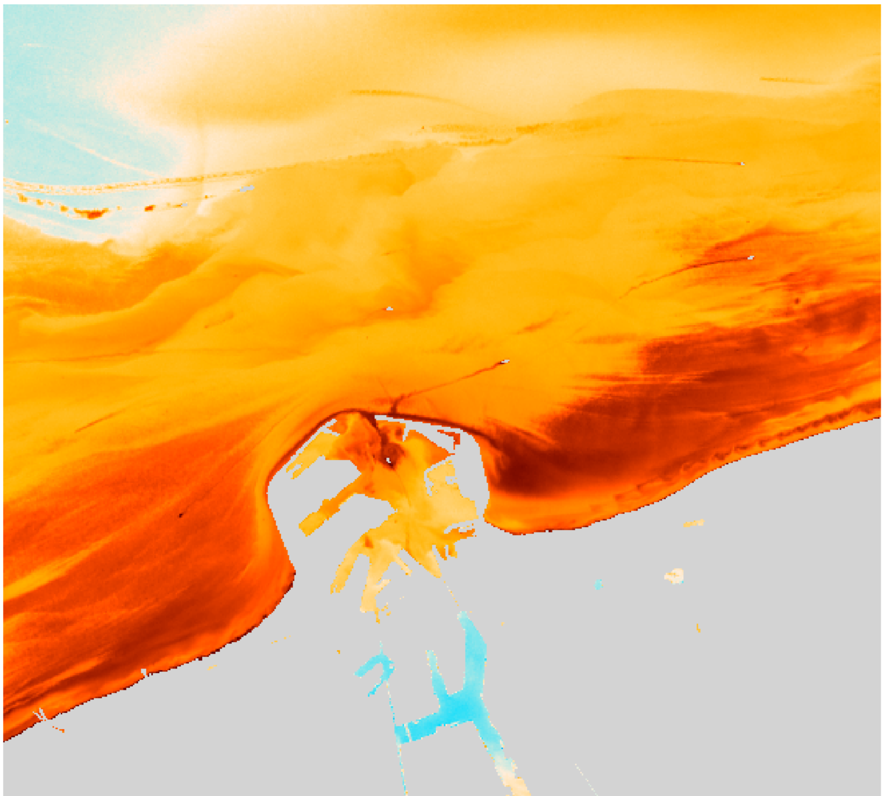
Koninklijk Belgisch Instituut voor Natuurwetenschappen
OD NATUUR – BEHEERSEENHEID VAN HET MATHEMATISCH MODEL

MOnitoring en MOdellering van het cohesieve sedimenttransport en evaluatie van de effecten op het mariene ecosysteem ten gevolge van bagger- en stortoperatie (MOMO)



Activiteitsrapport (1 juli 2018 – 31 december 2018)

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MOMO/8/MF/201906/NL/AR/4

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1. Inleiding

1.1. Voorwerp van deze opdracht

Het MOMO-project (monitoring en modellering van het cohesieve sedimenttransport en de evaluatie van de effecten op het mariene ecosysteem ten gevolge van bagger- en stortopera-tie) maakt deel uit van de algemene en permanente verplichtingen van monitoring en evaluatie van de effecten van alle menselijke activiteiten op het mariene ecosysteem waaraan België gebonden is in overeenstemming met het verdrag betreffende de bescherming van het mariene milieu van de noordoostelijke Atlantische Oceaan (1992, OSPAR-Verdrag). De OSPAR Commissie heeft de objectieven van haar Joint Assessment and Monitoring Programme (JAMP) gedefinieerd tot 2021 met de publicatie van een holistisch "quality status report" van de Noordzee en waarvoor de federale overheid en de gewesten technische en wetenschappelijke bijdragen moeten afleveren ten laste van hun eigen middelen.

De menselijke activiteit die hier in het bijzonder wordt beoogd, is het storten in zee van baggerspecie waarvoor OSPAR een uitzondering heeft gemaakt op de algemene regel "alle stortingen in zee zijn verboden" (zie OSPAR-Verdrag, Bijlage II over de voorkoming en uitschakeling van verontreiniging door storting of verbranding). Het algemene doel van de opdracht is het bestuderen van de cohesieve sedimenten op het Belgisch Continentaal Plat (BCP) en dit met behulp van zowel numerieke modellen als het uitvoeren van metingen. De combinatie van monitoring en modellering zal gegevens kunnen aanleveren over de transportprocessen van deze fijne fractie en is daarom fundamenteel bij het beantwoorden van vragen over de samenstelling, de oorsprong en het verblijf ervan op het BCP, de veranderingen in de karakteristieken van dit sediment ten gevolge van de bagger- en stortoperaties, de effecten van de natuurlijke variabiliteit, de impact op het mariene ecosysteem in het bijzonder door de wijziging van habitatten, de schatting van de netto input van gevaarlijke stoffen op het mariene milieu en de mogelijkheden om deze laatste twee te beperken.

Een samenvatting van de resultaten uit de voorbije vergunningsperiode kan gevonden worden in het Syntheserapporten over de effecten op het mariene milieu van baggerspeciestortingen (Lauwaert et al. 2016) dat gepubliceerd werd conform art. 10 van het K.B. van 12 maart 2000 ter definiëring van de procedure voor machtiging van het storten in de Noordzee van bepaalde stoffen en materialen.

1.2. Algemene doelstellingen

Het onderzoek heeft als doel om de effecten van baggerspeciestortingen op het mariene ecosysteem (fysische aspecten) te onderzoeken en kadert in de algemene doelstellingen om de baggerwerken op het BCP en in de kusthavens te verminderen en om een gedetailleerd inzicht te verwerven van de fysische processen die plaatsvinden in het mariene kader waarbinnen deze baggerwerken worden uitgevoerd. Dit impliceert enerzijds beleidsondersteunend onderzoek naar de vermindering van de sedimentatie op de baggerplaatsen en het evalueren van alternatieve stortmethoden. Anderzijds is vernieuwend onderzoek vereist om een beter inzicht te bereiken over de fysische processen van slibtransport en het inschatten van de effecten van het storten van baggerspecie. Dit is specifiek gericht op het dynamische gedrag van slib in de waterkolom en op de bodem en zal uitgevoerd worden met behulp van modellen, in situ metingen en remote sensing data.

<u>1) In situ en remote sensing metingen en data analyse</u>

De monitoring van effecten van baggerspeciestortingen gebeurd met behulp van een vast meetstation in de nabijheid van MOW1, en met meetcampagnes met de RV Belgica (een 4 tal meetcampagnes voor het verzamelen van traject informatie, profielen en de calibratie van sensoren; en een 10 tal campagnes voor het onderhoud van het meetstation te MOW1). De geplande monitoring is gericht op het begrijpen van processen, zodoende dat de waargenomen variabiliteit en de effecten van baggerspeciestortingen in een correct kader geplaatst kunnen worden. Een belangrijk deel is daarom gericht op zowel het uitvoeren van de in situ metingen, het garanderen van kwalitatief hoogwaardige data en het archiveren, rapporteren en interpreteren ervan. Remote sensing data afkomstig van onder andere satellieten worden gebruikt om een ruimtelijk beeld te bekomen.

2) Uitbouw en optimalisatie van het modelinstrumentarium

Het tijdens de voorbije jaren verbeterde en aangepaste slibtransportmodel zal verder worden ontwikkeld. Dit zal parallel gebeuren met de nieuwe inzichten die voorvloeien uit de metingen en de proces gerichte interpretatie van de metingen.

3) Ondersteunend wetenschappelijke onderzoek

Monitoring gebaseerd op wetenschappelijke kennis is essentieel om de effecten van menselijke activiteiten (hier het storten van baggerspecie) te kunnen schatten en beheren. Om te kunnen voldoen aan de door OSPAR opgelegde verplichtingen van monitoring en evaluatie van de effecten van menselijke activiteiten is het ontwikkelen van nieuwe monitorings- en modelleeractiviteiten nodig. Dit houdt in dat onderzoek dat de actuele stand van de wetenschappelijke kennis weerspiegelt wordt uitgevoerd en dat de hieruit voortvloeiende nieuwe ontwikkelingen geïntegreerd zullen worden in zowel de verbetering van het modelinstrumentarium als voor het beter begrijpen van het fysisch milieu.

1.3. Onderzoek Januari 2017 – December 2018

In het bijzonder is bij het opstellen van de hieronder vermelde taken rekening gehouden met de aanbevelingen voor de minister ter ondersteuning van de ontwikkeling van een versterkt milieubeleid zoals geformuleerd in het "Syntheserapport over de effecten op het mariene milieu van baggerspeciestortingen (2011)" dat uitgevoerd werd conform art. 10 van het K.B. van 12 maart 2000 ter definiëring van de procedure voor machtiging van het storten in de Noordzee van bepaalde stoffen en materialen. De specifieke acties in de periode 2017-2018 zullen uitgevoerd worden om de algemene doelstellingen in te vullen zijn de volgende:

Streven naar een efficiënter stortbeleid door:

- Optimalisatie van de stortlocaties. Bijkomende simulaties worden uitgevoerd voor het opzetten van een MER voor een alternatieve stortplaats (zie taak 2.2). Verder zullen de effecten van een efficiënter verplaatsen van het gebaggerde materiaal te Nieuwpoort en Blankenberge naar de stortzones (lozen i.p.v. storten) geëvalueerd worden (zie Taak 3.4);
- Onderzoek naar de mogelijkheden voor het opzetten van een operationeel stortmodel in overleg met aMT (Taak 2.3). Dit model zal geïntegreerd worden in de binnen BMM-OD Natuur beschikbare operationele modellen. Het model zal gebruikt worden om in functie van de voorspelde fysische (wind, stroming, golven, sedimenttransport, recirculatie), economische (afstand, grootte baggerschip) en ecologische aspecten op korte termijn een keuze te kunnen maken tussen de beschikbare stortlocaties. Hiervoor zal binnen de huidige periode het slibtransportmodel gevalideerd worden op de geografische variabiliteit van de turbiditeitszones en de flocculatie van het slib.

Continue monitoring van het fysisch-sedimentologische milieu waarbinnen de baggerwerken worden uitgevoerd (Taak 1) en aanpassing van de monitoring aan de nog op te stellen targets voor het bereiken van de goede milieutoestand (GES), zoals gedefinieerd binnen MSFD;

Uitbouw en optimalisatie van het numerieke modelinstrumentarium, ter ondersteuning en verfijning van het onderzoek (Taak 2.1).

Taak 1: In situ en remote sensing metingen en data analyse

Taak 1.1 Langdurige metingen

Sinds eind 2009 worden er continue metingen uitgevoerd te MOW1 met behulp van een meetframe (tripode). Met dit frame worden stromingen, slibconcentratie, korrelgrootteverdeling van het suspensiemateriaal, saliniteit, temperatuur, waterdiepte en zeebodem altimetrie gemeten. Om een continue tijdreeks te hebben, wordt gebruik gemaakt van 2 tripodes. Na ongeveer 1 maand wordt de verankerde tripode voor onderhoud aan wal gebracht en wordt de tweede op de meetlocatie verankerd. Op de meetdata wordt een kwaliteitsanalyse uitgevoerd, zodat de goede data onderscheiden kunnen worden van slechte of niet betrouwbare data.

In 2013-2016 werden enkele langdurige metingen uitgevoerd met behulp van een OBS-5 sensor vastgemaakt aan de AW boei; deze metingen zullen verdergezet worden. De data geven informatie over de SPM concentratie aan het oppervlak en zijn aldus complementair aan de bodemnabije metingen met de tripode. De data zijn ook van belang voor het calibreren en valideren van de oppervlakte SPM concentraties uit satellietbeelden.

Taak 1.2 Calibratie van sensoren tijdens in situ metingen

Tijdens 4 meetcampagnes per jaar met de R/V Belgica zullen een voldoende aantal 13-uursmetingen uitgevoerd worden met als hoofddoel het calibreren van optische of akoestische sensoren en het verzamelen van verticale profielen. De metingen zullen plaatsvinden in het kustgebied van het BCP. De optische metingen (transmissometer, Optical Backscatter Sensor) zullen gecalibreerd worden met de opgemeten hoeveelheid materie in suspensie (gravimetrische bepalingen na filtratie) om te komen tot massa concentraties. Naast de totale hoeveelheid aan suspensiemateriaal (SPM) wordt ook de concentratie aan POC/PON, TEP, chlorofyl (Chl-a, Chl-b) en phaeofytine (a, b) bepaald. Stalen van suspensiemateriaal zullen genomen worden met de centrifuge om de samenstelling ervan te bepalen.

Taak 1.3 Kwaliteitscontrole van de data

In situ metingen zijn steeds onderhevig aan onzekerheden ten gevolge van random meetfouten (gebrek aan precisie), systematische fouten (onnauwkeurigheid), menselijke fouten, en de statistische variabiliteit van de parameter. De fouten hebben hun oorsprong in de onnauwkeurigheid en het gebrek aan precisie van het meetinstrument of de procedures (bv. waterstaalname en filtratie). Doel is om de fout op de verschillende onderdelen van de metingen (filtratie, calibratie, langdurige trends...) te schatten. Een procedure die de best practice beschrijft zal worden opgesteld.

Een belangrijk aandachtspunt bij deze langdurige datareeksen is het garanderen van een gelijke kwaliteit in de tijd van de verzamelde data. De vraag die zich bij onze SPM concentratiemetingen stelt is niet zozeer het opmeten van hogere of lagere waarden, mogelijks veroorzaakt door het toepassen van een andere stortstrategie, maar het garanderen dat deze waarden inderdaad veroorzaakt worden door menselijke activiteiten (bv storten) en niet het effect zijn van natuurlijke fluctuaties. Om kwaliteitsvolle data te kunnen leveren over een lange periode, die gebruikt kunnen worden om langdurige trends te identificeren, is het nodig om een rigoureuze kwaliteitscontrole uit te voeren. OBS alsook akoestische sensoren zijn gevoelig aan de samenstelling en korrelgrootte van het gesuspendeerde materiaal. Dit kan variëren in functie van de boven vermelde frequenties, maar hieromtrent is er nog geen afdoende duidelijkheid wat de metingen te MOW1 betreft. De wetenschappelijke vragen die daarom moeten worden, hebben betrekking tot in situ en in lab calibratie van de OBS sensoren en van akoestische backscatter sensoren en de meetfouten.

Taak 1.4: Verwerking en interpretatie van de data

De metingen vergaard tijdens de 13-uursmetingen aan boord van de Belgica en met de tripode worden verwerkt en geïnterpreteerd. Hiervoor werden in het verleden al heel wat procedures (software) toegepast of ontwikkeld, zoals de berekening van de bodemschuif-spanning uit turbulentiemetingen, entropieanalyse op partikelgrootteverdelingen, de op-splitsing van multimodale partikelgrootteverdeling in een som van lognormale verdelingen, het groeperen van de data volgens getij, meteorologie, klimatologie en seizoenen. Deze methodes zijn opgenomen in de standaardverwerking van de data. De aldus verwerkte data dienen als basis voor het verder gebruik binnenin wetenschappelijke vragen.

Taak 1.5: Sedimentologie van zeebodem

De sedimentologie van stortplaatsen en referentiezones zal, in samenwerking met het ILVO, worden bestudeerd met alternatieve meettechnieken, zoals de Sediment Profile Imaging (SPI).

Taak 1.6: TBT analysen

TBT analysen op stalen aangeleverd door het ILVO zullen door het chemisch labo van het KBIN (Ecochem) worden uitgevoerd. Het betreft de analyse van 6 stalen (2 replica's).

Taak 2: Uitbouw en optimalisatie van het modelinstrumentarium

Taak 2.1: Verdere ontwikkelingen en validatie van een slibtransportmodel voor het BCP gebaseerd op Coherens V2

Het tijdens de voorbije jaren verbeterde en aangepaste slibtransportmodel zal worden gevalideerd met behulp van de langdurige meetreeksen en de satellietbeelden. Hierbij zal dezelfde methode als in Baeye et al. (2011) en zoals in taak 1.4 worden gebruikt om de modelresultaten te groeperen en te klasseren volgens windrichting, weertype en getij. Het voordeel van deze werkwijze is dat niet zozeer gekeken wordt of de correlatie tussen meting en modelresultaat in één of meerder punt goed is, maar dat globaal nagegaan wordt of het model de SPM dynamica op het BCP goed kan reproduceren.
Verdere ontwikkelingen aan het model parallel met nieuwe inzichten die voorvloeien uit de metingen en de proces-gerichte interpretatie van de metingen zullen worden geïmplemen-teerd in het model.

Taak 2.2: Ondersteuning bij de MER studie van een alternatieve stortlocatie

Op dit moment worden op het BCP vijf stortplaatsen gebruikt voor het gebaggerd materiaal afkomstig uit de vaargeulen op zee en de zeehavens: Zeebrugge Oost, S1, S2, B&W Oostende en Nieuwpoort. Door OD Natuur- BMM werd in het kader van het MOMO project onderzoek gedaan naar de efficiëntie van de stortplaatsen. Daaruit blijkt dat de recirculatie naar de baggerplaatsen het grootste is vanuit de stortplaats Zeebrugge Oost. Met behulp van numerieke modellen werden een aantal alternatieve locaties voor de stortplaats Zeebrugge Oost bestudeerd. In 2012-2013 werd een terreinproef uitgevoerd om de resultaten van de numerieke modellering op het terrein te valideren. Uit de resultaten van de terreinproef bleek dat er aanwijzingen zijn die de resultaten van de numerieke modellering bevestigen.

