when mud deposits are not immediately removed, a large part will be resuspended within a year. Agents for this can for instance be spring tidal flow or storm surges. From spring onwards, but in particular in late summer and early autumn (Stratingh & Venema, 1855; Van Es et al., 1980), fine-grained material accumulates on the tidal flats until the autumn storms remove it partly or fully (Figure 2.1; Kamps, 1956).
Ultimately, currents and wave climate determine how much can settle permanently. This is why sheltered embayments and higher mudflats are characterized by a higher mud content than the rest of the Wadden Sea. Because mud settles at different hydrodynamic conditions than does sand, the two tend to be deposited separately. Especially bioturbation (= the sediment reworking and mixing actions by organisms) leads to homogenization of the sediment.

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[1] *It is realized that during the high water slack tide not all mud may settle in the channels, whereas also during low water slack tide sediment will settle in the channels: the number here is given as an indication of the potential.*

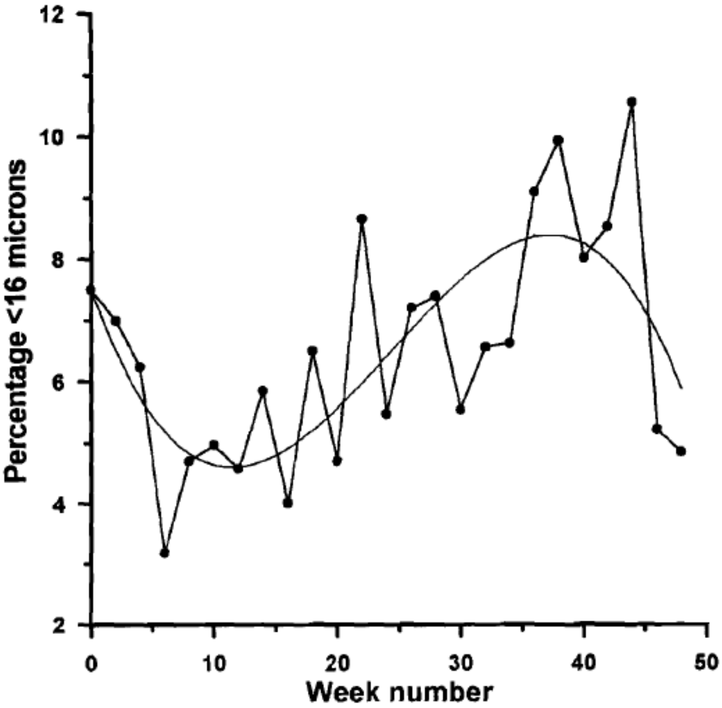

Figure 2.1 Annual variation of the percentage of sediment <16 micron in the top 0.5 cm of the intertidal flats near the mainland (average of 15 separate observations). The smooth line is a third order polynomial fit (Oost, 1995; data from Kamps, 1956)

2.3 Conversion of mud weight percentage to mud volume percentage

Not all mud which settles in the Wadden Sea contributes to the to long-term sediment volume increase. Part of the mud is worked into the pores between the sand grains by bioturbation and mixing and thus does not contribute to the sediment volume[2]. As long as the contact between sand grains is not broken, the framework of the sediment, and thus its volume, is determined by the space taken by the accumulated sand grains and their pore spaces. As long as this is the case, mud will only be present within the pores between the sand grains. Hence, it will not contribute to the sediment volume. Only if the mud weight percentage is above 15% it will contribute to the sediment volume, because at that moment the sand grain contacts start to be broken. Above 22% (by weight) the sand grains will be fully ‘floating’ in unconsolidated mud (Winterwerp & van Kesteren, 2014).

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[2] It should be noted that it is assumed that all sediments are well mixed: flakes of mud are not taken into account.

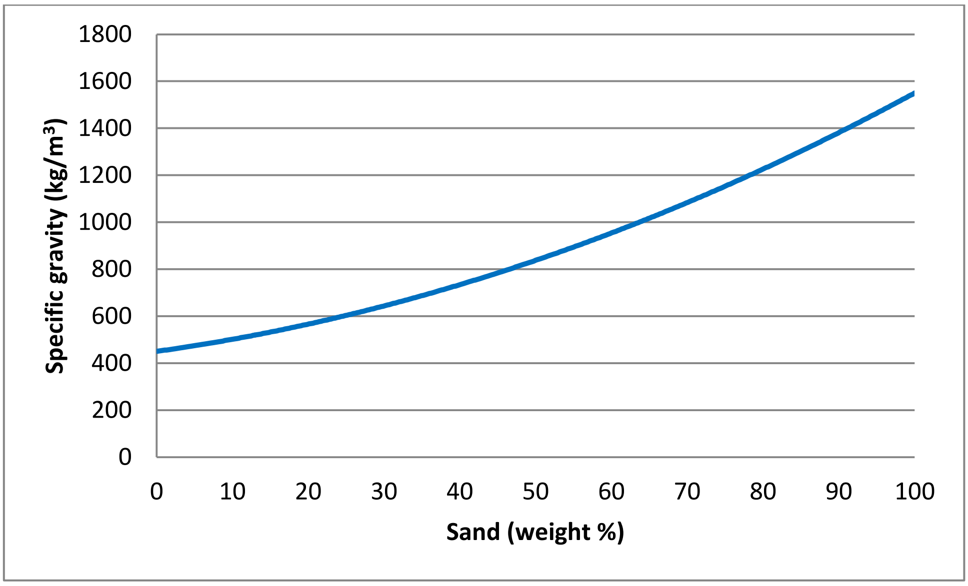

Figure 2.2 Sand by weight percentage to density (based on Mulder, 1995).

For the Wadden Sea densities of sediment can best be calculated by the formula proposed by Mulder (1995; Figure 2.2; Arcadis, 2013). According to the relation of Mulder (Figure 2.2) the density D of unconsolidated sediment can be calculated according to:

$D = 450 + 4.5*Wsand + 0{,}065* Wsand^2$

In which Wsand is the sand content in weight-percentages. Using a similar approach as Eysink (p. 227) in Oost et al. (1998) the volume contribution Vmud (in volume percent) can thus be calculated:

$Vmud = 100 – Vsand$

Where Vsand = volume contribution of sand (in volume percent).

If sediment has a specific density D, it can be calculated by which ratio the volume would be reduced if it was consisting of 100% sand via D/Dsand. If we know the weight percentage of the sand Wsand in the original sample we can calculate the volumetric percentage of the sand Vsand via:

$Vsand = Wsand * D/Dsand$

Thus:

$V_{mud} = 100 – (W_{sand} * D/D_{sand}) = 100 – (W_{sand}*((450 + 4.5*W_{sand} + 0{,}065* W_{sand}^2)/1550))$ (%)

The result of the equation is given in Table 2.2. For the moment, it is assumed that up to a 15 weight percentage of mud the mud, this sediment is situated between the sand grains and does not give a volumetric contribution[3]. Therefore it seems prudent to adjust the relation

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[3] *We realize that this might lead to an underestimation of the volumetric contribution of mud, as mud will not always be distributed homogenous in the sediment. An alternative approach using the middle column of table 2.,2 was dis-*

somewhat in order not to overestimate the contribution of mud to the sediment volume (Table 2.2, right column; Figure 2.3). With this system any weight percentage of sand can be recalculated to mud volume.

Table 2.2 Volume contribution of mud (in volume %) as a function of the sand weight content (W_{sand} in weight %); left column adjusted

W_{sand} (weight %)	V_{mud} (volume %)	Adjusted V_{mud} (volume %)
0	100	100
10	97	97
20	93	93
30	88	88
40	81	81
50	73	73
60	63	63
70	51	51
80	37	37
85	29	0
90	20	0
100	0	0

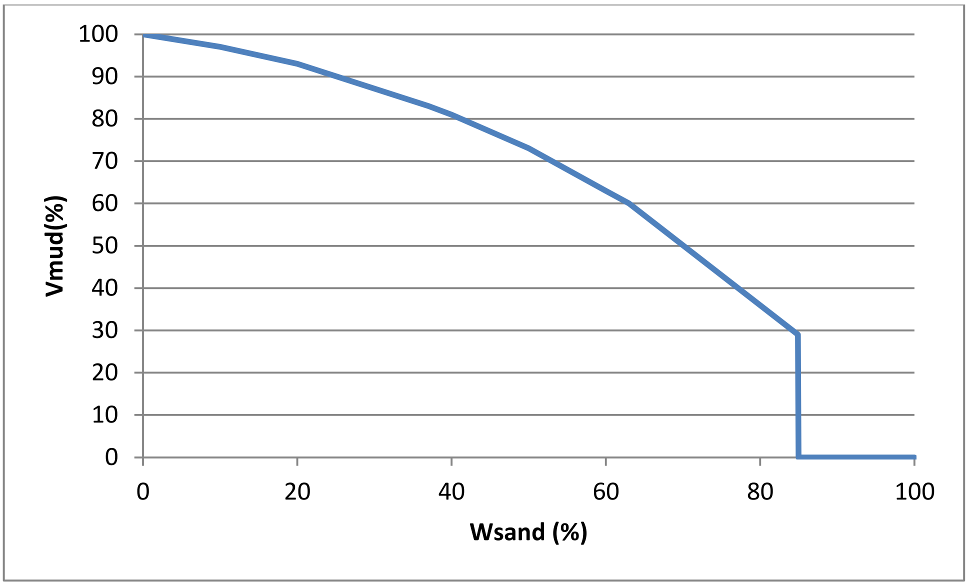

Figure 2.3 Relation of sand weight percentage to volumetric contribution of mud.

2.4 Estimates of mud deposition by weight and total sedimentation

The unconsolidated mud present in the top sediment has a low density of some 450 kg/m^3. However, upon compaction densities increase considerably. Hence, sediment volume of mud

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cussed, but given the uncertainties involved it was decided to choose for the more conservative approach of using the right column.

decreases. An often used density for mud after several decades of compaction is about 1000 kg/m^3 (Van Maren et al., 2016) Thus, the initial mud sediment volume will be reduced by a factor of more than 2 (multiplied with 0.45. If it is assumed that all 1.2-3* 10^9 kg/year as given by various studies (Table 2.3; Figure 2.4) is 100% mud (by weight; thus: no sand), it would result in a volumetric contribution of 2.7-6.7*10^6 m^3/year unconsolidated mud and 1.2-3*10^6 m^3/year volumetric contribution of consolidated mud.

Table 2.3 various estimates of the contribution of mud deposition to Wadden Sea sedimentation. For calculation of the last row see subchapter 2.5.5.

