# Mud dynamics in the Wadden Sea

**Towards a conceptual model**

Deltares

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Peter M.J. Herman
Thijs van Kessel
Julia Vroom
Petra Dankers
Jelmer Cleveringa
Bente de Vries
Nicky Villars

Deltares

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**Trefwoorden**
Mud, Sediment Suspended Particulate Matter, Wadden Sea, North Sea

**Samenvatting**
Zie Nederlandstalige samenvatting in hoofdstuk 1.

**Referenties**
Rijkswaterstaat en Programma naar een Rijke Waddenzee zijn in 2016 gestart met een programma voor de ontwikkeling van kennis over de morfologie van de Nederlandse Waddenzee en voor het inbedden hiervan in beleid en beheer. In het programma wordt morfologische kennis op een structurele manier verzameld, geanalyseerd, geordend en geborgd. Daarnaast wordt de kennis toegankelijk gemaakt voor beleids- en beheervraagstukken op het gebied van veiligheid, bereikbaarheid, natuur en overige gebruiksfuncties. Hiertoe wordt afstemming gezocht met beleidsmakers, beheerders, adviseurs, wetenschappers en gebruikers van het wad.

In het kader van het programma worden ter bevordering van de onderlinge uitwisseling en borging van de morfologische kennis ook onderzoeksopdrachten uitgevoerd vanuit een specifiek project. Het voorliggende rapport wordt uitgebracht als onderdeel van het onderzoek naar de slibhuishouding van de Waddenzee voor het project Kaderrichtlijn Water Waddenzee, in opdracht van Rijkswaterstaat Noord-Nederland.

| Versie | Datum | Auteur | Paraaf | Review | Paraaf | Goedkeuring | Paraaf |
|---|---|---|---|---|---|---|---|
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| | | T. van Kessel | | D.S. van Maren | | | |

**Status**
definitief

# Inhoud

# 1 Nederlandstalige samenvatting

## 1.1 Doelstelling van de studie

De hoofdvraag in deze studie is hoe de concentratie van slib in de waterkolom en het slibpercentage in de bodem van de Waddenzee bepaald worden door menselijke en natuurlijke processen. Op basis van een beter begrip van de slibdynamiek, te formaliseren in conceptuele en numerieke modellen, kunnen de beleidsdoelstellingen voor de Kaderrichtlijn Water worden vastgesteld, en kan het beheer worden aangepast om deze doelstellingen te bereiken.

De hoofdvraag wordt opgesplitst in vier subvragen, waarin gekeken wordt naar:

- de dominante factoren die de slibdynamiek in de Waddenzee bepalen, en naar hun relatie met gelijkaardige factoren in de Noordzee
- de verblijftijd van slib in de Waddenzee, en de respons van het systeem op pulsen in de toevoer van slib
- het belang van slib voor de ecologische functies van de Waddenzee
- aangepaste beheerstrategieën voor slib en ontwikkeling van de kustlijn, die leiden tot de optimalisatie van de ecologische kwaliteit van het systeem.

Dit rapport is een eerste stap in de ontwikkeling van het conceptuele model voor slibdynamiek in de Waddenzee. Het is gebaseerd op analyse van beschikbare gegevens en oudere modelberekeningen. Daarmee wordt een aanzet gegeven voor de verdere ontwikkeling van numerieke modellen, en een basis gecreëerd voor beleidsstrategieën. Dit rapport is een tussenrapportage op weg naar het conceptuele model; verdere ontwikkelingen zullen in de toekomst toegevoegd worden.

## 1.2 Belang van slibdynamiek voor het beheer van de Waddenzee

Slib speelt een cruciale maar vaak slecht begrepen rol in de ecologie, de geomorfologie en de hydrografie van de Waddenzee. Die rol is niet eenduidig causaal. Enerzijds worden ecologische, geomorfologische en hydrodynamische processen aangestuurd door de dynamiek van slib op korte of lange termijn, maar anderzijds hebben deze processen zelf invloed op de slibdynamiek. Het ontrafelen van de causale mechanismen in deze wederzijdse beïnvloeding is complex.

### 1.2.1 Ecologie

Voor de ecologie is vooral van belang dat slib in de waterkolom de lichtdoordringing vermindert. Daardoor heeft het slibgehalte van het water een grote invloed op de primaire productie, de groei van microscopische algen die aan de basis van het voedselweb liggen. Slib in het water bepaalt ook de voedselkwaliteit van schelpdieren, die een cruciale rol spelen in dat voedselweb, en een link vormen tussen algen en vogels.

Slibgehalte van de bodem bepaalt het habitat voor het bodemleven, omdat andere dieren voorkomen in slibrijke dan in zandige bodems. Ook dit vertaalt zich door in het voorkomen van vis en vogels. Slib is een essentiële karakteristiek van kwelderbodems, als gevolg van een wederzijdse beïnvloeding van vegetatie en (slib)sedimentatie.

In de Kaderrichtlijn Water, die ook voor overgangswateren als de Waddenzee de goede ecologische kwaliteit moet garanderen, is begrip van de slibdynamiek essentieel. De goede ecologische kwaliteit weerspiegelt immers (aspecten van) het voedselweb en de structuur van aanwezige populaties die in belangrijke mate door slib worden bepaald. Daarom is het van belang te weten welke ontwikkelingen en trends zich rond het slibgehalte in water en bodem voordoen en hoe deze de ecologische ontwikkeling beïnvloeden. Dat laatste aspect is in deze studie niet uitgewerkt.

### 1.2.2 Geomorfologische veranderingen

In toenemende mate realiseren we ons dat slib ook een grote rol speelt in de geomorfologische veranderingen in de Waddenzee. Alle sediment dat zich netto in de Waddenzee afzet bevat een kleine of grote hoeveelheid slib. Vooral bij hogere percentages slib in de bodem draagt dat slib netto bij aan het volume sediment dat wordt afgezet. Slib zet zich bovendien stabiel af op andere plaatsen dan zand. Het meest extreme voorbeeld zijn kwelderbodems, die voor een groot deel uit slib bestaan en door vegetatie worden gestabiliseerd.

Via de geomorfologie, en in een duidelijke interactie daarmee, speelt slib ook een rol in de hydrodynamiek van de Waddenzee. Als zich langs de vastelandskust grote volumes slibrijk sediment afzetten, dan heeft dat gevolg voor de komberging van de kleinere geulen en daarmee op de stromingspatronen. Dit op zijn beurt bepaalt de transportmechanismen en de afzettingsmogelijkheden van slib.

### 1.2.3 Dynamiek, tijdschalen en mechanismen en uitwisseling

Vanuit het beheer van vaarwegen en de zorg voor goede ecologische kwaliteit is het van groot belang een goed inzicht te hebben in de dynamiek van slib, de tijdschalen die hierbij van belang zijn en de belangrijkste mechanismen die het slibgehalte van het sediment in de waterkolom bepalen.

Bovendien kan slib in de Waddenzee niet in isolatie worden beschouwd. Het is bekend dat er grote uitwisselingen zijn van slib met de Noordzee, waardoor ontwikkelingen rond slib in de Waddenzee kunnen worden gekoppeld aan de slibdynamiek in de gehele Nederlandse kustzone.

### 1.2.4 Studies uit het verleden

In het verleden zijn meerdere modelstudies naar slibdynamiek in de Waddenzee uitgevoerd. Deze hebben ons begrip van de slibdynamiek aanzienlijk verbeterd. Zij hebben ook geholpen om de invloed van meerdere menselijke ingrepen (bv. vaargeulonderhoud, visserij, lokale ingrepen, suppleties, zeespiegelstijging) onderling te vergelijken en de belangrijkste termen te selecteren. Toch is het moeilijk om op basis van deze resultaten te schakelen tussen meerdere tijdschalen, vanaf de zeer korte schaal (binnen een getij) waarin de belangrijkste processen van transport, depositie en erosie optreden, tot de langjarige tijdschaal waarop morfologische aanpassingen worden geobserveerd.

## 1.3 Doelstellingen en aanpak deze studie

In dit rapport wordt daarom een omgekeerde benadering gekozen. Er wordt gebruik gemaakt van gegevens die op grote schaal in tijd en ruimte zijn verzameld, om op basis van een analyse van deze gegevens te besluiten wat de dominante mechanismen of openblijvende vragen zijn. Dit vormt, samen met de beleids- en beheerscontext, de basis voor verdere modelontwikkelingen en beleidsanalyses.

## 1.4 Statistische analyse van Zwevende Stof (SPM) in de waterkolom

De statistische analyse van de tijdseries sinds 1989 van zwevend stof, verzameld in het kader van MWTL, leverde een aantal opvallende en soms onverwachte karakteristieken van de series op. Die karakteristieken hebben te maken met het type statistische waarschijnlijkheidsverdeling, het feit dat die verdelingen in verschillende stations opvallende gelijkenissen vertonen in de (relatieve) mate van variatie en het feit dat de seizoensvariatie op alle plaatsen, relatief tot het langjarig gemiddelde, zeer gelijkaardig is. De statistisch-technische details van al deze patronen worden in het rapport uitvoerig besproken en geïllustreerd. Hier worden zij slechts kort samengevat.

Uit de statistische verdeling van de waarnemingen van gesuspendeerd materiaal aan de oppervlakte van de waterkolom kan worden afgeleid dat de processen die deze concentratie bepalen vooral *multiplicatief* zijn, d.w.z. hoeveelheden toevoegen of wegnemen die in verhouding staan tot de hoeveelheden die in de waterkolom aanwezig zijn. Dit lijkt voor de hand liggend voor processen als sedimentatie of verticale herverdeling van het gesuspendeerd materiaal, maar het is niet vanzelfsprekend voor resuspensie. Of dat zo is, en zo ja, waarom, is een belangrijk punt om nader uit te zoeken.

Het feit dat de variabiliteit van de statistische verdeling in alle stations ongeveer gelijk is, relatief tot het gemiddelde, is eveneens moeilijk te verklaren. Ondiepere stations hebben een veel grotere dynamiek van sedimentatie en resuspensie hebben dan diepere stations. Het feit dat de variabiliteit ongeveer gelijk is suggereert dat een andere factor, bv. verticale herverdeling of zinksnelheid van de deeltjes, in diepere stations een rol vervullen die toch zorgt voor een gelijkaardige variabiliteit. Ook hiervoor moet nog een afdoende verklaring worden gevonden.

Hetzelfde geldt eveneens voor de seizoenale component van de tijdseries. Niet alleen is die, relatief tot het gemiddelde, in alle stations ongeveer even groot. Ook de fase is gelijk, met maxima in januari en minima in juli. Er is enige variatie in het belang van de seizoenale component als fractie van de totale variantie: deze neemt af met de diepte van het station. Toch is de gelijkenis veel belangrijker dan de verschillen. Verticale herverdeling in diepe stations neemt misschien de rol van sedimentatie/resuspensie in ondiepe stations over, en ook hier moet de zinksnelheid van de deeltjes een belangrijke rol spelen.

Deze waarnemingen hebben geen onmiddellijke implicatie voor het beheer, maar zijn van groot belang voor het fundamentele begrip van de tijdsevolutie van gesuspendeerd materiaal in de waterkolommen van Noordzee en Waddenzee. Zij vormen een toetssteen voor numerieke modellen, die kunnen worden gebruikt om te onderzoeken onder welke voorwaarden de statistische eigenschappen van de observaties kunnen worden gereproduceerd.

De meerjarige trendcomponenten zijn in de meeste watersystemen een belangrijke component van de tijdseries. Variaties over de jaren tussen 50 en 200 % van het langjarige gemiddelde worden gevonden. De patronen van meerjarige trend zijn coherent tussen verschillende stations binnen een watersysteem (bv. Waddenzee), maar er is geen duidelijk verband tussen deze trendpatronen in verschillende watersystemen (bv. tussen Waddenzee en noordelijke Noordzee). Zo is het onduidelijk of, en hoe, meerjarige variatie in zwevend stof in de Noordzee doorwerkt in de concentraties zwevend stof van de Waddenzee. Wij hebben geen duidelijke correlaties kunnen ontdekken tussen deze meerjarige patronen in de Noordzee en bekende antropogene verstoringen. De meerjarige patronen kunnen dus niet worden geïnterpreteerd als het gevolg van verstoringen elders die verhoogde (of verlaagde) concentraties naar elders verplaatsen.

Het feit dat belangrijke meerjarige trends worden gevonden in de tijdseries is consistent met de waarneming dat de statistische autocorrelatie in de tijdseries groot is (tot langer dan een jaar wordt statistisch significante autocorrelatie gevonden). Dit betekent dat als een waarneming hoger is dan het gemiddelde (na correctie voor seizoen), de kans groot is dat de daaropvolgende waarnemingen ook allemaal hoog zullen zijn. Waar dergelijke autocorrelatie wordt gevonden, heeft de tijdserie de neiging om relatief langzaam en quasi-trendmatig aanzienlijk te fluctueren.

De dominante processen van depositie en erosie spelen zich voornamelijk binnen een getij (of een doodtij-springtij cyclus) af, en worden bepaald door weerpatronen die ook slechts over korte tijd gecorreleerd zijn. Het is dus merkwaardig dat de tijdseries van gesuspendeerd materiaal wel belangrijke autocorrelatie over langere termijn hebben. Het suggereert dat er buffersystemen actief zijn, die ervoor zorgen dat hoeveelheden die voor resuspensie beschikbaar zijn op een bepaald moment, ook gerelateerd zijn aan de hoeveelheden die voordien in suspensie in de waterkolom aanwezig waren. Dergelijke buffer moet zich in het sediment bevinden, en zou verband kunnen houden met zowel ecologische als fysische processen in het sediment. Verschillen tussen jaren in weerpatronen of andere factoren zouden de opbouw van deze buffers kunnen beïnvloeden. Dit is bijvoorbeeld eerder aangetoond voor microfytobenthos (zie verder). De belangrijkste conclusie uit deze waarneming is dat er bij de modellering actief moet worden onderzocht welke processen op de mesoschaal (d.i. tussen de springtij-doodtij schaal en de seizoenale schaal) voor deze buffering verantwoordelijk kunnen zijn.

## 1.5 Statistische analyse van slibgehalte van de (intertidale) sedimenten in de Waddenzee

Voor de SIBES dataset, verzameld door NIOZ en beschikbaar gesteld voor dit onderzoek, zijn jaarlijks in de periode 2008-2013 4500 sedimentmonsters genomen in de intertidale zone van de Waddenzee. De horizontale resolutie van de bemonstering is ongeveer 500 m. De dataset laat toe om met hoog oplossend vermogen een analyse uit te voeren van het slibgehalte van het sediment op de wadplaten.

Het ruimtelijk patroon van de slibverdeling over de platen is vergeleken met historische bronnen die een periode van ongeveer 125 jaar beslaan. De oudste bron is de gedeeltelijke kaart van Lely (1892). Volgende ruimtedekkende inventarisaties zijn uitgevoerd door de Glopper (1967, data zijn van de jaren 1950) en Zwarts (2004, data van de jaren 1990). Tussen de verschillende kaarten zijn grote gelijkenissen aangetroffen, maar ook markante verschillen. Deze verschillen hebben te maken met twee factoren. De eerste en wellicht belangrijkste factor vormen de grootschalige ingrepen in het systeem, zoals de afsluitingen van de Zuiderzee en de Lauwerszee, en de daaropvolgende veranderingen van de wantijen en de getijregimes. In de Westelijke Waddenzee heeft dit geleid tot een tendens van vermindering van het slibgehalte op de platen, en dan vooral op de wantijen. In de Oostelijke Waddenzee zijn er verschuivingen van wantijen, vooral onder Schiermonnikoog. Over het algemeen zijn de wantijen in de Oostelijke Waddenzee bovendien slibbiger geworden. De tweede factor heeft te maken met de ontwikkelingen langs de vastelandskust van de Waddenzee. De Friese kust rond Harlingen blijkt altijd al slibbige sedimenten te hebben gehad, maar die waren in de negentiende eeuw subtidaal en zijn sindsdien gedeeltelijk intertidaal geworden. Elders hebben de kwelderwerken veel invloed gehad. De gordel van kwelders langs de vastelandskust is in breedte toegenomen, en ten noorden van deze zone heeft zich een slibbigere zone ontwikkeld. De ontwikkeling van de kwelders als gevolg van de kwelderwerken heeft invloed gehad op de komberging van de kleinere zuidelijke geulen. Door de afname van die komberging is wellicht verdere opslibbing bevorderd. Mogelijk verklaart dit ook het slibbiger worden van de wantijen in de Oostelijke Waddenzee.

De statistische verdeling van de waarnemingen vertoont een zeer opvallend en relevant kenmerk. De waarnemingen zijn bimodaal verdeeld. De meeste waarnemingen betreffen ofwel zandige sedimenten met een laag slibgehalte (~5 %) ofwel slibbige sedimenten met een hoog slibgehalte (25-50%), maar er vallen opvallend weinig waarnemingen tussen deze twee modes. Stations die in de hoge of lage mode vallen zijn weinig variabel in de tijd. Stations met intermediaire gemiddelden vertonen de hoogste variabiliteit in de tijd, wat suggereert dat een toestand met intermediair slibgehalte weinig stabiel is, terwijl stations met een hoog of een laag slibgehalte wel stabiel zijn en meestal weinig veranderen.

Zowel ecologische als fysische processen zouden dit kunnen verklaren. Deze mechanismen hebben gemeenschappelijk dat sedimenten met een hoog slibgehalte de neiging hebben meer slib aan te trekken, terwijl zandige sedimenten de neiging hebben zandig te blijven. De fysische mechanismen werken via de ruwheid van de bodem. Slibbige bodems zijn gladder, waardoor voor een gelijke stroomsnelheid de bodemschuifspanning afneemt en dus ook de erosie van slib afneemt met toenemend slibgehalte. Fysisch-ecologische mechanismen werken via microfytobenthos, de algen die op het sediment groeien. Aanwezigheid van deze algen wordt bevorderd door slibgehalte, omdat slibbige bodems meer nutriënten bevatten en graas op algen bemoeilijken. Anderzijds verminderen de algen de erodeerbaarheid van slib, waardoor het sediment slibbig zal blijven.  Beide mechanismen sluiten elkaar niet uit, en de huidige gegevens laten ook niet toe om een duidelijke keuze te maken tussen beide verklaringen. Observaties jaarrond zouden beter uitsluitsel kunnen geven, omdat er een duidelijke seizoenscomponent is in de ecologische factor, terwijl dat voor de fysische factor niet het geval is. Helaas beschikken we nu alleen over zomerwaarnemingen.

Er is geen duidelijke correlatie tussen het gemiddelde slibgehalte van het sediment, waargenomen in de zomer, en de concentratie zwevend stof in het betreffende jaar. Er is een zwakke aanwijzing dat een hoog slibgehalte in het sediment tijdens een zomer, correleert met een hoog gehalte zwevende stof in het daaropvolgende jaar, maar de aanwijzingen zijn zwak en laten geen sterke conclusie toe.

Wij stellen als hypothese dat de mechanismen die verantwoordelijk zijn voor de bimodale verdeling van slibgehalte in het sediment, een relatie hebben met de ‘mesoschaal’ fluctuaties in de tijdseries van het gesuspendeerd materiaal. Deze mechanismen zorgen immers voor het type buffer dat kan verklaren waarom concentraties van gesuspendeerd materiaal zo lang in de tijd kunnen gecorreleerd blijven. We besluiten daaruit dat het van belang is aandacht te besteden aan deze mechanismen, zowel in de data-analyse als in de modellering, omdat hier wellicht een sleutel ligt om de fluctuaties van gesuspendeerd materiaal in de waterkolom beter te begrijpen. In dit document hebben we enige aandacht besteed aan het microfytobenthos, omdat daarvan data voorhanden waren. Het onderzoek van fysische mechanismen kan beter in de context van een model gebeuren.

## 1.6 Ruimtelijke en temporele verdeling van het microfytobenthos

Het microfytobenthos, de algen die op de bodem groeien in de intertidale zone van de Waddenzee, heeft een ruimtelijke verspreiding die opvallend sterk gecorreleerd is met het slibgehalte van het sediment. In de tijd is er een opvallende omgekeerde correlatie tussen microfytobenthos en concentratie zwevende stof, tenminste voor wat betreft de seizoenale variatie. De gegevens over het microfytobenthos laten slecht toe te controleren of er een correlatie is met de meerjarige trend in zwevende stof, al zijn de gegevens ook niet in flagrante tegenspraak met deze hypothese.

De sterke ruimtelijke correlatie tussen slibgehalte van het sediment en biomassa van het microfytobenthos verlenen geloofwaardigheid aan de hypothese dat de bimodaliteit van slibgehaltes via het microfytobenthos zou kunnen verlopen. Toch zou bijkomend onderzoek nodig zijn om deze hypothese verder te toetsen.

## 1.7 Gevolgtrekkingen voor de modellering van slib

Wij concluderen uit de statistische analyse van de gehaltes zwevende stof in de MWTL meetstations dat er variatie optreedt op drie belangrijke tijdschalen. De korte tijdschaal, weliswaar niet gevangen door de MWTL metingen, is de schaal van getijden en spring/doodtij variaties. Op deze tijdschaal vinden de belangrijkste processen van transport, erosie en depositie plaats. Ook windgerelateerde extreme omstandigheden spelen zich af op deze tijdschaal. De lange tijdschaal is de tijdschaal van decennia en langer, waarin morfologische ontwikkelingen gebeuren waarin slib (althans in de Wadden) een significante rol speelt. Tussen beide in speelt echter nog een derde tijdschaal, de mesoschaal, die loopt van seizoensvariatie tot enkele jaren. Wij hebben aangetoond dat er aanzienlijke variatie in de tijdseries van zwevend stof voorkomen op deze schaal. Het is de schaal waarin het ‘geheugen’ van het systeem resulteert in aanzienlijke (factor 2) variaties van jaar tot jaar en van seizoen tot seizoen. In vergelijking met de korte tijdschaal is het procesmatig inzicht in de belangrijkste processen op deze tijdschaal minder goed ontwikkeld. We stelden de hypothese dat microfytobenthos mogelijk een belangrijke rol speelt in variaties op deze tijdschaal, maar we kunnen niet uitsluiten dat eerder fysische processen zorgen voor een aantal positieve feedbacks waardoor het systeem als geheel tussen meerdere toestanden kan variëren. We relateren de bimodale verdeling van slibgehaltes in het sediment met variaties en stabiliteit van de dynamiek op deze mesoschaal. Wellicht is er een verband met weerpatronen, maar dit moeten we in een vervolg nader onderzoeken.