OD Natuur-BMM zal in deze studie instaan voor het uitvoeren van de nodige numerieke modelleringen in de eerste helft van 2017. Hiervoor zal gebruik gemaakt worden van het geüpdatete 3D stromingsmodel dat beschikbaar is bij OD Natuur-BMM. Het model is opgebouwd in Coherens V2, inclusief sedimenttransportmodule en flocculatiemodel. Meer specifiek zal de OD Natuur-BMM betrokken zijn bij:

Fase 1 (long list van mogelijke locaties en exploitatiescenario's opgemaakt worden): berekening van de recirculatie voor maximaal 10 mogelijke locaties en/of stortscenario's. Voor iedere berekening zullen voor een aantal combinaties van hydro-meteo randvoorwaarden simulaties uitgevoerd worden. Deze randvoorwaarden zijn zo gekozen dat ze optimale aansluiting verzekeren met de al eerder uitgevoerde simulaties.

Fase 2 (opmaak Milieu Effect Rapport): Bij de opmaak van het MER zelf is geen specifieke modellering nodig voor de inschatting van de effecten. Indien uit overleg met de vergunningverlenende instanties blijkt dat simulaties moeten uitgevoerd worden ter onderbouwing van de gemaakte keuzes (recirculatie bij een bepaalde locatie/stortstrategie) kan dit uitgevoerd worden.

Taak 2.3: Operationeel stortmodel (vanaf 2018)

Overleg met aMT over het opstellen van een operationeel stortmodel om de noden en de mogelijkheden te definiëren. Het model zal later (vanaf 2018) kunnen opgesteld worden en kan dan geïntegreerd worden in de binnen BMM-OD Natuur beschikbare operationele modellen. Het model zal kunnen gebruikt worden om in functie van de voorspelde fysische (wind, stroming, golven, sedimenttransport, recirculatie), economische (afstand, grootte baggerschip) en ecologische aspecten op korte termijn een keuze te kunnen maken tussen de beschikbare stortlocaties.

Taak 3: Ondersteunend wetenschappelijk onderzoek

Monitoring gebaseerd op wetenschappelijke kennis is essentieel om de effecten van menselijke activiteiten (hier het storten van baggerspecie) te kunnen schatten en beheren. Om te kunnen voldoen aan de door OSPAR opgelegde verplichtingen van monitoring en evaluatie van de effecten van menselijke activiteiten is een verdere implementatie van huidige en het ontwikkelen van nieuwe monitoringsactiviteiten nodig. Meer specifiek gericht op de activiteit 'storten van baggerspecie' worden hier – wat het fysische milieu betreft - turbiditeit, samenstelling van de zeebodem, bathymetrie en hydrografische condities beoogd. Deze taak speelt hierop in door de ontwikkeling van nieuwe tools die de actuele stand van de wetenschappelijke kennis weerspiegelen teneinde de mathematische modellen te optimaliseren en verfijnen.

Taak 3.1: Sedimentuitwisseling tussen de zee en de haven van Zeebrugge

Slib stroomt de haven van Zeebrugge binnen rond HW, wanneer de stroming maximaal is. Gezien de grote turbulentie op dit moment op zee bestaat het SPM uit voornamelijk kleine vlokken met een lage valsnelheid. Eens het suspensiemateriaal de haven binnenkomt, neemt de turbulentie plots af, ontstaan er grotere vlokken en treed er een snelle bezinking op. Het verloop van de SPM concentratie in de haven zelf is goed gekend (zie onder andere de SPM concentratie metingen in de haven tijdens de terreinproef en de metingen van de topsliblaag), maar aan de havenmond zijn minder data beschikbaar om de sediment-uitwisseling in kaart te brengen en dit tijdens verschillende getij- en meteocondities. In deze taak zal de sedimentdynamica bestudeerd worden gebruikmakend van ADCP transects gemeten met de RV Belgica, van verticale profielen van SPM concentratie en vlokgrootte in en uit de haven, en van remote sensing beelden.

Taak 3.2: Microbiologische activiteit en de wisselwerking met sedimentdynamica

Een sleutelelement in het functioneren van kustnabije ecosystemen is de aanwezigheid van biotische en abiotische partikels. Verticale en dus ook horizontale fluxen van SPM worden bepaald door hun valsnelheid, die afhangt van de capaciteit van de deeltjes om te flocculeren. Flocculatie beïnvloedt de grootte van de gesuspendeerde deeltjes en bepaald daardoor de depositie van het slib. Op zijn beurt wordt flocculatie gestuurd door turbulentie, de SPM concentratie, en de oppervlakte eigenschappen van de deeltjes, die van elektrochemische of biologische oorsprong kunnen zijn. Wat dit laatste betreft heeft dit een wederzijdse invloed tot gevolg tussen het SPM en de primaire productie doordat stoffen zoals TEPs (transparent exopolymeric particles), die vrijkomen door het fytoplankton en de bacteriën, de vlokgrootte en dus ook de valsnelheid van het SPM beïnvloeden. Het belang van deze processen voor de slibdynamica in onze kustzone en dus ook voor de aanslibbing van havens en vaargeulen wordt gegeven door de uitzonderlijk hoge primaire productie in de Belgische kustzone ten gevolge van eutrofiëring (algenbloei). Dat er een effect is werd al aangetoond door de metingen te MOW1 die lieten zien dat het SPM zich anders gedraagt in de winter dan in de biologisch actieve zomerperiode. In de winter is het SPM beter gemengd in de waterkolom dan in de zomer en treden er dus hogere concentraties op in de waterkolom. In de zomer bevindt zich meer suspensiemateriaal dicht tegen de bodem en daalt de SPM concentratie in de waterkolom. Dit roept volgende vragen op, in het bijzonder 1) Hoe moet het modelinstrumentarium (flocculatiemodule) worden aangepast om deze seizoenaliteit te kunnen modelleren? 2) Wordt de seizoenaliteit in SPM concentratie en biologische activiteit veroorzaakt doordat de algen TEP produceren, dat aanleiding geeft tot de vorming van grotere vlokken en dus een hogere bezinking van het SPM als gevolg heeft, of daalt eerst de SPM concentratie ten gevolge van fysische processen (afname van de stormfrequentie in de lente) en start de algenbloei nadat het water minder troebel is geworden?) De troebelheid in de waterkolom is in de Belgische kustzone altijd hoog en de lichtindringing is ook in de zomer beperkt. Speelt troebelheid (en dus ook SPM concentratie) een belangrijke rol bij start van de algenbloei bepaald of is dit eerder een secundair proces?

Het onderzoek zal gericht zijn op het verzamelen van in situ meetdata van TEP, SPM en Chl concentratie te MOW1 en op andere plaatsen; het analyseren van de data in functie van boven aangehaalde vragen; het incorporeren van de biologische activiteit in een flocculatiemodel en het uitvoeren van modelberekeningen.

<u>Taak 3.3: Overgang kustzone – offshore: Waarom is het turbiditeitsgebied beperkt tot de kustzone?</u>

Turbulentie samen met de SPM concentratie bepalen de lichthoeveelheid in het water. De cross-shore stroming in vele kustgebieden is gekenmerkt door landinwaarts gerichte stroming dicht tegen de bodem en een zeewaarts gerichte aan het wateroppervlak (estuariene circulatie). Het is op dit moment niet duidelijk hoe het Schelde estuarium deze circulatie beïnvloed. Hierdoor wordt het SPM (en het fytoplankton) naar de kust getransporteerd in de bodemlaag nadat het eerst naar offshore werd getransporteerd in de oppervlaktelaag. Dit mechanisme is mogelijks verantwoordelijk voor de scherpe gradiënt in SPM concentratie langsheen onder andere de Belgische kust en de Westerscheldmonding. Ook turbulentie is gekenmerkt door een gradiënt: hoog dicht tegen de kust en afnemend naar offshore toe. Dit komt overeen met een toename in waterdiepte naar offshore toe. Bij geringere waterdieptes is de turbulentie hoger, de verticale menging dus sneller en dus de tijd met lage SPM concentratie korter. Naar offshore toe zal de lichthoeveelheid in de waterkolom dus toenemen in de oppervlaktelaag omdat de diepte toeneemt. Vanaf een bepaalde diepte bereikt het SPM niet meer de oppervlakte tijdens verticale menging. De afname in SPM concentratie is dus mogelijks een afspiegeling van de gradiënten in diepte en turbulentie. Dit proces werd aangetoond in andere delen van de Noordzee (Duitse Bocht), maar nog niet in de Belgische kustzone.

Het onderzoek zal gericht zijn op het verzamelen van in situ meetdata van TEP, SPM en Chl concentratie op een drietal locaties gelegen op verschillende afstanden van de kust; het varen van ADCP transects dwars op de kust; en het analyseren van de data. TEP en Chl zijn een onderdeel van het SPM, die een significante invloed heeft op de seizoenaliteit van de

SPM dynamica.

Taak 3.4: Alternatieve Stortstrategie Nieuwpoort

Er zal ondersteuning gegeven worden aan afdeling kust in verband met het opzetten van een wetenschappelijke terreinproef om de impact van het verpompen van baggerspecie uit de haven van Nieuwpoort op een stortzone te evalueren. Details hiervan zullen op een vergadering van de technische werkgroep besproken worden.

1.4. Gerapporteerde en/of uitgevoerde taken

Periode Januari 2017 – Juni 2017

Taak 1.1: De meetreeks te MOW1 werd verdergezet.

Taak 1.2: Calibratie van sensoren werd uitgevoerd tijdens campagne 2017/20 (21-23/06/2017).

Taak 2.1 De bodemschuifspanning gemodelleerd met het hydrodynamisch model werd gevalideerd met in situ data te MOW1. Dit is een eerste stap bij de validatie van een slibtransportmodel voor het BCP gebaseerd op Coherens V2, zie Appendix 2 van activiteitsrapport MOMO/8/MF/201707/NL/AR/1.

Taak 2.2 Simulaties met de nieuwe versie van het COHERENS V3 model voor de Belgische kustzone werden uitgevoerd ter ondersteuning van de MER studie voor een alternatieve stortlocatie, zie Hoofdstuk 2 in activiteitsrapport MOMO/8/MF/201707/NL/AR/1

Taak 3.2 Waterstalen voor de bepaling van TEP concentratie werden 1-2 wekelijks genomen te Oostende.
Een 1 klasse flocculatiemodel werd aangepast om biologisch flocculatie te simuleren. De resultaten werden gevalideerd met metingen te MOW1, zie Hoofdstuk 3 in activiteitsrapport MOMO/8/MF/201707/NL/AR/1.

Periode Juli 2017 – December 2017

Taak 1.1 De meetreeks te MOW1 werd verdergezet. Het factual data rapport voor 2016 werd opgesteld.

Taak 1.2 Calibratie van sensoren werd uitgevoerd tijdens campagne 2017/24 (16-18/08/2017), 2017/34 (21-22/11/2017), 2017/38 (18-21/12/2017).

Taak 1.3 Een uitgebreide onzekerheidsanalyse van de optische en akoestische sensoren gebruikt bij langdurige metingen is in uitvoering. Resultaten werden op de INTERCOH conferentie getoond, zie Appendix 1 van activiteitsrapport MOMO/8/MF/201801/NL/AR/2

Taak 3.2 Waterstalen voor de bepaling van TEP concentratie werden 1-2 wekelijks genomen te Oostende. TEP werd tijdens de 13 uursmeting als standaard parameter opgenomen.

Taak 3.3 De stalen en data genomen tijdens 13 uursmetingen (vanaf 2003 t.e.m. nu) in de kustzone en offshore werden geanalyseerd om de geografische verschillen in SPM eigenschappen tussen het kustgebonden turbiditeitsmaximum en het offshore gebied met lage turbiditeit te beschrijven, zie Hoofdstuk 2 in activiteitsrapport MOMO/8/MF/201801/NL/AR/2.

Periode Januari 2018 – Juni 2018

Taak 1.1 De meetreeks te MOW1 werd verdergezet. Het factual data rapport voor 2017 werd opgesteld.

Taak 1.2 Calibratie van sensoren werd uitgevoerd tijdens campagne 2018/01 (23-26/01/2018), 2018/08 (27-30/03/2018), 2018/13 (15-16/05/2018).

Taak 1.3 De uitgebreide onzekerheidsanalyse van de optische en akoestische sensoren gebruikt bij langdurige metingen werd afgewerkt en is gerapporteerd in activiteitsrapport MOMO/8/MF/201807/NL/AR/3. De bevindingen werden op het Liège Colloquium voorgesteld, zie Appendix 1 van activiteitsrapport MOMO/8/MF/201807/NL/AR/3

Taak 3.2 Waterstalen voor de bepaling van TEP concentratie werden 1-2 wekelijks genomen te Oostende. TEP werd tijdens de 13 uursmeting als standaard parameter opgenomen.

Taak 3.3 13 uursmetingen worden uitgebreid naar de kustzone (MOW1) en offshore (monitoring punt W05 en W08) om de geografische verschillen in SPM eigenschappen tussen het kustgebonden turbiditeitsmaximum en het offshore gebied met lage turbiditeit te beschrijven.

Periode Juli 2018 – December 2018

Taak 1.1 De meetreeks te MOW1 werd verdergezet. Het factual data rapport voor 2017 werd opgesteld.

Taak 1.2 Calibratie van sensoren werd uitgevoerd tijdens campagnes 2018/18 (21-22/08/2018) en 2018/29 (17-21/12/2018).

Taak 3.1 De sedimentuitwisseling tussen de zee en de haven van Zeebrugge (ADCP transect) werd afgewerkt en is gerapporteerd in het activiteitsrapport MOMO/8/MF/201906/NL/AR/4. In samenwerking met het WL werd een publicatie opgesteld over de slibdynamica in de haven (zie appendix 2).

1.5. Publicaties (januari 2017 – december 2018)

Hieronder wordt een overzicht gegeven van publicatie met directe betrokkenheid van het KBIN waar resultaten en data uit het MOMO project in werden gebruikt.

Activiteits-, Meet- en Syntheserapporten

Fettweis M, Baeye M, Francken F, Van den Eynde D. 2019. MOMO activiteitsrapport (1 juli – 31 december 2018). BMM-rapport MOMO/8/MF/201906/NL/AR/4, 25pp + app.

Fettweis M, Baeye M, Francken F, Van den Eynde D. 2018. MOMO activiteitsrapport (1 januari – 30 juni 2018). BMM-rapport MOMO/8/MF/201808/NL/AR/3, 61pp + app.

Backers J, Hindryckx K, Vanhaverbeke W. 2018. Rapport van de RV Belgica Meetcampagnes en Verankering van Meetsystemen MOMO - 2017. BMM rapport ODNatuur-MDO/2018-03/MOMO/2017, 164pp + CD.

Fettweis M, Baeye M, Francken F, Van den Eynde D, Lee BJ. 2018. MOMO activiteitsrapport (1 juli – 31 december 2017). BMM-rapport MOMO/8/MF/201801/NL/AR/2, 27pp + app.

Backers J, Hindryckx K, Vanhaverbeke W. 2017. Rapport van de RV Belgica Meetcampagnes en Verankering van Meetsystemen MOMO - 2016. BMM rapport ODNatuur-MDO/2017-04/MOMO/2016, 103pp + CD.

Fettweis M, Baeye M, Francken F, Van den Eynde D, Chen P, Yu J. 2017. MOMO activiteits-rapport (1 januari – 30 juni 2017). BMM-rapport MOMO/8/MF/201707/NL/AR/1, 32pp + app.

Conferenties/Workshops

Fettweis M. 2018. Variations in SPM characteristics in a nearshore marine environment and its consequences for long-term in situ measurements using optical and acoustical sensors. Particles in Europe Conference, 14-17 October, Lissabon (Portugal).

Fettweis M. 2018. Long-term observations of SPM characteristics in the Belgian nearshore area using water samples and optical and acoustical sensors. NCK Theme day on Mud dynamics in the Southern North Sea. 3 July, Rotterdam (The Netherlands).

Fettweis M, Riethmüller R, Verney R, Becker M. 2018. Uncertainties associated with long-term observations of suspended particulate matter concentration using optical and

acoustic sensors. 50th International Liege Colloquium on Ocean Dynamics, 28 May-1 June, Liège (Belgium).

Fettweis M. 2018. Long-term and continuous measurements of SPM dynamics in the Belgian nearshore area. Lifewatch Data Analysis Workshop, 22-23 February, VLIZ, (Belgium).

Fettweis M. 2018. Dynamics of SPM on regional scales: Challenges and research opportunities. Workshop on Algae-Silt Interactions, 31 January, Delft (The Netherlands).