Weight (10^9 kg/year)	**Volume (10^6 m^3/year)**	**Remarks**	**Author**
	1	Historical long-term mud sedimentation in the Wadden Sea. Rough estimate based on Van der Spek (1994))	This study (see Appendix A)
	0.5	Dollard, calculations	Reenders & Van der Meulen, 1972
2		Dollard & polders, 450 yr period	De Smet & Wiggers, 1960
5		Wadden Sea long term average including polders	Salomons, 1978
3	3	Wadden Sea long term average including polders	De Glopper, 1947
3-4		Historical mud deposition	Eysink, 1979
2–3		Eems Dollard, historical	Van Maren et al., 2016
1		Eems Dollard, present	Van Maren et al., 2016
2.05		Present day mud balance excl. Eems	Salden & Mulder, 1996
2.5-3		Recent mud deposition	Eysink, 1979
3		Recent mud deposition	Essink et al., 1983
1.2		1982-1986	Eisma, 1993
2.2		Modelling: with additional 6*10^9 kg/year deposited on the tidal marshes	Van Kessel, 2015
1.5		Wadden Sea, based on 9.3*10^6 m^3/year and average 11.7% (dry weight) mud (Table B.1).	This study, % based on Wadden Atlas
0.7-4.1	0.7-3.4	Dry weight consolidated	This study

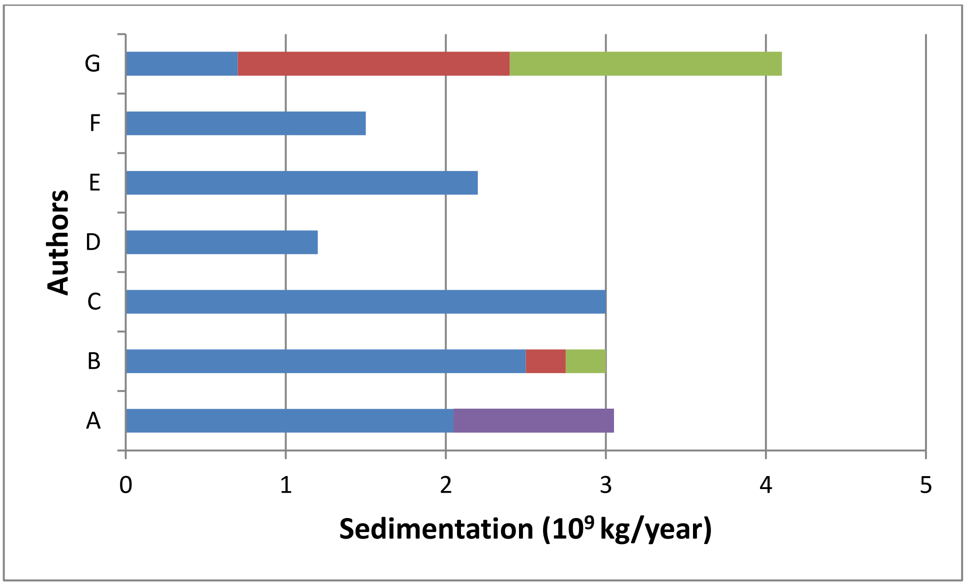

Figure 2.4 Comparison of estimates of recent annual mud sedimentation with uncertainties given as red and green bars (A = Salden & Mulder, 1996 (in blue) + Van Maren et al., 2016 (in purple); B = Eysink, 1995; Essink et al., 1983; D = Eisma, 1993; E = Van Kessel, 2015; F = this study based on average of Wadden Atlas; G = This study, first rough calculation.

Table 2.4 overview of the annual average net sedimentation in the various backbarrier basins

	Sedimentation (10^6 m^3/year)	***Period***	***Reference***
Marsdiep	*-1.3*	*1990-2005*	*Elias et al., 2012*
Eierlandse gat	*-0.2*	*1990-2005*	*Elias et al., 2012*
Zeegat van het Vlie	*3.5*	*1990-2005*	*Elias et al., 2012*
Borndiep	*1.4*	*1990-2005*	*Elias et al., 2012*
Friesche Zeegat	*0.2*	*1990-2005*	*Elias et al., 2012*
Eilanderbalg	*0*	*1990-2002*	*Cleveringa, 2008*
Zeegat van de Lauwers + Schild	*1*	*1990-2005*	*Cleveringa, 2008*
Eems	*4.7*	*1985-2002*	*Cleveringa, 2008*
Estimated Total sedimentation[4]	***9.3***		

How does this figure compare to the estimated total sedimentation in the backbarrier basins below MHW? Calculations over the recent past are given in Table 2.4, resulting in an average sedimentation of some 9.3 $*10^6$ m^3/year over the long term (thus including consolidation of muds). Comparing these data with the above calculated volumes of mud, it can be concluded that mud sedimentation might be some 13-32% in volume of the total sedimentation, if all

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[4] Note that periods are different: hence total sedimentation is necessarily an estimate.

mud would be deposited as 100 weight percentage mud. However, in reality mud percentages in the sediment are generally less than 100%. In Section 2.5 we will first determine where mud content is sufficient to contribute to the sediment volume and then make an estimate of the annual mud sedimentation using several assumptions and grain size distribution maps.

2.5 Estimate of mud deposition by volume and contribution to total sedimentation

High mud percentages in the bed, which can contribute to the volume are only found in abandoned channel deposits, in inner bends of tidal channels, under mussel beds, on sheltered sub- to intertidal flats (e.g. embayment's such as the Dollard), in estuaries and on tidal marshes. Some of these subenvironments, however, will not be taken into account for the sediment budgets:

Tidal marshes form one such a group. A major part of the tidal marshes consists of mud (and organic) deposits. As such, the tidal marshes require only limited contribution of sand in order to raise the bed level. Furthermore tidal marshes are situated mainly above MHW and as such have little impact on the sediment balance of the Wadden Sea below MHW[5].
Also mussel beds can be neglected, even though they can store considerable amounts of mud. In most of the cases this mud will be resuspended over time, when the mussel beds decay. So, although there is storage during several years in mussel beds, there is no significant net accumulation of mud to be expected (Oost, 1995).

Inner bend deposits store mud during migration of the channels and during storm-surges. These deposits will also be neglected as it is difficult to map how much mud is stored in them on the long run, as old deposits will be reworked after some time.

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[5] *However, on the long term this may be different: as the tidal marshes grow vertically, the intertidal area gradually evolves into a supratidal area. As a result, tidal prism slowly decreases and due to this, the tidal channels become shallower. Because of the relatively slow pace of these changes, the currents in the channels will also decrease only very gradually. The filling up of the channels will therefore mostly be done with sand, instead of mud. It can thus be concluded that, although the marsh itself mainly needs mud in order to grow, this process also requires sand to fill up the channels. Therefore it leads to an increase of the sand demand of the basin.*

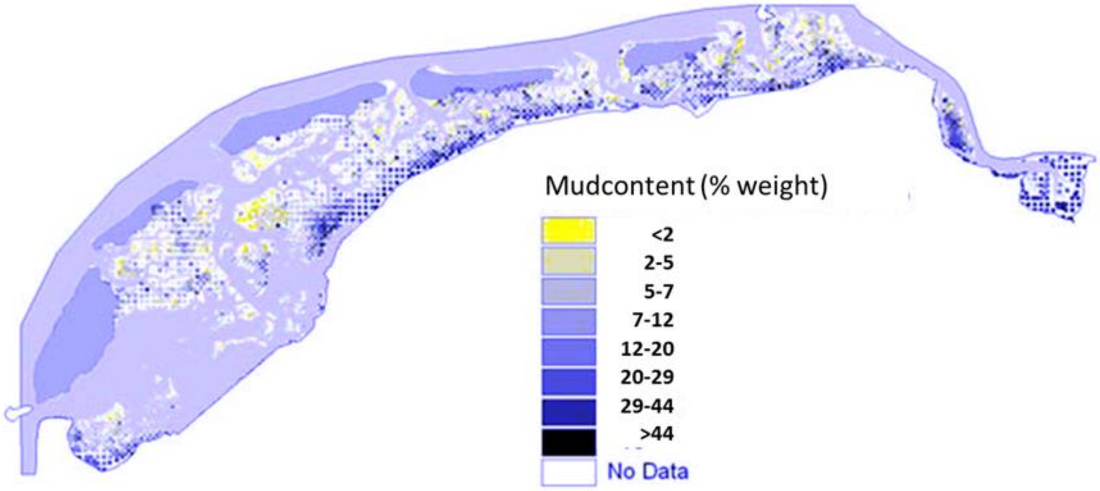

Figure 2.5 Combined mud content (% weight) based on figure 5.8 of Zwarts et al. (2004) which is a combination of Malvern samples, coulter samples and mud measurements for the fraction <16 micron on intertidal flats. The translation to mud content <63 micron is based on figure 2.11 of Zwarts et al. (2004).

Here we calculate a rough estimate to come up with estimates of the weight and volumetric contribution of mud in the Wadden Sea. From these figures and earlier estimates it can be judged if mud matters and adds to the sediment volume. First, the area where mud may contribute considerably to the sediment volume is calculated. From the previous alineas it follows that there are three important areas: estuaries, abandoned channels, and sub- to intertidal mudflats. In the western Wadden Sea subtidal mudflats are relatively common near the Afsluitdijk, as are abandoned channels due to the closure (e.g. De Vlieter & Javaruggen). The Wadden Sea maps of Dankers et al. (2002) use data from the RIKZ mapping of the mud (<63 micron) content. Arcadis (2013) shows that this has to be reduced by a factor of 1.7. Thus the 25% contour as marked by Dankers is in reality the 15% contour. The Wadden Sea maps of Dankers et al. (2002) show that a mud content > 15% can be found on:

- about 10% of the intertidal flats (ca. 120 km^2);
- about 25% of the Marsdiep subtidal backbarrier area including (abandoned) channels (ca. 150 km^2);
- some 10% of the channels from Eierlandse Gat to Ems (ca. 70 km^2);
- about half of the Ems-Dollard estuary (ca. 150 km^2).

In total this is an area of 490 km^2, ca. 18% of the Dutch Wadden Sea area below MHW. The map from the 1990’s of Zwarts et al. (2004; Figure 2.) reveals that mud contents of ca. 37% (29-44%) are frequently found on the intertidal flats.

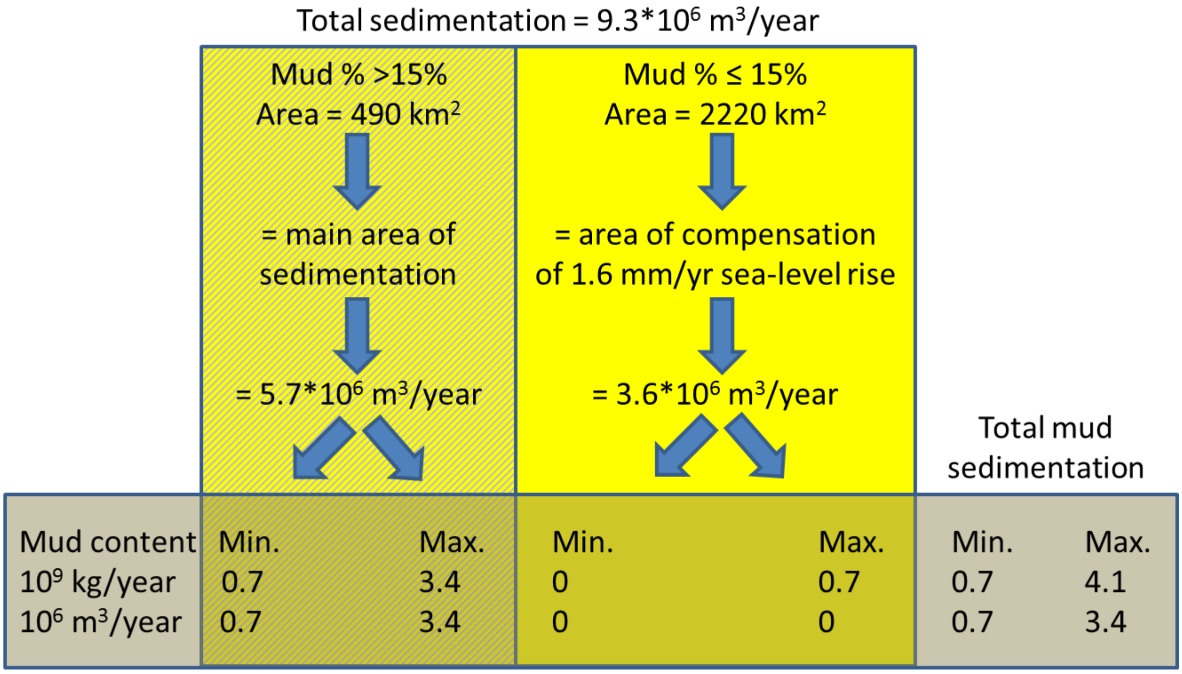

Figure 2.6: scheme explaining the estimate of the annual contribution of mud to the sedimentation.