Voor de Noordzeestations vonden we ook belangrijke schommelingen in zwevend stof op de mesoschaal. Onduidelijk is waarom deze schommelingen binnen deelsystemen (bv. binnen de Waddenzee) onderling gecorreleerd zijn, maar tussen systemen (bv. Waddenzee - Noordzee) weinig samenhang lijken te vertonen. Ook het feit dat de seizoenale component in alle tijdseries gelijk is qua fase en amplitude blijft onverklaard. Nadere studie van het verticaal gedrag van zwevend stof in de waterkolom zou kunnen bijdragen aan een beter begrip.

## 1.8 Conclusies

Onze studie heeft geresulteerd in een conceptueel model (zie Figuur 21 en Figuur 22) met drie tijdschalen (kort, middel en lang) en drie invloedsfactoren (hoeveelheid slib, slibeigenschappen en hydrodynamica) voor de slibdynamiek. Op de korte tijdschaal (uren tot dagen) wordt de slibdynamiek gedomineerd door de hydrodynamica gegeven de aanwezige hoeveelheid slib en de eigenschappen hiervan. Op de midellange tijdschaal (weken tot enkele jaren) kunnen de hoeveelheid en eigenschappen van slib gaan variëren door fysische en biologische invloeden en hierdoor neemt de complexiteit toe. Op de lange tijdschaal (vele jaren) komt hier nog de interactie met morfologische ontwikkeling bij.

Terugkomend op de hoofvraag van deze studie wordt geconcludeerd dat de slibconcentratie in de waterkolom en de slibfractie in de bodem wordt bepaald door de interactie van deze invloedsfactoren op verschillende tijdschalen. De verblijftijd van slib in de Waddenzee bepaalt op welke tijdschaal de hoeveelheid slib wezenlijk varieert en deze verblijftijd is vermoedelijk meerdere jaren. De analyse van de toestand van de Waddenzee m.b.t. slibdynamiek en de implicaties voor KRW-doelen moet tenminste op deze tijdschaal plaatsvinden. Het belang van slib voor ecologische doelen is in dit rapport nog niet verder uitgewerkt, maar lichtklimaat en bodemsamenstelling zijn in ieder geval twee belangrijke koppelingen. Wat betreft beheerstrategieën moeten deze aangrijpen op een of meer van de drie invloedsfactoren. Denk hierbij aan alternatieve spuiscenario's, alternatieve stortstrategieën voor baggerspecie of het onttrekken of vastleggen van slib d.m.v. luwtezones en bio-bouwers.

De in het conceptuele model geïdentificeerde stuurfactoren voor de slibdynamiek en de invloed van menselijk handelen hierop kunnen worden gekwantificeerd met een mathematisch model. Vanwege het grote aantal wisselwerkingen en tijdschalen is dit zonder een dergelijk model niet goed mogelijk.

In meer detail heeft onze studie aangetoond dat slib een belangrijke rol speelt in de morfologische processen op langere termijn in de Waddenzee. In sedimenten met relatief hoog slibgehalte draagt slib aanzienlijk bij tot het totale sedimentvolume. De tweedeling in de sedimenttypes (m.b.t slibgehalte) suggereert dat hiervoor alleen de tweede, hogere, mode van de distributie echt van belang is. Dat betreft echter tientallen procenten van het totale intertidale areaal van de Waddenzee (waarbij rekening moet gehouden worden met het feit dat kwelders niet zijn bemonsterd in SIBES). Slibsedimenten zetten zich op andere plaatsen af dan zand, en ook om die reden is het meenemen van slib in de morfologische evolutie op langere termijn van groot belang. Onze resultaten suggereren dat slibafzettingen bij de vastelandskust, deels als gevolg van kwelderwerken, ook een uitstralend effect hebben op de aangrenzende zone van de Waddenzee en wellicht op de wantijen, omdat zij komberging reduceren en daardoor via de hydrodynamiek weer de dynamiek van slib verder beïnvloeden. Ons onderzoek heeft verder het belang aangetoond van de mesoschaal in de slibdynamiek, tussen de tijdschaal van het getij en die van de langjarige morfodynamiek. Het systeem beschikt over aanzienlijk langer geheugen, bv. in de SPM concentraties, dan op basis van getijdendynamiek zou verwacht worden. Wij suggereren dat belangrijke buffers, misschien via fysisch-ecologische interactie en beïnvloed door relatief grootschalige processen als het weer, deze mesoschaal dynamiek bepalen. Het beter begrijpen van deze dynamiek is noodzakelijk als men de meerjarige trendcomponenten beter wil evalueren op hun belang voor het beleid.

We hebben geen duidelijk causaal verband kunnen aantonen tussen trends in het SPM van de Noordzee, en trends in de Waddenzee. Binnen beide systemen is er wel samenhang, wat suggereert dat er ruimtelijk grootschalige fenomenen aan ten grondslag liggen, maar tussen

beide systemen zijn de fluctuaties verschillend. We vonden ook geen duidelijk verband met gedocumenteerde slibbronnen zoals zandwinning, storten van havenslib en dergelijke. Nader onderzoek zal moeten uitwijzen of dit binnen het systeem van de Waddenzee ook geldt, maar voorlopig zijn ook hier geen voor de hand liggende aanwijzingen voor directe menselijke invloed gevonden.
We hebben in deze studie geen aandacht besteed aan effecten van slib, zowel SPM als slibgehalte in het sediment, op ecologische processen. Dat is uiteraard een belangrijk deel van de studie als geheel, maar moet nog nader worden ingevuld.

Het omgekeerde, effect van ecologische processen op slibdynamiek, heeft aandacht gekregen in de vorm van onderzoek naar tijdsdynamiek van microfytobenthos in relatie tot de dynamiek van SPM en van slibgehalte in het sediment. Wij vonden dat de biomassa van het microfytobenthos ruimtelijk zeer sterk correleert met de verspreiding van slibgehalte in het sediment. We vonden verder dat de dynamiek van microfytobenthos in de tijd, zeker op seizoenale schaal, zeer sterk correleert met de dynamiek van SPM. Of dit op de langere tijdschaal ook zo is, blijft relatief onduidelijk omdat de tijdserie van microfytobenthos daarvoor te kort is. Het is anderzijds ook niet uitgesloten. We stellen dat microfytobenthos een belangrijk kandidaat is voor de veronderstelde 'bufferfunctie' die verantwoordelijk is voor het lange geheugen in het SPM.

Het belang van slib voor de morfologische evolutie op langere termijn, en zeker ook het belang van de 'kwelderwerken' daarin, kan helpen om de context van praktische problemen zoals het onderhoud van vaarwegen beter te begrijpen. Het kan ook aanleiding zijn om de doelstellingen van het beleid aan te passen, zoals het zoeken naar oplossingen op basis van gebruik van slib buiten het systeem. Daarvoor is echter nader onderzoek nodig.

Ook voor de verwachte effecten van versnelde zeespiegelstijging op de Waddenzee is de rol van slib in de morfologie van belang. Voorspellingen kunnen niet alleen gebaseerd zijn op zandtransport en -afzetting, maar moet ook de stabiliteit van kwelders en hun voorland bij zeespiegelstijging onderzoeken.

Begrip van de tijdsdynamiek van SPM helpt om de tijdschaal vast te stellen waarop doelen van de Kaderrichtlijn Water worden gedefinieerd. Het lange geheugen van het systeem suggereert dat die op de tijdschaal van een decennium moeten worden gesteld, en dat jaar-tot-jaar variaties inherent zijn aan het systeem. Vragen naar het effect van slib op het ecologisch functioneren moeten ook op die tijdschaal worden benaderd. Het lange geheugen van SPM in het systeem kan ook van belang zijn bij het bepalen van optimale strategieën voor het behandelen van baggerslib. Het terugstorten van dit slib kan aanleiding geven tot een verhoogde massa van SPM die lang in het systeem blijft hangen, wat misschien reden is te zoeken naar alternatieve behandelingen. Dit vergt echter nadere en nauwkeurigere studie.

## 1.9 Aanbevelingen

Wij bevelen aan om een aantal observaties uit te voeren die kunnen helpen om een beter inzicht te verwerven in de dynamiek van slib in de Noordzee en Waddenzee:

- routinematig niet alleen zwevend stof meten aan de oppervlakte, maar ook verticale profielen in samenhang met CTD opnames maken. Dit zou een relatief beperkte uitbreiding van MWTL kunnen vormen.
- een aantal permanente meetstations installeren in Noordzee en Waddenzee die over langere periodes de verticale verdeling van zwevende stof monitoren, en in verband brengen met stroomsnelheden en golfactiviteit.

- de beschikbare gegevens over microfytobenthos uitbreiden voor de periode 2008-2018. Dit kan gebruikmaken van bekende en uitgeteste methodologie.
- In een aantal stations van het SIBES programma met hogere temporele resolutie (maandelijks) het slibgehalte van het sediment opvolgen.

Daarnaast bevelen wij aan de huidige analyse op een aantal kritische punten nader aan te scherpen. De analyse van oude kaarten van slibgehalte van de bodem kan worden geformaliseerd in GIS en in groter detail methodologisch worden gekalibreerd. Beter gebruik maken van permanente meetstations met hoge resolutie, bv. in het kader van SEAWAD, zou het inzicht in processen op relatief korte termijn kunnen bevorderen, maar zou ook kunnen leiden tot inzicht in processen op de mesoschaal. Op de langere termijn bevelen wij aan nader te onderzoeken en te kwantificeren welke invloed de ‘kwelderwerken’ hebben gehad op morfologische ontwikkelingen in de Waddenzee.

Tenslotte bevelen wij aan om het bestaande modelinstrumentarium kritisch te onderzoeken op het vermogen om de gesignaleerde statistische patronen in de waarnemingen te reproduceren, en waar nodig aan te passen. Wij zijn van mening dat modelformuleringen op de mesoschaal noodzakelijk zijn, en dat deze testbaar moeten worden gemaakt in een vereenvoudigde ruimtelijke set-up, zodat de gevoeligheid van het model gemakkelijk kan worden onderzocht zonder beperkende rekentijden. Tenslotte bevelen wij aan een morfologisch model voor evolutie op de lange termijn te maken dat rekening houdt met de zand-slib interactie en daardoor beter in staat is de veranderingen in de Waddenzee, vooral langs de vastelandskust, te voorspellen.

# 2 Preface

This conceptual analysis is a follow-up of the memo ‘Mud dynamics in the Wadden Sea’ (Herman, 6 June 2018, in Dutch) that defined the main research questions of this project. These are:

Main Research Question
*How is the concentration of suspended sediment in the water, and the fraction of mud in the sediment, determined by anthropogenic and natural processes? How can the knowledge on mud dynamics be formalized in conceptual and computational models, and form the basis for the definition of management goals, as well as appropriate management strategies, in the framework of the Water Framework Directive?*

There are four subquestions:

1. *What are the dominant factors steering the dispersion of mud in the Wadden Sea in space and time and how are mud concentration levels in water and sediment related with those in the North Sea?*
2. *What is the residence time of mud in the Wadden Sea and what is the system response to pulses in mud supply?*
3. *What is the importance of mud on the ecological functions of the Wadden Sea?*
4. *What are appropriate strategies for mud management and coastline development in the Wadden Sea to improve the ecological quality?*

The present report is a first step towards a conceptual model for mud dynamics in the Wadden Sea. The conceptual analysis is based for an important part on a new analysis of suspended and bed sediment data as presented below and in the accompanying data analysis reports (De Vries, Dankers and Vroom, 2018) and Cleveringa (2018). However, also previous data analyses and model exercises have been taken into account. They are not discussed extensively in this report, but an overview of some recent examples of these studies has been presented in the previous memo.

The conceptual model resulting from this conceptual analysis is not at all meant as final, but rather as a vehicle for further discussion and development to gradually reach more focus and identify and clearly explain the best mud management strategies.

# 3 Introduction

In shallow coastal areas of partly estuarine character like the Wadden Sea, mud dynamics play a pivotal role in the morphological and ecological development of the system, as well as in the management of the system. Mud is an important component of the sediment, changing by its presence the erosion/deposition rates of the sediment, as well as the dynamics of the sandy fraction in the sediment. Mud content of the water column (the major fraction of 'Suspended Particulate Matter', SPM[1]) attenuates light in the water column, which is a primary driver of ecology in the system. Mud dynamics also influences management of the system, as mud deposits in fairways and harbours are an important management issue, involving dredging and dumping of considerable volumes of sediment.

The mud fraction of sediments has consequences for the morphological development of the system. Mud deposition contributes significantly to the total sedimentation in the Wadden Sea (Nederhoff en Smits, 2018). Where mud deposits are stabilized by physical or ecological processes, in particular in salt marshes, long-term deposition may take place that feeds back to the hydrodynamics of the system and thereby further influences erosion/deposition processes.

At the same time, the mud fraction in the sediment influences the habitat quality of this sediment for sediment-dwelling (benthic) organisms (e.g. Cozzoli et al., 2013). The mud fraction determines the stability of the sediment grains and with this the solidity of burrows and other benthic structures. It also co-determines the organic content as well as the nutrient and oxygen contents of the sediment, and it largely determines the possibilities for benthic algae biomass development. Ecological processes such as benthic algae growth, vegetation development, burrowing and faecal pellet deposition by benthic animals, in turn influence the mud content of the sediment and the longer-term stability of mud deposits. Ecological and morphological processes therefore mutually influence each other.

Suspended mud in the water column is the major influence on light attenuation in the Wadden Sea. Although algae in the water column are nutrient-limited during late spring/early summer, light limitation is the most important factor determining primary production during most of the year. Thus the light climate in the water column has direct consequences for the base of the food web in the ecological system, but through this process also on the major biogeochemical fluxes in the system, e.g. oxygen production and consumption, organic matter cycling, nutrient and carbon cycling.

There is a direct link between suspended mud in the water column and mud stored in the sediment, but the relation is skewed as the total mass of mud suspended even in a deep water column, is only a tiny fraction of the mud stored in the underlying sediment. Moreover, gross exchange fluxes between sediment and water column during a tidal cycle, are much larger than net exchanges integrated over the tide. The same is true for exchanges of mud into and out of the Wadden Sea: gross fluxes are at least an order of magnitude larger than net exchange. These discrepancies make it extremely difficult to assess what determines the

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[1] *'Suspended Particulate Matter' is operationally defined as all material suspended in the water column that is retained on a glass fibre filter. It includes organic (living and dead) as well as inorganic material. In the Wadden Sea and in most stations of the North Sea the inorganic fraction is largely dominant. Most of it is fine-grained and can be classified as mud (grain size below 63 micrometer).*

mud concentration of the water column at short and long timescales, and how it relates to mud content in the sediments.

In this report we analyse some of the available empirical data on mud dynamics in the Wadden Sea and surrounding marine systems. The analysis is based on long-term observations of suspended mud in the water column, as well as on long-term changes in observed mud distribution in the system at high spatial resolution. The focus is on understanding the statistical properties of the observations, and on determining the type of functional relationships that can be expected to govern mud dynamics in the Wadden Sea. Ecological effects of mud are not exhaustively studied, as these will be the subject of separate projects. We focus here on those processes that might be involved in important feedback relations, such as stabilisation of mud deposits that can influence morphology and hydrodynamics. The overall aim of the analysis is to improve understanding of processes in order to improve management. We take these relations into account, but generally do not provide the necessary quantitative detail to directly underpin management decisions. Rather, this analysis aims at providing guidance for more detailed quantitative and modelling studies in the rest of this project.

The report is structured as follows. In a first chapter, we explore relevant statistical properties of the time series of SPM in the Dutch MWTL monitoring stations. All available series of sufficiently long duration, and ending not earlier than 2000, were used. In a next chapter we discuss the available data on mud content of the (intertidal) sediments in the Wadden Sea. This analysis is largely based on the recently assembled SIBES data set, but also takes into account older (and very old) data. The emphasis is double. For small-scale variation in space and time, we mostly concentrate on the results of the SIBES data set and its statistical characteristics. For long-term changes we compare available overviews of sediment mud content between 1890 and now, and discuss major changes as related to the morphological development of the Wadden Sea. A next chapter adds information on microphytobenthos distribution in the Wadden Sea, as this may constitute an important biological control on mud dynamics in the sediment surface.

After presenting the different analyses and the results, we devote the last chapter to a discussion of possible regulation mechanisms of mud dynamics in the Wadden Sea and propose a conceptual model hereof. In this chapter we indicate subjects for further study in the rest of the project, and also indicate possible management importance of some of the findings or questions raised in this report.

# 4 Statistical properties of time series of suspended matter concentration in Dutch coastal waters

## 4.1 Introduction

In the framework of the Dutch national water monitoring programme MWTL, SPM was monitored since the start of this programme in the 1970s. In the first years several methodological changes disrupted the time series. We have restricted the analysis to the time series since 1989.

Our main interest in the analysis is the detection of the statistical properties of the series, such as the type of statistical distribution of the measurements, the relative contributions of seasonality, long-term trend and stochastic variation and the similarity between the series within water bodies (e.g. Wadden Sea) and across these water bodies. The major questions behind this analysis are technical on the one hand and conceptual on the other hand. Technical questions relate to the best methods to statistically treat the data, e.g. accounting for log-normality and the presence of autocorrelation. We also investigated the levels of variation that can be observed at different scales of time and space. Conceptual questions relate to the major mechanisms explaining variation over time in the series, and on the coherence of the time series obtained in several sampling points in different water bodies.

## 4.2 Methods

All available MWTL SPM measurements were downloaded as netcdf files from the OpenEarth Repository. Only series with a sufficient time coverage, and an end date not prior to the year 2000 were selected. The different sampling points were assigned to different water bodies. For the Wadden Sea we also included stations in the Ems-Dollard, as these appeared in general to be rather similar to the series in the Wadden Sea proper.

All basic observations were log-transformed for reasons explained in the results section.

Observations were averaged per year and month in order to have as regular a spreading of observations as possible. Months without observation were treated differently according to the analysis. For the calculation of moving averages, missing observations were neglected. This can have biased the results slightly as in some years a month may be missing, but it does not introduce artificial estimates into the time series. For the more elaborated time series decomposition and analysis of autocorrelation, missing observations were imputed with a simple decomposition algorithm. Observations are assumed to be the sum of a year effect, a month effect and a random error. Missing observations are replaced by the sum of the average of the year and month to which the observation belongs. The algorithm then recomputes yearly and monthly averages and repeats the replacement until convergence is reached.

Time series decomposition into a seasonal component, a year-scale trend component and a random error term was performed in a non-parametric analysis using lowess smoothers to derive the components. Lowess smoothers are locally weighted smoothers, i.e. trend functions that are mainly determined by the values in the neighbourhood: a trend value at, e.g., 2012 is mostly dependent on the values in the range 2010-2014, and much less by earlier or later values. The exact weighing, i.e. the length of the period determining the trend value, is an adaptable parameter. This approach is in contrast to a parametric decomposition, where the seasonal and trend components are given a fixed functional form (e.g. a sine wave for the season, or a linear form for the trend). The advantage of the non-parametric approach is that the data can determine the form of these components. A slight disadvantage is that the method is not fully orthogonal, i.e. the three components are not fully uncorrelated to one another. Because of this, the sum of the variances of the three components is not exactly equal to the variance of the original series, but the deviation is usually small (note that, in general, the variance of a sum is only equal to the sum of the variances of the components if these components are not correlated to one another).

## 4.3 Results

### 4.3.1 Log-normal distribution of observations

A striking statistical property of the observations is that they are very close to a log-normal distribution, and that moreover the variance of the log-transformed observations is remarkably constant across sampling points, even if the average values differ widely. Figure 1 illustrates the distribution of sample values in three different stations that span the range of average concentrations. The station with the highest average concentration has a back-transformed average concentration (which corresponds to the geometric mean of the original concentration values[2]) of 124 g.m$^{-3}$, whereas at the other extreme the station with lowest concentration just reaches 1.9 g.m$^{-3}$ for this average. Nevertheless, the variances of the sample distributions are very similar, and the form is quite regular and symmetric. There might, however, be some influence of the detection limit in the distribution of the values at the station with low concentrations. Across all sampling points in the MWTL monitoring program, the standard deviation of the log-transformed values ranges between 0.4 and 0.8.