Adriaens R, Zeelmakers E, Fettweis M, Vanlierde E, Vanlede J, Stassen P, Elsen J, Środoń J, Vandenberghe N. 2017. Quantitative clay mineralogy as provenance indicator for the recent muds located in the southern North Sea. INTERCOH, 13-17 November, Montevideo (Uruguay). Poster

Fettweis M, Riethmüller R, Verney R, Becker M, Backers J, Baeye M, Chapalain M, Claeys S, Claus J, Cox T, Deloffre J, Depreiter D, Druine F, Flöser G, Grünler S, Jourdin F, Lafite R, Nauw J, Nechad B, Röttgers R, Sotollichio A, Vanhaverbeke W, Van Hoestenberghe T, Vereecken H. On best practice for in situ high-frequency long-term observations of suspended particulate matter concentration using optical and acoustic systems. INTERCOH, 13-17 November, Montevideo (Uruguay).

Shen X, Toorman E, Fettweis M. 2017. A tri-modal flocculation model coupled with TELEMAC for suspended cohesive sediments in the Belgian coastal zone. INTERCOH, 13-17 November, Montevideo (Uruguay).

Vanlede J, Dujardin A, Fettweis M. 2017. Mud dynamics in the harbor of Zeebrugge. INTERCOH, 13-17 November, Montevideo (Uruguay).

Adriaens R, Zeelmakers E, Fettweis M, Vanlierde E, Vanlede J, Stassen P, Elsen J, Środoń J, Vandenberghe N. 2017. Quantitative clay mineralogy as provenance indicator for the recent muds located at the marine limit of influence of the Scheldt estuary. Schelde-Ems workshop, 16-17 February, Antwerp (Belgium). Poster

Publicaties (tijdschriften, hoofdstuk in boeken)

Adriaens R, Zeelmaekers E, Fettweis M, Vanlierde E, Vanlede J, Stassen P, Elsen J, Środoń J, Vandenberghe N. 2018. Quantitative clay mineralogy as provenance indicator for recent muds in the southern North Sea. *Marine Geology,* 398, 48-58. doi:10.1016/j.margeo. 2017.12.011.

Chen P, Yu JCS, Fettweis M. 2018. Modelling storm-influenced SPM flocculation using a tide–wave-combined biomineral model. *Water Environment Research, 90.* doi:10.2175/ 106143017X15131012152799

Fettweis M, Lee BJ. 2017. Spatial and seasonal variation of biomineral suspended particulate matter properties in high-turbid nearshore and low-turbid offshore zones. *Water*, 9, 694. doi:10.3390/w9090694.

Fettweis M, Riethmüller R, Verney R, Becker M, Backers J, Baeye M, Chapalain M, Claeys S, Claus J, Cox T, Deloffre J, Depreiter D, Druine F, Flöser G, Grünler S, Jourdin F, Lafite R, Nauw J, Nechad B, Röttgers R, Sotollichio A, Vanhaverbeke W, Vereecken H. Uncertainties associated with in situ long-term observations of suspended particulate matter concentration using optical and acoustic sensors. Progress in Oceanography (revisie werd opgestuurd).

Shen X, Lee BJ, Fettweis M, Toorman E. 2018. A tri-modal flocculation model coupled with TELEMAC for estuarine muds both in the laboratory and in the field. Water Research 145, 473-486.

Shen X, Toorman EA, Lee BJ, Fettweis M. 2018. Biophysical flocculation of suspended particulate matters in Belgian coastal zones. Journal of Hydrology 567, 238-252.

Vanlede J, Dujardin A, Fettweis M, Van Hoestenberghe T, Martens C. 2019. Mud dynamics in the port of Zeebrugge. Ocean Dynamics. doi:10.1007/s10236-019-01273-3

2. Sedimentuitwisseling tussen de zee en de haven van Zeebrugge

The port of Zeebrugge is subject to high siltation rates of mainly mud and, as a result, huge maintenance dredging works are mandatory (Fettweis et al.; 2011; 2016; Vanlede et al., 2019). The amount of sediments to be dredged depends to a large part on the suspended particulate matter (SPM) concentration in the coastal area and on the flow exchange meachnism at the harbor entrance that include tides, horizontal entrainment, and density currents (Vanlede et al., 2014). The SPM entering the harbor settles quickly within the first hundreds of meters. The influencing factors and time scales that describe the mud dynamics in the harbor basin have been analysed in Vanlede et al. (2019), based on depth soundings (1999-2011) and in situ measurements from ADCP transects and at fixed stations (march 2013-April 2014). The present chapter is based on a more extended ADCP data set and uses further satellite data and webcam images. The ADCP transects were sailed with RV Belgica using the hull mounted 300 kHz ADCP (Figure 2.1) in the period between 2012 and 2016 (Figure 2.2). Remote sensing data are from the polar orbiting Landsat 8 (2013 onward) and the geo-stationary Sentinel 2 (2015 onward) satellites. The oblique RGB webcam images of the harbor entrance have been used in a qualitative way to illustrate the inflow of sediments into the harbor.

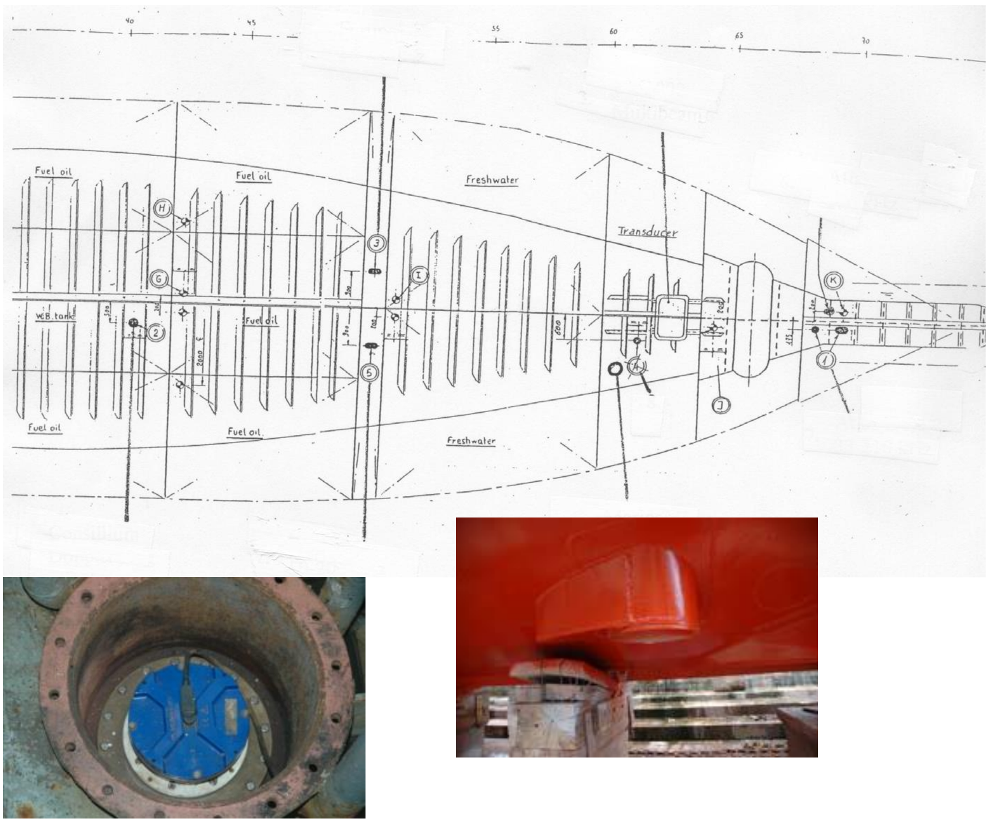

Figure 2.1: Location of the ADCP integrated in the hull of RV Belgica.

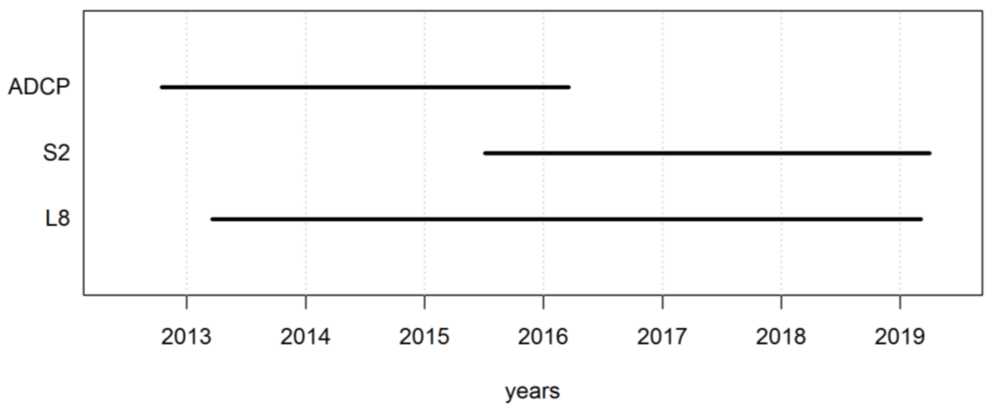

Figure 2.2: Time spans of the 300 kHz ADCP data used in this study and the satellite imagery collected by Landsat-8 and Sentinel 2.

2.1 ADCP data

The echo intensity recorded by the 300 kHz WH Monitor was subject to an acoustic-to-suspended particulate matter concentrations inversion (*cfr.* method by Kim et al., 2004). This is typically realized by applying the necessary corrections for water absorption, beam spreading – SPM absorption was not included here since in situ tests did not show a significant absorption effect of the signal (Montereale-Gavazzi et al., 2019). The corrected dB values in association with SPMC calibration was then run with average slope and intercept coefficients (resp. 0.45 and -83.27) derived from several 13 hours SPMC filtration measurements conducted in the period between 2010 and 2014 for both offshore and mostly near-shore Belgian stations. The vertical high-resolution (0.25 m) ADCP data were used and spatially subsetted according the referential 1 km transect line at the harbor entrance (-500 m is seaward, +500m is landward), see Figure 2.3.

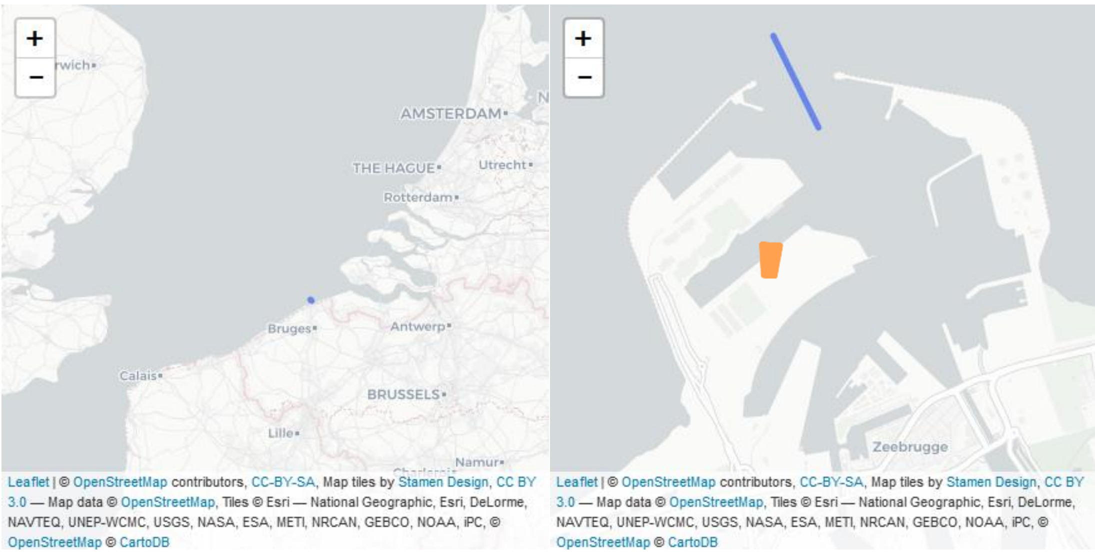

Figure 2.3: Location of harbor of Zeebrugge (blue dot) in the southern North Sea (left). The 1 km transect line (blue line) at the entrance of the harbor of Zeebrugge (right). The orange shape is the RMI webcam location looking into NNE direction (see further).

The seabed depth discrimination was used for vertically normalizing each transect allowing proper group-averaging. Regarding group-averaging of the in total 245 transects, 4 different intra-tidal phases were considered (low water, low water slack tide, high water, high water slack tide) as well as spring and neap tide cycles (threshold of 3.8 m TAW) and semi-annual (6 'winter' months and 6 'summer' months) cycles, resulting in a total of 16 groups. An overall average (mean and median) together with standard deviation is shown in Figure 2.4. The surface refers actually to approximately 5 m below sea surface and the bottom to approximately 0.5 m above the real seabed. The closer to the bottom the higher the standard deviation becomes as a result of most sediment transport occurring in this layer. The frequency distribution of transects occurrence with regards to HW and LW is nicely spread as shown in Figure 2.5.

Figure 2.6 is an example of ADCP derived SPMC dynamics in a 3-hrs HW centered window (~flood) showing high-turbidity seawater entering the harbor. On the other hand, when harbor is subject to tide-flushing in a 3-hrs LW centered window (ebb) the harbor water mass (most of the SPM settled out in the harbor) pushes the more turbid seawater away from the harbor entrance.

Average transects around LW and HW are shown in Figure 2.7 and illustrate again the contrast between incoming turbid seawater during HW and outflowing of less turbid water during LW. Additionally, surface and bottom data for HW and LW phases of the tide are shown in Figure 2.8.

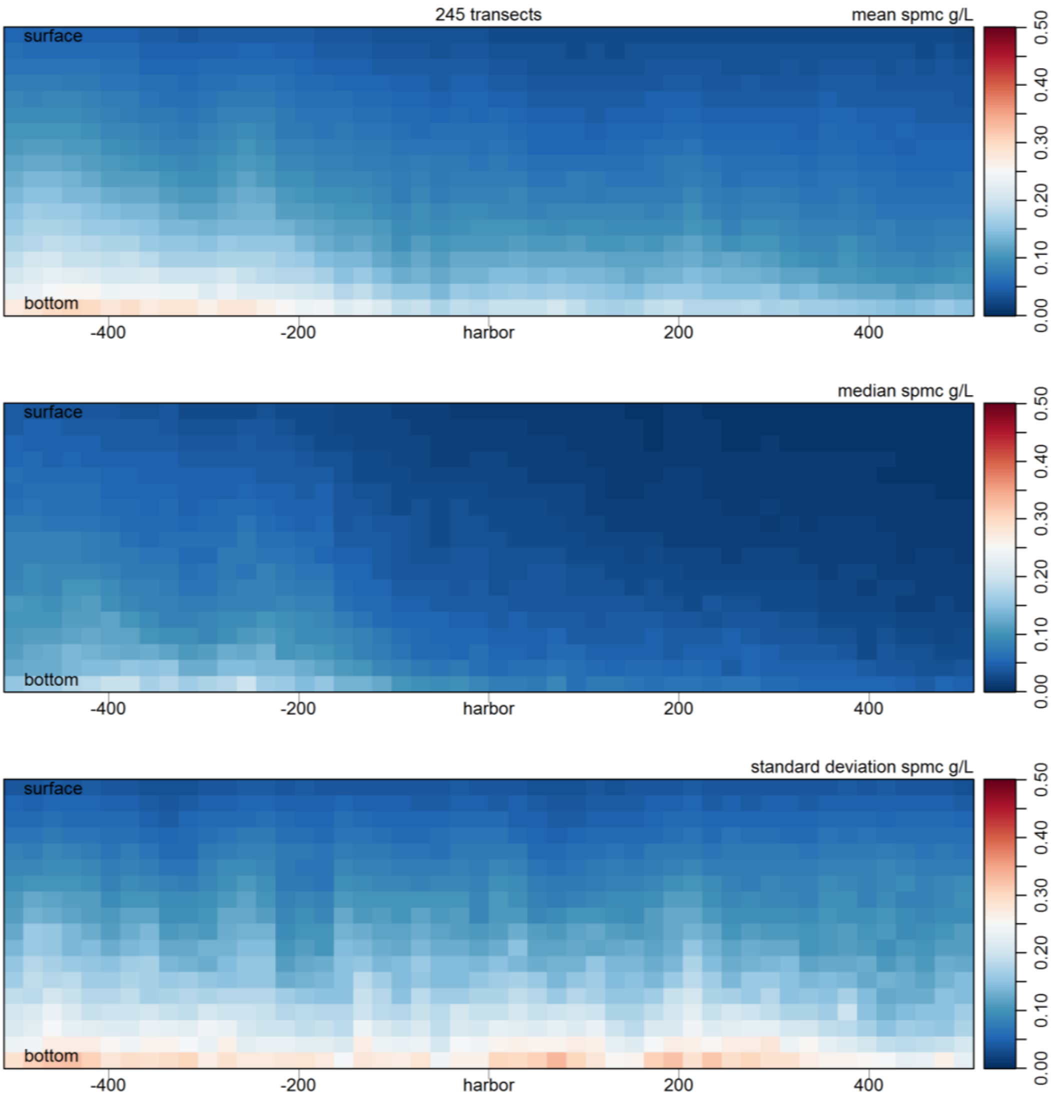

Figure 2.4: Mean SPMC (upper), median SPMC (middle) and standard deviation of all 245 transects.