An estimate of the annual contribution of mud to the sedimentation in the Wadden Sea can now be made on the basis of the following assumptions (Figure 2.6):

- The total sedimentation (mud and sand) in the whole Wadden Sea is estimated to be on average $9.3*10^6$ m^3/year
- The 2220 km^2 large area, outside of the >15% mud area, net sedimentation is determined by compensation of an average annual sea-level rise of 1.6 mm/year (Wadden Academy, in prep.), resulting in a deposition of $3.6*10^6$ m^3/year.
- outside of the >15% mud area mud contribution to volume can be neglected: the average mud weight percentage lies somewhere between 0 and 15%.
- the remaining volume of $5.7*10^6$ m^3/year is mainly deposited as a result of human induced disturbances and preferentially deposited in the area where shear stresses have become lower due to the changes, and that is in the >15% mud area;

Based on these 3 assumptions it can be calculated that outside of the >15% mud area, by weight some $0\text{-}0.7*10^9$ kg/year[6] of mud will be stored; the rest will be stored in the remaining 18% of the Wadden area.

The volume of the sediment in the >15% mud area is (9.3 - 3.6 =) $5.7*10^6$ m^3/year. In this area the mud content is assumed to be on average between just above 15% and 37% by weight[7]. Furthermore, the sedimentation in this area can either be considered as exclusive or inclusive compaction. Exclusive would mean that no compaction has taken place. We might also consider the sedimentation values in Table 2.4 to be including compaction, as they are long-term averages over more than a decade. Also, due to the rather constant locations of mud-sedimentation, the sedimentation which is measured should necessarily also include the

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[6] *at 15% mud the density of the bulk sediment is 1302 kg/m^3. Of this 0-15% is mud or 195 kg. With a deposition of $3.6*10^6$ m^3 in this zone some $0\text{-}0.7*10^9$ kg will be deposited*

[7] *Judging from the observations of Zwarts et al. (2004) a mud content of ca. 37% may be a fair average.*

compaction of the mud which was already deposited in a previous period. For that reason, it seems valid to conclude that the compaction has already been accounted for and no further adjustments are needed. Based on the 15-37% mud and ex- or inclusive compaction a minimum and maximum estimate can be made for the amount of mud deposited in the area.

- Minimum estimate: at 15% mud weight the unconsolidated mud contributes 29% to the volume, and 0.7 $*10^9$ kg/year to weight. After consolidation the volume will go down by a factor of 0.4 to 13% or $0.7*10^6$ m^3/year.
- Maximum estimate: at 37% mud weight and assuming no compaction needed the mud contributes 60% in volume or $3.4*10^6$ m^3/year, or $3.4*10^9$ kg/year.

The total mud deposition in the Wadden Sea can thus be estimated to be between 0.7 and $4.1*10^9$ kg/year. The estimates for annual mud deposition are in reasonable agreement with the earlier estimates ($1.2\text{-}3*10^9$ kg/year; Table 2.3; Figure 2.4). Volume contribution of mud is estimated to be between 0.7 and $3.4*10^6$ m^3/year (or 8-37% by volume of the total annual sedimentation. These numbers are a clear indication that mud might very well matter when considering sediment volumes in the Wadden Sea.

3 Discussion, conclusions and recommendations

3.1 Discussion

3.1.1 Reliability of the outcomes

Obviously the results obtained in chapter 2 are ball-park figures which are to some extent determined by the assumptions made. Here we will shortly discuss these:

- That the volume of sediment of $3.6*10^6$ m^3/year is evenly distributed over the 2220 km^2 of the Wadden Sea in reaction to an annual sea-level rise of 1.6 mm/year is suggested by the fairly comparable hypsometric curves in the eastern part of the Dutch Wadden Sea. However, the –out-of-balance western part of the Wadden Sea and the Ems might behave somewhat different. Sediment will most likely deposit especially where the balance is disturbed the strongest (see also Table 2.4[8]). To get an idea where most of the sediment is settling the development of the hypsometric curves should be compared and related to grain size distributions as well.

- That the remaining volume of $5.7*10^6$ m^3/year will be mainly deposited as a result of human induced disturbances and preferentially settle in the area where shear stresses have become lower due to the changes (thus in the >15% mud area) seems a fair assumption. Indeed, after the closure of the Lauwerszee it was observed that massive mud-sedimentation occurred in the main channel (see Appendix C abandoned channels; Oost, 1995). However, the grain sizes of the infill in the main channel varied from mud near the closure dam towards sand near the inlet. This indicates that part of the remaining volume might consist of sediment with high sand percentages. This would lower the amount of mud annually deposited. On the other hand: calculations show that, on average, the 490 km^2 of muddy areas would heighten with some 1.2 cm/year if the remaining volume would be deposited there. Such net sedimentation rates are observed at the mudflats E of Harlingen and may even be higher in abandoned channels.

- That outside of the >15% mud area mud contribution to volume can be neglected is a somewhat crass assumption. There will be areas with mud weight percentages will be higher. Such areas will also contribute to the volume of mud, all be it less than areas with >15% mud. This would increase the volumetric contribution of mud to the sediment volume.

There is a fourth assumption which was not mentioned: the maps of the mud content of the Wadden Sea are all based on data mainly collected somewhere in the summer half year (April – September: Figure 2.1). This might lead to an overestimation of the annual average mud content of the sediments (Zwarts et al., 2004). Judging from Figure 2.1, the average annual mud content might be some 2/3 of the measured mud content. However, this is not known in detail.

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[8] *Table 2.4 gives a somewhat faulty overview as the measurements are made based on fixed borders of the watershed: Marsdiep and Vlie are both disturbed by the closure and should be regarded in combination*

Furthermore, the outcome of only 15% mud within the >15% mud area is not likely as large parts of the muddy intertidal are characterized by very high mud contents such as the Dollard (De Haas, pres. com) and the Vlakte van Oosterbierum (van Maren pers. com).

All in all it seems likely that the estimates of chapter 2 give lower and upper values for the mud deposition and its volumetric contribution. The mud deposition and contribution cannot be determined exactly, but is most likely (see also Table 2.4) within lower and upper values. This assumption is also supported by earlier estimates of the annual mud sedimentation (compare Table 2.3).

3.1.2 Effect on required nourishment volumes

How would volumes formed by mud deposition affect the required nourishment volume for the coastal foundation? Required nourishment volumes are calculated based on preservation of the Coastal Foundation plus the sediment losses to the Westerschelde and the Wadden Sea. If the total sediment demand of the Wadden Sea is translated as “sand demand” this will obviously result in an overestimation of required sand nourishment volumes.

To determine the real sand demand of the Wadden Sea, the contribution of mud to the Wadden Sea sedimentation volume has to be known with some accuracy. The outcome of this inventory study indicates that mud might contribute roughly somewhere between 8 and 37% of the total volume. This will reduce the need for sand. Therefore, it might be interesting to obtain a more detailed insight in the exact numbers.

A more exact volumetric contribution of mud can be determined by multiplying the sedimentation rates for every grid cell and the percentage of mud of the cell, using the above relation between mud volume and sand percentage (by weight). The reason for this is that sedimentation rates may differ strongly from area to area (e.g. Mulder, in Hoeksema et al. (2012)). The same is true for the mud content. Preferably such research has to be done for as much time slices as possible to obtain insight in possible fluctuations (e.g. storm surge climate changes) and trends (e.g. waning influence of closure of the Lauwerszee). Of course, to that end the mud weight measurements should be unambiguous and comparable to the measurements used to establish the equation of Mulder (1995). All in all such mud volume calculations would be a considerable task; a reason why such calculations have not been done in this first reconnaissance study.

3.2 Conclusions

The central questions for this literature study within Kustgenese 2.0 were:

> *SVOL-10 “What are the separate contributions of sand and mud to the sedimentation in the Wadden Sea, as a consequence of human interventions and sea level rise? And how does this affect the required nourishment volume for the coastal foundation?”*

In this study we focused on the availability of mud in the water column and the sedimentation of it. From the observations it is concluded that gross suspended sediment transport in the water column is an order higher than net sedimentation.

A large part of the mud which has settled during a tide to the bottom is resuspended during the following tides or during the more turbulent winter half year. Exact data are not known, but studies suggest that annual average mud content of the sediment is about 2/3 of the percentages measured in the summer half year.

Sedimentation of mud does not automatically imply a contribution to volume. The mud percentage (by weight) in the bed has to be higher than 15% in order to contribute to the sediment volume, otherwise the mud will remain ‘hidden’ between the interstitial pores of the sand grains. In this study some simple graphs are given to calculate the density of the sediment (Figure 2.2) and the volume percentage of the mud (Figure 2.3).

A first estimate of the net sedimentation of mud indicates that this is somewhere between 0.7 and $4.1*10^9$ kg/year. The annual contribution to the sediment volume is estimated to be 0.7-$3.4*10^6$ m^3, or 8 to 37% of the sediment volume annually deposited in the Wadden Sea. Discussion of the underlying assumptions suggests that these lower and upper weight and volume estimates might be too low and too high, respectively. This is also indicated by other estimates which give values for the mass between 1.2 and $3*10^9$ kg/year. As long as more detailed calculations are missing the exact contribution remains uncertain.

To what extent formation of mud volume affects the required nourishment volumes depends on the approach which is taken. If one of the elements of the required volume of nourishments is the total annual sediment demand of the Wadden Sea, the figure might be reduced with the annual volume of mud deposition. If the approach is based on the observed development of the Basal coastline then the mud contribution is automatically included in the nourishment volume and it will not make a difference.

3.3 Recommendations

One of the few ways to make a more solid estimate of the contribution, both in terms of mud by weight and of mud by volume is to calculate it from field observations. This can be done by using grain-size distribution measurements, such as the SIBES measurements or the data sets used by Zwarts et al. (2004), over a period between two depth soundings. For each observation, a distinction can be made between mud percentages adding to the volume or not, based on the approach given in chapter 2. Assuming linear height change between to depth soundings the (positive or negative) change in mud content and the contribution of mud to sediment volume can be calculated. Given the rather high areal extent of mud rich deposits it is highly recommended to make such a calculation for as many periods as possible. It should be kept in mind that both heights and sediment distribution measurements are mainly carried out in the summer half year. This may lead to an overestimation of the mud content. An additional study into that problem is recommended.

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A Regional trends and patterns of mud deposition in the Dutch Wadden Sea

A.1 Introduction

Mud sedimentation is determined by (changes in) the hydrodynamic and ecological conditions which are influenced by natural and human induced changes. In this appendix, we will discuss regional patterns in mud erosion and deposition in the Dutch Wadden Sea and the Ems estuary. The reason for this is that such large scale patterns will be mostly long-lasting and will overprint local patterns on a tidal inlet scale. These patterns govern to a large extent the mud sedimentation in the Wadden Sea and thus determine the contribution of mud to the sediments of the Wadden Sea.

A.2 Mud deposition development Western and Eastern Dutch Wadden Sea

Zwarts et al. (2004) tried to adjust for the various differences in methods of mud percentage calculation and compared the mud percentage on the intertidal flats as measured in the fifties and nineties. They conclude that, on average, the mud percentage of the intertidal flats of the present-day Dutch Wadden Sea did not increase during the second half of the 20th century. This seems logical because the average distance from the inlet to the settling place has remained more or less identical, which would imply that in large parts of the Wadden Sea the energy gradient will have remained more or less the same. This allows mud the same opportunity to settle as before the big closure works. However, from the regional shifts that are observed in the mud deposition patterns, it is clear that – at least on the tidal flats – energy gradients have shifted (Figure A.1).