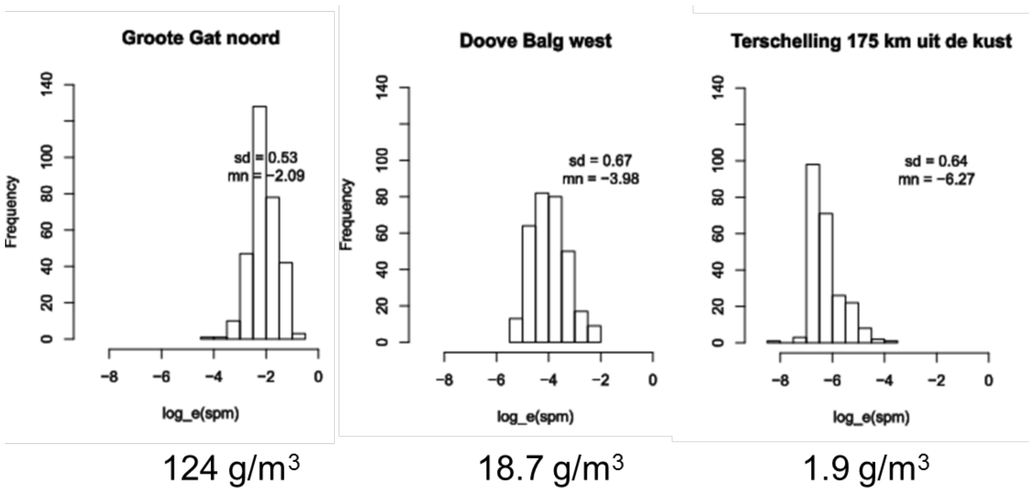


*Figure 1. Three examples of (natural log transformed) sample value distributions of SPM (mg/l), for stations that differ widely in geometric mean concentration (indicated below the figures), but with approximately similar standard deviations.*

[2] *The geometric mean of a series of n observations is defined as* $= (\prod_1^n x_i)^{\frac{1}{n}}$ *. The logarithm of the geometric mean is thus equal to:* $log(GM) = \frac{1}{n}\sum_1^n log(x_i)$*, which is the mean of the log-transformed observations. Back-transforming the mean of the log-transformed observations therefore yields, by definition, the geometric mean of the observations.*

The log-normal distribution of sample values suggests that the major factors influencing SPM concentration are multiplicative rather than additive. Data tend to be normally distributed when they are the result of many contributing factors with a more or less similar variability, under the condition that these factors operate in an additive way: the observation is the result of summing the different contributions. When the factors contributing to an observation operate in a multiplicative way, the resulting observations will not be normally distributed. However, as log(a*b)=log(a)+log(b), a multiplicative relation is transformed into an additive one by log-transformation. It follows that, when many factors contribute to an observation in a multiplicative way, the observations will tend to be log-normally distributed. In reverse, the observation of a log-normal distribution of values leads to the conclusion that the underlying processes are generally operating in a multiplicative way. This appears to be the case for SPM concentrations.

We conclude from this (and similar - see below) observations that the time series of SPM should always be studied after log-transformation, as this is much more likely to result in the observation of some of the causal factors determining the series.

### 4.3.2 Patterns in mean SPM concentration

Whereas the standard deviation of the distributions of SPM values is remarkably constant, the mean varies largely with station. Within the North Sea transects (off Zeeland, off Noordwijk and off Terschelling), depth of the water column appears to be a master variable determining the (geometric) mean concentration. More precisely, the geometric mean concentration depends linearly on the logarithm of depth, as was earlier described by Eleveld et al. (2008) Figure 2 shows this dependency for the North Sea stations. For comparison, the stations in the Wadden Sea are also added to this graph, with an artificial depth of 5 m. Most Wadden Sea stations have a mean concentration well above that of the North Sea levels, but the difficulty in the Wadden Sea is that it is not very obvious what depth to use. SPM in a channel station, e.g., is also influenced by processes in the intertidal and thus the depth-related processes are relatively undetermined.

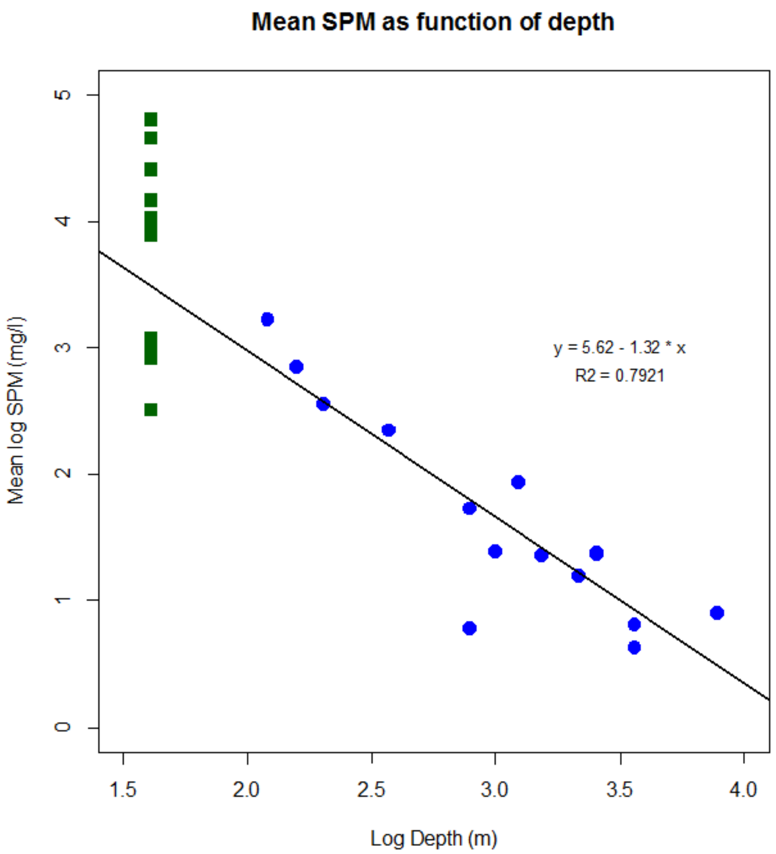


*Figure 2. Mean SPM concentration after natural log-transformation versus natural log of the station depth for North Sea stations (blue dots). The regression equation is valid for these points. For comparison, Wadden Sea stations are added as green squares.*

### 4.3.3 Similar seasonal cycles across stations

All time series of SPM are characterized by seasonal cycles, with winter values exceeding summer values. These seasonal factors also appear to be multiplicative. When expressed relative to the overall mean, the monthly multiplication factors of the different series (ranging from high-concentration inner estuary sites to low-concentration sites far offshore) remarkably coincide. Most of the common variation can be represented by a single simple periodic function (Figure 3). However, a plot per water body (where the North Sea stations have been divided into North, Middle and South regions) show that some systematic deviations by region occur. The southern part of the North Sea seems to have a higher amplitude than average, and so is the suggestion for the Wadden Sea. Both systems also show some phase difference, with highest values tending to fall in February rather than January, and lowest values in May-June, rather than July. Other systems, such as the middle part of the North Sea and the Oosterschelde seem to have slightly lower seasonal amplitude. However, by and large the overwhelming impression is that of similarity, despite the very different nature of these systems.

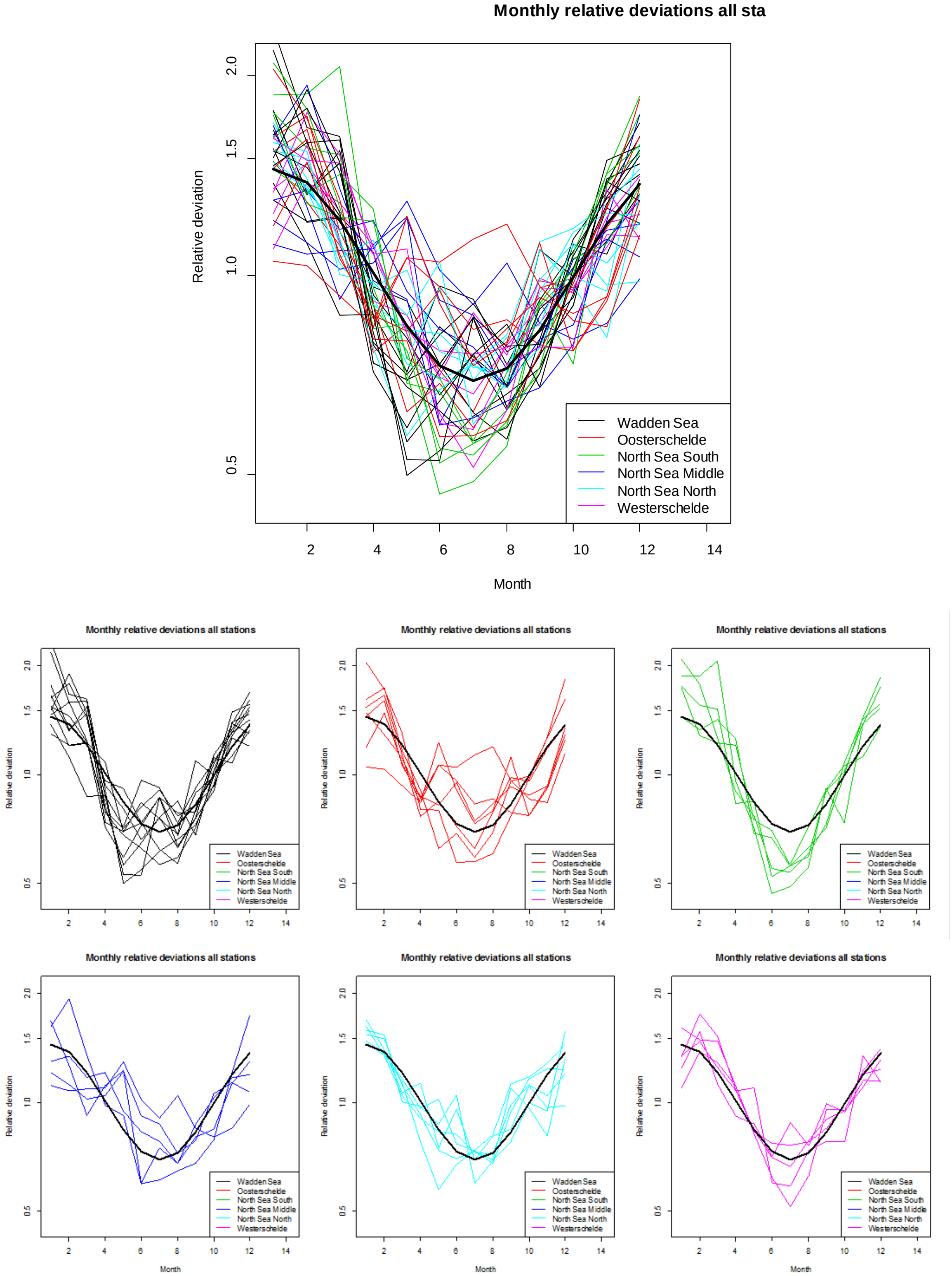


*Figure 3. Monthly relative deviations from the long-time average concentration of SPM in the different systems of the Netherlands continental shelf. The top figure compares all systems. The figures below concentrate on one system only in order to better reveal differences between the station groups. The thick black line is a fitted periodic function and is the same in all graphs.*

In shallow coastal systems, the seasonal pattern can be ascribed to a seasonally shifting balance of mud exchange with the sediment, as a consequence of shifting wave activity and probably also biological activity. This cannot explain, however, the similar seasonal pattern in the offshore deeper stations, where direct resuspension from the sediments can be assumed to be rare. However, as the samples are taken near the surface, it is possible that the seasonality in the series is caused by sinking of particles in stratified deep water columns, and remixing upon termination of the stratification. This could also be partly biologically mediated, as algae can be agents in the flocculation/sinking of mud particles. Alternatively, advection of particles from shallower places may also explain the seasonal cycle in offshore stations. Seasonal cycles could also be observed if phytoplankton cells were the dominant component of the suspended particulate matter (i.e. SPM is primarily organic). However, this would give rise to peaks in spring and summer, not to troughs in that period.

Excluding dominance of living particles in the SPM mass, we can conclude that whatever the dominant mechanism, particle settling velocity in the deep stations must be extremely small, in order to maintain non-zero concentrations over prolonged periods of time. This is confirmed by results from the ZUNO-DD model, a numerical SPM model for the North Sea. Observed offshore concentrations of 1-2 mg/l are only reproduced by the model if a very slow settling sediment fraction is added.

#### 4.3.4 Yearly-scale variations caused by generally elevated or depressed values, not by outliers

When decomposing the time series into a seasonal, long-term (yearly-scale) non-linear trend and a remainder variation, the pattern is quite similar for all time series. The seasonal component, as argued before, is relatively similar across time series, and essentially the same is true for the other two components. Yearly-scale trend values are typically varying between half the long-term average and twice the long-term average. The remaining short-term variation has a slightly larger range, from roughly 1/3 to 3 times the long-term average. Figure 4 illustrates the decomposition for the station Dantziggat. It also shows the deseasonalized series (obtained by subtracting the seasonal component from the original series), as well as the observed autocorrelation function of this deseasonalized series. Both the original time series and the deseasonalized series show that the years with high yearly-averaged SPM contents (e.g. the years around 2010) do not show these high yearly averages because of exceptionally high peak concentrations. The primary reason for high yearly averages is that the lowest values are considerably higher than those of other years. The lows, rather than the highs, therefore determine the yearly-scale trend. This can also be seen in the ‘remainder’ variation: the range of this variation does not increase with the yearly-scale trend (i.e., the residue is stationary). A formal test for stationarity indeed confirms that the distribution does not change in time. It can also be observed in the time series that yearly-scale periods of high concentration are not preceded by exceptionally high values in the observations. The highest peaks are found in the 1990s, and are usually followed by a steep decline rather than an extended high. However, peaks in SPM are known to be of short duration (order of days) and could be missed in the sampling programme, especially as they tend to occur during bad weather when observation is difficult. The pattern is general throughout all series, however, suggesting that it is unlikely that extended periods of high concentration are caused by exceptional events with a long trace in the concentration series.

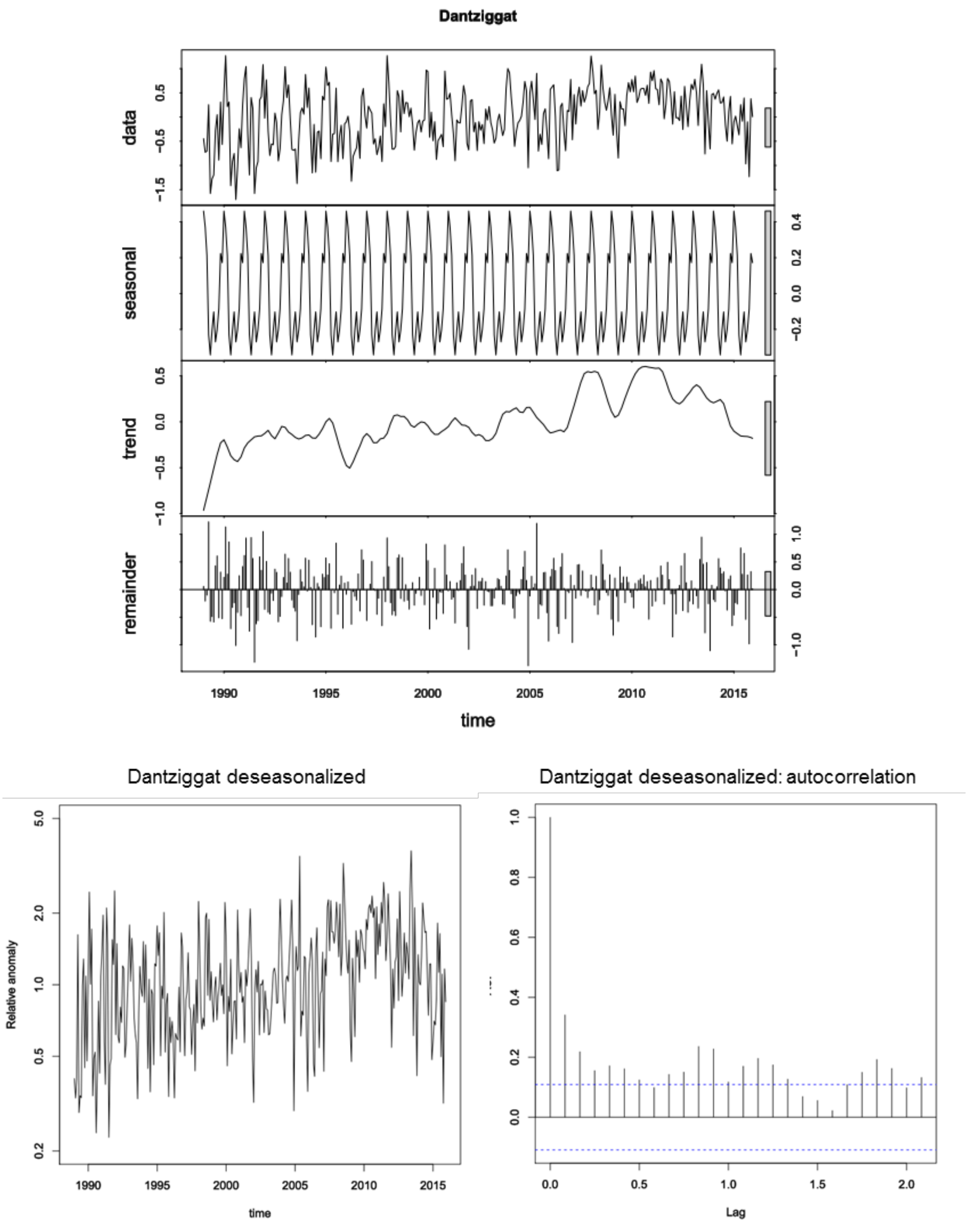


*Figure 4. Decomposition of the (log-transformed) time series of SPM at Dantziggat into a seasonal, yearly-scale trend and remainder component. The deseasonalized series and its autocorrelation graph are shown below.*

The autocorrelation graph shows, for Dantziggat as for most other stations, that there is temporal autocorrelation over considerable periods of time, up to over one year. An autocorrelation graph essentially shows the correlation between all observations and the observations some time (the “lag”) earlier. Thus the autocorrelation with lag 1 month (1/12 year) shows the correlation of all observations with the preceding observation. The autocorrelation with lag 2 months (1/6 year) is the correlation of all observations with the observations 2 months earlier. Autocorrelation values are significant in this figure if the values exceed the blue dotted line. Significant autocorrelations are found up to considerable lags, even exceeding one year. This conclusion contrasts to that of Blaas and Van den Boogaard (2006) who state that apart from seasonality, autocorrelation in SPM time series is restricted to the spring/neap tidal cycle. The discrepancy in results is most likely due to the log-transformation of the series in our analysis, while Blaas and Van den Boogaard worked on raw observation values that are much more dominated by the rare but very high spikes. A long autocorrelation time is consistent with the existence of a significant yearly-scale trend. It is a remarkable observation, as most processes determining SPM in the water column, such as erosion and deposition, operate at much shorter time scales (tidal to spring/neap tide scale) and seasonal effects (both biological and wind-driven) have been filtered out. Also advective exchange (of water) between the Wadden Sea and the North Sea has a time scale of weeks only. However, advective exchange of mud can have much longer time scales, because large quantities of mud are stored within the bed. Based on tracer studies, it is estimated that the residence time of mud in the Dutch coastal zone is multiple years (Van Kessel et al., 2012, Laane et al., 1999).

### 4.3.5 General patterns in decomposition of North Sea stations

Within the North Sea stations, but excluding Haringvlietsluis, Maassluis and IJmuiden as these show different behaviour and are probably strongly influenced by freshwater discharge, we can find some systematic pattern in the decomposition of the series.

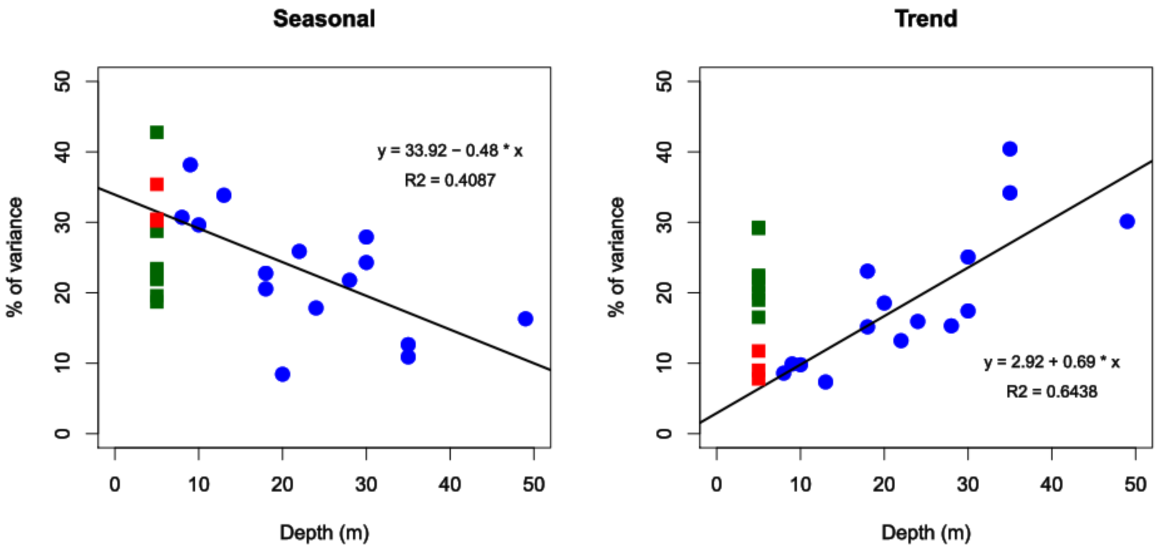


*Figure 5. Fraction of the variance of the time series explained by season (left) and by trend (right) as a function of station depth in the North Sea stations. For comparison, the fractions in the Wadden Sea stations are plotted versus a depth of 5 m. In general, the contribution of trend increases and the contribution of season decreases with increasing depth. Wadden Sea stations, indicated in green, have a strong contribution of trend and a weaker contribution of season, comparable to relatively deep (20-30 m) stations in the North Sea. Coastal Wadden Sea stations are an exception to this tendency (indicated in red, see text for details).*

We expressed the variance in the seasonal and trend components relative to the total variance in the series, and plotted these versus depth of the sampling stations. The relative variation in the seasonal component is stronger in the shallow waters of the Zeeland transects, as well as in the shallow onshore stations of the Noordwijk and Terschelling transects, compared to the deeper offshore stations. The reverse is true for the trend. Only small fractions of the variance are explained by trend in the shallow stations. This fraction increases with increasing water depth. The relations are shown in Figure 5. Also indicated in these figures is the position of the Wadden Sea stations, which were assigned an artificial depth of 5 m. In the Wadden Sea there are three stations (Zoutkamperlaag zeegat, Zoutkamperlaag and Vliestroom, all three located at the transition with the North Sea, that show characteristics more similar to North Sea inshore stations than to the other Wadden Sea stations. All other Wadden Sea stations have a much stronger trend than the shallow North Sea Stations. The seasonal component is variable, but generally comparable to the strength of the seasonal component in the deeper (20-30 m) stations in the North Sea.