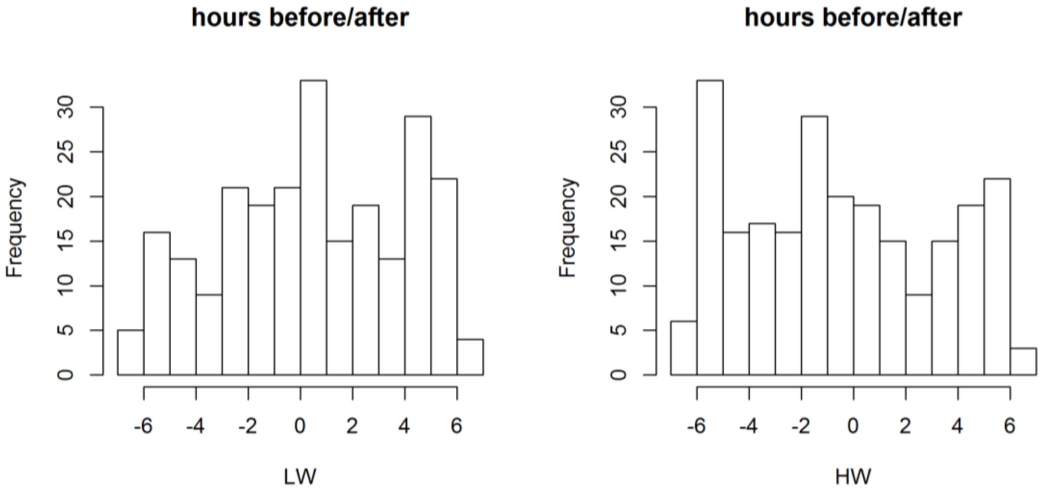

Figure 2.5: ADCP sailed transects with regards to LW (left), and with regards to HW (right) in hours.

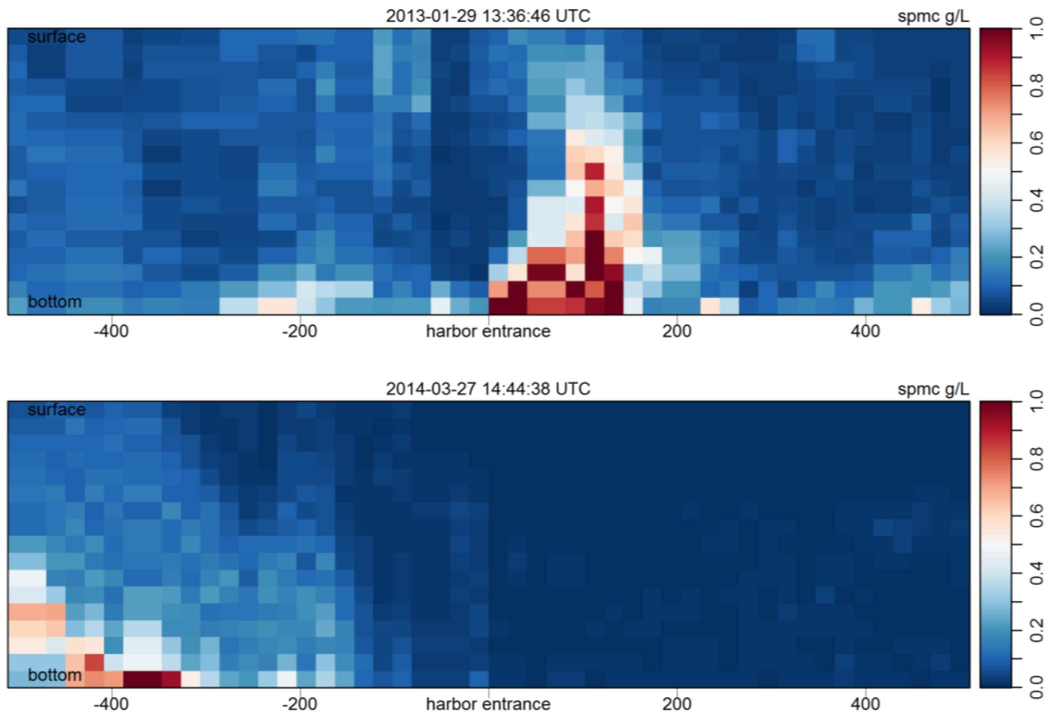

Figure 2.6: An example of incoming turbid seawater (top) and outgoing low SPMC harbor water (bottom).

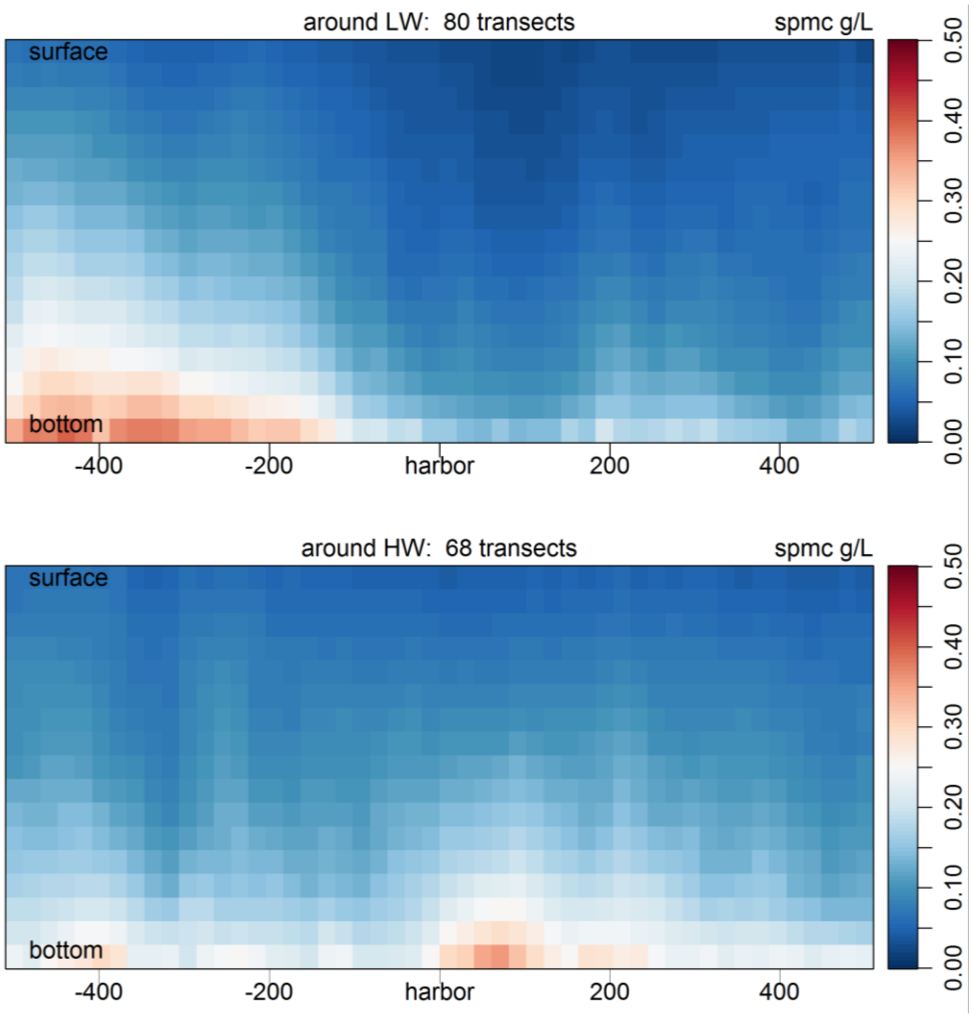

Figure 2.7: Mean SPMC transects around LW (upper) and HW (lower).

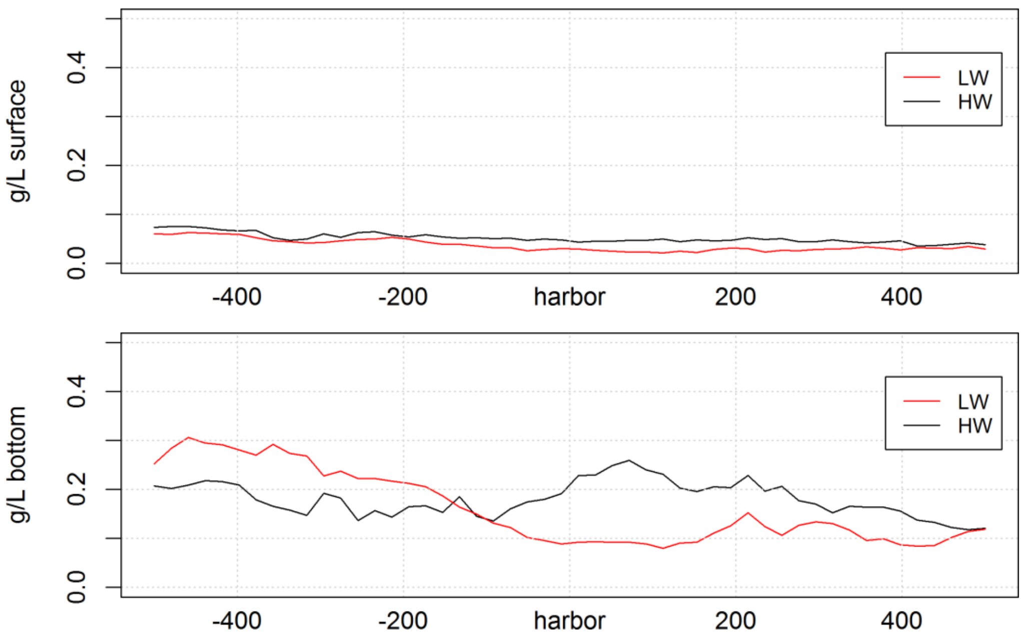

Figure 2.8: Near-surface SPMC during LW and HW (upper), and near-bed SPMC during LW and HW.

Difference between bottom HW and LW SPMC averages are much larger than between surface HW and LW SPMC averages, again implying that most of the sediment transport at the harbor entrance is concentrated near the bottom. The following Figures (2.9, 2.10) correspond to all 16 groups with mentioning of the number of transects per group (sometimes too low to be considered representative). The summer (April, May, June, July, August, September) and winter (October, November, December, January, February, March) SPMC are also considered resulting in a quite unexpected outcome with overall higher SPMC during summer than during winter. This needs further investigations - for example: Is the ADCP echo intensity (300 kHz ADCP frequency issue in fact) more sensitive towards stickier (hence bigger) particles in suspension commonly present in summer months?

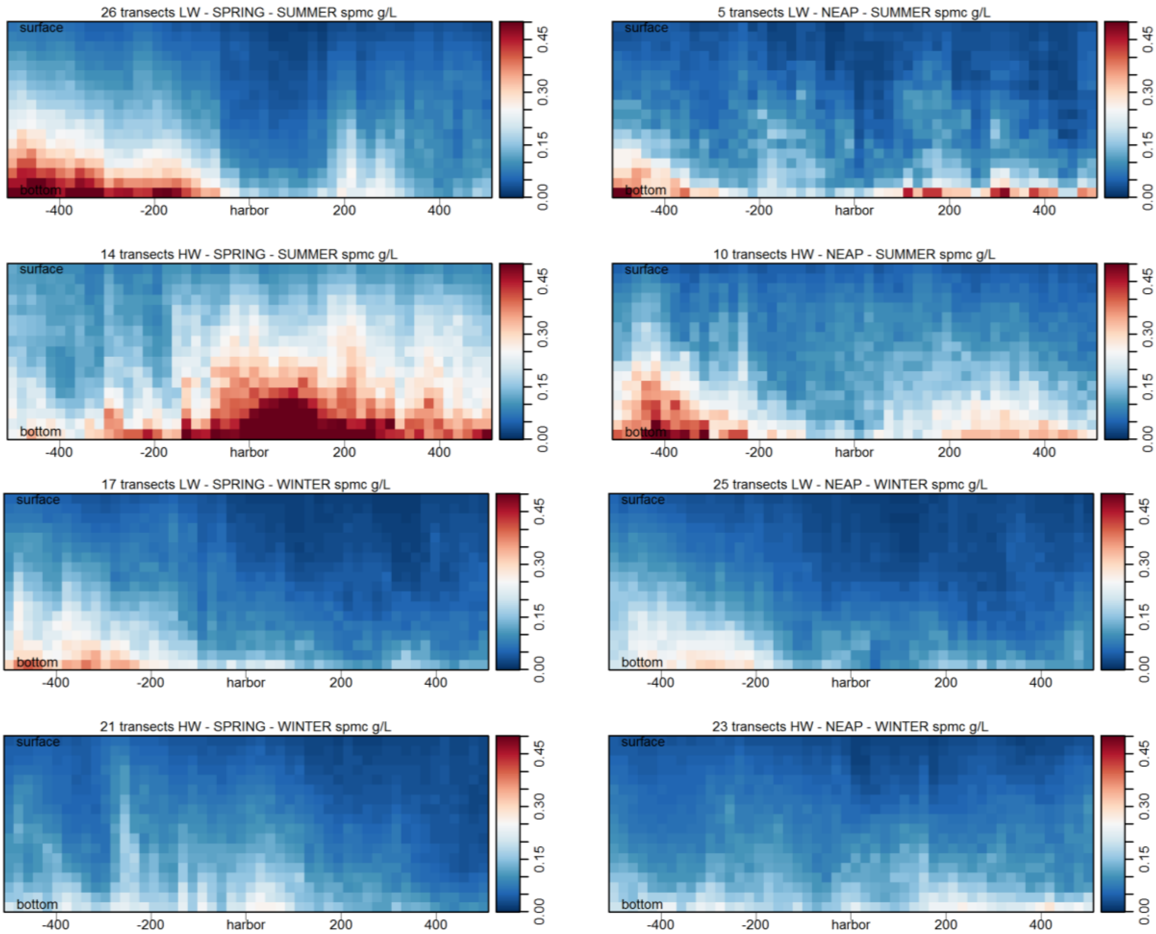

Figure 2.9: Average SPMC in summer (above) and winter (below) for 4 cases (LW and HW during spring and neap tide). The number of transects is indicated.

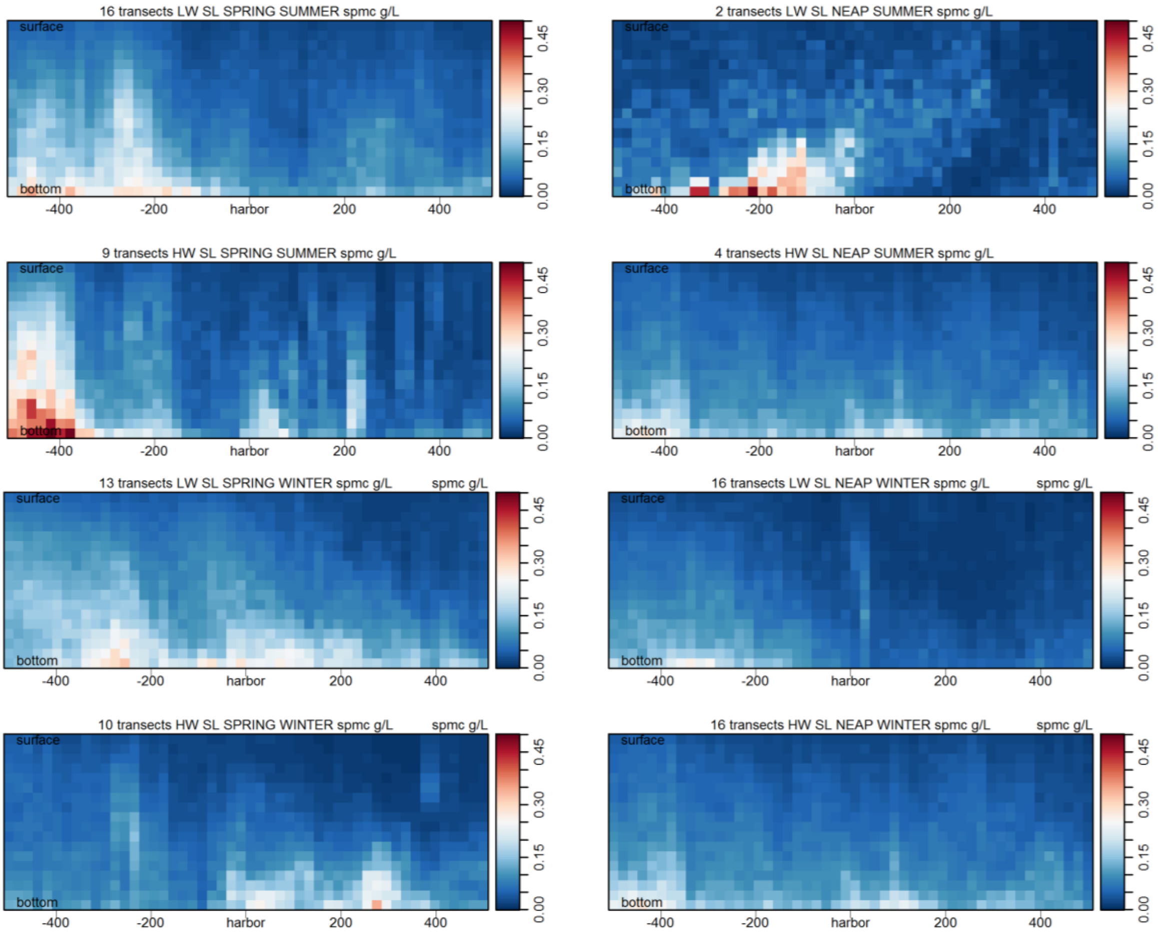

Figure 2.10: Average SPMC in summer (above) and winter (below) for 4 cases (LW slack and HW slack during spring and neap tide). The number of transects is indicated.