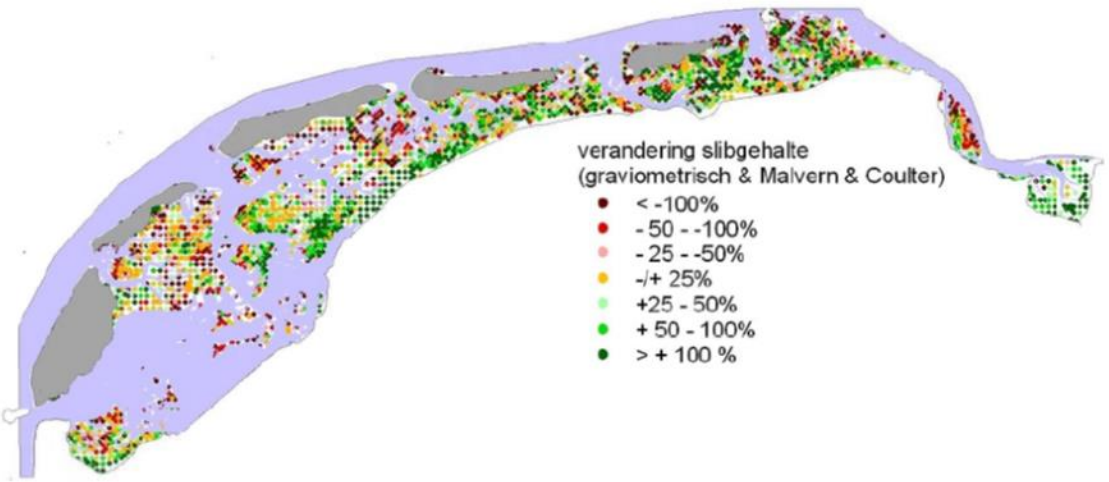

Figure A.1 Change of the mud content on the tidal flats between the fifties and the nineties (Zwarts et al., 2004)

Muddy intertidal areas decreased in the Western Dutch Wadden Sea (Marsdiep to Vlie) and increased in other parts of Wadden Sea between the fifties and the nineties (Zwarts et al., 2004). Before and shortly after the closure of the Zuiderzee, large muddy areas were present in the Western Wadden Sea. These areas became gradually became less muddy. The Eastern Wadden tidal flats as well as the intertidal area along the mainland between Harlingen to the Zoutkamperlaag gradually became muddier and up to a meter higher. Towards the Afsluitdijk, mud deposition is strong in the abandoned former channels (Vlieter, Javaruggen: Berger, 1978). Also the surrounding subtidal flats are rich in mud, but net sedimentation there is low to negative (Elias et al., 2012). Given the long duration and large-scale pattern of this development, it may be expected that this trend will continue for a longer time. However, shorter term variations may still occur. Using the SIBES data Folmer et al. (2017) concluded that the annual mud fraction on the intertidal flats decreases with several % per year during the period 2008-2013 (Figure A.2). This coincides with a general decrease (factor 2) in suspended matter concentration during this period. For this there is presently no explanation known (Herman, pers. Comm.).

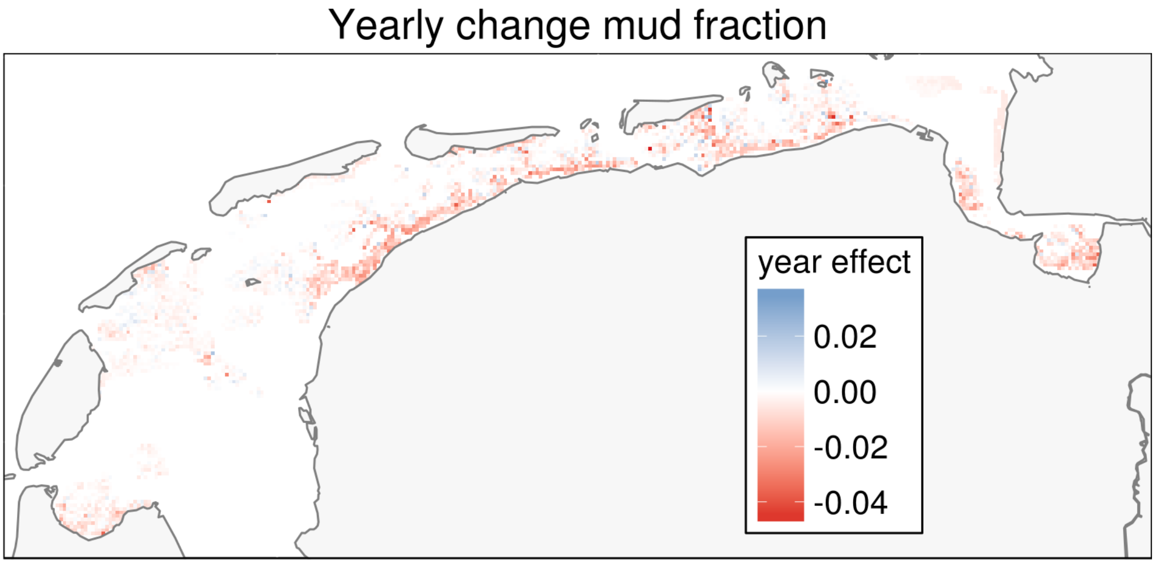

Figure A.2 Short term alternations on the general trend (Figure A.1). Annual change in mud content (1 = 100%) on the tidal flats over the period 2008-2015 based on the SIBES observations. The yearly change in mud fraction were back-transformed by means of the inverse logit (Folmer et al., 2017).

There are several (possible) causes underlying the large-scale regional changes in the pattern of mud deposition. It turns out that it is a combination of natural developments, as well as human interventions. This shows that these both play an important role in the spatial distribution of mud. Below, we briefly discuss the most important causes. Some of these causes have already been demonstrated (Zwarts et al., 2004; Van Maren et al., 2016), some have been hypothesized (van Maren et al., 2016) and some are likely to be important, but have not yet been reviewed in literature as far as known.

- **Closure of mud deposition sites**. Closure of mud settling areas of the Zuiderzee (3600 km^2) and Lauwerszee (90 km^2) and Amstelmeer led to a reduction of the overall settling possibility for mud (Van Maren et al., 2016). Given the high volumes of mud deposited in the former Zuiderzee and Lauwerszee, we can conclude that important mud deposition sites were lost. With less mud being able to settle, the average concentration of suspended mud will have increased after the closures (Van Maren et al., 2016). Giesen et al. (1990) compiled visibility observations in the Wadden Sea, collected between 1920 and 1980, and observed an increase in light attenuation over time, indicating an increase in suspended sediment concentration. The effect is to be expected when natural sinks become less available (Van Maren et al., 2016).

- **Increase in tidal range and flow velocities in the Western Wadden Sea.** Before the closure of the Zuiderzee, the Marsdiep inlet system drained a large part of the area (4000 km^2). The length of the basin (ca. 160 km) was such that half a tidal wave matched in the basin, leading to tidal amplitude decrease. Due to the closure of the Zuiderzee (1925-1932) the backbarrier basin surface was brought back to around 712 km^2 and a length of only 30 km, or 0.15 times the tidal wave length. The tidal wave transformed from a propagating and dampened tidal wave to a standing wave, and the tidal amplitude increased with about 26% (Rietveld, 1962; Thijsse, 1972). As a result of the amplification, the tidal prism increased from 700*10^6 m^3 to ca. 1000*10^6 m^3 (Elias et al., 2014). The changes of the tide and propagation characteristics, the basin geometry and the abandonment of some of the main channels (Elias et al., 2014), resulted in increased velocities over the intertidal shoals of the Western Wadden Sea. This led to erosion (Elias et al., 2012), and hence to the removal of the muds present on these tidal flats. Also, high current velocities will have prevented net deposition of mud on the tidal flats.

- **Shift of watersheds Western Wadden Sea.** The watershed between Marsdiep and Vlie shifted to the east. Such a shift implies erosion at the W side and deposition on the E side. In combination with the velocity increase discussed in the previous point the changes for mud deposition will likely have been reduced. Indeed, the few remaining points which could be compared on the watershed show an increase in grainsize (Figure A1). During this shift mud will be washed out with little chance to deposit again as the process is still on-going.

- **Deposition of sand in the western Wadden Sea.** Sedimentation in the backbarrier areas of Marsdiep and Vlie amounted to 553*10^6 m^3 over the period 1935-2005 (fixed borders, adjusted for dredging and dumping; Elias et al., 2012). A large part is sand, derived from the ebb-tidal deltas of Marsdiep and Vlie.

- **Deposition of fines in the Afsluitdijk area.** The biggest changes occurred along the Afsluitdijk, where in the closed abandoned channels the flow rate reduced to almost zero. These were rapidly filled up by a mixture of mud and sand layers (Berger et al., 1987; pers. Obs.). Also, the subtidal flats near the Afsluitdijk have a high mud content (Dankers et al., 2002), but it is not certain that the mud percentage increased after closure of the Zuiderzee.

- **Disappearance of Eelgrass fields.** Originally, extensive sub- to intertidal Eelgrass fields were present on the shoals of the Western Wadden Sea, which are known to strongly dampen the wave impact. This will have enhanced mud deposition. Shortly after the construction of the Afsluitdijk, the Eelgrass fields disappeared, as did the shelter they provided (Giessen et al., 2014).

- **Change of the nature and location of fresh water outflow.** Before the closure of the Zuiderzee and the Lauwerszee, brackish water would flow out of these embayments over a broad front. After the closure, water is sluiced, leading to a strong local outflow of fresh water. Calculations for the situation with the Afsluitdijk show that this water frequently floats at the surface, causing a pronounced estuarine circulation. With winds from the west, such waters could migrate along the mainland coast to the east and possibly boost local mud deposition. But this has not yet been investigated.

- **Increase in amount of fresh water which flows out.** The Western Wadden Sea is becoming less saline (Van Aken, 2014). This trend is caused by an increase in discharge of river water towards the sea. This is largely due to changes in the water balance in Netherlands. Climate change also plays a role, with an increase in rain and thus more water to be sluiced out into the sea. This could have the same effect as discussed in the previous point.

- **Fill of embayments.** Before the construction of dikes on the landward borders of the Wadden Sea, the original landscape was characterized by valley-like depressions. These were usually, but not necessarily, formed by local brooks and rivers, which were present between higher sand ridges. The valleys and the lower areas around it became initially filled up with peat. The peat was sometimes eroded again in later stages. Due to sea-level rise, the valleys changed into tidal embayments (see, e.g., van der Spek, 1994, for an example). Hence, the basins have orientations perpendicular to the general orientation of the coast and run inland. In the course of time, the landward parts of these basins, where predominantly mud was deposited, have been reclaimed (Figure A.3). Consequently, the quietest sub-environments of tidal basins have been excluded from tidal action and the supply of sediment. This caused a decrease in the surface area where mud can settle more or less permanently and an increase in the average energy level in the basin (Figure A.3). See Flemming & Nyandwi (1994) and Mai & Bartholomä (2000) for details. In most of the present-day basins, pure muddy intertidal flats account for only a small percentage of the total basin area. From the cross-section it can be concluded that approximately 1/9th (or ca. 11%) of the Holocene sedimentary infill outside of the dikes consists of predominantly muds. Assuming the present day sedimentation rates this would amount to $1*10^6$ m^3/year.