### 4.3.6 Coherent trends in SPM across sites within a system

Within spatially contiguous groups of stations the multi-year trends of SPM are usually coherent, but across station groups no clear pattern of coherence, time lags or other structure can be seen. Within the Wadden Sea and Ems (Figure 6) most time series are coherent, but Zoutkamperlaag and Zoutkamperlaag zeegat (and to a lesser extend Vliestroom) seem to be exceptions. It is possible that the closure of the Lauwersmeer still has noticeable influence on the Zoutkamperlaag series, but we also observed that these three series have statistical properties that are more similar to North Sea coastal stations than to Waddenzee stations.

At the same time comparison across systems (Figure 7) shows that the patterns in these different systems differ in timing, extent and form, without any clear indication of a correlation between them.

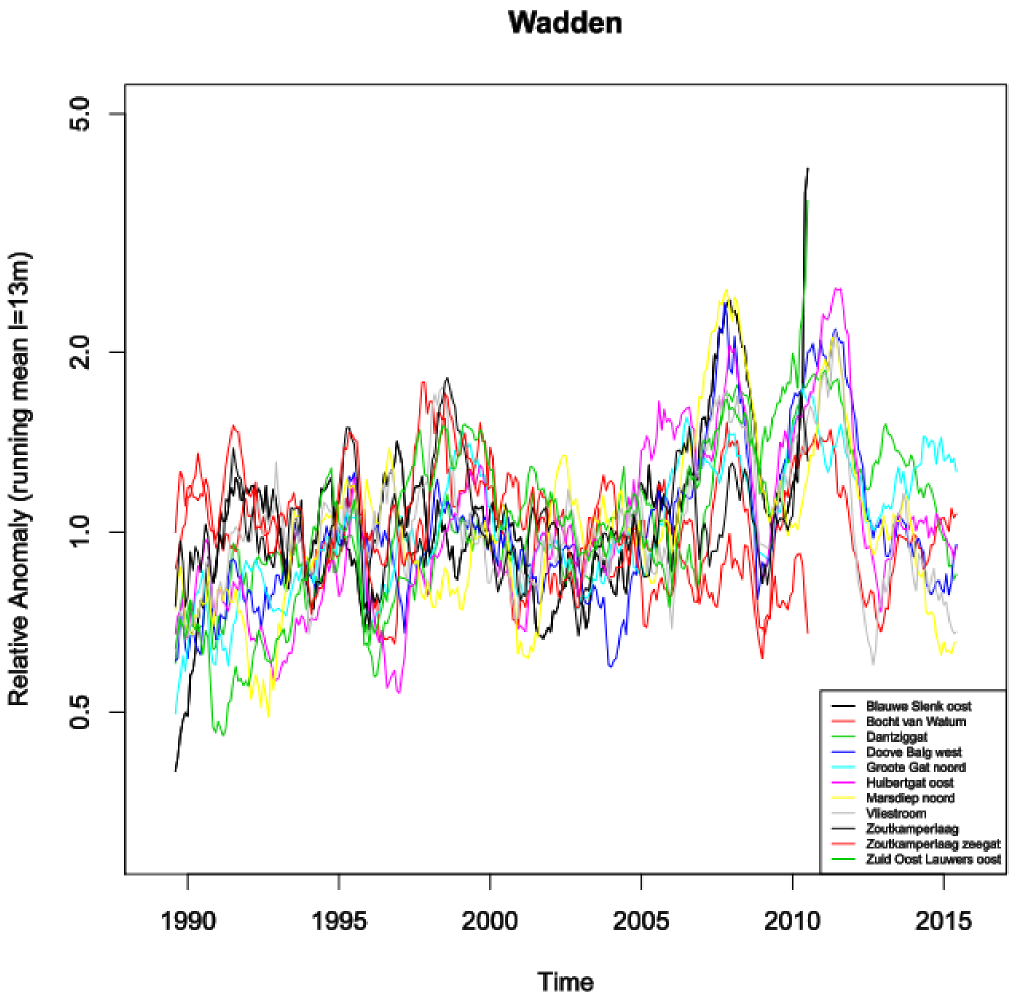


*Figure 6. Long-term trends, here expressed as 13-month moving averages, in SPM content at different sampling stations in the Wadden Sea. The trends are expressed relative to the long-term average SPM of the different series.*

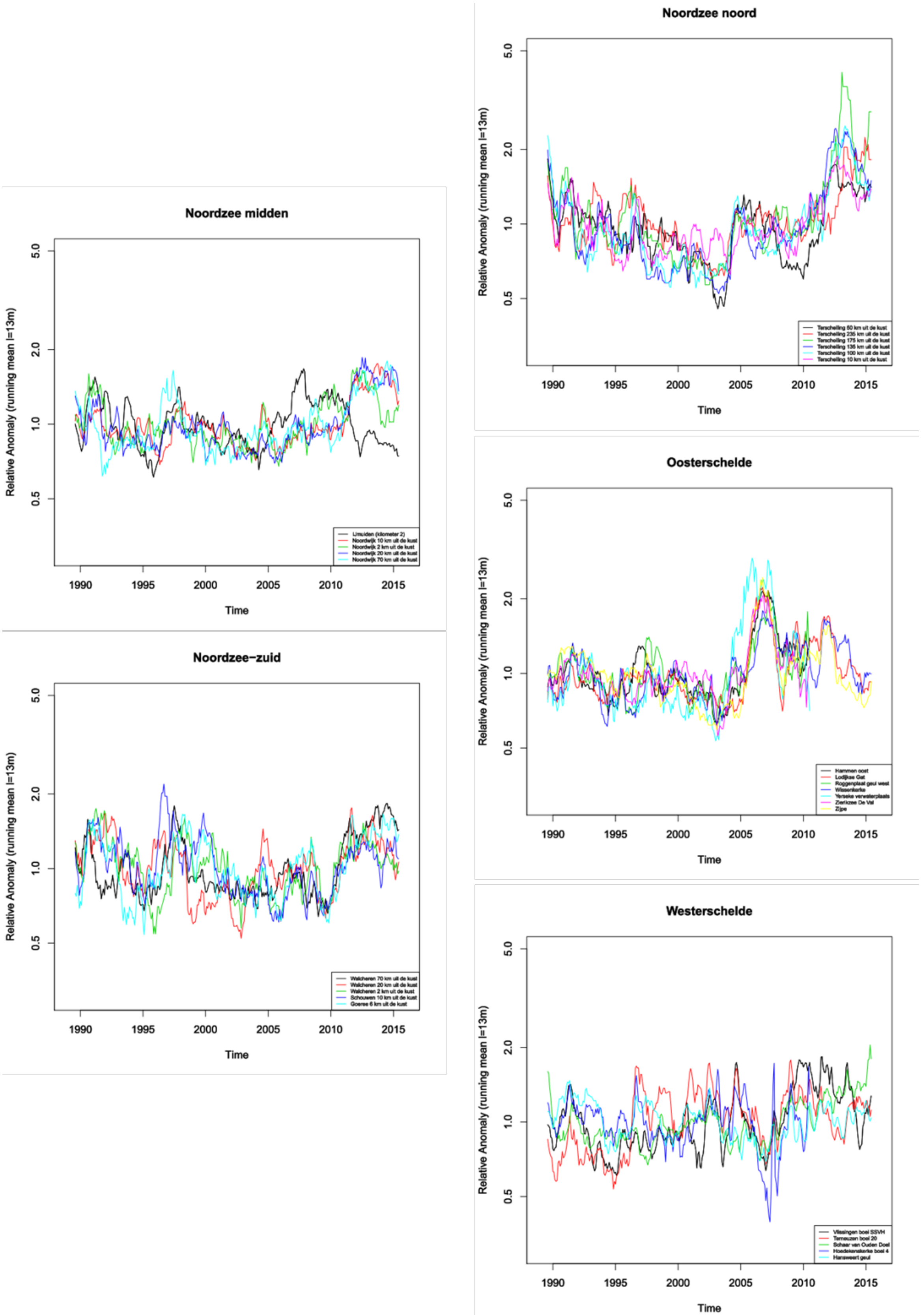


*Figure 7. Long-term trends, expressed as 13-month moving averages, in different subsystems of the Dutch coastal waters.*

The most striking features in the coherent pattern in the Wadden Sea are the high concentrations (double the long-term average) in the years 2007-2008 and 2011-2012. We have found no obvious explanation for the pattern. It differs in timing and form from patterns found in other water systems, and cannot be explained by advection of ‘plumes’ of SPM from elsewhere. We argued earlier that there is long autocorrelation in SPM series, probably as a consequence of relatively long times required to stably accommodate mud once it is in suspension. From the coherence of spatially contiguous time series, we conclude that the processes causing elevation in the SPM levels must also have a relatively large spatial scale, such as large-scale disturbances or, more likely, weather patterns. However, as the horizontal dispersion of mud is fast (tidal excursion in the order of 10 km within a single tide), it cannot be excluded that local processes have a large-scale imprint. Therefore, a source or sink for suspended mud should not necessarily be spatially homogeneous over a large area in order to produce large-scale coherent trends in time. It would suffice, for instance, that mud-rich sediments (mostly at the mainland coast in the Wadden Sea) undergo a slightly elevated resuspension, in order for the SPM to rise in the whole of the Wadden Sea.

Although we investigated possible causes in human activities, we have been unable to find any correlation in time and space of elevated trend values in SPM and activities such as sand mining, mud dumping or other practices.

# 5 Spatial and temporal patterns in mud distribution in Wadden Sea intertidal sediments

## 5.1 Introduction

Interest in the spatial distribution of mud in the Wadden Sea intertidal sediments dates back to the nineteenth century, and has given rise to several extended data sets that allow comparison of trends over time.

Originally, the interest in mud distribution was inspired by the plans for land reclamation in the Zuiderzee and possibly also in the Wadden Sea. The first synoptic map of mud distribution was produced by Lely in 1892, as part of his function as head of the technical services of the Zuiderzeevereniging. We have scanned and color-coded the resulting map in this report. The map was the scientific-technical basis for the decision not to reclaim the Wadden Sea but to restrict efforts to the Zuiderzee, as the sandy soils in the Wadden Sea would yield very poor agricultural soils. Later, when the closure of the Zuiderzee was completed, the Rijksdienst voor de Zuiderzeepolders continued contemplating plans for reclamation of the Wadden Sea. In the 1950s, an extensive survey of sediment quality was performed. It was only published by de Glopper in 1967. The map was based on extensive samples, taken approximately every 1000 m across the intertidal area of the entire Wadden Sea. It essentially yielded the same result (poor agricultural soils), but was part of an effort to better understand mud dynamics in the Wadden Sea. Classic studies, e.g. by Postma (1954), van Straaten (1954), Kamps (1956), have contributed greatly to the understanding of the physical and biological mechanisms of mud transport into and out of the Wadden Sea. This knowledge was applied when designing the ‘kwelderwerken’, attempting to create mud-rich deposits along the mainland coast of the Wadden Sea, that could profitably be reclaimed and used as clay-rich agricultural soils.

Later efforts to map mud distribution in the Wadden Sea were mostly related to ecological questions, as mud was increasingly recognized as one of the main driving factors for the distribution of benthic animals, including shellfish, in the Wadden Sea. Zwarts (2004) has summarized many of these data. The period witnessed strong methodological innovations with the introduction of particle sizers (Coulter, Malvern), but also strong methodological problems in comparing several data sets. Zwarts (2004) has spent considerable effort in trying to reconcile different data sets, but was not entirely successful in the endeavour. The map he produced has been based on the methodologically most reliable data available.

In comparison with the historical sources, the availability of the SIBES dataset with approximately 4500 samples taken yearly at 500 m distances during the years 2008-2013 presents some new possibilities. The large database allows probing the statistical characteristics of the data, check for the consistency of distributional patterns and examine year-to-year variability at the scale of the entire Wadden Sea.

In our analysis we will first focus on small-scale spatial and temporal variations, as revealed in the SIBES data set. Next, we will also pay attention to the large-scale long-term changes by comparing four different data set spanning 125 years.

## 5.2 Methods

The methods used to analyse the SIBES data set, as well as the full set of results and graphs, are presented in De Vries et al. (2018). In short, data were collected from the top 5 cm of the sediment and analysed by Coulter particle sizer. The resulting data set was log-transformed and grouped by year and tidal basin. Some very low values appeared to be influenced by detection limits and were statistically aberrant. They were removed from the dataset prior to analysis of means and variances, as they produced artefacts in the results.

## 5.3 Results

### 5.3.1 General spatial pattern

Based on the SIBES data between 2008 and 2013, a map of average mud content of the sediment was produced (Figure 8). The map shows limited resolution in the low range of mud content, but after log-transformation this variation is much better displayed. This type of mapping corresponds to historical traditions, e.g. the map of de Glopper (see below).

The major patterns shown in the map are the relatively high mud concentrations in stations close to the mainland coasts, in the Dollard and Balgzand areas, across the tidal divides and, to a limited extent, in some pouches close to the southern shore of the islands. The latter places are usually close to saltmarshes, where mud deposition occurs.

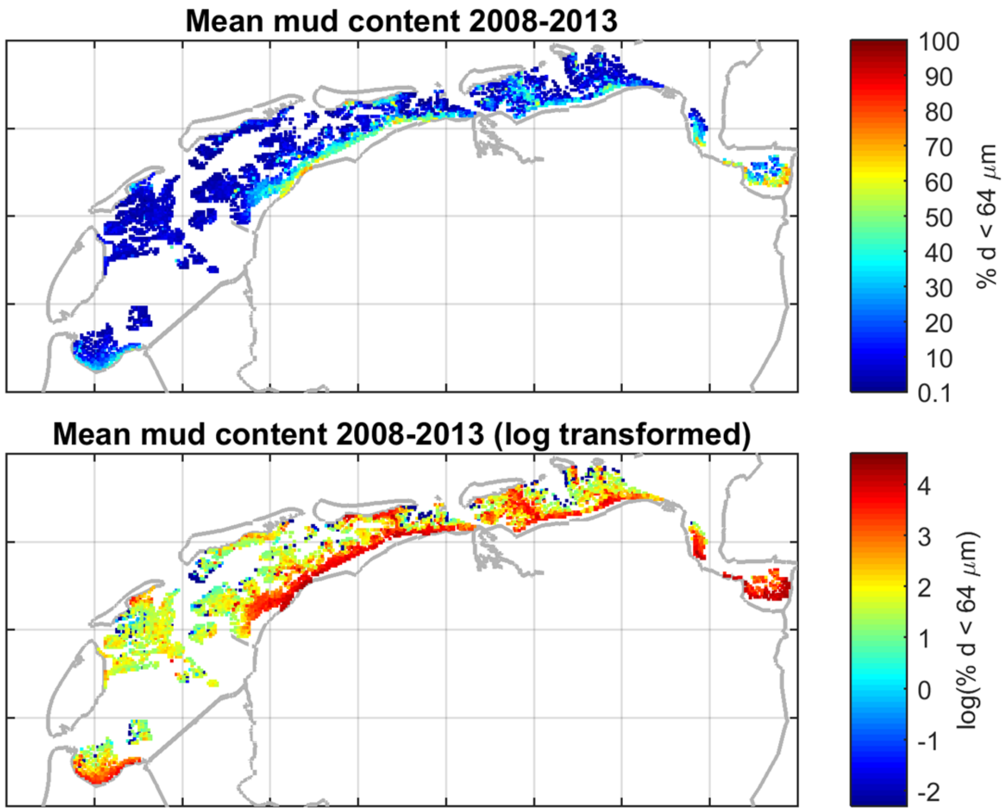


*Figure 8. Map of the mud percentage in the sediment of the intertidal Wadden Sea, based on the SIBES campaigns of 2008-2013. Untransformed values (top) and natural log-transformed values (bottom) are shown.*

### 5.3.2 Statistical distribution of observation values

After elimination of some problematic data with very low values (see De Vries et al. 2018), the statistical distribution of the values of % mud (<63 µm) shows two striking features. First, the observations show a clear bimodality (Figure 9). There are many low observations (range 2-7 %, mode 4.5 %) and many high observations (range 20-50 %, mode 35 %), but fewer observations in between.

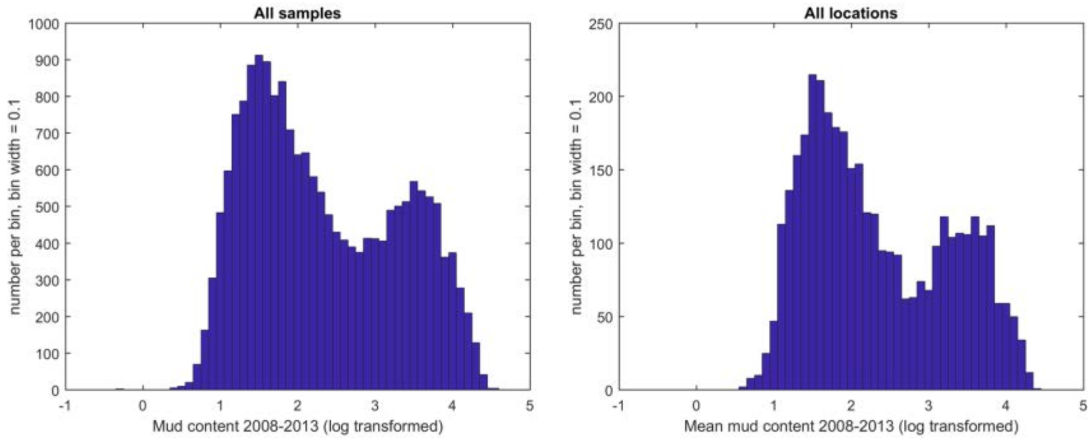


*Figure 9. Statistical distribution of the observed values of sediment mud content in the SIBES data base (left) and of the station means over the period 2008-2013 (right). Values (%) were natural log-transformed. Very low observations close to detection limit (< 0.1%) were discarded.*

The bimodality is even more expressed in the distribution of the station temporal means (Figure 9 right). This indicates that some of the observations falling in between the two modes tend to belong to stations with an average that is closer to one of the modes.

Second, if we plot the variability of the observations per sampling point over the years 2008-2013 (calculated as the standard deviation of the log-transformed observed values) versus the mean of this point over the same period (Figure 10), we observe that stations with a mean close to the modes of the statistical distribution (either low or high) are relatively stable in time, whereas the more rare observations with a mean in between the modes tend to have a higher standard deviation. Simulations show that this pattern is not an artefact following from the nature of the bimodal distribution, but reflects a true pattern in the data. The standard deviation in this graph is reflecting variability over time (the different samplings in the period 2008-2013). Low standard deviation therefore corresponds to stability, or at least constancy in time, whereas high standard deviation corresponds to relatively larger temporal variations and could indicate instability of the condition.

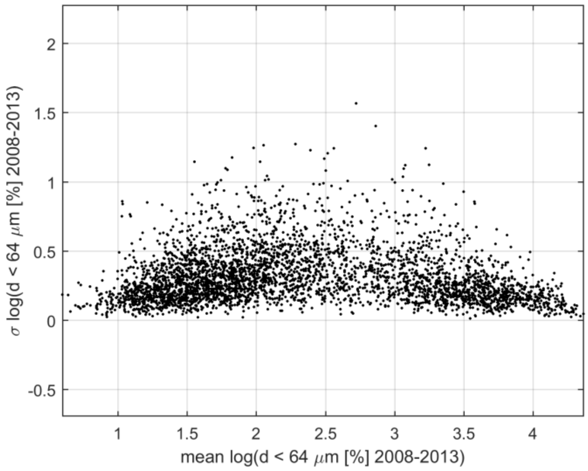


*Figure 10. Relation between standard deviation over the time period 2008-2013 and mean of the log-transformed mud content observations per sampling point.*

From the particular correlation between mean and variability, as shown in Fig. 9, it can therefore be concluded that the modes are associated with temporal constancy, but that sediments with a mud content in between the mode tend to switch to either of the modes. We suggest that this reflects the stability of the different states, where both modes can be characterized as stable conditions, whereas in between the modes instability is more likely.

### 5.3.3 Temporal changes of mud content over the period 2008-2013

Figure 11 illustrates the temporal variation of the sediment mud content as derived from the SIBES samples. The temporal variations are small, approximately a year-to-year variation of 10-15% of the long-term mean mud content. They are correlated between the different tidal basins of the Wadden Sea, although some variation is inevitable. This leads to the conclusion that temporal variation in sediment mud content across the Wadden Sea is regulated by relatively large-scale causes and is not very dependent on local conditions. The local scatter that is obviously present does not have any apparent structure.