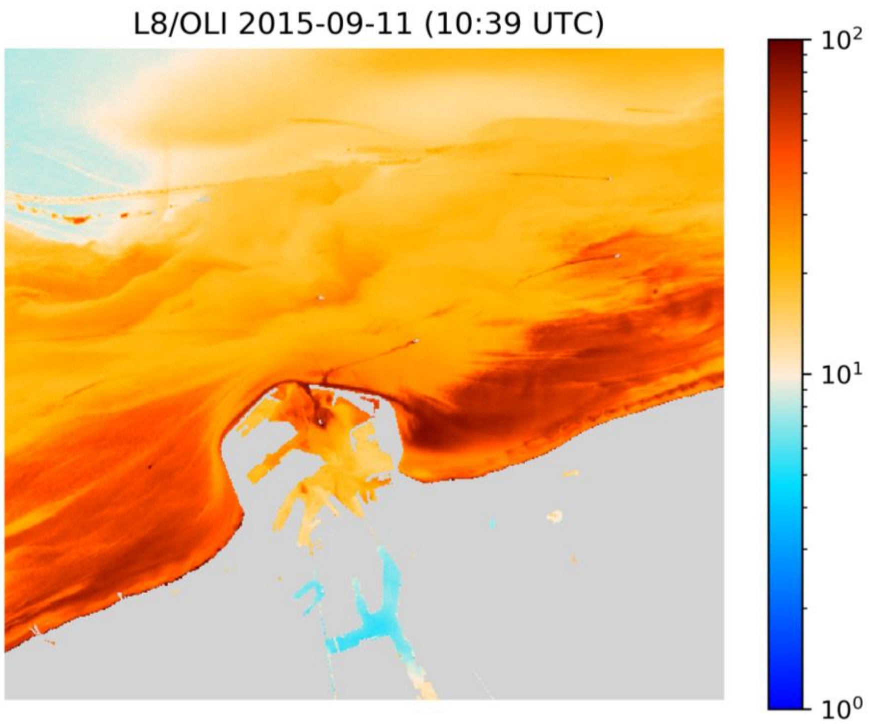

Figure 2.11: Landsat-8 image from 11 September 2015 showing the surface SPMC (mg/l) at 1 hour before HW. The incoming turbid water is clearly visible.

2.2 Satellite data

An example of a satellite image is shown in Figure 2.11. The images were treated in a very similar way as the ADCP transects. First, the satellite data were systematically extracted along the reference transect line at the harbor entrance and grouped according to tidal and lunar phase and season (intra-tidal phase, spring and neap tide, and semi-annual cycles), see Figures 2.12-2.15. From the available 605 satellite images 214 images were used for the SPMC statistics. Note that summer SPMC's are overall lower than winter SPMC's.

2.3 Webcam images

The RMI (*https://www.meteo.be/nl/weer/waarnemingen/webcams/webcam-zeebrugge*) has a permanent webcam station with 5-minute interval photo acquisition. On a cloud-free day (for avoiding cloud shadows on the water surface) and during HW, a first and small test (Figure 2.16) of balanced histogram thresholding with RGB ratios was conducted. These ratios likely refer to water quality such as chlorophyll and yellow substance (Goddijn-Murphy et al., 2009). In this study, the G/R ratio seemed to be useful discriminating between the incoming turbid water mass (lower G/R value) and the calmer and cleaner harbor water (by settled out sediment), see Figure 2.17.

The attempt to geo-reference/orthorectify the extreme oblique photo was unsuccessful. Future analysis, however, could still include more analysis of the location of the frontier between turbid and less turbid water in the harbor as a function of the groups (incl. meteo cases). Additionally, the webcam images also help in better interpreting the ADCP SPMC transects. For example, outgoing cruise ships tend to disturb the seabed. In Figure 2.18, when ADCP data was acquired 1.5 hours before LW, the water outside the harbor with higher turbidity is pushed more offshore by the outflowing low turbid harbor water. However, inside the harbor there are subtle elevated SPMC, which can be associated to the passage of a cruise ship (Figure 2.19).

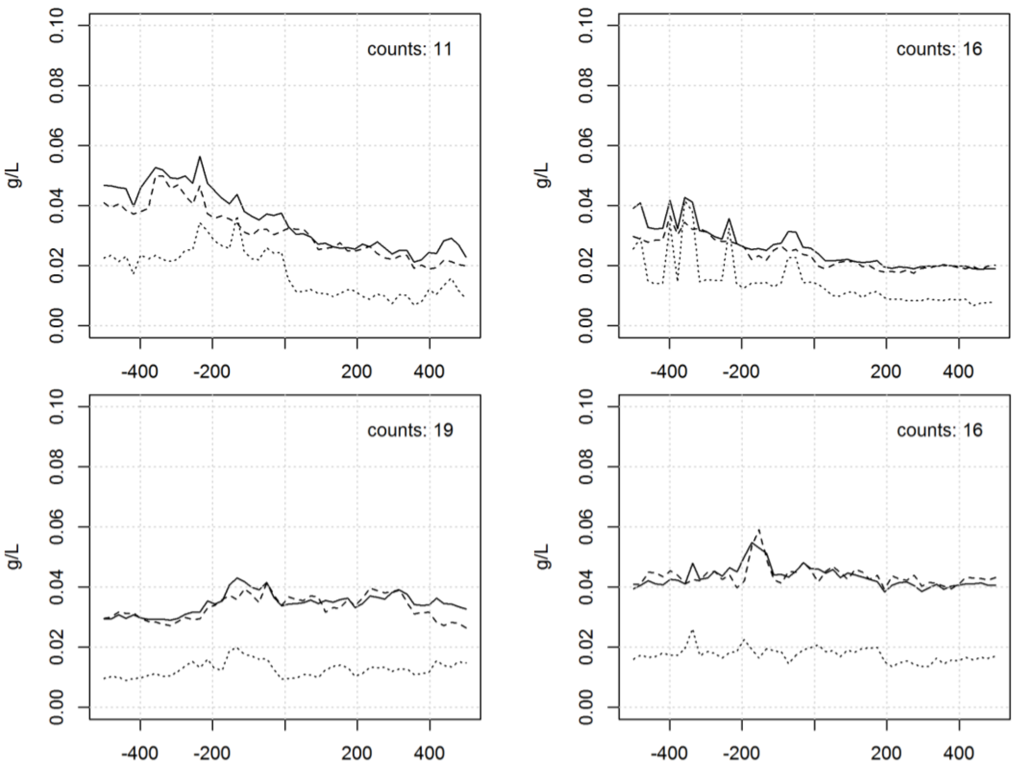

Figure 2.12: Mean surface SPMC derived from satellites along the reference transect during summer. On the left side are the SPMC values during spring tides and on the right during neap tides. Upper graphs are at LW and the lower ones at HW.

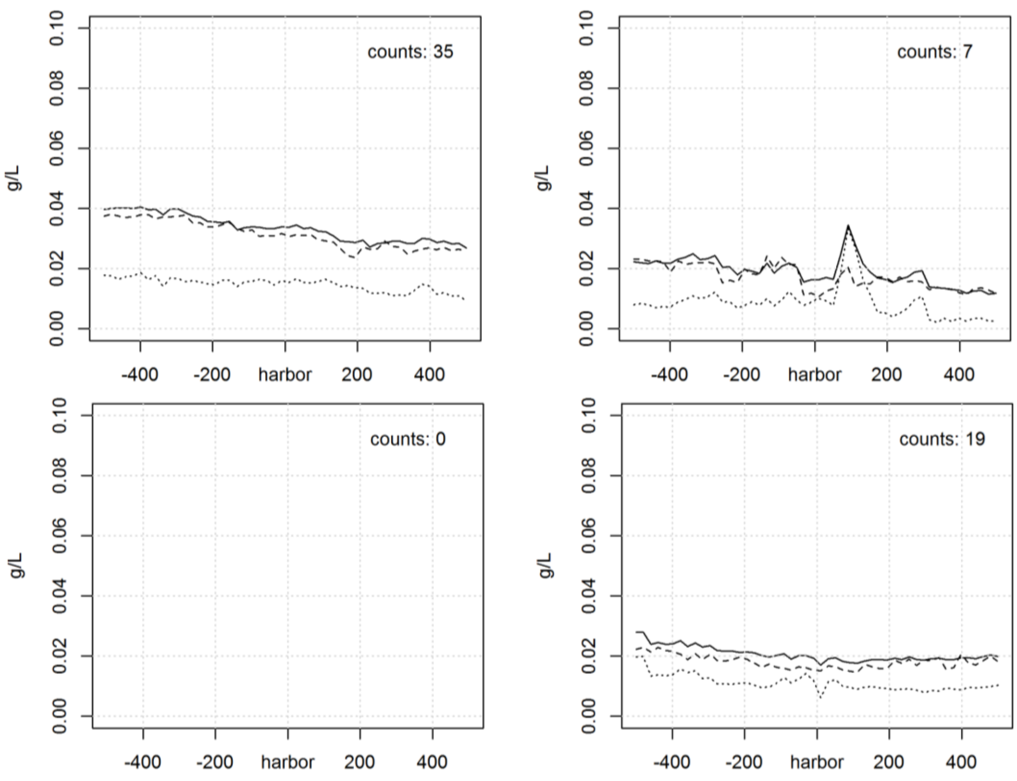

Figure 2.13: idem 2.12 but now during LW slack (upper) and HW slack (lower).

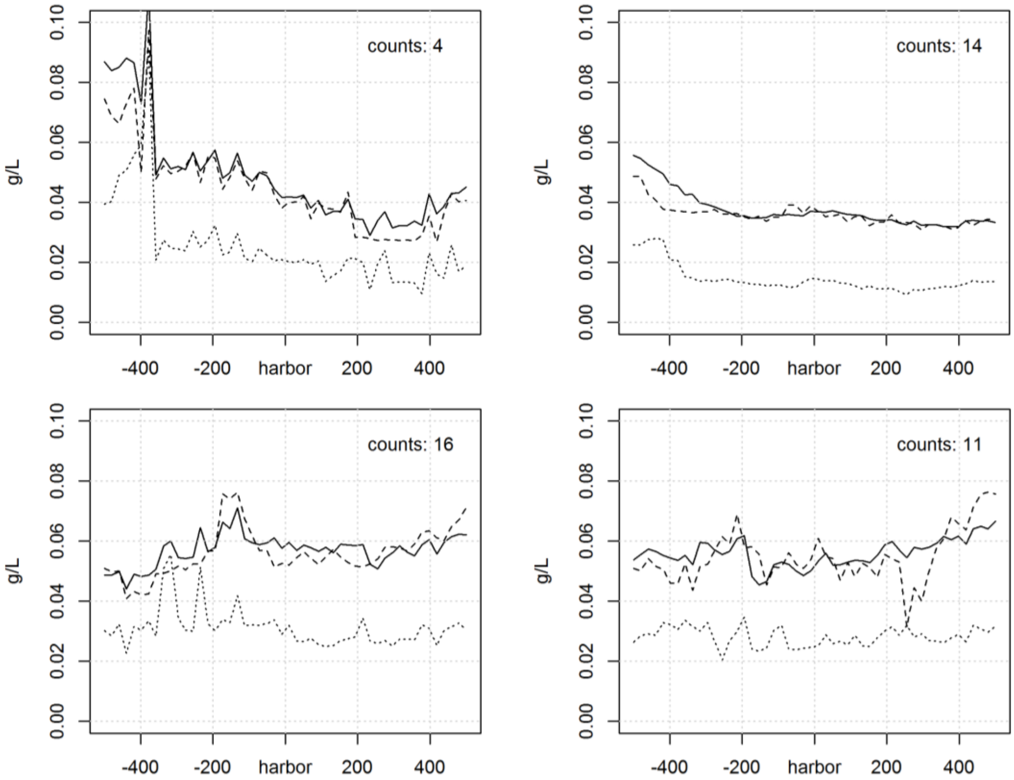

Figure 2.14: Mean surface SPMC derived from satellites along the reference transect during winter. On the left side are the SPMC values during spring tides and on the right during neap tides. Upper graphs are at LW and the lower ones at HW.

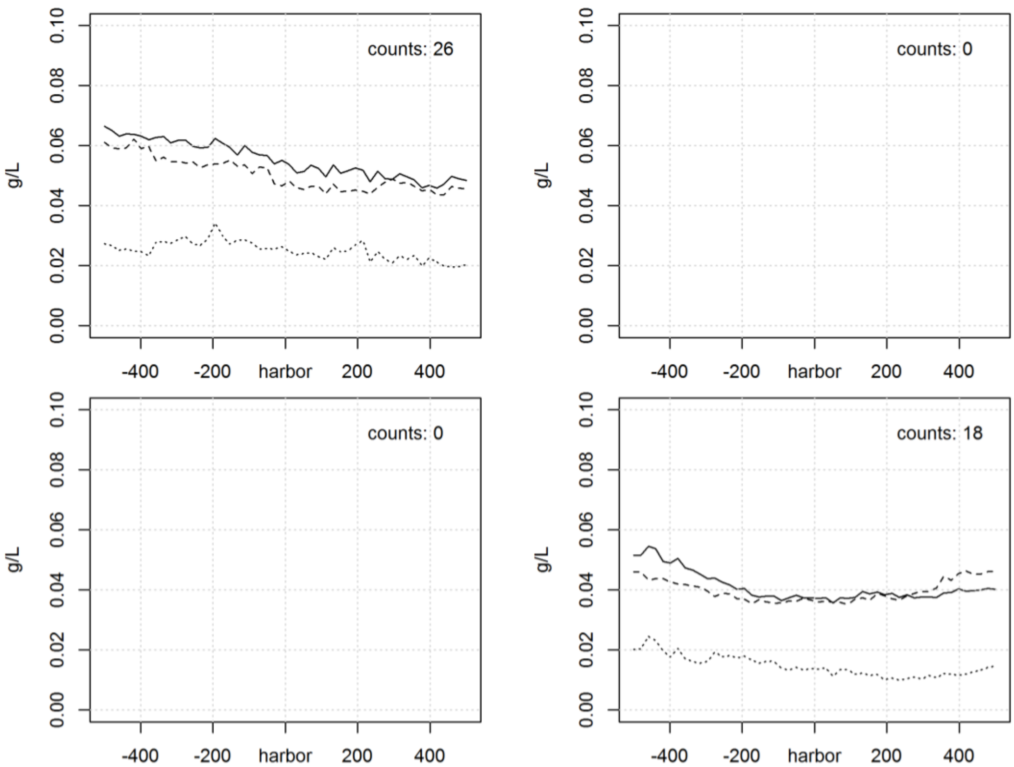

Figure 2.15: idem 2.14 but now during LW slack (upper) and HW slack (lower).

Figure 2.16: RMI webcam image shot on a cloud-free day

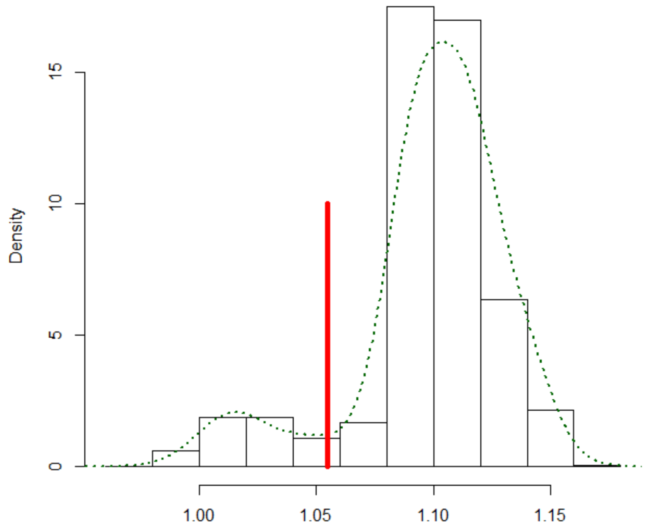

Figure 2.17: Illustration of how BHT discriminates between incoming turbid water (left from the red line) and the much less turbid harbor water mass.

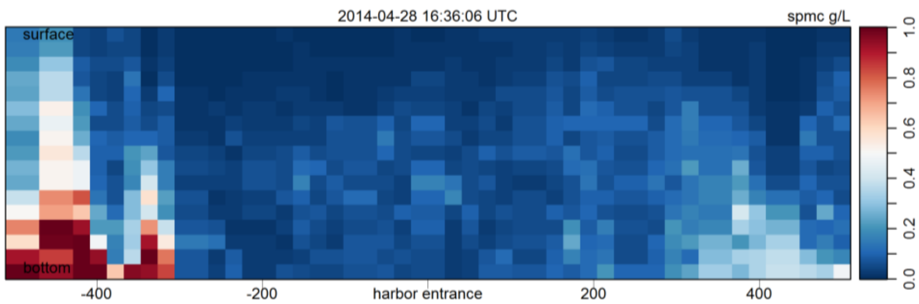

Figure 2.18: Transect around 1.5 hours before LW. The low turbid harbor water flows towards the sea. The slightly higher SPMC is caused by an outgoing cruise ship.