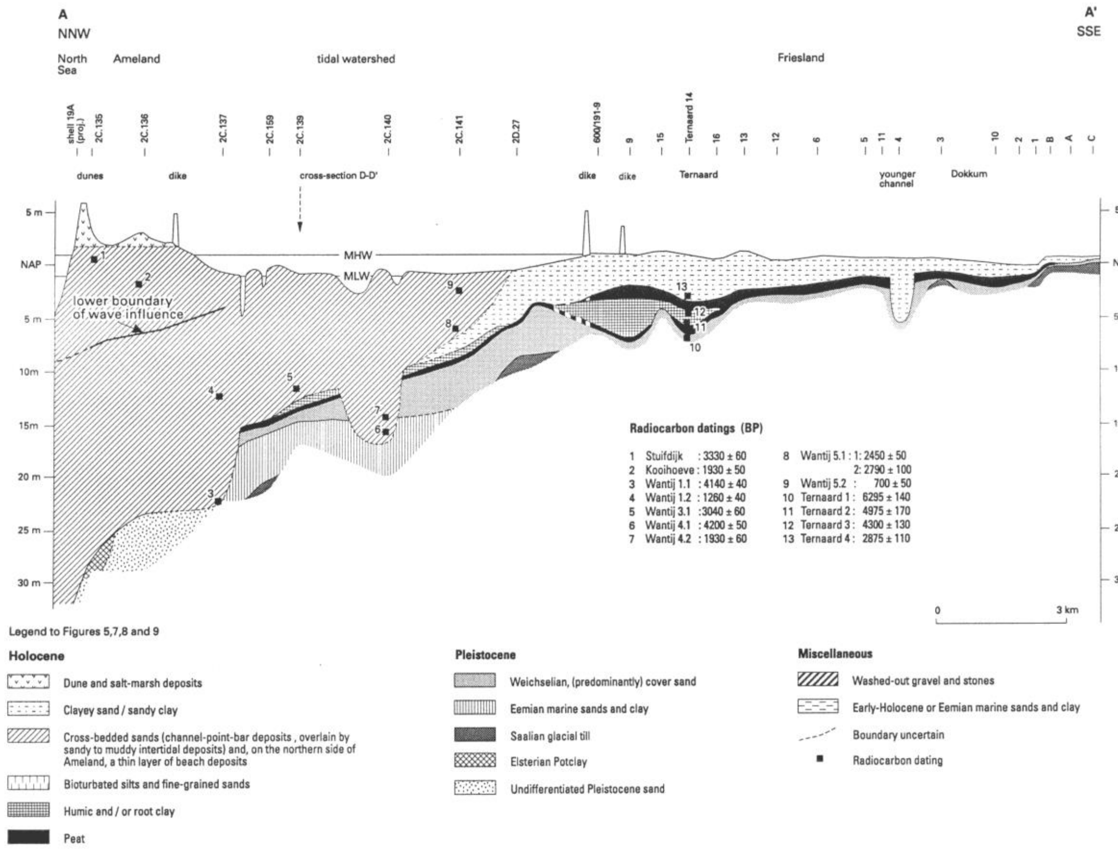

Figure A.3 Cross-section running from the North Sea coast of Ameland, through the Wadden Sea onto the mainland of Friesland, showing the distribution of fine-grained deposits. Note the decrease in basin length of the original basin versus the present-day basin bounded by dikes. (From: Van der Spek, 1994.)

The process of infill, in combination with spit formation along the mainland coast, led to a straightening of the coast as the embayments were filled up. This natural process is still going on in a limited number of places, such as between Zwarte Haan and the watershed of Ameland, where mud deposition can still take place.

- **Salt marsh development.** Since salt marshes can be transformed in rich farmland humans tried probably since 100 BC to enhance the mud deposition to create salt marshes. By building small walls on the lower tidal marshes, the hydrodynamic energy was artificially reduced, leading to an increase in mud deposition. Salt marsh development became quite intensive in the 1950's. The larger part of the tidal marshes and the mudflats in front of them along the mainland originate from that time. Tidal marshes along the Frisian mainland have been growing with some 50% in the past decennia, and Groningen has been relatively stable. The active encouragement of tidal marsh formation might partly explain the strong mud deposition that is observed between Zwarte Haan and wantij Ameland and between Eemshaven in the Lauwersmeer in the second half of the 20th century. Mud temporarily deposited in the brushwood groin areas will also form a source of mud for the adjacent tidal flats. It remains uncertain how much mud deposition would have occurred without these works. Based on the total size of the tidal marshes of the Dutch Wadden Sea (ca. 68 km^2) and a sedimentation rate of about 1-2 cm/year and an estimated mud content of 80% (volume) it may be estimated that the tidal marshes store about $0.5\text{-}1*10^6$ m^3/year (consolidated). This is a rough estimate in order to get an indication of the order of the volume of mud which is stored annually.

  In the past 25 years, much attention was paid in optimizing to the role of the brushwood groins (Dutch: rijshoutdammen, see Figure) to protect the tidal marshes and pioneer zone (Dijkema et al., 2013). In the province of Friesland, the maintenance in the western part (Zwarte Haan to Nieuwe Bildtzijl) has stopped, because of the extremely fast mud deposition. The current practice is that no new settling fields are built on the mudflats, but that the more landward fields of pioneer zone and tidal marsh are maintained. As of 2010, the Frisian tidal marsh management has changed and now aims strictly at protecting the pioneer zone up to <HW –50 cm seaward, and at flexible maintenance of the coast-parallel brushwood groins.

Figure A.4 Holwerd, near the mainland: brushwood groins, 8-10-2014. (RWS, Harry van Reeken)

- **Dam construction.** Mud deposition is also enhanced by the construction of dams. This can be seen by the strong marsh formation on either side of the dam to the ferry at Holwerd, which was built in the 20th century. Also at other locations (such as Ameland, Schiermonnikoog, Lauwershaven, Harlingenhaven, Eemshaven and the training dam of Harlingen) dam-like constructions have likely enhanced mud deposition in the eastern part of the Dutch Wadden Sea.

- **Culture of mussel beds.** In (especially) the western Wadden Sea, extensive fields are present for mussel cultivation. As the mussels produce a lot of faeces, these beds are regularly “flushed” by the fishermen, to avoid suffocation of the mussels. The somewhat consolidated mud is resuspended, and it is not yet clear whether this consolidated mud will settle relatively more easily and could thus enhance mud sedimentation elsewhere.

- **Dumping of dredged sediments.** The mud which settles in the harbor of Harlingen is dumped into the Wadden Sea, especially east of the harbor. Mud which settles in the channel from the ferry station of Holwerd is mainly dumped seaward of the dredging area. Comparable to the consolidated mud of mussel beds, this mud might also settle more easily.

- **Shift in wind direction**. For the period 1948-2007, the share of westerly winds increased in the late winter and early spring, but the number of north to northwest winds did not change (Van Oldenborgh & Van Ulden, 2003; Van Oldenborgh et al., 2009). This may have resulted in less wave energy on the Frisian and Groningen coasts and thus could have helped to enhance mud sedimentation.

A.3 Mud deposition development Eems Dollard (Summary of van Maren et al., 2016)

Mud deposition has decreased in the Eems Dollard system, as natural and artificial sediment sinks have been removed. The resulting loss in accommodation space is thought to have led to an increase in the suspended sediment concentration. Coastline reconstructions and stratigraphic observations indicate that approximately 2–3*10^9 kg/year (dry weight) mud accumulated in the estuary from the end of the 16th century up to the beginning of the 20th century. In the meantime, the Dollard embayment decreased in size and mud deposition became more difficult. A part of the sink function was taken over by the Bocht van Watum, an arm of the estuary which gradually became abandoned.

The removal of large amounts of mud from the Ems estuary by German dredging activities also functioned as a large sink, especially between 1960 and 1994. But since the 1990’s, sediment removal rates through dredging activities sharply decreased, while available monitoring data show that the average suspended sediment concentration in the estuary increased during this period. Mass balances and numerical models indicate that the reduction in sediment sinks led to an increase in suspended sediment concentration in the order of several 10’s of mg/l averaged over the estuary, and locally even over 100 mg/l.

B Mud distribution in a tidal basin

B.1 Introduction

In the first part of this chapter, we will discuss the spatial scale of a tidal (backbarrier) basin, with special attention for the Borndiep (Amelander Zeegat), to understand which mechanisms determine the mud distribution on a basin scale. This may help to understand where sufficient high percentages of mud are deposited to add to the backbarrier basin sediment volume.

B.2 Grain size distribution

Grain size fractions in tidal basins are deposited according to an energy gradient (see e.g., Nyandwi, 1998, and Flemming & Ziegler, 1995). The general trend shows a decrease in both tidal and wave energy and, hence, in grain size from the inlet to the landward side of the basin. Mud ($d < 0.063$ mm, $ø > 4$, where $ø = -2\log d$) is deposited in the lowest-energy parts of the tidal basin.

Grain sizes < ca. 0.16 mm (diameter) are sometimes called the suspension population, as the differences between current velocities needed for entrainment of a grain or to suspend them in the water are very low (van Rijn, 2008). Thus, a distinction can be made between finer sediments which are almost totally transported in suspension (the ‘suspension population’) and a so-called ‘bed load population’ of coarser grains. The latter group is partly transported over the bottom and will only be suspended at fairly high current velocities (>0,4 m/s). Under normal conditions, such current velocities can occur for longer periods during the tidal cycle in the deeper channels, but only occur for a short period in the shallower channels, gullies, shoals, marshes, creeks, etc. Near the inlet and in some parts of the main channel the current velocities are sufficiently high that even coarse sand will be picked up.

Going from the inlet towards the end of the channel systems, under normal conditions, a decrease of grain sizes can be observed in the water column of the channels (Postma, 1961). The two main sediment populations (suspension population and bed load population) are clearly separated here. The coarser sands of the bed load population are mainly to be found near the inlet and show a fast decrease towards the backbarrier. From channel lags (the shells and stones which are left behind after the washing out of sands) down to sand of ca. 0.16 mm, the distribution is clearly determined by the current velocities in the channel. The suspension population in the channel is separated by a clear distance from the bed load population, and is situated in her entirety much closer to the end of the channels (Figure B.1).

Within this suspension population, there is also a very clear decrease in the median grain size towards the end of the channels. The same is also true for the median grain size and the clay content at the sediment surface of the channels (Eysink, 1993). The observations strongly suggest that the suspension transport in channels functions to sort the various grain size fractions. Although tidal currents dominate the bigger channels, wave- and wind-generated turbulence does influence the smaller channels (Figure B.2; Postma, 1961). It is important to realize that also the shoals become muddier in the direction of the mainland by settling lag and scour lag effects. A part of this material will be brought back from the shoals towards the channels. This implies that the concentrations of suspended matter do not have to correlate completely with the local current velocities in the channels (Eysink, 1993).

In this report, we argue that the sorting of mud is determined by the currents and waves both in the smaller channels and on the shoals, because:

1. Selection to grain size is clearly visible in the water column of the channels;
2. In the channels parallel to the mainland in Figure B.1 (stations 5, 6 & 7), the grain size clearly decreases towards the end. At the same time the intertidal to supratidal coast is very rich in mud. This can only be explained by washing out the finer suspended material of the mud rich water and transporting it to the end of the channel;
3. The sediment on the shoals in the shelter south of the islands is somewhat muddier, but a clear and strong decrease in grain size can be observed in the direction of the mainland (Flemming & Nyandwi, 1994). This is most easily explained by selection by the channels according to grain size and the shelter provided by the mainland.
4. Model studies show that in subtidal areas the concentrations of mud are low near the inlet due to tidally driven bed shear stress. Also, mud concentrations are high towards the end of the channels due to a combination of tidal and wave-driven shear stress. This is in good accordance with field data. In general it is observed (Nieuwenhuis, 2001) and predicted (Van Prooijen & Wang, 2013) that mud will be encountered some 10 km distance from the inlet in the case of the Ameland inlet (Figure B.2; Nieuwenhuis, 2001; Van Prooijen & Wang, 2013).