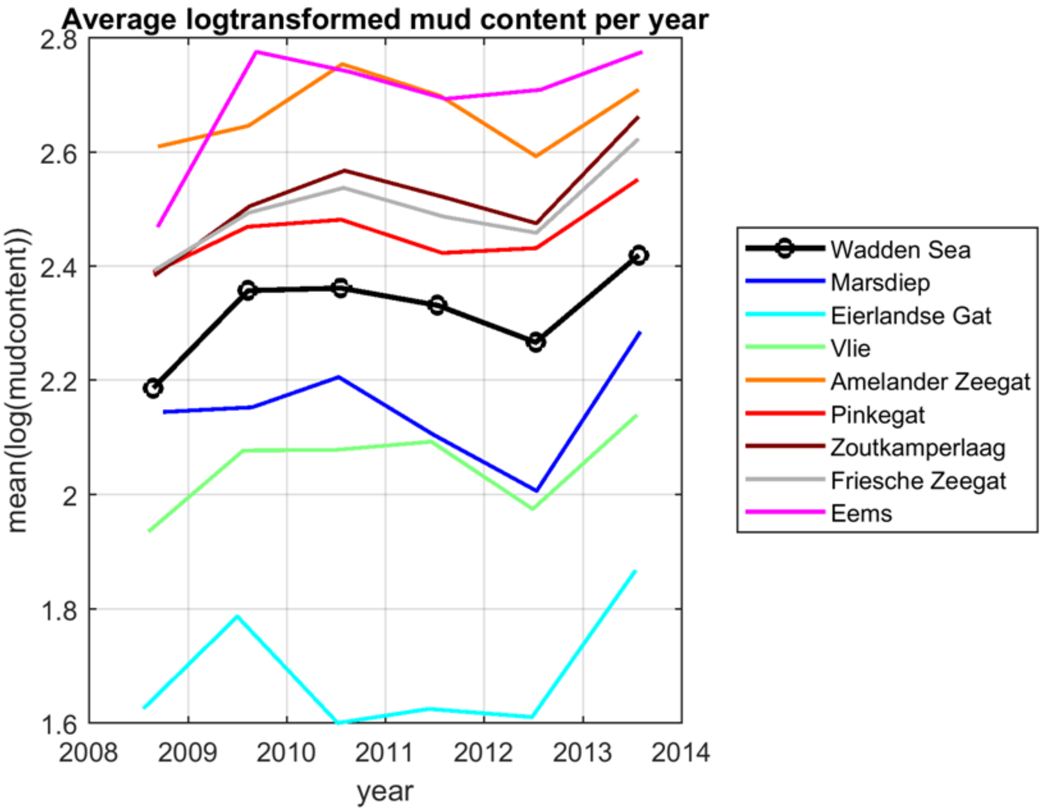


*Figure 11. Temporal variation over the period 2008-2013 in average mud content of the sediment in the different tidal basins of the Wadden Sea. Means are calculated after log-transformation. The different tidal basins differ in the mean mud content of their sediments (see also the map in Figure 8), but the relative temporal pattern is similar.*

When looking for a correlation between average mud content of the sediment and SPM in the water column, it is important to take the time lag into account. Sediment samples are taken in summer, whereas SPM is sampled year-round. Two possible causal mechanisms could be envisaged: high SPM in winter means much mud availability in the water column for incorporation into the sediment, and cause high mud content in the following summer. This would mean correlation between SPM centered around the preceding winter, and mud content in the following summer. Alternatively, high mud content in the sediment during summer might mean high availability of sediment to be resuspended in the next winter, causing a correlation between sediment mud content in summer and SPM in the period centered around the following winter.

Neither of the two hypothesis yields a very strong correlation in the data, but the second hypothesis, relating summer mud content of 2008 to SPM centered around winter 2008-2009 is clearly better than the first one (Figure 12). At least the two lows in mud content and in SPM seem to coincide approximately with this time shift. This mechanism would implicitly assume that the amount of mud available for incorporation into the sediment is not limiting, but that the summer conditions determine how much of it is effectively fixed, which in turn determines how much can be resuspended during the following winter. However, it is likely that the real interaction between mud content of the sediment and SPM in the water column is more complicated than the simple hypotheses put forward, resulting in the rather poor observed correlation.

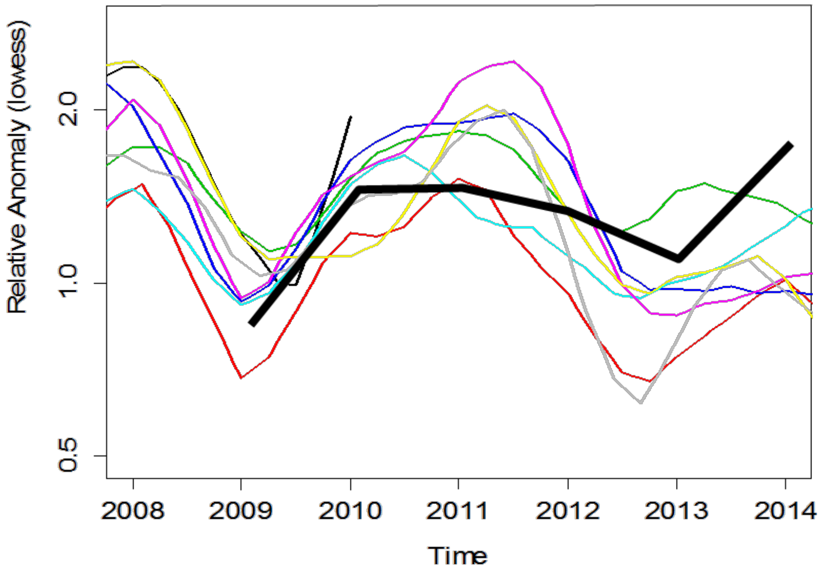


*Figure 12. Long term trends in SPM concentration of the different MWTL stations in the Wadden area, after removal of the stations Vliestroom, Zuidkamperlaag and Zuidkamperlaag zeegat. These trend values are compared with the average mud content of sediments in the entire Wadden Sea (thick black line) after the latter has been shifted by half a year (displaying the value of summer 2008 in the middle of the winter 2008-2009).*

There must be an interaction between SPM concentration inside and outside the Wadden Sea and the quantity of net import. There should also be a relation between SPM concentration and the rate of incorporation of mud into the sediment. Upon resuspension mud content of the sediment will in turn influence SPM. The number of causal pathways is thus large, and it is unclear what pathways dominate. We are convinced that further investigation of these relations requires a process-based modelling approach. This will be a major point of analysis for the mud dynamics model of the Wadden Sea.

### 5.3.4 Long-term changes in mud content of Wadden Sea sediments

Figure 13 summarizes 125 years of study of the mud content of sediments in the Wadden Sea, by comparing the maps of Lely (1892), de Glopper (1967), Zwarts (2004) and the recent map based on SIBES. As far as possible, and currently with the exception of the map of Zwarts (2004), the colour coding of the classes distinguished by the different authors has been homogenized, but this is only approximate, especially in the low mud classes. The exercise will be improved, using proper georeferencing of the maps and clearly documented transformation rules, in a later stage of the project. Especially Lely (1892) was not interested in variations in low mud contents, as below a mud percentage of 5 % the soils would be unsuitable for agriculture anyway. Therefore the lowest class of the map of Lely is 0-5 % of mud, without any more distinction within this class. de Glopper (1967) used an approximately logarithmic scale, but in the lowest mud classes based his classification on the diameter of the sand grains rather than on the mud content. We have assumed here that the finer sand class had a slightly higher mud content than the coarser sand class.

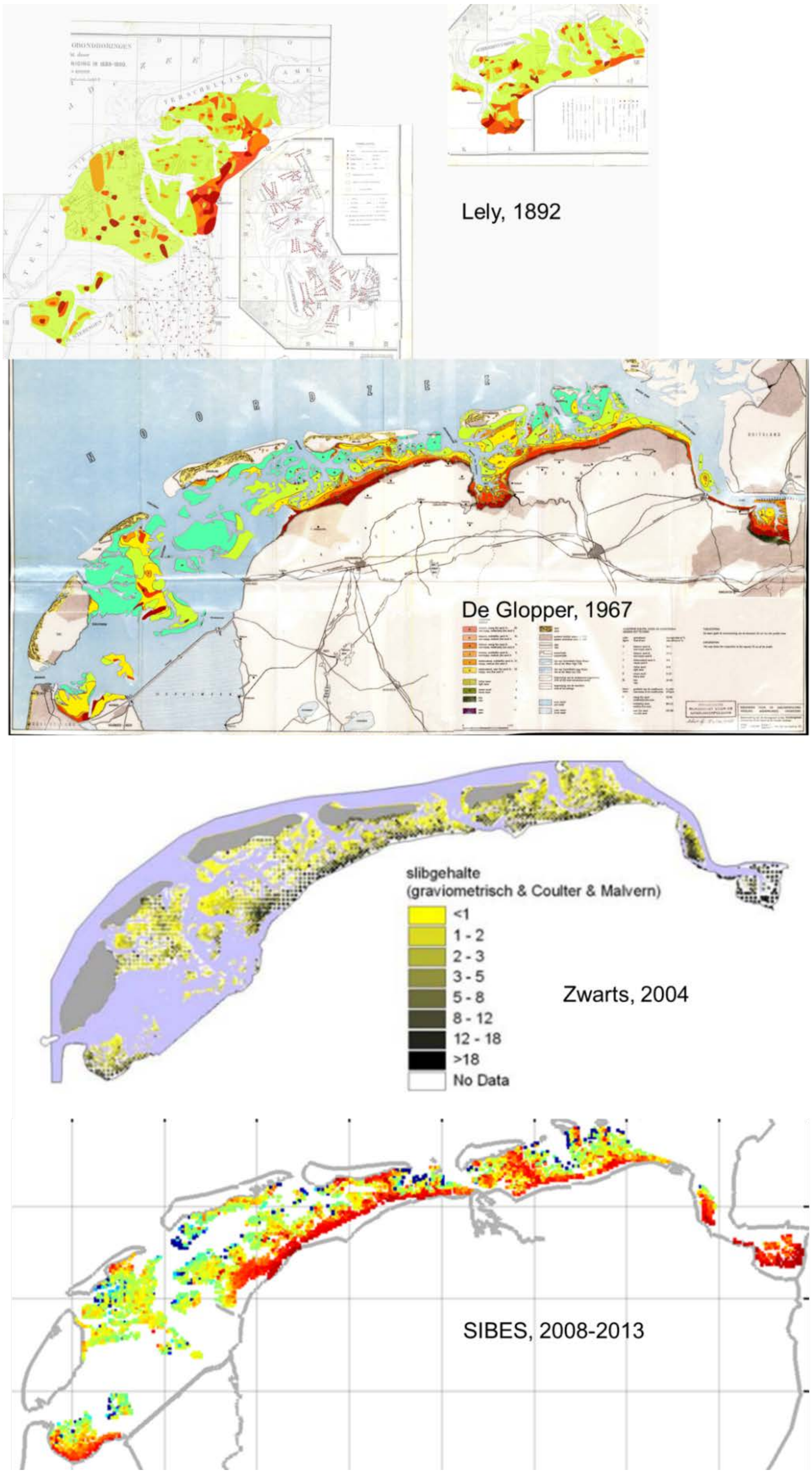


*Figure 13. 125 years of mud maps in the intertidal Wadden Sea. All maps, except that of Zwarts (2004) approximately follow the colour coding of the SIBES map. Conversion factors were based on Zwarts (2004).*

The maps are generally similar, and often show higher mud percentages in patches of very similar location throughout time. There are, however, also a number of significant differences.

The Balgzand area, which was not fully enclosed by dikes at the southern side before the closure of the Zuiderzee, has evolved from a set of tidal flats around a channel that was participating in the circulation around Wieringen to a semi-enclosed bay that has been accumulating mud on its southern (extended) shore. This change had already taken place before the 1950s, but developed further into a higher and muddier area nowadays.

The tidal divide south of Vlieland has always been rather sandy, although in 1890 some quite muddy patches occurred. These have decreased in number and surface by the 1950s, and have not returned. Some isolated high-mud patches are still present, but overall the divide seems to have become more sandy.

Large apparent changes are observed along the mainland coast around Harlingen, but these must be partly cartographic artefacts. The large muddy patch on the map of Lely was actually shallow subtidal area, and must have remained so until the 1950s. It was not mapped by de Glopper, but further accretion has created a relatively large intertidal patch that is very muddy and noticeable in the Zwarts and SIBES maps. Comparison between the Lely and SIBES maps shows that considerable amounts of mud must always have been present in the region, so that the major evolution over time is the change from subtidal to low-lying intertidal. The large difference suggested in the comparison between de Glopper and SIBES is therefore, in reality, probably rather subtle.

Compared to the Lely map, the mud content in the tidal divide south of Terschelling seems to have decreased in the map of de Glopper to purely sandy flats. More recently, mud content has increased again and the situation in the SIBES map is not unlike that in the 1890s, but still rather more sandy. Mud patches along the southern coast of the island have developed in the eastern part of the island.

The tidal divide south of Ameland cannot be compared with the 1890’s, as this area may already have been allotted for enpoldering at the time and was therefore not useful for further study by the Zuiderzeevereniging. Between the 1950s and today the southern shore of Ameland seems to have become muddier, and the tidal divide also has gained mud content. Along the mainland coast south of Ameland, the muddy area has developed northwards and connected better with the tidal divide.

Muddy patches in the tidal divide south of Schiermonnikoog have moved eastward, compared with the Lely map but also in the comparison between de Glopper and SIBES. The tidal divide also has gained much mud. Both evolutions are most probably linked to the closure of the Lauwerszee.

The Groningen coast has developed a muddy margin that was largely absent in the map of Lely, most probably as a result of the kwelderwerken, but maybe also partly caused by the closure of the Lauwerszee.

The tidal divides to Rottum and Rottumeroog seem to have become muddier, but the difference between SIBES and the Lely map are smaller than the differences with the map of de Glopper. Even nowadays, the tidal divide does not have a continuous muddy structure but is rather patchy, and this seems to have been the case in the 1890s also. It is possible that de Glopper missed some patches, giving an impression of purely sandy divides. Lely had a quite dense sampling programme in this area. The eastern part of the Groningen coast has always been muddy, and this has not changed greatly between the maps.

In summary, we see a tendency for the Western part of the Wadden Sea towards more sandy intertidal flats and less mud on the (poorly developed) tidal divides. Along the southern shore near Harlingen, mud has always been abundantly available in the sediment and differences are cartographic and a consequence of muddy subtidal becoming low intertidal. In the eastern part of the Wadden Sea we see the reverse tendency, with fuller development of muddy tidal divides and increased width of the muddy area along the mainland coast that is influenced by the kwelderwerken.

A more quantitative comparison between the maps, in combination with bathymetric changes, would shed more light on the accumulation of mud mass in the Wadden Sea. This is highly relevant in combination with recorded sediment import or export from the different tidal basins, as it would link mud and sand dynamics on the long term. A first step towards such an analysis has been made by Smits and Nederhoff (2018), but needs extension to other parts of the Wadden Sea. It is currently restricted to the Western Wadden Sea. Estimates of mud contribution to net sediment accretion in the Western Wadden Sea are surprisingly high (up to 40 % of the volume) but are uncertain as the volume fraction may be overestimated especially for sediments with low mud content where the mud fraction resides in between grains of sand and does not linearly contribute to volume.

# 6 Biomass distribution of microphytobenthos in space and time

## 6.1 Introduction

Microphytobenthos, the benthic algae growing on the sediment surface, is known as an important factor influencing the erodibility of sediments. The excretion of extracellular polymeric substances (EPS) leads to binding of sediment particles, that therefore become less mobile and more difficult to resuspend. Many experiments and field measurements have explored the topic, that was exhaustively reviewed by Grabowski et al., 2011. Not all measurements and experiments confirm the strong role of microphytobenthos, which seems to be modulated by other factors that are not always well known. However, the general tendency is for EPS to stabilize sediments, and for EPS to increase with increasing biomass (or chlorophyll) of microphytobenthos.

Van der Wal et al. (2010) have studied the biomass distribution of microphytobenthos on intertidal sediments in the Wadden Sea and other intertidal areas with the aid of remote sensing. All available remote sensing images between 2003 and 2008 were used to derive the spatial distribution of microphytobenthos. This work thus provides a detailed spatial distribution of mean microphytobenthos biomass, as well as measures of temporal variability of this biomass. Several images per month were analysed, and the results were binned per month for presentation in the paper.

## 6.2 Methods

Full methodological details are given in Van der Wal et al. (2010). In short, biomass estimates are based on the NDVI, a spectral ratio index often used to reveal vegetation based on remote sensing. In the publication, a map of average biomass over the entire period is given, as well as time series of average biomass for the Wadden Sea. We have based our analysis on these published results, that were kindly made available by Daphne van der Wal (NIOZ). A more thorough analysis could be done on the basis of the maps produced for every month, but this has not been part of our study.

## 6.3 Results

### 6.3.1 Spatial distribution of microphytobenthos biomass

We reprojected the spatial map of average microphytobenthos biomass in van der Wal et al. (2010), and used the same colour coding as was used for the map of mud content of the sediment, in order to compare both maps (Figure 14). There are differences in spatial resolution and also in extent covered, but overall the similarity between the two maps is the most obvious feature. Down to relatively small-scaled features, there is correspondence between sediment mud content and microphytobenthos biomass. The correlation in this picture is much closer than the correlation with mud content as analysed by van der Wal et al. (2010), based on less detailed maps of mud content of sediments that were available at that time. Also, it is clear that the log-transformation of sediment mud content has helped considerably in revealing the correspondence between the two maps. A formal correlation analysis, requiring extensive geocorrection and proper interpolation methods, will be performed in a later stage of the project.

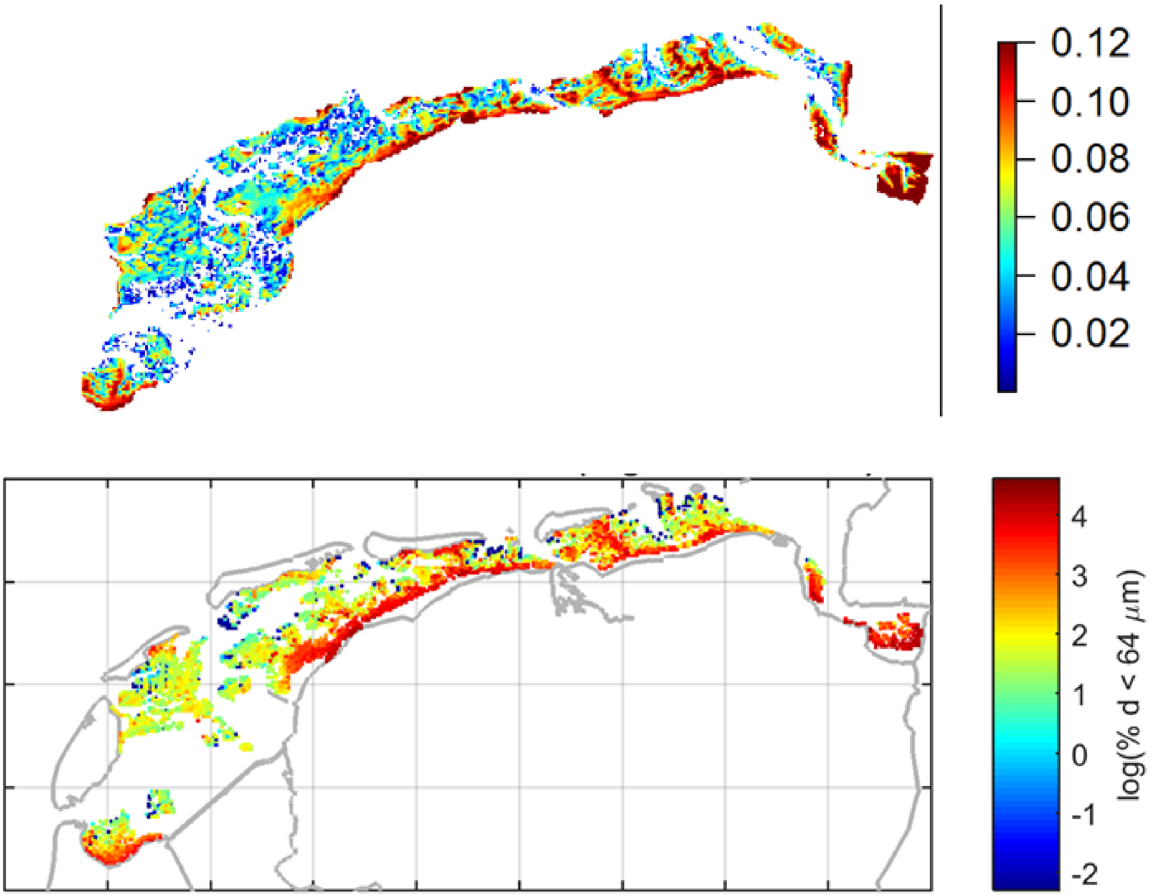


*Figure 14. Maps of (upper) time-averaged (2003-2008) microphytobenthos biomass estimated from NDVI in remote sensing (van der Wal et al., 2010) and of (lower) time-averaged mud content of the intertidal sediments measured in the SIBES programme (2008-2013). The color scheme of microphytobenthos biomass distribution has been adapted for maximal visual correspondence. The relatively rare observations with NDVI>0.12 have been grouped into the 0.12 class.*

### 6.3.2 Temporal evolution of average microphytobenthos biomass in the Wadden Sea

Figure 15 shows the decomposition of the time series of microphytobenthos biomass, measured as NDVI, in the Wadden Sea. The same decomposition method as applied earlier to SPM was used. The series has a strong seasonal component, that explains most of the variance. The trend is relatively weak, one order of magnitude weaker than the variation in the original series.