Figure 2.19: The two white rectangles indicate the outgoing cruise ship and the incoming RV Belgica while measuring the transect shown in Figure 2.18.

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Vanlede J, Dujardin A. 2014. A geometric method to study water and sediment exchange in tidal harbors. Ocean Dynamics 64, 1631–1641.

COLOPHON

Dit rapport werd voorbereid door de BMM in juni 2019
Zijn referentiecode is .MOMO/8/MF/201906/NL/AR/4

De scheepstijd met de RV Belgica werd voorzien door BELSPO en KBIN-OD Natuur

Indien u vragen hebt of bijkomende copies van dit document wenst te verkrijgen, gelieve een e-mail te zenden naar mfettweis@naturalsciences.be, met vermelding van de referentie, of te schrijven naar:

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BEHEERSEENHEID VAN HET MATHEMATISCH MODEL VAN DE NOORDZEE

APPENDIX 1

Bijdrage Particles in Europe Conference 14-17 October, Lissabon (Portugal)

Variations in SPM characteristics in a nearshore marine environment and its consequences for long-term in situ measurements using optical and acoustical sensors

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Knowledge on the dynamics of Suspended Particute Matter (SPM) is relevant for most oceanographic disciplines. SPM is a mixture of clay to sand sized particles in suspension that consists of varying amounts of minerals from physico-chemical (e.g. clay minerals, quartz, feldspar) and biogenic origin (e.g. calcite, aragonite, opal), living (bacteria, phyto- and zooplankton) and non-living organic matter (fecal and pseudo-fecal pellets, detritus and its decomposed products from microbial activity such as mucus, exopolymers), and particles from human origin (microplastics). The SPM characteristics (concentration, size and composition) are varying through the mutual interactions between physical forcings (tides, meteorology, climate), biological cycles (algae blooms), chemical processes (carbon cycle) and human activities (nutrient and pollutant release, dredging and dumping activities, offshore constructions).

In situ water samples have been collected since 2000 in the turbide Belgian coastal area to determine the biogeochemical characteristics (mineral, organic matter, chlorophyll and phaeophytine, exoploymers). Long-term time series of SPM concentration from acoustical and optical backscatter sensors and particle size from laser diffraction are available since 2004. Figure 1a shows that Chlorophyl-a concentration (Chl-a) is high between March and September (with the prominent algae bloom in spring and a secondary peak in summer) and low during winter. For the particulate organic carbon (POC) content in the SPM, the values are almost similar during whole the year, except during the spring bloom when the POC content also increases. The POC represents the refractory fraction of the organic matter (OM), while the Chl-a can be seen as a proxy for the labile fraction of the OM that is associated with the seasonal formation and decay of fresh organic matter by e.g. algae bloom, bacterial activity. The freshness of the organic matter is further detectable in the chl-a versus phaeophytine-a content of the SPM, the latter being associated with decaying chlorophyll (Figure 1b).

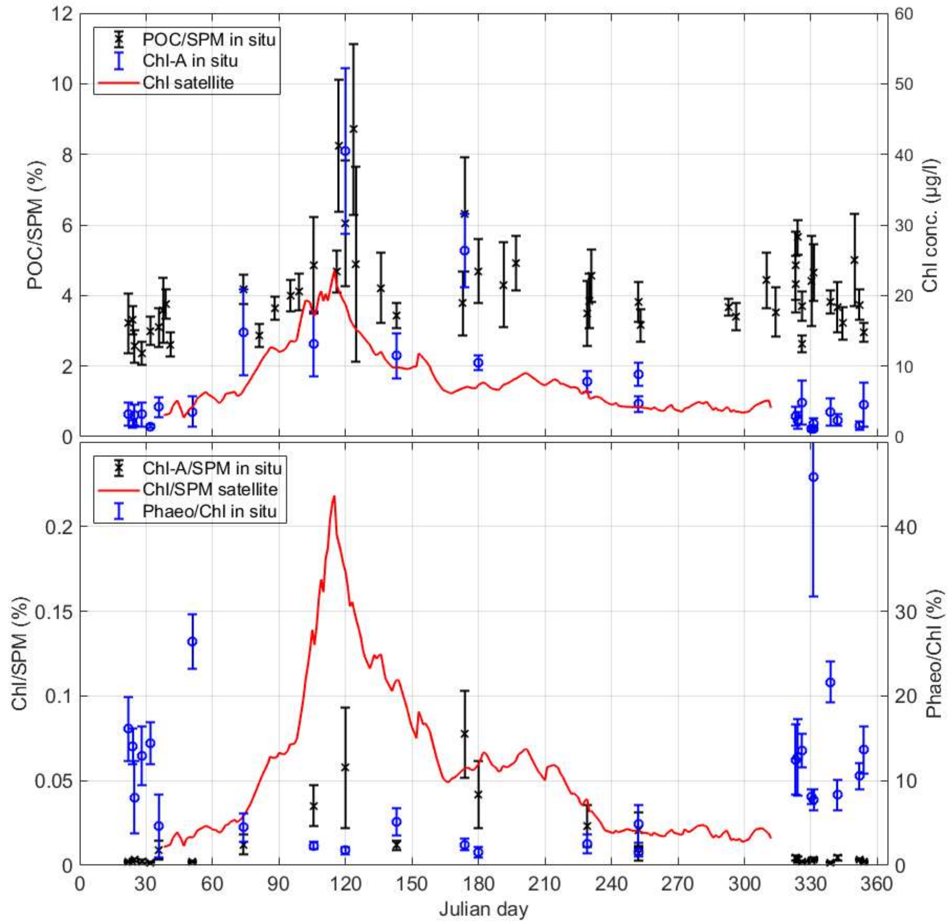

Figure 1 : Seasonal variation of the OM (above) and the Chlorophyl-A and Phaeophytine-A content of the SPM (below) derived from water samples over the period 2000 to 2018 in the Belgian nearshore area (at about 3 m above the bed). Each dot and errorbar represents the mean and standard deviation of 13 samples taken during a tidal cycle. The solid line are the surface Chl and SPM concentration from MERIS satellite over the period 2002-2012.

Further to seasonal changes the SPM characteristics exhibit substantial gradients with distance from the coast. The SPM concentration is generally higher in the nearshore areas, than in more offshore deeper areas of the continental shelf, while the composition of the SPM becomes more organic, see Figure 2. Although SPM in the high turbidity and the offshore zone had similar mineralogical composition, they encountered different fates in association with biomass (Fettweis and Lee, 2017). While in the high turbidity zone the SPM consist of mineral-enriched, dense, and settleable biomineral aggregates, the SPM in the offshore zone is composed of biomass-enriched, less dense and less settleable flocs, see Figure 3.

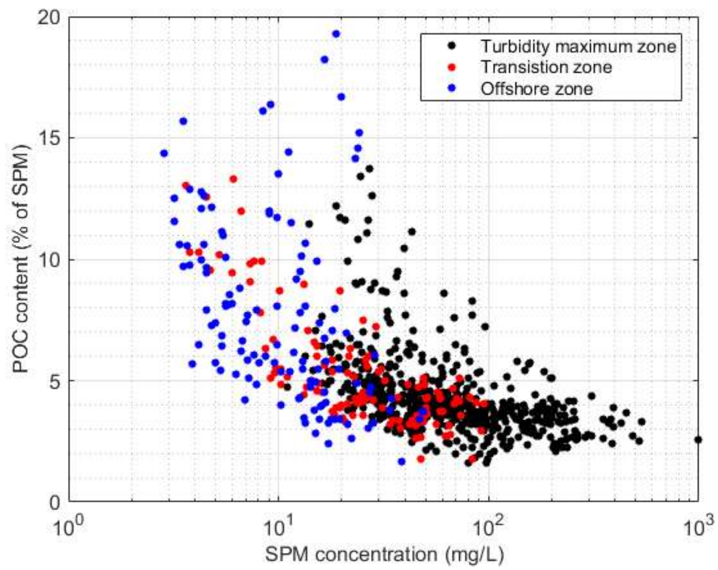

Figure 2 : POC content (% of SPM) as a function of SPM concentration in the high turbid nearshore and the low turbid offshore areas of the Belgian continental shelf.

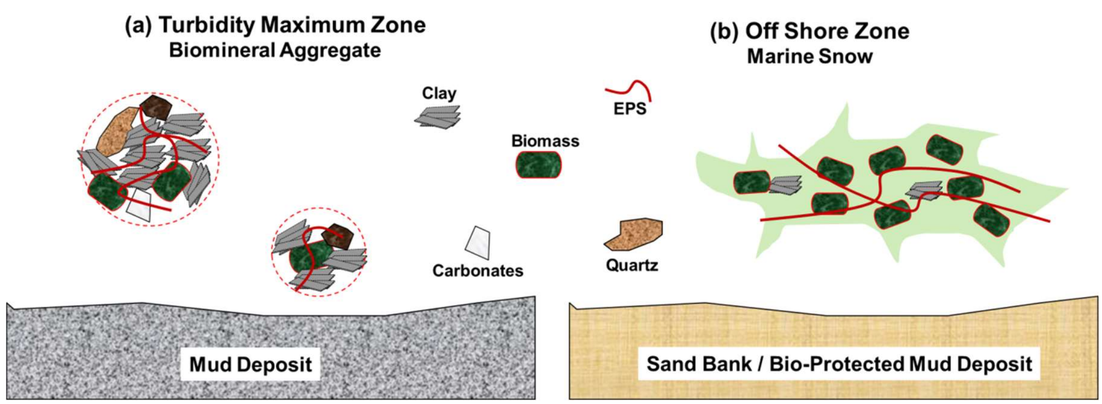

Figure 3 : Schematic diagrams of (a) biomineral aggregates in the turbidity maximum zone and (b) in the offshore zone. EPS: extracellular polymeric substances.

The influence of biological cycles on SPM dynamics are multiple and mutual. A prominent example is the seasonality in floc size and thus settling velocity of the SPM that impacts the surface and near-bed SPM concentration in winter and summer and thus the water clarity, the formation of fluid mud layers, the smothering of benthic ecosystems, and the fate of carbon and SPM on a regional scale (Fettweis et al., 2014). Changes in the concentration and the composition of the SPM influences the optical and acoustical properties of the particles in suspension and if not calibrated for these conditions also the sensor derived SPM concentration. This has as consequence that the calibration of these sensors used in long-term and continuous measurements has to be adapted in order to reduce the uncertainty associated with the sensor-derived SPM concentration. Controling uncertainties will become an important issue when observation comprises systems of sensors spanning large spatial and temporal scales in order to detect trends in the data, to separate anthropogenic impact from natural variations or to evaluate numerical models over a broad ensemble of different conditions using validated field data.

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Variations in SPM characteristics in a nearshore marine environment and its consequences for long-term in situ measurements using optical and acoustical sensors

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What is SPM?

Suspended Particulate Matter (SPM) is a mixture of clay to sand sized particles in suspension that consists of minerals from geological (e.g. clay minerals, quartz) and biogenic origin (e.g. calcite, opal), living (e.g. bacteria, phytoplankton) and non-living organic matter (OM) (e.g. detritus, exopolymeric particles), and particles from human origin (microplastics).

The SPM characteristics (concentration, size, shape, composition) are varying with physical forcing's (tides, meteorology, climate), biological cycles (algae blooms), biogeochemical processes (carbon cycle) and human activities (nutrient and pollutant release, dredging and dumping activities, offshore constructions). Further the SPM characteristics exhibit substantial gradients with distance from the coast. The SPM concentration is generally higher in the nearshore areas, than in more offshore deeper areas of the continental shelf, while the composition of the SPM becomes more organic towards offshore, see Figure 1.

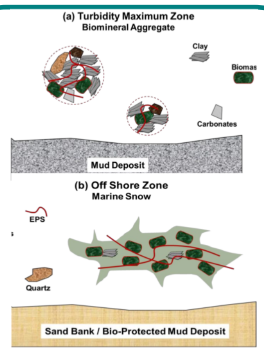


Figure 1: Schematic diagrams of (a) biomineral aggregates in the turbidity maximum and (b) in the offshore zone.

Objective

Investigate how changes in the concentration and the composition of the SPM influences the optical and acoustical properties of the particles in suspension and if not calibrated for these conditions also the SPM concentration.

SPM composition: Spatial variations

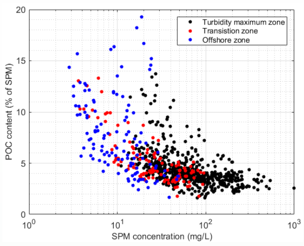


Figure 2: POC content (in %) as a function of SPM concentration in the Belgian continental shelf. Data are derived from filtered water samples (from Fettweis & Lee, 2017).

In situ water samples have been collected since 2000 in the turbid Belgian coastal area to determine the biogeochemical characteristics (mineral, organic matter, chlorophyll and phaeophytine, exoploymers). Long-term time series of SPM concentration from acoustical and optical backscatter sensors and particle size from laser diffraction are available since 2004.

Although SPM in the high turbidity and the offshore zone has similar mineralogical composition (Figure 3), they encounter different fates in association with biomass. While in the high turbidity zone the SPM consist of mineral-enriched, dense, and settleable biomineral aggregates, the SPM in the offshore zone is composed of biomass-enriched, less dense and less settleable flocs, see Figures 1 and 2.

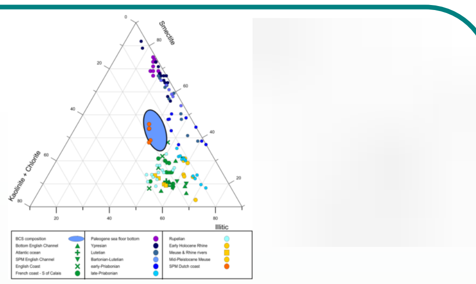
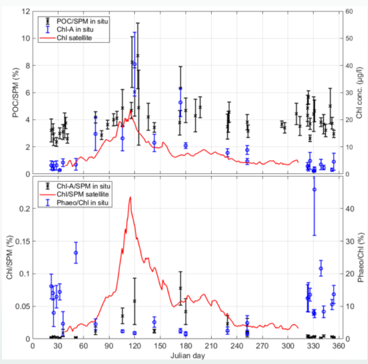


Figure 3: Clay composition of the SPM and the seabed on the Belgian Continental Shelf (BCS) and other locations in the North Sea and (right) the carbonate, clay and non clay content of the SPM and seabed on the BCS (from Adriaens et al., 2018).

SPM composition: Seasonal variations



The Chlorophyl-a concentration (Chl-a) is high in spring/summer and low in winter. For the POC content in the SPM, the values are almost similar during whole the year, except during spring bloom (Figure 4).

The POC consists mainly of the refractory fraction, while the Chl-a is a proxy for the labile fraction of the OM. The fresh part is associated with the seasonal biological cycles. The freshness of the organic matter is visible in the Chl-a versus phaeophytine-a content of the SPM, the latter being associated with decaying chlorophyll (Figure 4).

The influence of biological cycles is prominent in the seasonality in floc size and thus settling velocity of the SPM that impacts the surface and near-bed SPM concentration in winter and summer (Figure 5).

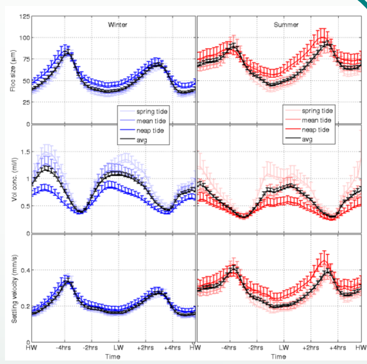


Figure 4: Seasonal variation of the POC and the Chl-A and Phaeophytine-A content of the SPM derived from water samples (from 2000 to 2018) in the turbid Belgian nearshore. Each dot is the mean and standard deviation of 13 samples taken during a tidal cycle. The solid line are the surface Chl and SPM concentration over 2002-2012 from MERIS satellite.

Figure 5: Seasonal variation of floc size, SPM volume concentration and settling velocity shown as ensemble averaged tidal cycle from 721 days of LISST measurements in the turbid Belgian nearshore area over the period 2006-2013. The floc size and settling velocities are lower in winter than in summer, while the volume concentration shows an opposite trend.

Consequences for measurements using optical and acoustical sensors

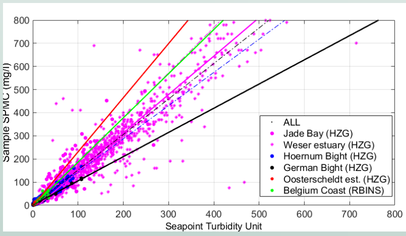


Figure 5: Variabilities in inherent optical properties of the SPM between different geographical areas influence the relation between SPM concentration from water samples and from Seapoint sensors (from Fettweis et al., submitted).

Variabilities of the inherent particle properties are caused by changes in particle size, shape, composition and density and may occur between different geographical areas (Figure 5) or within a same measuring location (Figure 6). These properties influence the measurements of SPM concentration using optical and acoustical sensors, such as OBS, ADCP.

Understanding of the processes that are causing these changes in SPM characteristics is required in order to estimate their importance and to possibly rescale the sensor data to some reference particle properties. Variabilities in particle properties occur on seasonal, neap-spring, tidal and even intra-tidal time scales and may lead to systematic uncertainties of 50-200% in the SPM concentration.