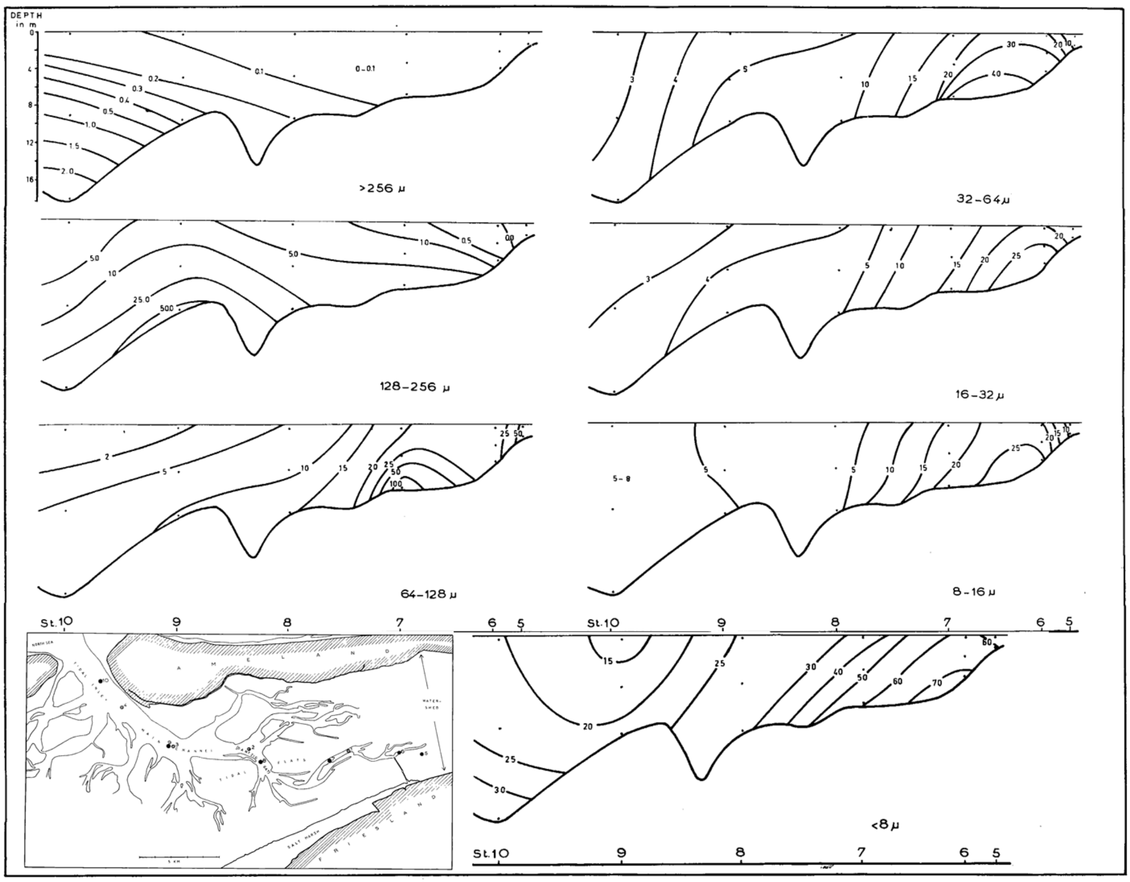

Figure B.1 Suspended sediment concentrations of various grain sizes in the Borndiep channels as measured in September 1958 (Postma, 1961).

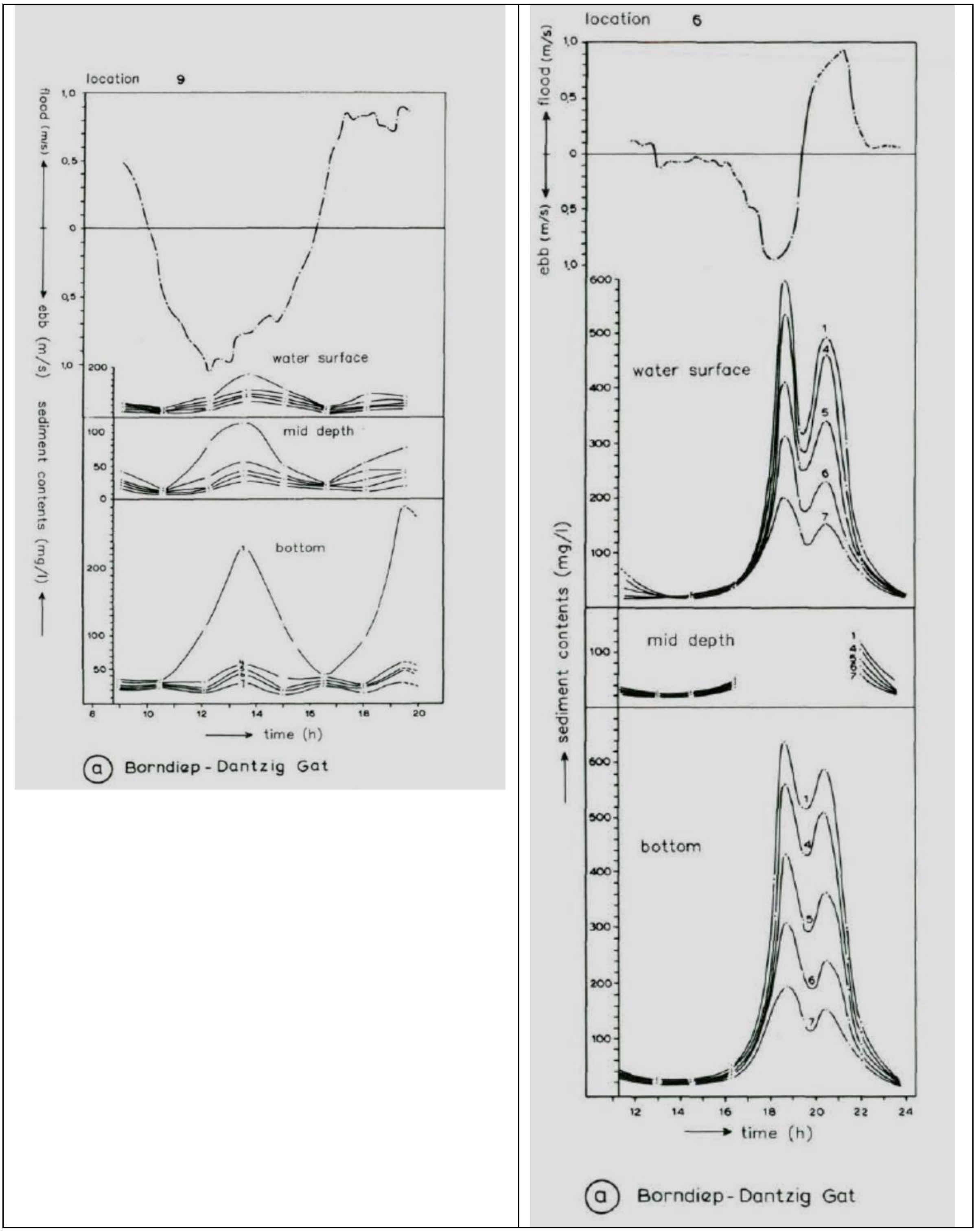

Figure B.2 Sediment concentrations during the tide on the locations 9 (large channel Borndiep) and 6 (small channel eastward of Veerdam, see locations in Figure B.1 for the different fractions (from: Postma, 1961). De numbers at the lines correspond to the fractions: 1: total suspended matter; 4: fraction < 63 µm; 5: Fraction < 32 µm; 6: Fraction < 16 µm; 7: Fraction < 8 µm.

Due to these mechanisms, it is not likely that coastal nourishments (which are placed outside or in the inlet) will have a significant influence on the grain size distribution in the channels and shoals, because these sediments will be sorted and distributed in the same way as any other sediments.

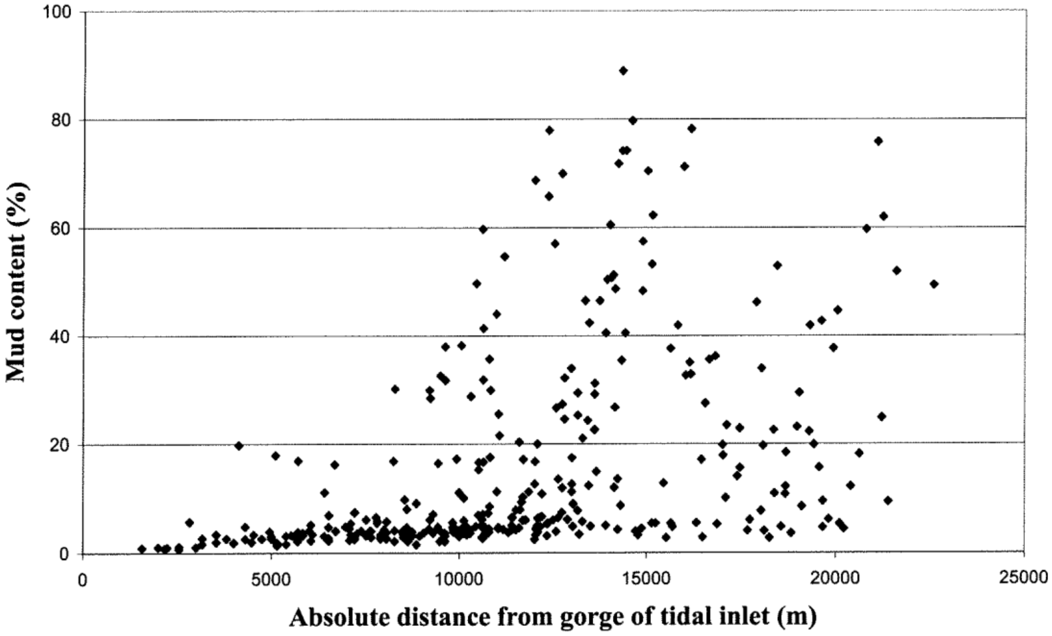

Figure B.3 Mud content versus distance from the gorge (Nieuwenhuis, 2001).

On the tidal flats, current velocities are generally low. As soon as the tidal flat is flooded, current velocities drop sharply. The coarser grains are deposited near the channel edge, forming the channel levees. During the ebb-phase, the highest current velocities occur when the flats are (almost) dry. As a consequence, suspension transport dominates on the intertidal shoals, with the exception of the levees. The mud-rich intertidal shoals are confined to the extensive high flats (above MSL) near the mainland and some smaller areas in the shelter of the barrier islands, and locally on the watersheds. On the intertidal flats, the influence of the waves reaches all the way to the bottom. This causes the sediment to be suspended from the bed. Eysink & Biegel (1992) agreed with Postma (1961) that wave action on the tidal flats dominated and that currents were not important. However, observations show that currents also play an important role:

1. The grain size decreases in general, going from the islands towards the mainland (Postma, 1954; Kamps, 1962; Flemming & Nyandwi, 1994; Flemming & Ziegler, 1995; sediment atlas RWS). This suggests that currents also must be of influence, otherwise the shelter of the islands would probably be muddier. The decrease in grain size towards the mainland (see Flemming & Nyandwi, 1994) can partially be explained from the settling lag and scour lag effects (Postma, 1954; Van Straaten & Kuenen, 1958), and partially by the sorting in the tidal channels, as discussed before.
2. In comparable sub environments, the median grain size decreases from west to east (Eysink, 1994). Since the tidal flats east of Schiermonnikoog are far less sheltered than the ones south of Ameland or Schiermonnikoog, this cannot be explained by wave influences. Obviously, there has to be a sorting mechanism over the watersheds and along the beaches from west to east, in which currents also play a role.
3. Kamps (1962) found that during storm surges, the tide and wind-driven currents determine the direction of sediment transport on the shoals. Model studies indicate that areas

where mud deposition occurs are mainly determined by the tide. Even though in shallow water depths waves determine how much and how fast mud can be suspended, the tidal currents determine the actual transport (Nieuwenhuis, 2001).

All in all, it can be concluded that grain size fractions in tidal basins are deposited according to an energy gradient (see Flemming & Ziegler, 1995; Nyandwi, 1998). The general trend shows a decrease in both tidal and wave energy and, hence, in grain size from the inlet to the landward side of the basin and from W to E (see Figure B.4 and Figure B.5). Local morphology determines second-order variations on top of this general trend, such as coarser grains in the channels and finer grains on tidal flats.