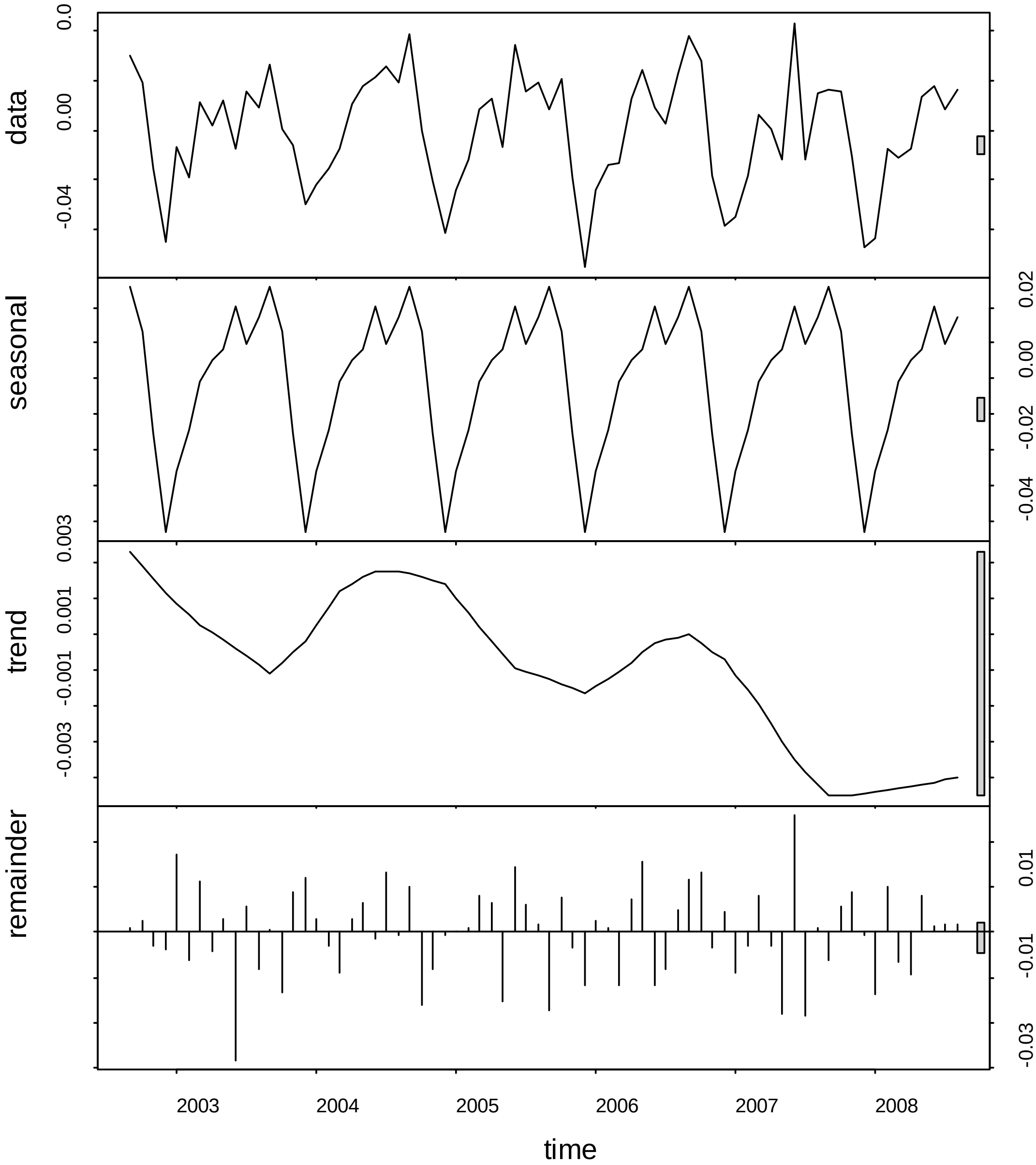


*Figure 15. Decomposition of the time series of microphytobenthos biomass, measured as NDVI, averaged over the Wadden Sea. This time series was published by van der Wal et al. (2010).*

There is a striking correspondence between the seasonal pattern in NDVI and the seasonal pattern in SPM, averaged over all observation stations in the Wadden Sea (Figure 16). For the comparison both series (measured in different units) were normalized to mean 0 and standard deviation 1. This correspondence does, obviously, not necessarily indicate any causal relations, but at least is also not inconsistent with it.

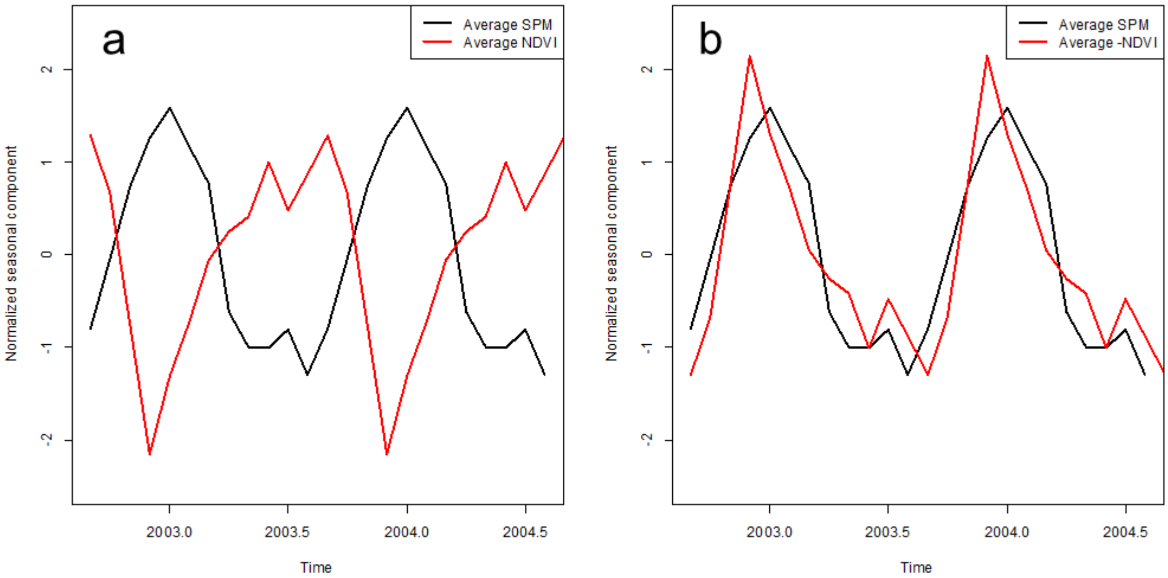


*Figure 16. Comparison of the standardized (mean=0, sd=1) seasonal component of microphytobenthos biomass measured as NDVI, averaged over the Wadden Sea (van der Wal et al., 2010), and the seasonal component of average SPM over the Wadden Sea (all time series, except Vliestroom, Zuidkamperlaag and Zuidkamperlaag zeegat). The data in (b) are the same as in (a), but the negative of NDVI is shown to highlight the correlation.*

With respect to multi-year trend, the comparison (Figure 17) is difficult as both series have a very different length. During the period 2003-2008 there was a negative trend in the NDVI series, and a positive trend in SPM. However, the NDVI trend also showed oscillations that were not apparent in the SPM trend series. One would need much longer remote sensing observations, and especially observations in the period around 2010 with elevated SPM values, in order to substantiate any long-term correlation between microphytobenthos biomass and SPM in the water.

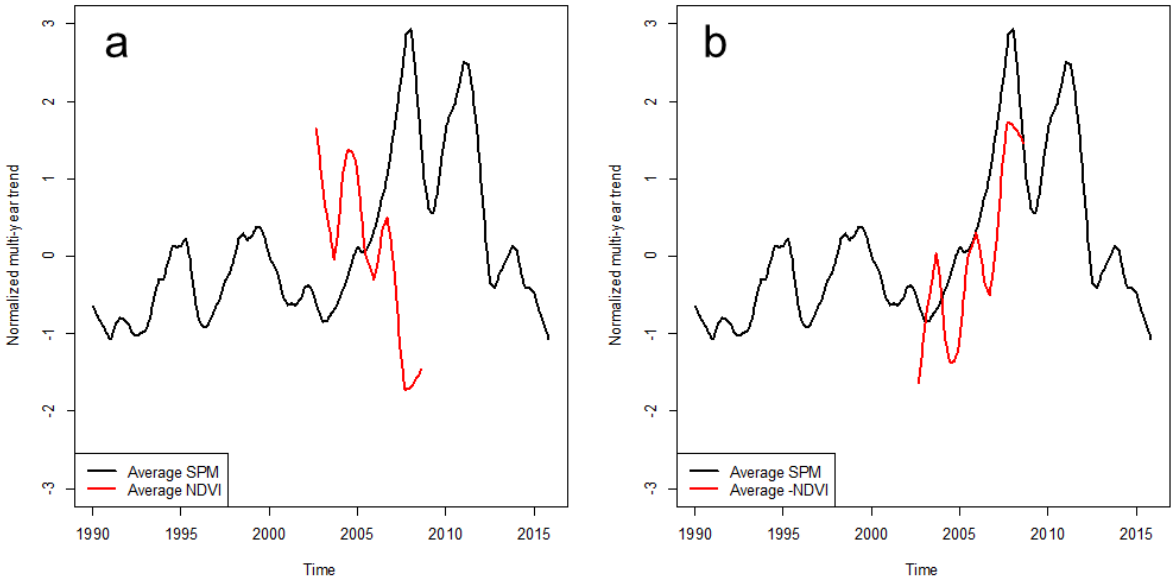


*Figure 17. Comparison of the standardized (mean=0, sd=1) trend component of microphytobenthos biomass measured as NDVI, averaged over the Wadden Sea (van der Wal et al., 2010), and the trend component of average SPM over the Wadden Sea (all time series, except Vliestroom, Zuidkamperlaag and Zuidkamperlaag zeegat). The data in (b) are the same as in (a), but the negative of NDVI is shown to highlight the correlation.*

In their own analysis, van der Wal et al. (2010) show that for the years 2003-2008, the monthly anomalies of microphytobenthos biomass correlate positively with the monthly anomalies of Secchi disk depth in the Wadden Sea, and thus negatively with SPM. They discuss that the causality is unclear: either increased SPM reduces light availability and thereby microphytobenthos, or enhanced microphytobenthos growth reduces sediment in suspension by stabilizing mud in the sediments. Quite plausibly, the causal relations are two-way, as both relations may operate together. In the high intertidal, there is also a positive correlation of microphytobenthos biomass with air pressure, and a suggestion of a negative correlation with wind speed. The latter is just not significant in the Wadden Sea, but it is significant in the Ems. It was also demonstrated that microphytobenthos monthly anomalies in the Wadden Sea correlate significantly with the anomalies in the Westerschelde and Ems, and negatively with the anomalies in the Thames estuary. That pattern also suggests that weather, and especially wind (which has different effects in the Thames because of orientation) plays a role in the yearly scale variations of microphytobenthos.

From this discussion we can conclude that our analysis of SPM and sediment mud content in the Wadden Sea presently lacks an analysis of correlation with weather patterns. At least through the effect on microphytobenthos, which is theoretically known to affect mud dynamics and is observed in the Wadden Sea to correlate with SPM, at least on a seasonal scale, weather should also have an influence on SPM. Besides, it is also known that there are direct influences of wind and waves on SPM, at least on a short time scale (de Jonge and van Beusekom, 1995). Whether, and how, this is also reflected in the longer-term trends of SPM remains to be studied.

# 7 Summary of observations and conceptual discussion

## 7.1 Decomposition of the SPM time series

It was a surprising finding that the total variance of the time series of SPM, when expressed on a relative basis (i.e. after log-transformation) is very similar for all time series, ranging in spatial location from inside estuaries to far offshore. There is some tendency, however, for change in the structure of this variance. The relative contribution of trend, compared to the other components, increases with water depth.

The seasonal component, expressed as relative changes to the long-term mean, is surprisingly constant over most of the locations. We could also not observe any systematic change in the timing characteristics of the seasonal components. Seasonal variation with spatially homogeneous high and low concentrations is also described based on remote sensing images (Eleveld et al., 2008). Pietrzak et al. (2011) describe the annual and spring/neap tidal cycles over space in the North Sea. Their analysis emphasized the high winter values in the East Anglian plume, as well as the role of the Rhine ROFI in determining surface SPM values. However, we have not been able to find an analysis of remote sensing data on a logarithmic scale, in order to check whether the relative constancy of the seasonal signal is a consequence of the choice of monitoring stations, or an ubiquitous feature in the Southern Bight of the North Sea. Qualitatively, Pietrzak et al. (2011) in their conceptual diagram suggest that seasonal variation should be much stronger in coastal and far offshore areas than in frontal areas, but we have not found this in the field monitoring data.

If the seasonal component in offshore stations would be mostly determined by advection with residual currents, such a time shift would be expected. Residual currents in the North Sea are of the order of a few cm/s (Sündermann & Pohlmann, 2011), and even if these would be directed entirely in cross-shore direction (which is not the case) it would take in the order of 50 days to cross a 100 km offshore distance. Such time lags should be visible in the long-term SPM time series, but they are not. Note that the distances discussed here are in the order of several tens of km, and thus much larger than the tidal excursion. Moreover, the tidal movement is largely shore-parallel, whereas we discuss here gradients perpendicular to the coast. We conclude that whereas the increasing autocorrelation and importance of trend with distance offshore could be explained by advection, the seasonal components are in opposition to this mechanism. Apparently, relatively local processes are dominant over advection processes, at least for the seasonal cycle.

The (seasonal) input of sediment by resuspension from the local bottom decreases with increasing depth, as it becomes increasingly unlikely that waves reach the bottom. In the North Sea mobilization of mud by storms with a frequency >1.year$^{-1}$ can take place down to a depth of appr. 30m (van Dijk and Kleinhans, 2005). However, also deeper stations are affected by waves that occasionally can resuspend considerable amounts of sediment, as was documented for a 47 m deep station in the Oyster Grounds by Jones et al. (1998). If the frequency of such events is not much below 1 yr$^{-1}$, they will show up in the long-term monitoring series as part of the seasonal component, because once resuspended the sediment will not easily be re-incorporated into the sediment and thus contribute to the SPM for a relatively long time. In practice, it becomes part of a fluff stock for prolonged periods (Jones et al., 1998) and can then be resuspended by tidal currents.
Although seasonality in storms can thus contribute to seasonal variation in the size of the suspended (or suspendable) SPM, also the degree of vertical mixing must be an important

component of the seasonal variation of surface SPM. This vertical redistribution depends on (1) vertical mixing by the hydrodynamics, and (2) the settling velocity of sediments. The strength of the wind stress at the water surface is a strongly seasonally varying component. It is strongest in autumn and winter, when moreover thermal stratification is weak or absent. It can be expected that this turbulent mixing is stronger in shallower water columns, but the deeper water columns have lower concentrations and most probably also slower sinking particles that have been able to withstand sinking out over longer periods. These particles are easier to mix vertically as the mixing has to oppose smaller sinking speeds. With respect to the second point, settling velocity of particles, there is a seasonal component in the flocculation of particles. This aggregation process of particles has a seasonally varying biological component, and is moreover affected by water viscosity. Flocculation by organic components leads to higher settling velocities in summer than in winter. Even without flocculation, the settling velocity of SPM is larger in summer than in winter because of the water viscosity. The Stokes settling velocity of particles scales inversely linear with viscosity. The viscosity of water of 19$^{o}$C is 2 times lower than water of 5$^{o}$C, which is close to the interannual variability in North Sea Temperatures. Note, however, that the seasonal cycle of SPM is not in phase with the seasonal temperature cycle that lags behind by approximately two months. However, taking different factors into account, ranging from (for deep columns) relatively rare resuspension events, to predictably increase in turbulent motion, water viscosity and biological flocculation processes, there are sufficient reason to expect that SPM is more uniformly distributed in winter than in summer and has higher winter surface concentrations. Nevertheless, it remains to be explained why this seasonal component has the same relative strength irrespective of all peculiarities of the monitoring stations.

In all of the processes discussed, size sorting of particles with distance offshore (correlated with station depth) must be a very important process. Most likely the source of suspended matter in offshore stations is less and less local and more dependent on advection as the distance offshore and station depth increase. This can explain the stronger contribution of long trends in the signal of offshore stations, as advection will average out variation over longer time periods. However, the measured concentration near the surface seems to be determined in the first place by the vertical distribution mechanisms within the water column and do not reflect source-sink terms of the total suspended mass in the column. Closer to the coast, where particles can be assumed to be faster sinking, the importance of source-sink terms may become dominant over vertical mixing within the water column. Within shallow systems such as the Wadden Sea, resuspension and deposition are probably the most dominant terms.

A number of studies have measured vertical profiles of CTD and SPM in the North Sea, but usually in the context of detailed process studies over relatively short periods of time. In the framework of Maasvlakte-2 monitoring, a large number of CTD and SPM profiles along the Dutch coastal zone are available (Borst et al., 2013). Extension of the routine monitoring programme with vertical casts would be a significant upgrade of the value of the monitoring data set. Such a long-term data set with sustained observations is currently lacking for the Dutch part of the North Sea.

Existing studies have shown that MWTL data alone are insufficient to link SPM concentration changes to human interventions such as Maasvlakte 2 construction. For example, a 50 year period would be required to detect a significant 10% change (Blaas and Van den Boogaard, 2006). Therefore SPM monitoring was extended with other in-situ and remote sensing measurement techniques in combination with a numerical model.

## 7.2 The long-term component in the time series of SPM in the Wadden Sea

The total mass of sediment present as SPM in the Wadden Sea is very small compared to the mass of sediment in the upper (20cm) mixed layer of the sediments. The average water depth in the Wadden Sea depends on the tidal basin, but is in the order of a few m only. Even at SPM concentrations of 100 $g/m^3$, the suspended mass of sediment is maximally a few hundred $g.m^{-2}$, which is not more than approximately one thousandth of the mass of sediment in the upper 20 cm. Although intertidal sediments with very low mud content are found in the Wadden Sea, the bulk of the measurements of mud content are on or above the level of a few % of mud, with a considerable number of observations having tens of % of mud. Therefore, only a tiny fraction of the total mud mass associated with the sediments in the Wadden Sea can be found suspended in the water column.

The processes of erosion and deposition of mud are the prime exchange mechanisms of mud between sediment and water column. These processes have short time scales. Erosion and deposition vary over time within a single tide, and often sequences of erosional and depositional phases occur at a particular site within a single tide. It could be expected, therefore, that short-term dynamics would govern the mass of suspended sediment in the water column, which would then reflect immediately the strength of the physical forces, in particular wave forcing, on the exchange of mud between water column and sediment.

It is very remarkable, therefore, to find long positive autocorrelation in the time series of SPM, even after de-seasonalizing the series. This long autocorrelation points at slow mechanisms determining the dynamics of SPM. Either there is slowly varying forcing from external sources, e.g. in the form of persistent clouds of SPM that drift into the Wadden Sea, or there are slow buffering mechanisms in the Wadden Sea. Such buffering would inhibit rapid incorporation of elevated SPM values into the sediment buffer, but reversely also inhibit stably bound sediment mud to be quickly resuspended. Buffers will only affect the time dynamics if their action is somehow related to the past conditions, over time scales of months. The pattern of long autocorrelation is reflected in the existence of substantial multi-year trend components in the series of SPM. We observed, moreover, that these trend components in different sampling stations within larger systems (e.g. within the Wadden Sea) are coherent, but that across systems they are showing different patterns.

Within the North Sea stations, the trend component is relatively weak in onshore stations, and increases in importance when going to deeper offshore places. The same onshore-offshore difference can also be seen in the autocorrelation graphs. There are low autocorrelation values that rapidly drop to zero in the inshore stations, and larger values that remain significant over much longer lags in the offshore stations. With respect to both characteristics, Wadden Sea stations are more like the deep offshore stations. Some Wadden Sea stations that lie close to the North Sea coast in the tidal channels, have time series characteristics more like the North Sea coastal stations. These are also the stations with deviant long-term trend patterns, compared to the other Wadden Sea stations. Functionally, Vliestroom, Zoutkamperlaag and Zoutkamperlaag zeegat seem to belong to the North Sea, rather than to the Wadden Sea. This is not the case for Marsdiep Noord, but this station likely represents Wadden Sea characteristics better than the other stations close to the North Sea, as has been previously concluded based on biological and chemical characteristics (Philippart et al. 2007).

The temporal patterns in the multi-year trend qualitatively differ between the Wadden Sea and the adjacent North Sea. This suggests that the explanation of SPM trends in the Wadden Sea by external forcing is not very likely. There are no clear signs of ‘clouds of elevated SPM’ drifting into the Wadden Sea.

We suggested that for offshore stations in the North Sea, local provenance of suspended matter from local resuspension becomes less likely as station depth increases. Provenance from relatively slow advection would be a likely cause for the long-term autocorrelation in these deeper stations, as the suspended mass present at a station integrates advection over relatively long time scales. The processes underlying trend and long autocorrelation in the shallow Wadden Sea stations may therefore differ from the processes underlying this phenomenon in deep North Sea stations. We hypothesize that slow internal buffers affecting the stable deposition of mud in the Wadden Sea are the prime responsible factors for the long autocorrelation.

Mud storage in the Wadden Sea occurs at a number of temporal scales, from temporary deposition on top of a sediment in between tidal deposition and resuspension events, to permanent deposition in saltmarshes or as a fraction of net accumulating sediment when the Wadden Sea follows sea level rise. For this discussion, intermediate temporal scales, in the order of months to maximally a few consecutive years, are important. At this scale both physical and biogenic processes are important. Physically, the seasonality in wind stress and wave action can change the balance between sedimentation and resuspension, and moreover variation in weather from one year to another can cause year-to-year variations in this balance. Biologically, a number of candidate processes are available. Most prominent, because of its ubiquitous distribution over the Wadden Sea, is the role of microphytobenthos. However, also filter-feeding shellfish beds are known to store considerable amounts of mud and could play a role. Saltmarshes, finally, are known to gradually accrete and store mud, primarily by enhanced sedimentation during high-water conditions in winter, when SPM is highest and wave action on the fringing tidal flat mobilizes sediment.

## 7.3 Importance of saltmarshes

Saltmarshes, and especially the human-induced defence of saltmarsh edges (‘kwelderwerken’) that have seeked to actively promote the deposition of mud near the mainland coast of the Wadden Sea, have been a prime factor in the long-term changes of mud distribution in the Wadden Sea. The mud-rich fringe along the mainland coast has expanded over the past century, and considerable amounts of mud (and sand!) have been stably stored in these saltmarshes. In Cleveringa (2018), sedimentation of mud in the salt marshes and mud flats outside the regular control volumes is estimated to be 0.4 to 1.2 $10^6$ $m^3$ per year, which is 55-68% of the total sedimentation volume in these areas.