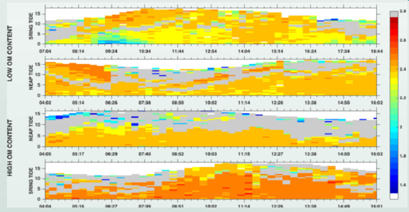


Figure 6: Time series of the best-fit fractal dimension (nf) derived from OBS and LISST data during 4 tidal cycles in 2016 in the Seine Bay. The variations during a tide are low except in January (upper panel). The significant decrease in the calculated nf is partially due to resuspension of large particles with higher density (bed aggregates or sand). The fractal dimension changes as the OBS is sensitive to particle composition (from Chapalain et al., 2018).

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Particles in Europe, 14-17 October 2018, Lisbon, Portugal

APPENDIX 2

**Vanlede J, Dujardin A, Fettweis M, Van Hoestenberghe T, Martens C. 2019.
Mud dynamics in the port of Zeebrugge. Ocean Dynamics**

Ocean Dynamics
https://doi.org/10.1007/s10236-019-01273-3

Mud dynamics in the Port of Zeebrugge

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Abstract
This paper presents the mud dynamics in the harbor basin of Zeebrugge in the Southern North Sea based on an analysis of field data. Mud is typically transported into and within the harbor basin through advection of suspended particulate matter (SPM). Three important timescales have been identified. On the intratidal timescale, sediment import occurs from 2 h before high water to high water. Flood currents in the North Sea (directed northeastward along the Belgian coast) drive the primary gyre in the harbor mouth which is advected into the basin during rising tide. This results in water inflow near the eastern breakwater and outflow near the western breakwater. Because of sediment settling in the harbor, this results in a net import of SPM. During spring tide, the SPM flux into the harbor basin is two to four times higher than during neap tide. However, the volume of sediment removed from the port by maintenance dredging is kept constant over the spring-neap cycle, causing the amount of mud in the harbor basin to grow around spring tide conditions. On the seasonal timescale, mud volume within the harbor basin is larger in winter and reaches a minimum at the beginning of autumn. Moreover, the measured densities within the deposited mud layers are lower in winter than in summer. The most shallow point of the 210-kHz reflector is also more shallow in winter. Finally, the profile of the interface of the mud layer in the sheltered Albert II dock is more horizontal in winter than in summer, suggesting seasonal variations in the strength of the mud layer. The question to what degree the seasonal variation of thickness and density of the fluid mud layer is related to differences in the suspended sediment input, to differences in the settling rates of suspended flocs, or to the mud consolidation rate remains open however. The data do not show a strong influence of meteorological conditions (waves, freshwater inflow) on siltation rates in the harbor basin.

Keywords Cohesive sediments · Harbor siltation · Fluid mud · Nautical depth · Zeebrugge

1 Introduction

The Port of Zeebrugge is subject to high siltation rates of mainly mud, and as a result, huge maintenance dredging works are mandatory (Fettweis et al. 2011, 2016). Obviously, the amount to be dredged depends on the inflow of mud into the harbor basin. Maintenance depth and dredging strategy in the port are guided by the principle of nautical depth. Pianc (1997) defines the nautical depth as the level at which physical characteristics of the bottom reach a critical limit beyond which contact with a ship's keel causes either damage or unacceptable effects on controllability and maneuverability. In Zeebrugge, the nautical bottom is defined as the density level of 1200 kg/m^3.

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Present regulations at Zeebrugge prescribe that in order to have safe maritime access to the port, the ship should have a positive under-keel clearance (UKC) of at least 10% (relative to its draft) above the nautical bottom and no more than 7% negative UKC below the mud-water interface, which is measured as the reflector of a 210-kHz echo sounder. This means that for the accessibility of the port, both the vertical position of the 210-kHz reflector and the 1200 kg/m^3 density level are important. Both levels (together with the 33-kHz reflector) are monitored regularly to steer maintenance dredging. This operational practice is the result of extensive investigations (Delefortrie et al. 2007) and is valid for the local mud and maneuvering conditions in the Port of Zeebrugge.

The sediments between the 210 and 33-kHz reflectors consist mainly of soft or even fluid mud. Fluid mud is a high-concentration suspension that typically behaves as a non-Newtonian fluid (McAnally et al. 2016). Fluid mud is formed if the rate of sediment deposition on the bottom exceeds the dewatering/consolidation rate of these deposits. Once formed, fluid mud may flow by shear flows, gravity, and/or wave-induced streaming. If not resuspended by entrainment processes, fluid mud slowly consolidates to form bed material (McAnally et al. 2007). Fluid mud typically has a volume fraction between 0.02 and 0.13 (Mehta 1991). We refer to Mehta et al. (2014) for a description of the properties and behavior of fluid mud in relation to nautical depth estimation.

Mud is generally transported in suspension or, in some cases, as near-bed fluid mud (Winterwerp 2005; Kirby 2011). Flow exchange mechanisms at a harbor entrance are well known and include tides, horizontal entrainment, and density currents (Vanlede and Dujardin 2014).

The aim of this paper is to describe the different influencing factors and timescales that are relevant to mud dynamics in the harbor basin.

2 Study site

Zeebrugge is a tidal port, situated in the dynamic and turbid Belgian coastal zone. There is a gradient in turbulence and in suspended particulate matter (SPM) concentration from high outside to low inside the harbor basin. The SPM entering the harbor settles quickly within the first hundreds of meters. The port was extended seaward to its present form in the period from 1980 to 1985, with the construction of two 4-km-long breakwaters extending about 3 km out to sea (see Fig. 1).

The outer port is maintained at a depth of up to 15.5 m below LAT (lowest astronomical tide) and the connection towards the open sea at 15.8 m below LAT; the port and the channels are thus substantially deeper than the nearshore area, where water depths are generally less than 10 m below LAT (Fettweis et al. 2009). The analysis in this paper is limited to the outer port; the inner port (which lies behind locks) is not considered.

About 5.3 million TDM (tons dry matter) per year or 15,000 TDM/day of mainly fine-grained sediments is dredged in the outer port (averaged over 1999–2011) and is disposed at authorized disposal sites in the North Sea, at 5–15 km from the harbor (Dujardin et al. 2016; Antea 2016). The sediments dredged in CDNB (the central part of the outer harbor) have an average mud content of 94% (Pieters et al. 2001).

The fluid mud layer inside the harbor basin (i.e., the layer between the 210 and 33-kHz reflectors) has a thickness of up to 3 m in front of the entrance of the Albert II dock, decreasing to 2 m at the harbor entrance (Fig. 2). The mud-water interface has a concave-down shape which remains more or less constant in space, though its level fluctuates over time.

Typical vertical density profiles inside the harbor basin are shown in Fig. 3. Note that since the vertical density profiles and the measurements along the leading light line are not performed on exactly the same time and location, the position of the 210 (or 33)-kHz reflector may differ slightly between both datasets. The vertical density profiles were measured with the Navitracker instrument, which is a continuous vertical profiling gamma-ray transmission gauge. Following the limiting volume concentrations given by Mehta (1991), the limiting bulk densities of fluid mud are 1060 and 1240 kg/m^3. The data in Fig. 3 confirm that the material found in between the 210 and 33-kHz reflectors has a density that corresponds with fluid mud.

The tides are semidiurnal with a mean tidal amplitude of 3.6 m. Peak ebb and flood velocities are high in front of the harbor entrance, due to the port protruding from the coastline, which deflects ebb and flood flow close to the coast. Flood flow (directed NE) occurs from 3 h before HW to 2 h 40 after HW during spring tide. Peak velocity in front of the harbor entrance reaches 2.1 m/s and occurs 40 min before HW during spring tide conditions (Flemish Government 2011). For deep-drafted ships, the nautical accessibility of the port is restricted to a tidal window with cross-currents less than 1.03 m/s (or 2 knots). For LNG carriers, stricter criteria are maintained and the acceptable cross-current at the breakwaters is reduced to 0.77 m/s or 1.5 knots (Eloot et al. 2009).

The flow field inside the harbor basin is characterized by a primary gyre (Fig. 4 shows the flow field at 1.5 h before HW), which is driven by the shear at the interface between water in the port and the flood flow in the North Sea. It is advected into the basin during rising tide. The primary gyre drives a smaller, secondary gyre deeper in the harbor (1 h before HW to HW), which is advected out of the basin during falling tide (HW to 2 h after HW).

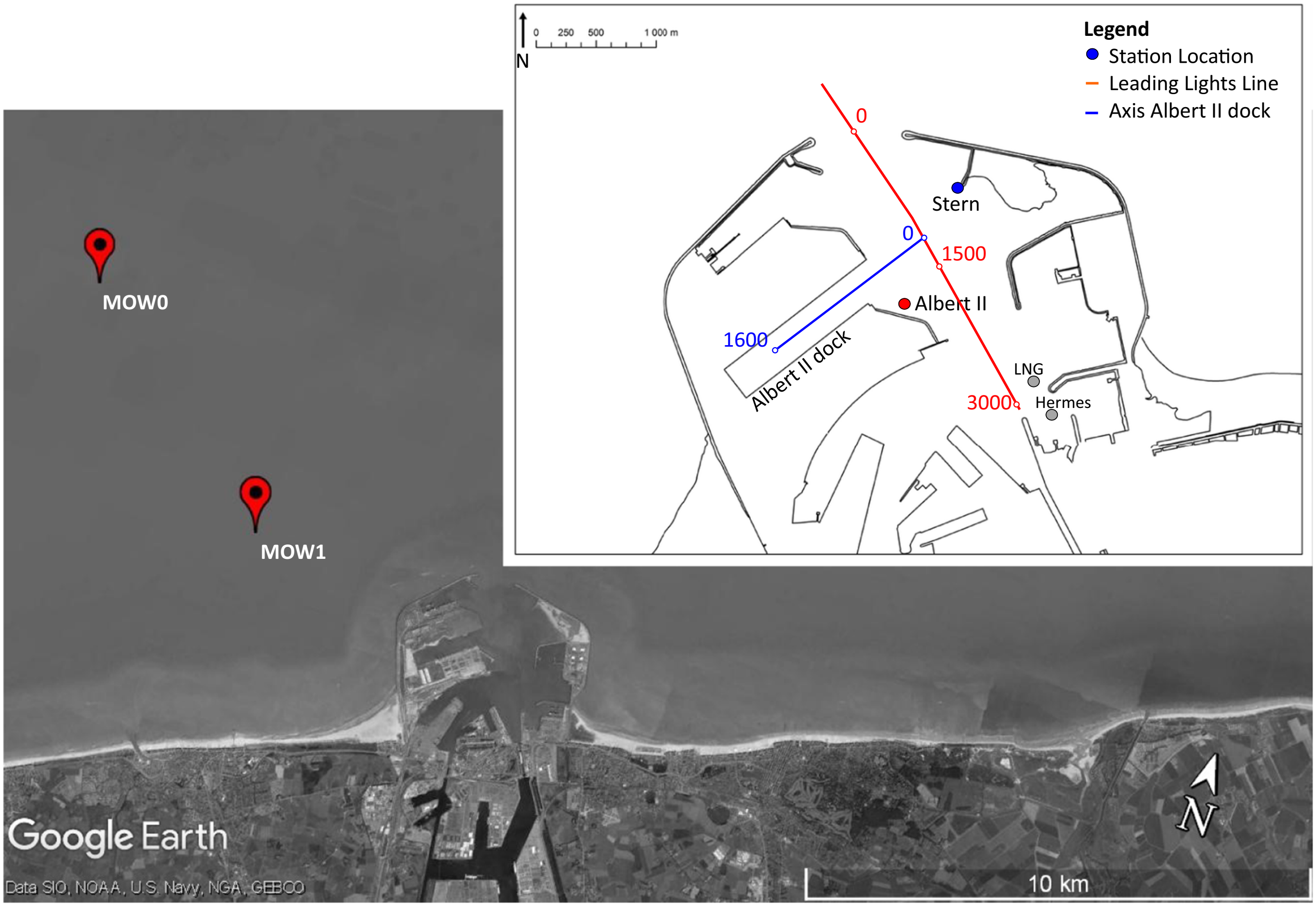


Fig. 1 Map of the Belgian coastal area (Southern North Sea) showing the measurement stations outside (MOW0, MOW1) and inside the harbor of Zeebrugge (Stern, Albert II, LNG, Hermes). The red line is the leading light line. The blue line is the axis of the Albert II dock. The background is a satellite image from Google Earth. The harbor entrance is located at 51° 21′ N 3° 11′ E

3 Materials and methods

3.1 Depth soundings

Different datasets with depth soundings during the period 1999–2011 were combined for the analysis in this study. The 210 and 33-kHz reflectors were sometimes measured as map data over larger areas in the harbor, and sometimes only as line data along the leading light line (indicated on Fig. 1). The map data was interpolated on the leading light line resulting in a combined dataset of depth along the leading light line over time.

Sounding data are used to compute changes in the volume of deposited sediments in the basin. Only those depth soundings that cover more than 50% of the leading light line are retained. Since the aim is to link observed sediment volume changes (from the soundings) with data on dredging activity and meteo conditions between two consecutive soundings, it is important that the time interval between pairs of depth soundings in the dataset remains more or less constant. Therefore, only those pairs of depth soundings are retained that have a sounding interval of less than 30 days. Following these selection criteria, 80% of data is retained.

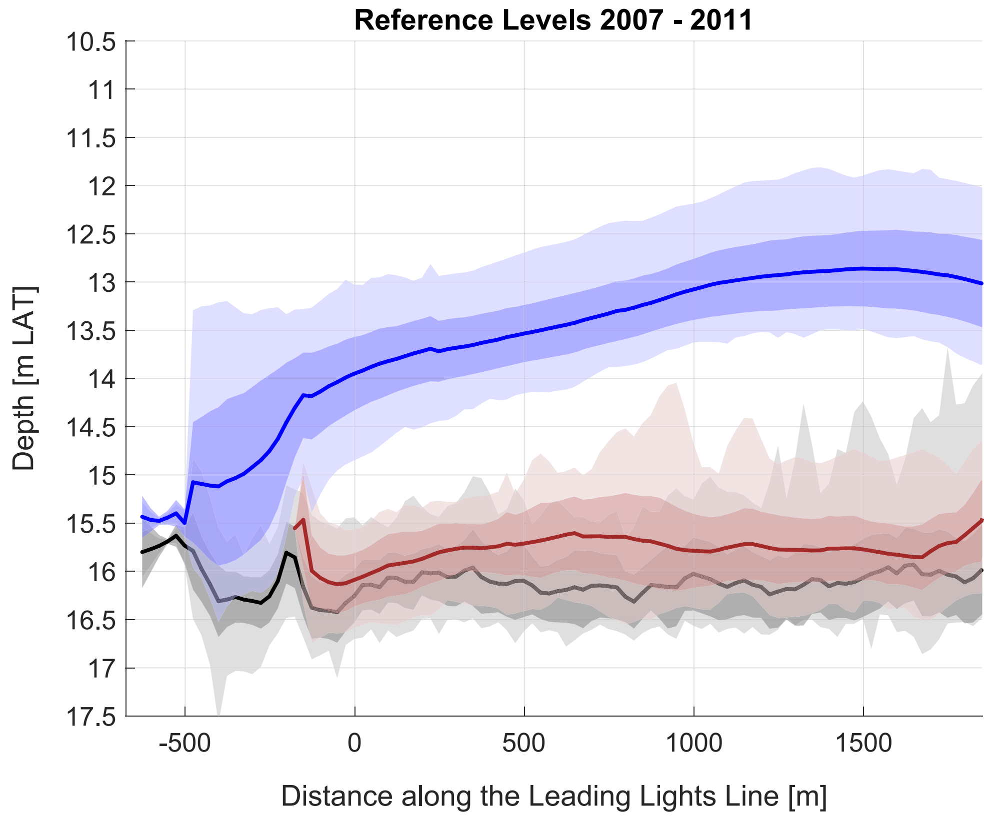
The volume change is then derived from the depth data on the leading light line by multiplying the average depth difference with the total surface area of the map data. The uncertainty in volume change when only line data is used has been estimated from the map data and is about 2% (Dujardin et al. 2016).