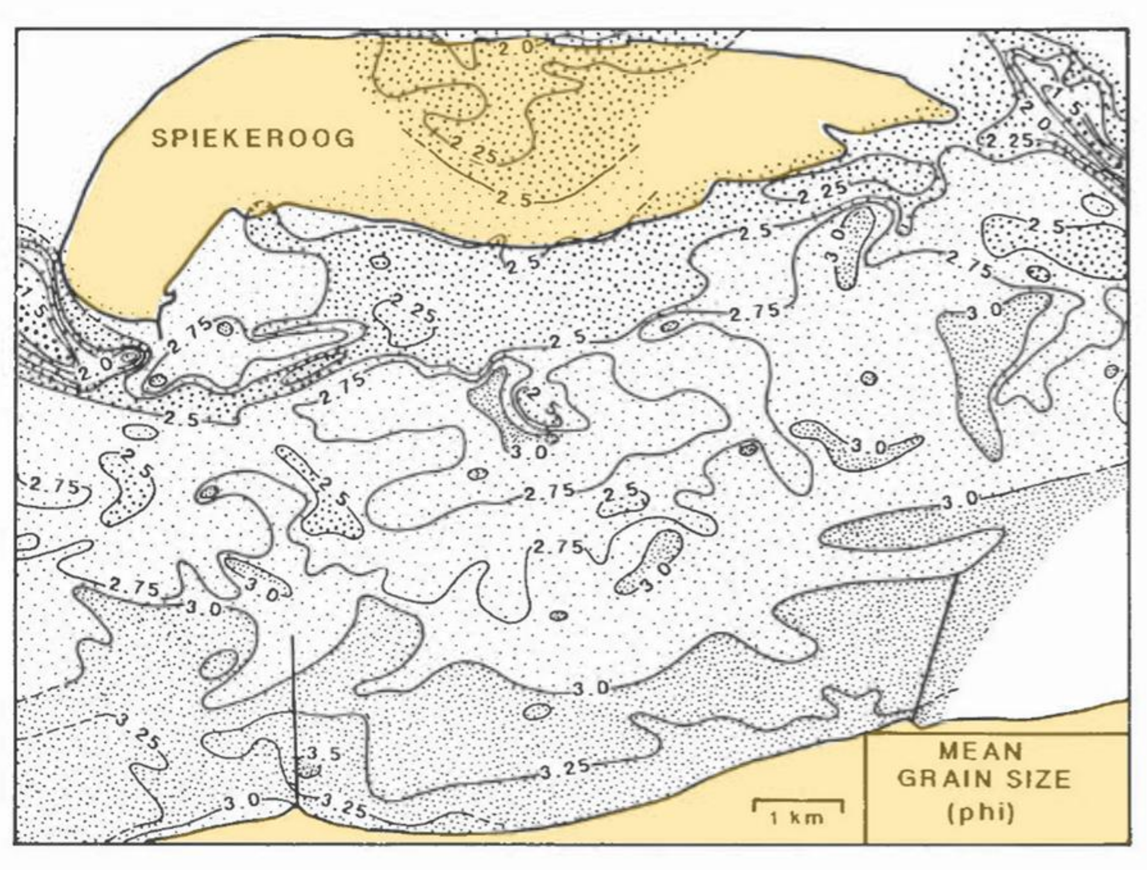

Figure B.4 Spatial pattern of the mean sediment grain-size in the back-barrier area of Spiekeroog Island. Note the landward-fining trend. Sediment grain sizes are indicated in phi classes. The phi unit (ø) is a logarithmic transformation of millimetres into dimensionless numbers, according to the formula: ø =2log-d, where d = grain diameter in millimetres. The grain size decreases with increasing phi number. (From Flemming & Ziegler, 1995).

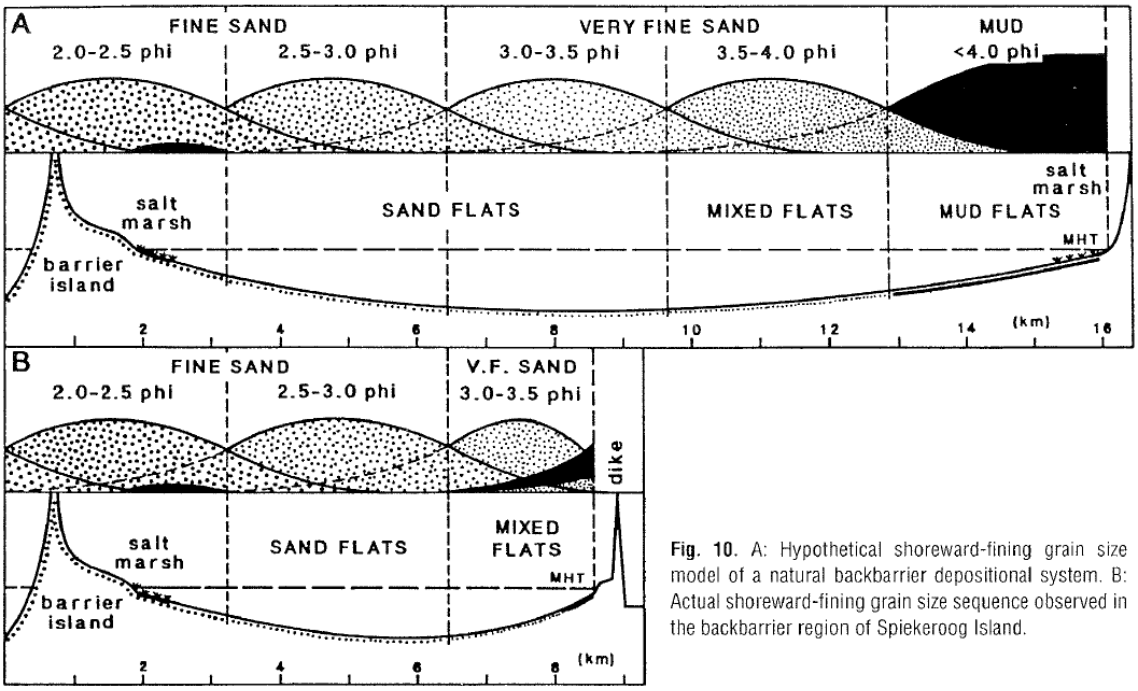

Fig. 10. A: Hypothetical shoreward-fining grain size model of a natural backbarrier depositional system. B: Actual shoreward-fining grain size sequence observed in the backbarrier region of Spiekeroog Island.

Figure B.5 A: Hypothetical shoreward-fining grain size model for a natural backbarrier depositional system. B: Actual shoreward-fining grain size sequence observed in the backbarrier region of Spiekeroog Island. (From Flemming & Nyandwi, 1994).

Rijkswaterstaat collected an extensive set of sea-bed samples from the Wadden Sea, including tidal basins, inlets and barrier-island coasts (Rijkswaterstaat, 1998). The mean grain size distribution for the Wadden Sea near Ameland is presented in Figure B.6. Figure B.7 presents the mud content of the samples. Mud is almost completely absent in samples from the North Sea beach, the ebb-tidal delta and the main tidal channels. The mud content increases in samples from the lee side of the island and in the direction of the sea dike of Friesland and the reclamation works in front of it. The average mud content (that is both the clay fraction (< 0,016 mm) and the silt fraction (0,016 – 0,063 mm)) of the bed samples from the Ameland tidal basin is 13% (see Table II.1).

Besides a clear trend in landward direction, it is also found that mud content is higher in the eastern area of the Ameland tidal basin than in the western area (Nieuwenhuis, 2001). This might be related to the distance from the inlet (van Prooijen & Wang, 2014; also see: Nieuwenhuis, 2001) and to maximum bed shear stress during the tidal cycle which is higher in the western area (Nieuwenhuis, 2001).

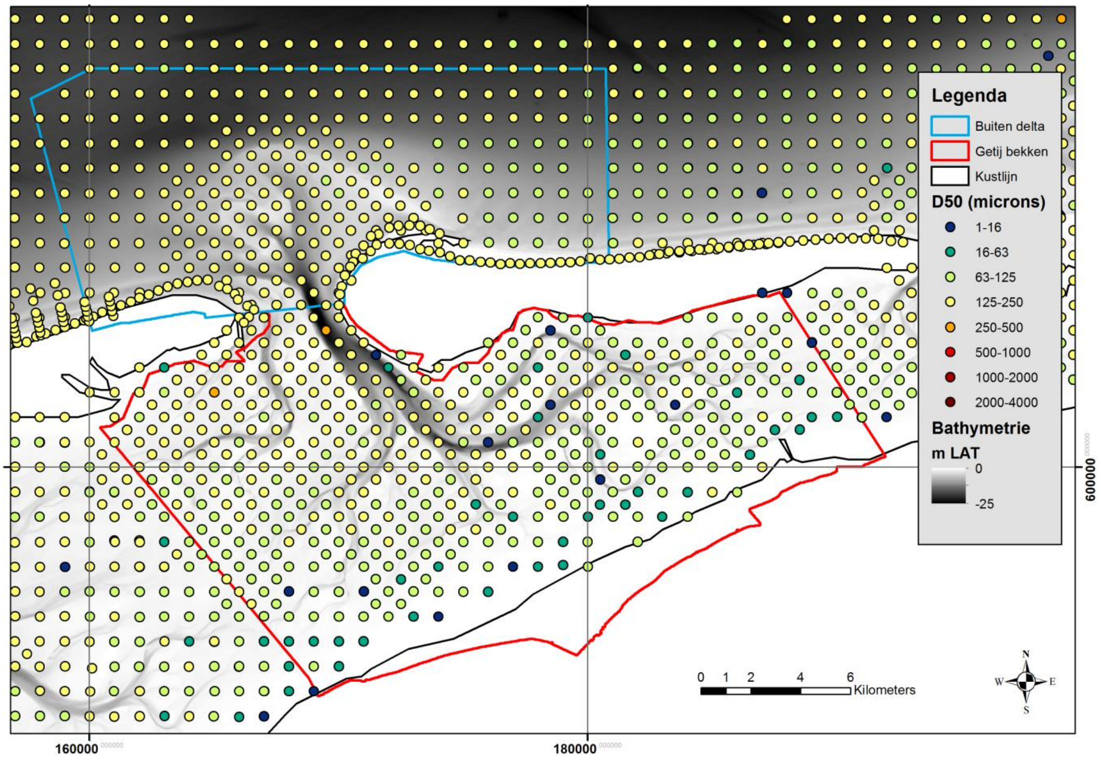

Figure B.6 Mean grain sizes of the sea-bed samples near Ameland. Data from Sediment-atlas Waddenzee (RWS, 1998).

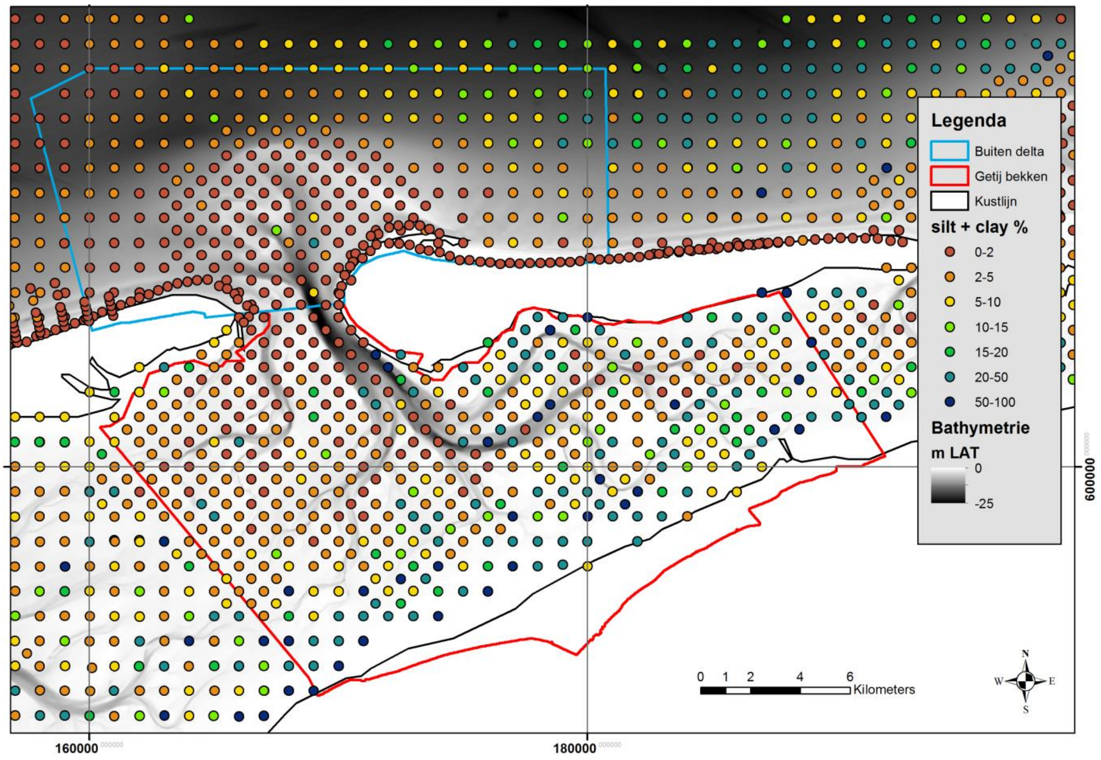

Figure B.7 Mud content of the sea-bed samples near Ameland. Data from Sediment-atlas Waddenzee (RWS, 1998).