We think that these ‘kwelderwerken’ are probably the most important human-induced driver of morphological development in the Wadden Sea as a whole. By slightly shifting the balance between erosion and deposition, a depositional area has been created that has collected sufficient volumes of sediment to significantly change the tidal volumes of the smaller channels reaching towards the mainland coast. As these creeks lose tidal volume, they will tend to become smaller, cause smaller velocities on the tidal flats and create additional areas for mud deposition. Where the creeks also serve as navigation channels and are dredged, their cross-section is maintained beyond the equilibrium level and considerable mud sedimentation (and dredging) follows. The navigation channel Holwerd-Ameland is an example of this development.

Whether the saltmarshes and 'kwelderwerken' have also played an active role in the yearly-scale trends in SPM concentrations in the Wadden Sea, is less certain. We have not been able to find variations in the management or the evolution of these saltmarshes, that correlates well with the considerable fluctuations of SPM over the past decades. This is an area where more research would be needed. The saltmarshes are large reservoirs of mud, and especially the muddy fringing flats have not stored this mud in an extremely stable way. Depending on weather conditions, this reservoir may have had variable resuspension rates and thus inputs into the suspended mass of sediment in the Wadden Sea. We have not sufficiently investigated weather patterns in the past decades to evaluate this hypothesis.

## 7.4 Importance of shellfish beds

Stocks of filter feeding shellfish have varied greatly during the past decades, after all intertidal mussel beds were fished away in the early 1990s, and cockle populations were thinned by fishery too. Over the following decades, these populations have recovered, and moreover new species of filter-feeding shellfish have invaded the area. In the intertidal, mainly the Japanese oyster was important. There is no correlation whatsoever between this time series and the observed SPM time series (Figure 18).

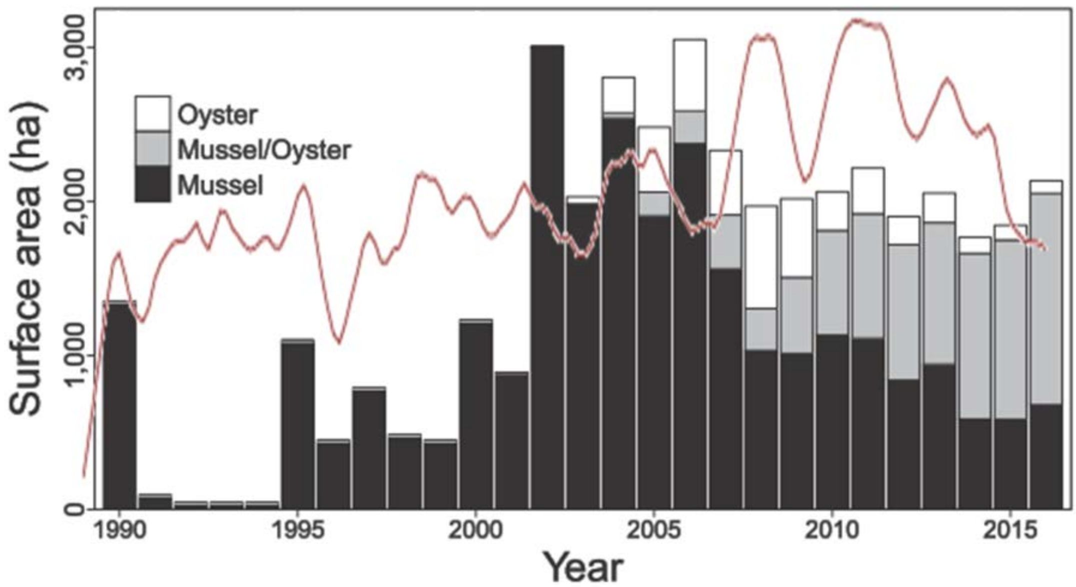


*Figure 18. Temporal variation in the surface of mussel, oyster and mixed mussel/oyster shellfish beds in the Wadden Sea (data: WMR), compared with (in red) the yearly-scale trend component of the SPM series at Dantziggat. The latter is only added for indication, details of scale can be found in Figure 4.*

The time series of extent of shellfish beds is primarily determined by recruitment processes: the probability of new beds forming by settlement of larvae. This recruitment process has been shown to depend on a number of factors. Severe winters tend to facilitate recruitment, probably by influencing the degree of filtration of larvae from the water column and/or food competition between adults and juveniles. Predation by shrimp has also been shown to be of great importance. Weather patterns and predation interact, as shrimp tend to migrate into the Wadden Sea later after severe winters. The lack of correlation between the extent of shellfish beds and SPM time series therefore leads to two conclusions: (1) SPM has no clear influence on the recruitment processes of shellfish beds and (2) filtration by shellfish beds has no clear influence on SPM concentrations.

In contrast to this lack of correlation between extent of shellfish beds and SPM, it has been shown previously, both in the Oosterschelde and in the Wadden Sea, that SPM influences food quality (expressed as Chla/SPM) and thereby also the condition index (expressed as % meat in the freshweight) of mussels. Years with low SPM show higher condition indices, and thereby provide clear evidence of the ecological influence of SPM. However, in contrast to growth, recruitment does not seem to depend on food quality and related parameters.

## 7.5 Importance of microphytobenthos

Microphytobenthos biomass, as measured by remote sensing, shows some strong correlations with patterns in mud distribution in the Wadden Sea. Spatially, the correlation between microphytobenthos biomass and mud content of the sediments is very strong. At the very least, microphytobenthos biomass is an excellent indicator for sediment mud content. In experiments, it has generally been observed that the presence of microphytobenthos mats reduces the resuspension of mud from mixed mud-sand sediments. This experimental evidence suggests a causal relation between microphytobenthos and mud dynamics. The tightly correlated spatial distributions show that wherever there is mud to be resuspended from the sediment, there is also microphytobenthos that can influence the resuspension of this mud.

It would be expected that a possible influence of microphytobenthos on resuspension would be most visible in the SPM contents of the water column, as this variable will respond most rapidly to variations in erosion rates of mud. The mass of sediment within the bed is much larger, and therefore a small change in mud erosion will likely not cause measurable differences in mud content.

At a seasonal scale, we observed a very close inverse correlation in time between the development of microphytobenthos biomass in the sediment and SPM in the water column. Even the small depression of microphytobenthos biomass in June, relative to May and July-August, seems to be reflected in the SPM seasonal component. Also at the longer (multi-year) scale, the limited observations we have are not in contrast to this role of microphytobenthos. However, the evidence is weak as the microphytobenthos time series is too short to make any strong statements.

We conclude that there is sufficient indication that microphytobenthos play a significant role in the suspended matter of the Wadden Sea water. Further elaboration of this role, by extending the observational time series of microphytobenthos variability, would be very worthwhile.

At the same time there is currently no direct proof that microphytobenthos-related processes really need to be taken into account when modelling mud dynamics in the Wadden Sea. It remains possible that microphytobenthos is rather an excellent tracer of mud presence in the sediment than a causal agent. Also, given the high spatial correlation between microphytobenthos and mud content, there is a possibility that simple parameterizations of microphytobenthos, e.g. in the form of a seasonally varying critical erosion threshold for mud, would be sufficient to improve the modelling and implicitly represent the most important consequences of microphytobenthos (e.g. Paarlberg et al., 2005; Borsje et al., 2007, Bashir, 2016).

Whatever the chosen way, closer investigation of the need to include microphytobenthos into dynamical mud models is a promising option for future research.

## 7.6 Positive feedbacks between sediment mud content and erodibility

We observed a bimodal distribution of mud content of sediments in the Wadden Sea. This bimodality is present in the raw observations, but is even more expressed in the time-averaged station means (Figure 9). Bimodality is often an indicator of a bistable system, where there are two equilibrium states but intermediate states are unstable. In the present case, the observation that bimodality of the temporal means is stronger than that in the raw observations adds credibility to this interpretation. We also observed that the variability in time is highest for observations falling in between the two modes. Bistability in a system is usually the consequence of positive feedback: once a particular condition is reached, it tends to maintain or strengthen itself in that condition, whereas when the system is flipped over to an alternative state, it tends to stay in that alternative condition.

With respect to mud content, there are both physical and ecological processes that may promote positive feedbacks. Physical processes include the erodibility of the mud and the hydraulic roughness of the bed. The erodibility of sand-mud mixtures is dependent on mud content. Usually, erodibility decreases when mud content increases from low to higher values. The threshold for cohesive behaviour plays an important role in this process, as the cohesive forces contribute to the strength of the sediment and reduce the erodibility. The subject is extensively reviewed by Grabowski et al., 2011. It was incorporated into a model for sand-mud sediment dynamics by van Ledden (2003) and van Ledden et al. (2004). Van Ledden (2003) used it in a local 1-D model application to calculate equilibrium mud content. He showed that the mud content will demonstrate a sharp transition, at a critical bed shear stress, between a high but relatively undetermined mud content (10-100 %) and a low (<10 %) mud content. He showed that this equilibrium prediction was an envelope to observations in the Molenplaat (Westerschelde), but did not predict any bimodality in the mud distribution. Van Ledden (2003) also showed that the transition between muddy and sandy sediments as a function of bottom shear stress is only sharp when total mud content of the water is relatively low (<100 mg/l) (Figure 19).

Positive feedback through roughness of the bed is caused by the fact that the hydraulic roughness of mud beds is lower than of that of sandy beds, because the larger sand grains generate more near-bed turbulence. The bed shear stress (the hydrodynamic stress exerted on the bed) increases with the hydraulic roughness, and is therefore lower over muddy beds. In addition, high concentrations of suspended matter in the water column generate a reduction of the apparent roughness, as sediment concentration gradients damp vertical mixing by turbulence. The consequence of both mechanisms is that, as the bed becomes muddier, the forces responsible for resuspension of the fines decrease in strength and chances are that the mud content further increases. However, this mechanism will only take place if the starting conditions are near the critical threshold for mud resuspension. When the bottom shear stress largely exceeds this threshold, the bed will remain sandy and mud incorporation will be limited to a small fraction, where mud particles are fully shielded in between the sand grains.

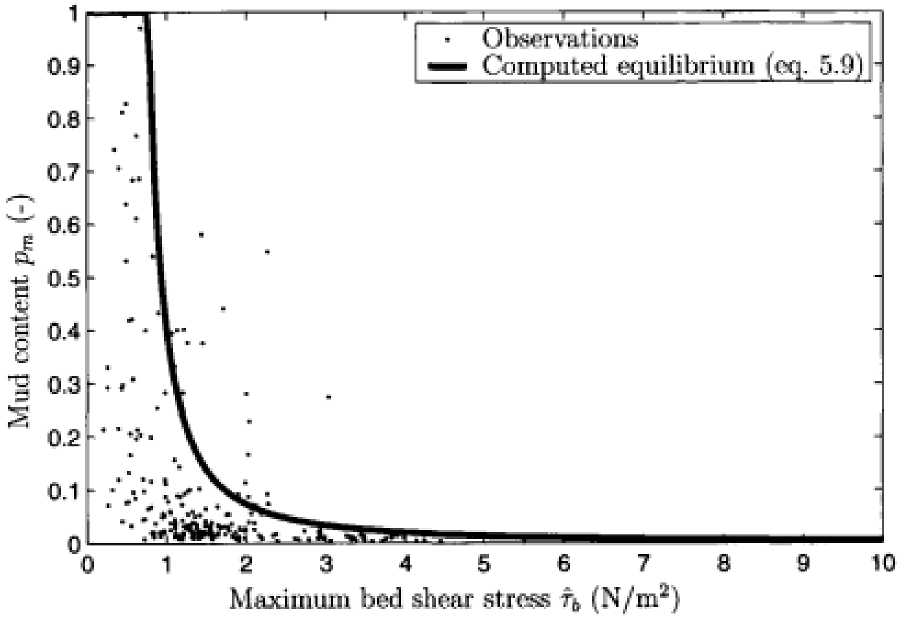


**Figure 5.9:** Correlation between observed mud content and maximum bed shear stress (De Bake, 2000) and derived equilibrium mud content (eq. 5.9) against maximum bed shear stress for Molenplaat area (the Netherlands).

*Figure 19. From van Ledden (2003)*

Grabowski et al. (2011) also extensively review evidence that microphytobenthos EPS can substantially increase the critical shear stress for erosion, and reduce erosion rates. This feature, together with the observation that the biomass of microphytobenthos tends to be higher in muddy than sandy sediments, was used by van de Koppel et al. (2001) as the basis for a model predicting bimodality of mud content in sediments. The generic modelling approach shows that if microphytobenthos biomass is stimulated by mud content, and mud loss is decreased by microphytobenthos biomass, a bistable equilibrium will follow. The model was validated by the same measurements at the Molenplaat, as used by van Ledden (2003), but emphasizing the bimodality of the observations at intermediate to high bottom shear stresses (not at low bottom shear stress) rather than the absolute relations with the bottom shear stress. Figure 20 shows the qualitative diagram illustrating the model's dynamics, as well as the validation dataset. Note that, in order to validate this model, estimates of bottom shear stress at all points were needed. The presently available dataset on mud contents in the Wadden Sea, showing clear bimodality, is not sufficient in that sense. The bimodality can also be the result of a bimodal spatial distribution of bottom shear stress, with a simple relation between stress and mud content. This aspect needs closer scrutiny, which could be done relatively easily based on existing physical models of the Wadden Sea from which bottom shear stress can be derived.

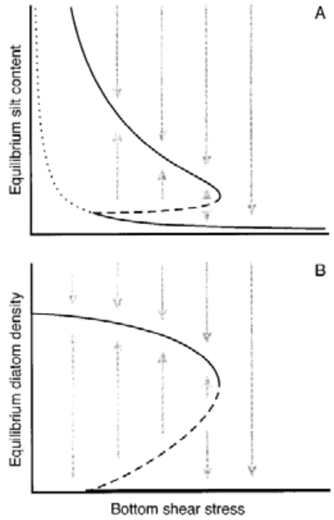


FIG. 2. (A) Equilibrium silt content, and (B) diatom density as a function of bottom shear stress ($\tau$). The dashed line depicts unstable equilibria. Two stable states are found at intermediate bottom shear stress. The dotted line represents the relationship between silt content and bottom shear stress in a system without diatoms. For further details on model specifics see Fig. 1.

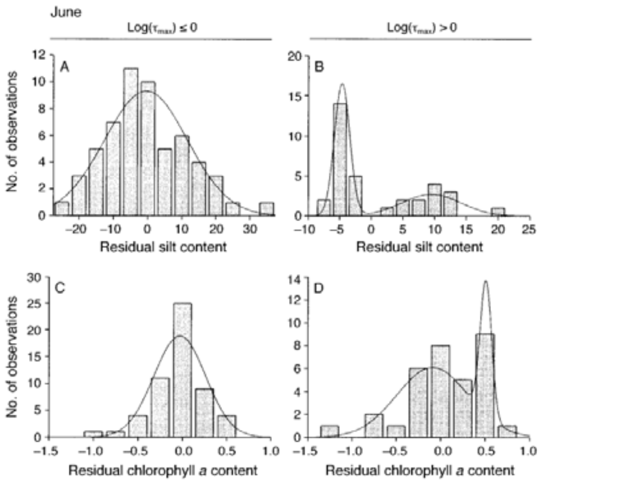


FIG. 6. Distribution of the residual silt fraction and chlorophyll *a* content after removal of the negative trend in the data. Left and right graphs represent the data at $\log(\tau_{max}) \leq 0$ (A, C) and $\log(\tau_{max}) \geq 0$ (B, D), respectively. Curves represent the fitted probability distribution; a bimodal distribution is shown when it explained the data significantly better than the normal distribution.

*Figure 20. From van de Koppel et al. (2001)*

Summarizing, the present data set of the Wadden Sea emphasizes (1) the high spatial correlation between microphytobenthos distribution and sediment mud content, (2) the high temporal correlation, at least on a seasonal scale, between microphytobenthos biomass and SPM, (3) the strong bimodality of observations of mud content in the sediment and (4) the high temporal variance of intermediate sediment mud contents. All of these observations are consistent with the model predictions in van de Koppel et al. (2001) and strongly point in this direction as an explanatory hypothesis. Four parts of evidence are currently lacking. (1) We have an insufficiently long time series to check if long-term trends in microphytobenthos and SPM correlate; (2) we have no sediment mud content measurements outside of the summer season. Observations of seasonality in both microphytobenthos (which are available for the period 2003-2008) and sediment mud content could provide much stronger evidence for a causal relation between microphytobenthos and SPM; (3) we have no direct field measurements of chlorophyll-a content that can verify the validity of the remote-sensing derived estimates of microphytobenthos biomass. The latter, however, are available in literature and are not a main point of concern (Daggers et al. 2018 and references therein); and (4) we have not related mud content of the sediment to estimates of bottom shear stress. This could be done on the basis of hydrodynamic modelling, however.

# 8 Towards a conceptual model for mud dynamics in the Wadden Sea

Based on the observations as discussed in this report, we recognize three important factors for SPM dynamics and three important time scales where processes operate to determine both the SPM in the water column and the mud content of sediments in the Wadden Sea. This discussion does not exclude other factors that may be important from a management point of view, such as influence of biota, fisheries, dredging etc., but we hypothesize that these anthropogenic influences operate mainly through changes in the important natural forces.

The important factors are (see Figure 21):

1 The quantity of mud, some of which is in suspension but most of which is stored in the seabed, in an either easy or difficult to erode state;
2 The properties of mud which determine both horizontal and vertical transport (i.e. sedimentation, erosion and transport), mainly characterised by settling velocity, critical shear stress for erosion and the erosion rate ;
3 The hydrodynamic forces acting on mud steered by the tide, wind, waves and freshwater discharge.

The important time scales are:

1 Short: tidal to spring/neap tidal (0.5 - 14 days)
2 Intermediate: seasonal to multi-year
3 Long: > 5 years, i.e. morphological time scale.

At the short time scale, most processes related to deposition, resuspension and transport exchange between the Wadden Sea and North Sea of suspended material take place. At the very long time scale (decadal) we observe interactions between major hydrological changes (e.g. changes in tidal volume as a consequence of kwelderwerken, closures of Zuiderzee and Lauwerszee, migrations of tidal divides) and mud content of the sediments. However, the observations also point to a third time scale, which ranges from seasonal to multi-year, where the surprisingly long 'memory' of the system resides. There are year-to-year variations both in mud content of the sediment and SPM concentrations, which have autocorrelations up to more than one year, and where as a consequence of this long 'swings' in the observations occur. This time scale is often neglected in conceptualisations of mud dynamics, but it appears to play an important role in the time dynamics of the observation series. However, this time scale is already taken into account into all present SPM models of the Dutch coastal waters (Western Scheldt, North Sea, Wadden Sea and Ems-Dollard (e.g. Van Kessel et al. 2012; Sittoni et al., 2012; Van Kessel, 2015; Van Maren et al., 2016).

The processes operating at the shortest time scale are generally well known and incorporated into existing mud dynamics models, although further refinement and calibration may be needed. In the Wadden Sea, this refinement currently focuses on the short-term effects of tide, wind and waves on the vertical profile of suspended mud, erosion and deposition processes and deviations from average transport pathways. An example of the latter is transport across tidal divides that has been observed under specific wind conditions. Many moorings are currently being deployed, e.g. in the framework of the mud motor and SEAWAD projects, that reveal the intricacies of these dynamics. In this report, we have not extensively treated these observations, as they are currently part of ongoing PhD projects.

However, we expect that they will give rise to improved process understanding and modelling on the small spatial and temporal scale. Existing mud dynamics models are perfectly suited to incorporate new insights and model parameters at this scale, and this will be an important aspect of model revision. With currently available measurements (mainly MWTL) we lack insight in and calibration data of SPM variations over the short time time scales. More intertidal SPM data may result in adjustment of the mud properties. Further model improvements can be mainly attained by improving resolution and local hydrodynamic and wave forcing.

The incorporation of meso-scale phenomena, i.e. processes responsible for the seasonal variation and the multi-year trend components of the series of SPM and sediment mud content, is fraught with more difficulties. Conceptually, the relative importance of physical and biological processes operating at this scale is much less clear. Examples are the feedback between mud content of the sediment and important parameters such as erodibility of mud, roughness of the sediment, development of microphytobenthos, activity of filter feeders and bioturbators. Many of these interactions are steered by seasonally varying factors such as light and temperature, but they can also be changed by weather patterns that affect the system over longer time scales. If summer storms resuspend microphytobenthos mats (and subsequently also large masses of mud), it may take a long time to redevelop the microphytobenthos. During this time the sediment may switch to an unfavourable state for this development and changes at the scale of the estuary (e.g. in SPM) may follow. That temporal scale transition between short-term events and long-term consequences is difficult to grasp, especially as the relevant time scale is at or above the time period that process-driven models can be run in practice (several years). In order to further develop process understanding and modelling at this time scale, the existing 3D SPM models are already suitable in principle, but important uncertainties are:

- seasonal changes or long-term trends in sediment properties induced by physical, chemical or biological factors (properties)
- uncertainty about the active mud mass and its residence time in the system (quantity)
- limitations in the accuracy of hydrodynamic forcing which may have a cumulative effect on residual transport and the evolution of mud quantity (forcing).

These uncertainties are likely to result in a deteriorating model performance in time, requiring either regular recalibration or, preferably, a better process description. The limitation of the accuracy of the hydrodynamic forcing also applies to the short time scale, but model resolution issues become more challenging at longer time scales. Instead of 3D models, also simplified physical representations (e.g. in 2DV) that shorten runtimes could offer additional opportunities for exploring process dynamics.