Table B.1 Average clay, silt and mud (= clay + silt) content in % and the mean grain size in µm of sea-bed samples from the North Sea coast, tidal inlet and tidal basin of Ameland. See Figs. 4 and 5 for the boundaries of the areas 'Tidal basin and 'Ebb tidal delta'. Data from Sediment atlas Waddenzee (RIKZ, 1998).

	Clay	**Silt**	**Sand**	**Clay + silt**	**D_{50} (micron)**
Tidal basin	7.6	5.4	87.0	13	106
Ebb-tidal delta	1.3	1.2	97.5	2.5	154
Ameland total	5.1	3.8	91.1	8.9	123
Wadden Sea	6.9	4.8	88.3	11.7	123

C Mud deposition in parts of a tidal basin

C.1 Introduction

As we have shown in the previous chapters, mud sedimentation is determined by (changes in) the hydrodynamic and ecological conditions which are subject to natural and human influences. In this chapter we will discuss patterns in mud erosion and deposition, on the local scale of parts of the backbarrier area. We will discuss: supratidal salt marshes, intertidal shoals, mussel beds, subtidal shoals, abandoned channels and ports. Can the storage of mud in these areas contribute to the net deposition volume of the basin, and thus influence the sand demand, on the long term? To answer this question, we will also briefly discuss the different possibilities of mud management, for each of these areas.

C.2 Tidal marshes

The development of tidal marshes in general will be determined by the hydrodynamics, sediment supply, relative sea level rise, accommodation space and the present condition of the marsh. These factors determine with some delay the development of the vegetation and morphology (Dankers et al. 1987). Erosion and net sedimentation on the marshes can alternate cyclically (Van de Koppel et al. 2005), and both processes may be active on the same tidal marsh at the same time (Van Wesenbeeck et al. 2008). Tidal marshes are considered to be biogeomorphological systems: landscape forms which form from the interaction between biology, hydrodynamics and sedimentation (Viles, 1988; Allen 2000, Temmerman et al. 2005, Van De Koppel et al. 2012). In the early stages of formation, physical processes may still dominate, but as the marsh grows in height and a dense plant cover develops, the ecological processes become increasingly important.

As described before (in paragraph 2.5.3), tidal marsh formation will also lead to extra deposition of sand, due to the decrease in tidal prism and the resulting filling up of tidal channels. Sand may also be stored in the tidal marshes themselves. Vice versa, when tidal marshes erode, the tidal prism will increase and channels will deepen, releasing sand in the process. With active tidal marsh management, it is possible to influence the sand balance as well. As far as information goes, the role of tidal marshes as sinks for the sediment balance and -management of the Wadden Sea has not yet been investigated.

C.3 Higher tidal flats

Grain-size maps reveal that especially the higher intertidal flats near the mainland and embayments such as the Dollard and the Mokbaai, and – to some extent – the island coasts of the Wadden Sea have a high mud content. From their location it is clear that mud deposition is to a large extent coupled to shelter from wave effects. In water depths smaller than 2 m below NAP mud contents range from high to low values. It implies that a small water depths are a precondition for high mud contents, but that also other factors (shelter) determine whether mud content will be high (Nieuwenhuis, 2001). Sassi et al. (2015) underline this conclusion, by comparing model calculations with measured data. Because mud deposition is quite substantial on the higher tidal flats of the Eastern part of the Dutch Wadden Sea (including Eems-Dollard) higher tidal flats will significantly contribute to the mud sedimentation both in weight and volume (see main text).

C.4 Mussel beds

The filter feeder Mytilus edulis significantly influences the fine-grained sedimentation in the Dutch Wadden Sea. Depending on the size of the population, variable, but large amounts of sediment are filtered from the water column and compressed into faeces and pseudo-faeces (in total 2.6-15.1 * 10^9 kg/year) minerals dry weight). Experiments show that these biodeposits have a larger grain size than the original sediment and may behave hydrodynamically as grains of sand size. Also, they are fairly resistant to decay during phases of transport and rest. In this way biodeposition, in combination with deposition of sand, leads to the formation of mussel mud mounds and muddy sand flats surrounding the mussel beds. The concentration of fine-grained material in the sediment decreases with increasing distance from the mussel beds. The most important concentration is to be found below mussel beds. It is estimated that under normal mussel densities (reference 1975-1978) the amount of mud under the intertidal mussel beds in the Dutch Wadden Sea amounts to 3.1 * 10^9 kg. By comparing the amount of fine-grained sediment below the intertidal mussel beds with the annual amount of faeces filtered from the water column 1.9 * 10^9 kg/y, based on data of Beukema et al. (1978), Dankers et al. (1989) and Dankers & Koelemij (1989), and taking also resuspension into account, it is clear that these accumulations must have been built up over a period of at least several years (Oost, 1995). On the longer run mussel beds disappear from time to time and the sediment accumulation which sticks out above the tidal flat levels will be eroded. Thus the sediment accumulation under the mussel beds cannot be expected to directly contribute on the average volume of mud being permanently deposited. However, there might be an indirect effect. The already somewhat compacted muds may be transported and may for some time settle much easier than normal mud particles. As such, they probably play an important role in the mud balance of the Wadden Sea. Unfortunately, little knowledge is available on this subject.

C.5 Abandoned channel deposits

Abandoned channel deposits are channels which have partially or completely lost their sediment transport function. In response, these channels start to fill up with sediments (Van den Berg, 1981). As can be learned from the partial infill of the Zoutkamperlaag, this can be filled up with sand near the inlet gorge, mud far from the inlet (near the mainland) or an alternation of mud being deposited during the quiet summer period and more sandy sediments during the more turbulent winter period (Figure C.1; Oost, 1995). Mud deposition in such abandoned tidal channels can initially be very substantial, but will decrease with ongoing infill of the channel.

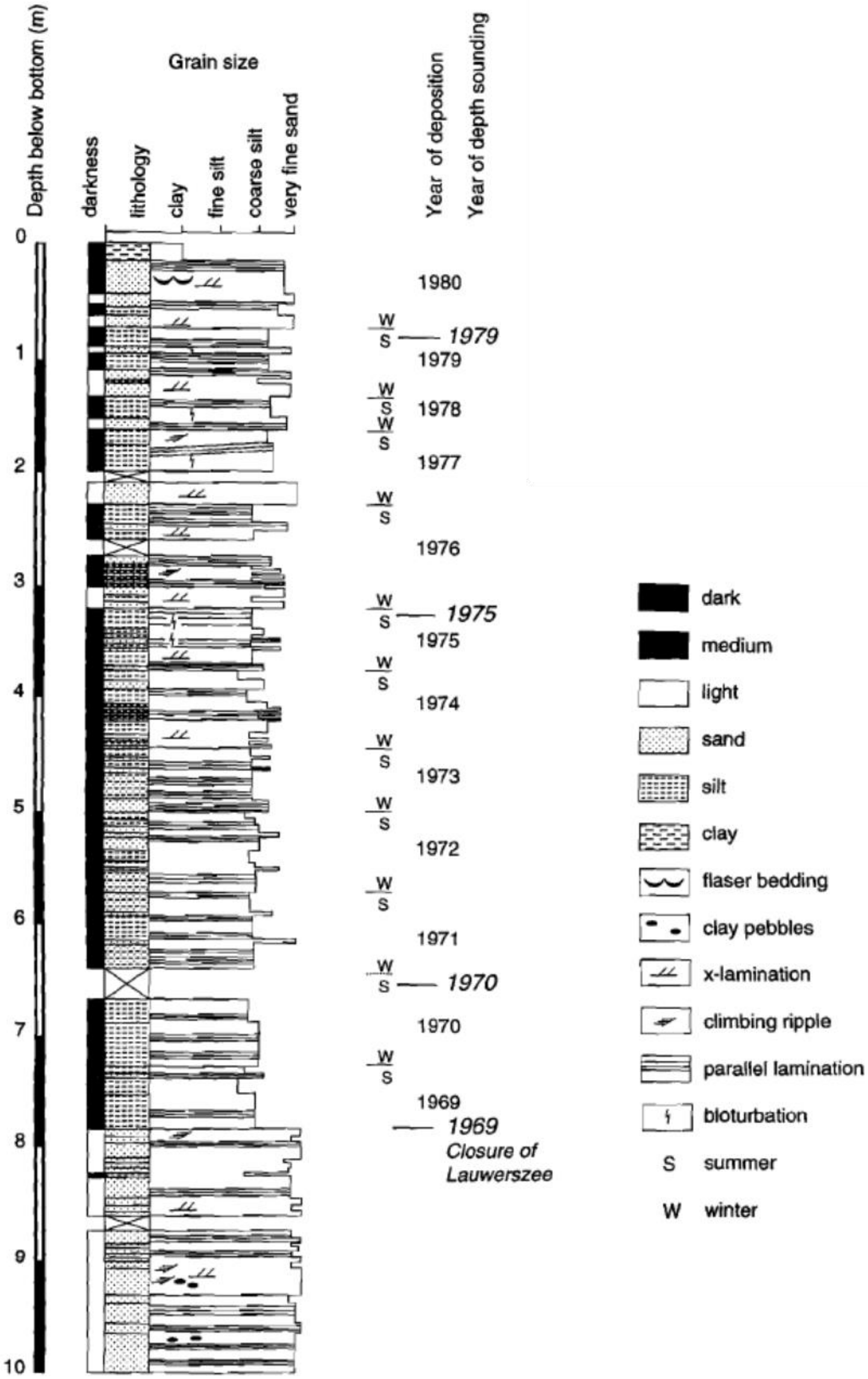

Figure C.1 Sedimentary log of core 2G.025, 30-10-1980; top -8.45 m below mean sea level, representing the sequence formed in the main backbarrier channel of the Zoutkamperlaag system after the closure of the Lauwerszee near the sluices. The inferred year of deposition given to the right of the log correlates with the available depth sounding data of 1969, 1970, 1975 and 1979 (after Oost et al., 1993). Winter(sand) - summer (clay, silt and muddy sand) alternation indicated with w, respectively (Oost, 1995).

C.6 Active channels

In active channels, the inner bends of the channels are characterized by relatively low current velocities, which result in conditions where mud can be deposited. Only if inner bend deposits are stored for a long term, this can lead to the storage of mud. However, on average only a modest net result might be expected as inner bend deposits will be eroded from time to time.

C.7 Harbours and fairways

In essence, harbours are artificial embayments. And to a certain extent this is also true for waterways which have overdepth and have to be dredged to depth. As such, these are areas where net sedimentation occurs. Whether these sediments are mainly sands (Den Helder) or muds (Emden), will be determined by the mud-sand concentration in the water and will depend on the distance from the inlet, the degree of shelter and other local conditions (for instance estuarine circulation.

Dredging mud from a harbour or fairway and dumping it into the Wadden Sea might at least locally influence the mud sedimentation patterns. The choice of dumping location, time and amounts may lead to either unwanted or wanted effects and are thus a way to manipulate the mud sedimentation in the Wadden Sea.

C.8 Summary

Tidal marshes, abandoned channels and the major waterway and harbour dredgings are thought to be of significant influence on mud sedimentation patterns. Local amounts may be of the order of a half to a few million m^3 annually, which is significant compared to the net annual sedimentation in terms of kilograms. To what extent the mud deposits contribute to the sediment volume will most likely strongly depend on the location where the sediment is deposited.