Modelling the long-term developments of mud distribution in sediments, for example to better model and understand the developments reflected in the different mud maps of the Wadden Sea discussed in this report, requires a different modelling approach altogether, as it is not possible to run detailed morphodynamic mud models at century scale. Also, many processes at shorter time scales can be assumed to be in immediate equilibrium at this time scale. Emphasis should go to the relation between morphological changes induced by mud accumulation and changes in the conditions that allow (or not) the transport and deposition of mud. Based on a proper time integration of process-based models, such long-term analysis could be feasible using simplified formulations. An example is given in van Maren et al. (2016) for the Ems-Dollard, and could be worked out further. However, in contrast to this approach for an isolated estuary only, we think it is important to link long-term evolutions in different systems to each other. At the long time scale, changes in all Dutch and surrounding estuaries and coastal zones are linked by important fluxes of mud, suggesting that the long-term modelling of these systems should also be linked.

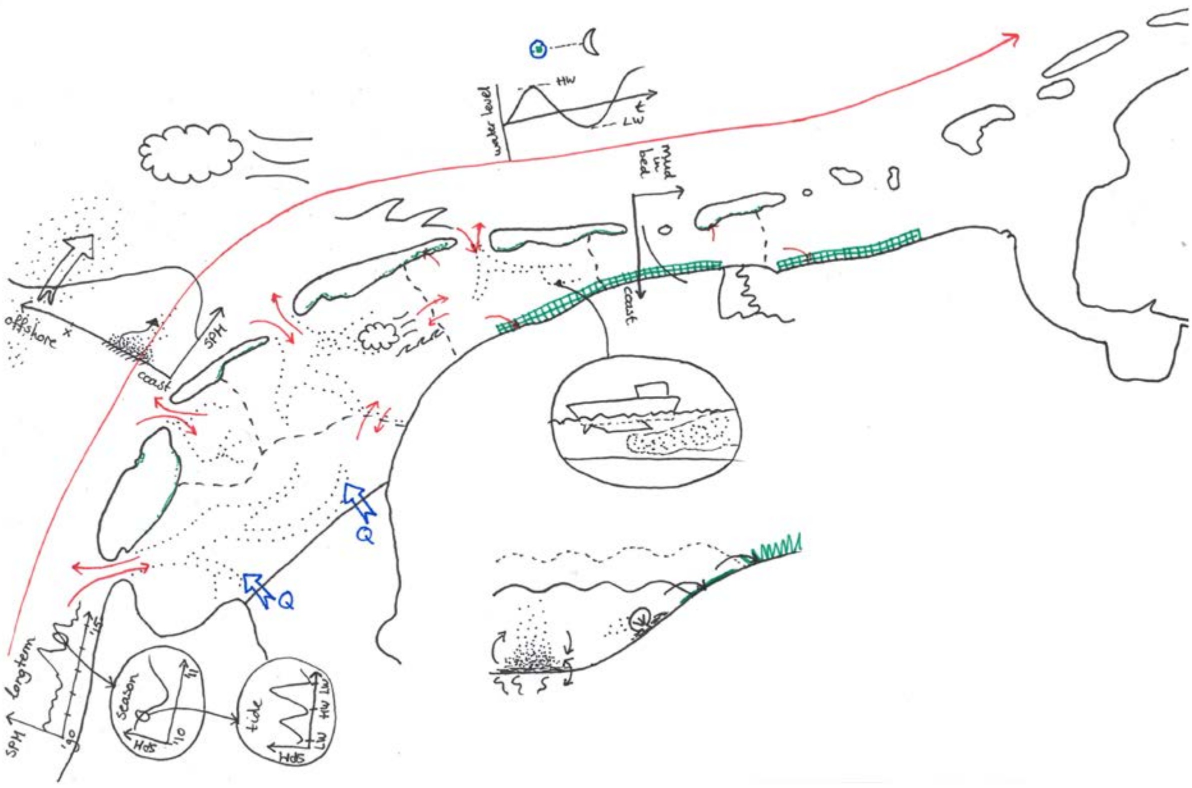


*Figure 21. Schematic diagram of the most important processes affecting mud dynamics in the Wadden Sea.*

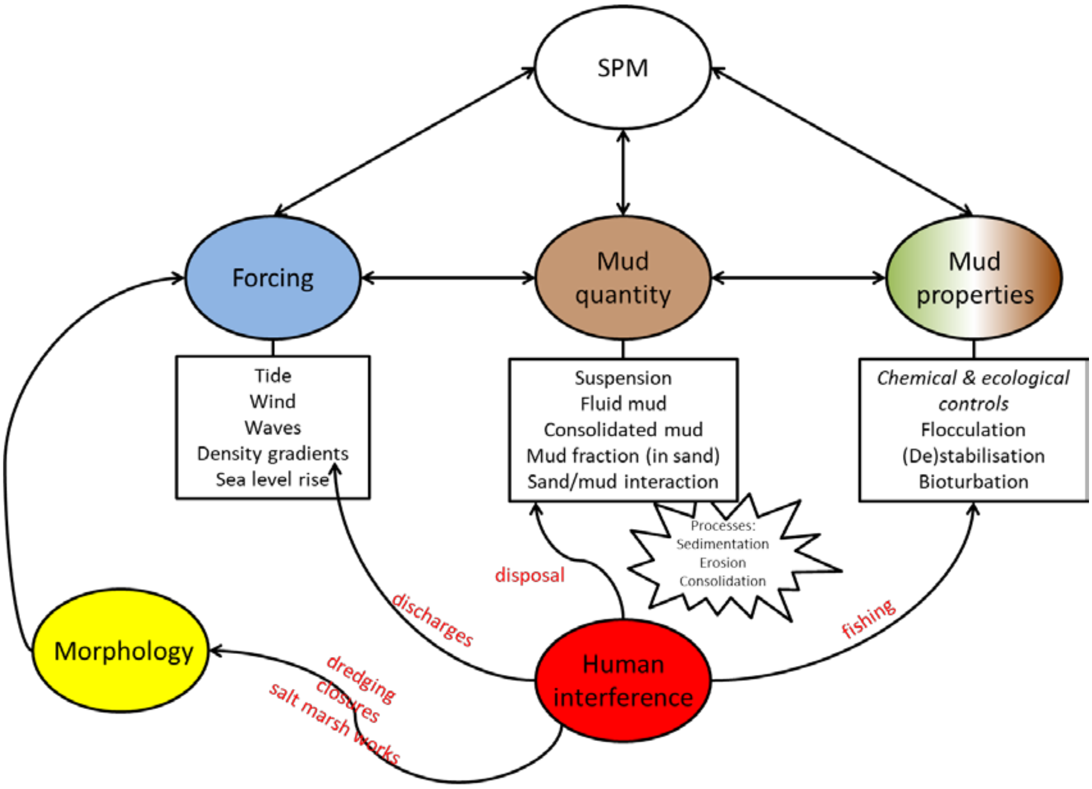


*Figure 22. Schematic and generic diagram of the most important processes affecting SPM levels.*

In the schematic diagrams (Figure 21 and Figure 22) the major processes discussed in this document have been indicated. At short time scale the quantity of mud and their properties are more or less constant and SPM dynamics are mainly driven by hydrodynamic forcing inducing horizontal transport and sedimentation/erosion. At long(er) time scale also changes in mud quantity and mud properties come into play and the level of system complexity increases markedly.

SPM dynamics in the North Sea contribute to the mescoscale and long-term scale processes in the Wadden Sea. We recognize as important elements: the residual flux of mud along the coast (in the order of 20 million tonnes/yr), the influence of tidal currents and waves on sedimentation/resuspension processes in the coastal zone, the inshore-offshore gradient in major factors affecting SPM dynamics in the North Sea, the long-term, as well as seasonal variations in SPM. In addition, short-term variations with tide and weather are recognized as important elements for the understanding of the mud time series in the North Sea.

Exchange processes between the Wadden Sea and surrounding systems include the North Sea coastal zone and freshwater discharge (average discharge of the largest fresh water source Lake IJssel amounts over 500 $m^3/s$, with peak discharges up to over 4000 $m^3/s$). Gross exchange rates between the North Sea and each of the tidal basins are in the order of 50 $10^6$ tonnes/yr, and nett import rates are roughly 1 to 5% of the gross exchange rate. Small-scale processes encompass sedimentation and resuspension, as well as wind-driven phenomena (resuspension, modification of transport pathways). Biological processes (microphytobenthos, saltmarshes, filter feeders, bioturbators) are indicated together with tidal phenomena in the small inset diagram. Human-induced disturbances that can be relevant at mesoscale are dredging and dumping. Dredging volumes have gone up tremendously in recent years, mainly as a result of dredging the fairway to Holwerd, and were in the order of 5.5 $10^6$ $m^3$ for all cumulated dredging works in the Wadden Sea (excluding the Ems estuary) in 2017 (source: H. Mulder, RWS, volume in dredger).

At the long time scale morphological changes such as closures are important. In addition we indicate 'kwelderwerken' as potentially very important drivers for long-term change. In Cleveringa (2018), an annual sedimentation rate of mud of 0.4 to 1.2 $10^6$ $m^3$/yr in the salt marshes and mud flats outside the regular control volumes ('kuberingsgebieden') was found, in addition to annual sedimentation of mud of 0.7 to 3.4 $10^6$ $m^3$/yr in the regular control volumes for the entire Wadden Sea and Ems estuary (Oost et al. 2018). These mud sedimentation rates for the entire Wadden Sea are still under debate. Also the shifts in tidal divides, which may or may not result from closures or other hydrographic interventions, play an important role at this scale.

# 9 Conclusions

This study has revealed a number of statistical properties of time series of SPM content in the water and mud content of Wadden Sea intertidal sediments that require further study and modelling to be fully explained. We mention in particular the following points:

- the multiplicative nature of the processes determining SPM contents, leading to log-normal distribution of observations that require log-transformation in order to detect meaningful characteristics
- the near-constancy of relative seasonal components in all SPM time series, (almost) independent of station location, depth, salinity etc. This seasonal component is related to erosion/deposition processes in shallow locations, but increasingly to vertical mixing process within the water column at deeper stations. It is likely, however, that both bear a similar relation to weather, especially wind, variations over the season.
- the existence, especially in deeper North Sea stations but also in estuarine stations, of significant autocorrelation in the deseasonalized time series over extended lags of over 1 year. As a consequence of this, the relatively high importance of multi-year trends in the data series. This points to the existence of storage or buffering mechanisms, probably different in nature for shallow and deep stations, but all leading to the observation that the short-term erosion/deposition processes are not the only factor of importance for SPM dynamics. This conclusion is consistent with numerical model results.
- a six-year time series of mud content of the sediment at many points in the intertidal (SIBES) revealed weak year-to-year variability of the mean mud content at the level of the Wadden Sea or of the different tidal basins. The small observed variability was difficult to relate to trends in SPM.
- on a much larger time scale of 125 years, changes in the mud distribution in the Wadden Sea sediments have occurred, but these remain relatively limited and can be summarized in a number of trends: coarsening of the tidal divides in the Western Wadden Sea, probably caused by the construction of the Afsluitdijk; increase in elevation of the area around Harlingen, rather than fining of the sediment in that area; clear effect of the ‘kwelderwerken’ in the expansion of the muddy fringe along the mainland coast; fining of the tidal divides in the eastern Wadden Sea, possibly related to changes in tidal volumes as a consequence of the ‘kwelderwerken’. These changes bear a clear relation to overall morphological developments and will no doubt be related to net sand import/export in the tidal basins. A closer examination of this relation is called for.
- A clear bimodal distribution of mud content of the sediment in the intertidal Wadden Sea. The bimodality is stronger expressed in the distribution of the temporal means than in the distribution of the raw observations. Stations with a mean mud content in between the two modes have a higher variability in time than stations with a mean in either of the two modes. This observation suggests bistability in the mud content of intertidal sediments, and is in accordance with existing models. However, further research would be needed to corroborate this hypothesis
- a tight correlation in space between the distribution of microphytobenthos biomass and mud content of the sediment. A tight correlation between the seasonal component of microphytobenthos biomass and SPM. This observation justifies the hypothesis that microphytobenthos may be involved in the bimodality or bistability of mud content observations, but does not provide any proof.

With respect to the main questions formulated in Chapter 0, we can only partly provide answers, but in most cases we can indicate clear progress of insight and suggestions for further clarification.

The main research question focuses on anthropogenic and natural processes influencing the suspended matter concentration in the water, and on how this knowledge can be formalized and form the basis for the clearer definition of management goals and appropriate management of mud dynamics for the Water Framework Directive. Subquestions focus on 1) dominant factors steering dispersion of mud in the Waden Sea and connection with the North Sea, 2) residence time of mud in the Wadden Sea and the system's response to pulses in the mud supply, 3) the importance of mud in the ecological functioning of the Wadden Sea and 4) appropriate strategies for mud management and coastline development in the Wadden Sea, with the aim of improving ecological quality.

Starting with the subquestions, our research has revealed that in the long-term morphological evolution of the Wadden Sea, mud deposition plays a more important role than previously thought. Where mud is deposited within the pore space of sandy sediments, this role is limited, but there are considerable areas where mud percentages are much higher and mud thus contributes substantially to the deposited volumes. Muddy sediments are also deposited in other places than sandy sediments, and thus influence the spatial distribution of net deposition. Substantial net deposition with concomitant reductions in tidal volumes has mostly taken place near the mainland coast related to saltmarsh development and 'kwelderwerken'. The long-term changes in sediment mud content revealed in this report confirm that important contribution, that should be better incorporated into long-term morphodynamic models.

Our research has further revealed the importance of mesoscale phenomena, that have a time scale that is considerably larger than the tidal scale and is modulated by the season. These processes are still poorly resolved mechanistically. We suggest that they are related to important buffering mechanisms, that may be related to microphytobenthos or other ecological mechanisms, and that integrate meteorological and possibly other forcing conditions. A consequence of this buffering is that the system has a relatively long 'memory' and thus displays significant trend components on a one to multi-year time scale. These trends are correlated between stations within a system, suggesting that relatively large-scale phenomena drive them. However, we have not been able to find clear causal links between the trends among different parts of the North Sea, or between the North Sea and the Wadden Sea. We found no evidence that external long-term trends are a major driver for the year-to-year differences in the Wadden Sea suspended sediment concentrations. We think that resolving the causality in these mesoscale processes is very important to get a better grip on mud dynamics in the Wadden Sea in general. This is also very important for management, as it reveals the time scale on which management goals must be set, as well as objectives for the management of processes contributing to these mesoscale variations. The question whether anthropogenic disturbances also contribute significantly to these trend components, has not been extensively analysed in the present document, and remains as an important item for continuation of the project. We did not, however, find any obvious candidate disturbance that can be directly linked to the observed variations in SPM in the Wadden Sea.

The present report has not gone into the influence of SPM on ecological processes in the Wadden Sea. The reverse, ecological influence on SPM dynamics and on mud content in the sediment, has however been given attention to. We found clear relations between microphytobenthos biomass and sediment mud content, and we also found possible relations at seasonal and even longer time scale (but very uncertain) between microphytobenthos biomass development and SPM content in the water column. This point needs further working out, as it could provide an important mechanism for the hypothesized buffer mechanisms leading to the long memory of the system with respect to SPM.

With respect to the goals to be set in the Water Framework Directive and management implications, a number of conclusions can already be drawn, although details need to be worked out. The role of mud in the long-term morphological evolution of the Wadden Sea, especially along the mainland coast but increasingly also on the tidal divides, points to the importance of interactions between the ‘kwelderwerken’, tidal volumes and other hydrodynamic changes and the morphological evolution. This can help to explain increasing problems (and ensuing dredging works) with fairway maintenance. Implications for alternative solutions to this fairway maintenance can be investigated on this basis. It also has relevance with respect to the expected effect of sea-level rise on the Wadden Sea. Although the muddy deposits are currently relatively stable, due to the stabilizing effects of vegetation, a relevant question is whether this stability remains guaranteed under increased rates of sea-level rise.

With respect to the mesoscale processes and the long memory of the system, leading to important multi-year trends in the SPM, a consequence of the current research is that goals for management should be set at an appropriate time scale, which is in the range of 5-10 years. The variability is inherent in the system, and any changes in management are not expected to be immediately effective. Important questions of ecological management, in the first place the question whether the Wadden Sea has become more turbid with concomitant negative ecological consequences, should also be addressed at this decadal time scale. In the data investigated here some indications of a decadal-scale positive trend in SPM are visible in some of the series, but the signal is not strong and should be carefully re-evaluated before important measures are considered. Other important questions that should be addressed relate to muddy dredge spoil. We found indications that once SPM values are high, they tend to remain high for considerable time and over large spatial scales. This may entirely be related to natural phenomena, in which case it should be no reason for change in management. However, if the release of important quantities of dredge spoil leads to a systematic increase of SPM that is subsequently maintained for a long period of time and in turn increases the need for more dredging, it could be considered to remove the spoil and use it in a beneficial manner. While it is much too early to suggest any particular measures in this respect, the question is relevant and the present research provides a number of elements that may help clarifying the issue.

# 10 Recommendations

Based on these observations and the hypotheses formulated to explain them, we recommend the following data acquisition activities:

- routinely collect information on the vertical distribution of SPM in the water column at all monitoring stations. This information can be collected with a CTD equipped with a turbidity meter or OBS and a fluorimeter, and would constitute a limited extension of the monitoring activities. This will reveal to what extent the observed variability in near-surface suspended sediment concentrations is the result of variability of the total sediment mass in the water column, or variability of the shape of the concentration profile. A point of attention that needs closer examination is whether the timing of the MWTL measurements (slack water) is suitable for this extension.
- equip a number of the long-term monitoring stations, both in the North Sea and in the Wadden Sea, with permanent stations that measure the vertical distribution of SPM in the water column at hourly time scales.
- extend the observation series from remote sensing of microphytobenthos biomass in the Wadden Sea for the period from 2009 to at least 2015, using the same methodology as van der Wal et al. (2010). Remote sensing observations of SPM are also valuable to determine the variability of horizontal SPM gradients as a function of forcing conditions (e.g. tide, wind, waves and freshwater discharge).
- extend the SIBES observations of sediment mud content with a limited number of stations that are monitored at a weekly to monthly time scale. Use the distribution of mud contents, as well as spatial layout, as a basis for the selection of stations. Measure chlorophyll-a content of the sediment simultaneously with mud content.

We further recommend a number of data exploration and analysis steps that have not been completed in this report, but appear to be essential for further testing of hypotheses:

- formalize the analysis of historic maps of mud content of the sediment by reading them into GIS systems
- better exploit the data generated from high-resolution stations in the Wadden Sea, e.g. in the framework of the SeaWad project
- complete the overview of morphological changes caused by the ‘kwelderwerken’ and calculate (model) their effect on tidal volumes, current velocities and mud deposition possibilities

Finally, and most importantly, we recommend fusing the present data-based analysis with dynamic modelling of mud dynamics. Several of the hypotheses posed based on the data analysis should be analysed with dynamic models, because the interactions are complex with many feedback loops. Models are particularly suitable to test whether the hypotheses can explain the patterns found in the statistical analysis of the data. In order to do this, it is not always necessary to produce full-scale detailed simulation models for the entire system. There is also a need for more analytically oriented models that allow improving insight in the system dynamics.

We think that such modelling development can advance existing mud dynamics models and contribute to a new generation of simulation models including mud dynamics in the Wadden Sea. Such a full-scale model should be designed to be of use not only for the present general questions regarding the Wadden Sea as a whole, but also as a management instrument suitable for specific cases at much smaller scales. That could constitute a critical step

between the present state of the project, and the ultimate goal of improving practical management in the Wadden Sea, based on improved understanding of the system functioning.
The model improvement and development should in particular focus on:

- critically examine if common formulations for mud dynamics in estuarine systems such as the Wadden Sea can be the same as for the coastal North Sea and the deeper North Sea. The need for inclusion of biologically mediated processes in shallow systems such as the Wadden Sea is a point of critical evaluation.
- examine model output for its ability to reproduce essential statistics of the series, such as mean, standard deviation, type of distribution, autocorrelation, importance of trend and seasonality etc. This applies to time series of SPM but also to spatial distribution of sediment mud content.
- formulate, ideally based on the essentials of a process-based short-term model, a model for the long-term evolution of sediment mud content (linked to morphology) of the Wadden Sea. It is not possible to simulate a century of morphological evolution with a standard mud dynamics model, but nevertheless evolutions on this time scale are extremely important.

# 11 Management implications

The observations in this report raise a number of important questions with respect to the management of the Wadden Sea. We only briefly discuss these questions here, as we rarely have final answers based on the present analysis. However, further work that is oriented towards these management questions would also be able to tackle some of the fundamental questions posed by the data analysis.

- One important question relates to the fate of dredge sludge dumping. When muddy material is dredged and dumped, there is no net change in the mud content of the system, and the resuspension of the dumped material is compensated by the renewed deposition in the dredging sites. However, given the long correlation times of SPM, the question is what these practices do to the SPM content of the water. Better insight into, and modelling of, these time dynamics may also improve the estimation of likely effects of dredging and dumping strategies. It can also be used to evaluate whether extraction of dredged material for beneficial use elsewhere is a worthwhile strategy, thereby also including effects on mud sedimentation elsewhere.
- Another important set of questions concerns the ‘kwelderwerken’. These activities have local effects on ecosystem services and natural values. Some of these values are in high esteem and are a reason to continue these activities beyond the times of land reclamation, but essentially they replace one valuable ecosystem (tidal flats) by another (saltmarshes). However, to the degree that the ‘kwelderwerken’ also affect the morphological development and the mud dynamics in the rest of the system, this may constitute a reason to reconsider their inclusive ecological effects. The question should also be investigated in the light of expected sea level rise.
- The future development of mud dynamics in the Wadden Sea will anyhow be linked to sea level rise. Changing average water depth or extent of intertidal area will directly affect many of the processes that are important for mud dynamics. A comparative approach within the Wadden Sea, comparing western to eastern Wadden Sea, and with outside systems, e.g. the Oosterschelde, could be very informative on possible future evolution. This would particularly depend on the ability to make longer-time model predictions of mud dynamics and its interaction with morphology.

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