3.2 Calculation of the natural depth change of the mud-water interface

The 210-kHz reflector is considered to be the mud-water interface. A depth change of this reflector corresponds to a change of the mud volume in the harbor by natural processes and dredging works. A simple volume balance is set up to decompose the measured depth change into the natural depth change and the effect of dredging.

$$\Delta h^m = \Delta h^d + \Delta h^n \quad (1)$$

Fig. 2 The level of the mud-water interface (210 kHz) in blue, of the 1200 kg/m^3 density level in brown, and of the 33-kHz reflector in black. Data of 2007–2011. Colored bands are plus and minus one standard deviation, and min and max values. Values on *x*-axis correspond to the distance along the leading light line (indicated on Fig. 1)



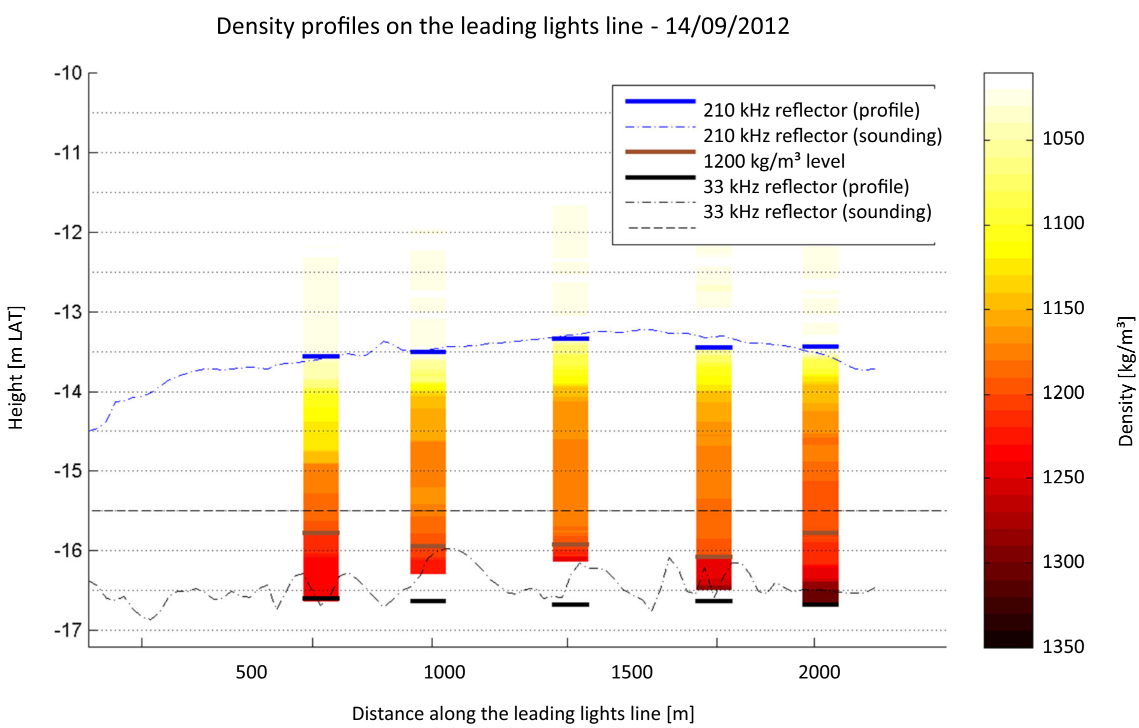


Fig. 3 Vertical density profiles measured on the leading light line. The 210-kHz reflector is indicated in blue, the 33-kHz reflector in black, and the density level of 1200 kg/m^3 in brown. The target maintenance depth of 15.5 m below LAT is indicated with a horizontal dashed line

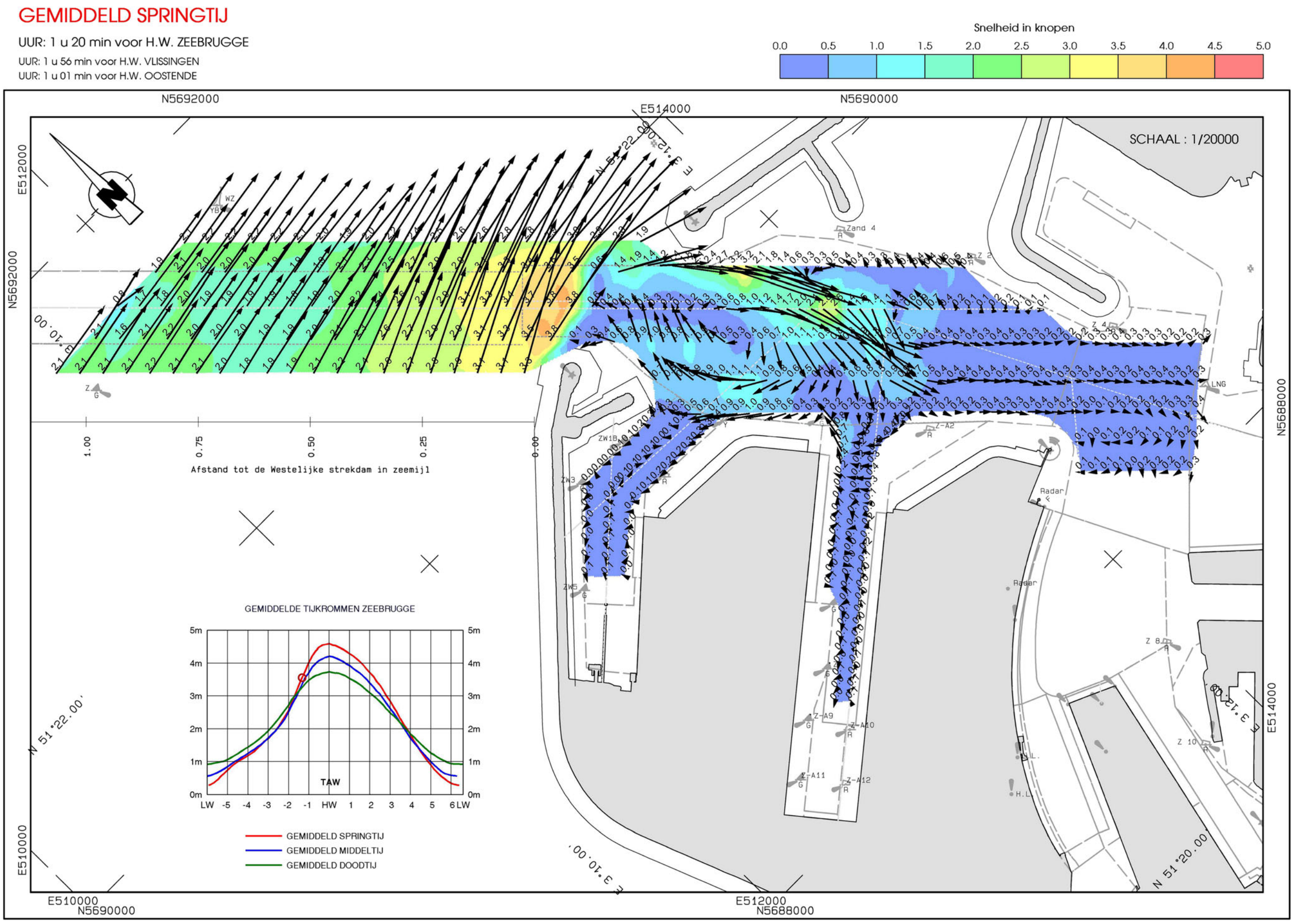


Fig. 4 Flow field (knots) in the port during spring tide and maximum flood flow (1.5 h before HW). Excerpt from the flow atlas of Zeebrugge. (Flemish Government 2011)

$$\Delta h^d = \frac{-m^d\left(\rho_g - \rho_w\right)}{A\rho_g\left(\rho_b - \rho_w\right)} \tag{2}$$

The natural depth change of the mud-water interface Δh^n corresponds to the cumulative effect of deposition (positive sign) and resuspension and consolidation (negative sign). It is calculated from Δh^m and Δh^d.

Δh^m is the measured depth change of the mud-water interface, taken from depth soundings. A negative sign corresponds to a depth increase.

Δh^d is the effect of dredging, which is calculated from the amount of dry matter dredged, m^d, with A the area over which dredging was executed, ρ_g the grain density (2650 kg/m^3), ρ_b the in situ bulk density, and ρ_w the density of seawater (taken here as 1025 kg/m^3). Note that m^d, the amount of dry matter dredged, is calculated and logged directly by the dredging information system on board of the dredging vessel.

Because the in situ bulk density ρ_b (see example in Fig. 3) is monitored at a lower sampling frequency than the daily dredging operations, it has to be estimated for each dredging campaign in order to calculate Δh^d. We choose to estimate the in situ bulk density ρ_b of the dredged material from the bulk density of the sediment in the hopper dredger, which is measured and logged during each dredging campaign. The conversion is done based on an analysis of the relation between in situ volume concentration (IVC) and hopper volume concentration (HVC). We call this relation between volume concentrations the bulking curve. Note that theoretically, this curve has to go through (0, 0) because pure water in situ will be pure water in the hopper dredger. For a similar reason, the curve also has to go through (1, 1). Physically, dredging-related processes such as water entrainment and de-gassing of sediment will influence this relationship. Figure 5 shows the observed part of the bulking curve as a scatterplot. It is based on available density and dredging data in the harbor basin of Zeebrugge for the period 2012–2014. Each data point corresponds to one dredging campaign. The HVC is calculated from the bulk density inside the hopper dredger, as logged in the dredging information system. The corresponding IVC is calculated from the density profile closest to the dredging location and measured prior to the dredging campaign, by vertically averaging it over 1 m, centered on the dredging depth.

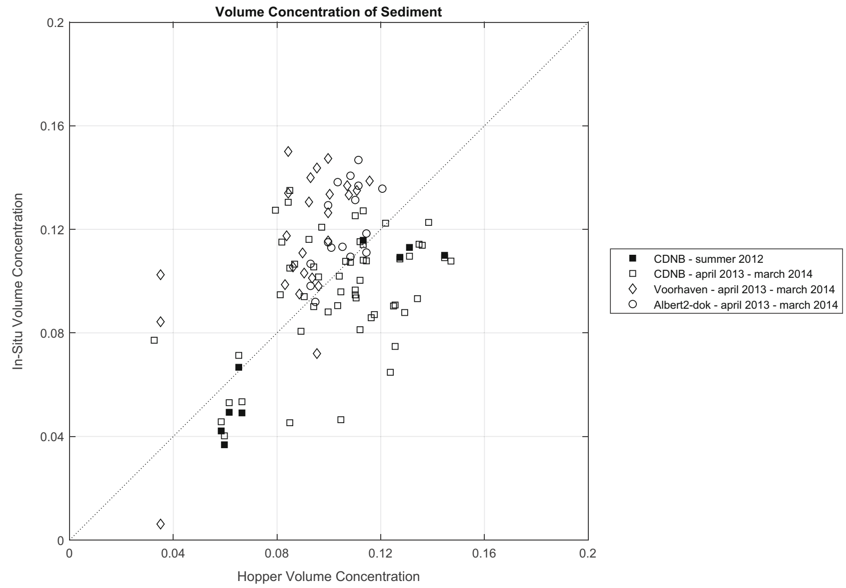


Fig. 5 Bulking curve of in situ volume concentration [−] vs hopper volume concentration [−], based on measurement data from the Zeebrugge harbor basin from 2012 to 2014

We took the reported bulk density in the hopper dredger as the estimate for the in situ bulk density ρ_b (shown as the dotted 1:1 line in Fig. 5). The substantial scatter in the plot is likely due to the fact that the dredging campaign and the corresponding density profile are not executed at the same time and place.

3.3 Measurements at fixed stations

Current velocity, salinity, temperature, and SPM concentration were measured at four stations inside the harbor (Stern, Albert II, LNG, and Hermes; see Fig. 1) at about 2 m below LAT and about 2 m above the bottom. Each measuring station was equipped with a point velocimeter (Aquadopp), an OBS3+, and a CT probe (Valeport 620). At station Hermes, the instrumentation was mounted on a fixed cable, attached to the gangway of the pier and a concrete anchor at the bottom. In the other three measuring stations, the instrumentation was fixed on a steel cable between an anchor and an underwater buoy. The data were collected every 10 min (averaged over 60-s bursts). The measurement campaign lasted for 400 days from 14 March 2013 to 18 April 2014. More details on the instrumentation can be found in Antea (2015a).

For salinity, on average, 76% of all data points are considered usable, for SPM 69%. The most important reasons for missing data were battery problems, bio-fouling with algae and barnacles, and technical problems with the sensors.

Because the measurement stations Stern, Albert II, and LNG are located at the edge of an area that is maintained at depth for navigation, these stations had to be installed on a sloping bed. This means that the absolute heights of the sensors may vary over time, as the instruments were taken out of the water and re-deployed every 2 to 4 weeks for checkup, cleaning, and data retrieval.

SPM concentration in the North Sea is an obvious boundary condition to mud dynamics in the port. Near-bed SPM concentration is measured with a benthic lander located about 5 km northwest of the port (MOW1) (see Fig. 1).

3.4 SPM concentration measurements from ADCP transects inside and outside the harbor

From March 2013 to April 2014, 113 longitudinal transects have been sailed in the harbor with the research vessel RV Belgica (see Fig. 1 for the location of the transect). The acoustic backscatter recorded from a hull-mounted 300-kHz ADCP was converted to SPM concentration (Thorne et al. 1994; Holdaway et al. 1999). Example SPM data is shown in Fig. 8.

The conversion from acoustic backscatter to SPM concentration was done as follows. During an 8-h period, water samples and vertical profiles have been collected inside and outside the harbor using a CTD, an OBS, and a LISST 100X. The water samples have been analyzed for SPM, particulate organic matter (POC), and chlorophyll concentration. The OBS signal was converted into SPM concentration through a linear relationship obtained after filtering and weighing of water samples. The relationship between the acoustic backscatter (in dB) and the SPM concentration was established using the SPM concentration derived from the OBS profiles. One relationship was applied to the whole dataset. The acoustic backscatter signal depends strongly on particle size and density however. The samples collected for calibration may not represent SPM properties in all 113 transects. Due to the rapid settling of sediment inside the harbor, strong gradients are expected in the size and composition of the remaining SPM. The SPM inside the harbor has larger floc sizes and lower densities with higher organic content, while outside the harbor, the SPM occurs as bio-mineral aggregates as described by Fettweis and Lee (2017). The echo intensity of the backscattered acoustic signal should therefore only be seen as an estimate of the SPM concentration.

It should be noted that only a low correlation ($R^2 = 0.35$) is found between the SPM concentrations from the bottom OBS sensor at station Albert II and the corresponding SPM concentration from the ADCP transects (Antea 2015b). The SPM concentration derived from the ADCP data is typically two times higher than the one derived at the fixed measurement station, with significant scatter between the two datasets. The scatter could be related to different calibrations to convert the acoustic and the optical backscatter to SPM and to spatial variation of the SPM concentration. Note that we only use the SPM concentration from the ADCP data to establish the intratidal timing; we do not use the absolute values of sediment concentrations.

3.5 Freshwater inflow into the port and salinity

Freshwater discharge can contribute significantly to the siltation rate of a harbor. The relative contribution is site-specific however (Winterwerp and de Boer 2016). Freshwater is discharged into the harbor through the Leopoldkanaal and the Schipdonkkanaal. Both canals discharge gravitationally during low water. The daily averaged total freshwater discharge of both canals has a positively skewed distribution with a low median of 1.1 m^3/s and a maximum of 80 m^3/s (Dujardin et al. 2016). Dry periods with no freshwater inflow occur typically during summer and autumn conditions. Because freshwater can only be discharged around low water, the freshwater distribution is tidally modulated. Vertical salinity profiles are available at 27 locations inside the harbor (IMDC et al. 2011). The profiles were measured during 44 campaigns in the period 2007 to 2008.

3.6 Wave data

Wave data from the directional wave buoy at Bol van Heist was analyzed for the period 1999–2011. The wave direction typically varies from north to west-southwest. The significant wave height has a log-normal distribution with a median value of 0.6 m in summer and 0.75 m in winter.

3.7 Data classification and ensemble analysis

The time series of SPM concentration and current velocity measured inside the harbor are split up into individual tidal cycles and interpolated with a 10-min interval on a local time axis relative to the moment of HW. The tidal cycles are grouped in three classes, according to the tidal amplitude at Zeebrugge, and labeled as spring, mean, or neap tide, respectively. All tidal cycles in a certain tidal class are combined in an ensemble, and the average and standard deviation are calculated on the local time axis (see Fig. 7). This ensemble analysis (or phase averaging) is used to gain insight in the intratidal (Section 4.3.1) and spring-neap modulation (Section 4.4.1) of the SPM concentration signal.

4 Results and discussion

4.1 Influence of freshwater inflow on sediment import

The salinity in the lower half of the water column inside the harbor basin shows no observable vertical gradient. During periods of high freshwater discharge (> 10 m^3), the water column inside the harbor becomes vertically stratified near the surface, with a thin layer (~ 1 m) of freshwater. This stratification typically dissipates through mixing in 6 to 8 h.

Freshwater import into the harbor may induce a density current into the harbor basin in the lower half of the water column. The velocity of the freshwater front on top of the saline water in the harbor can be estimated following Kranenburg (1998) as

$$c = \sqrt{\varepsilon g \frac{a_1}{a} \frac{(a - a_1)(2a - a_1)}{(1 - \beta_1)a_1 + (1 + \beta_1)a}} \tag{3}$$

with ε the relative density difference $\Delta\rho/\rho$, a_1 the height of the freshwater front, a the water depth, and β_1 a loss term (between 0 and 1). Note that in case $a_1 = a/2$ and $\beta_1 = 0$, this formulation collapses to the relation $c = 0.5\sqrt{\varepsilon g a}$, which is often used to describe lock-exchange flow. A freshwater front of 1-m height in a water column of 15 m has a propagation speed of 0.6 m/s ($\beta_1 = 0$), which would (assuming no net water exchange) induce a depth averaged return flow of only 0.05 m/s into the harbor. This is consistent with an analysis of the velocity field around the harbor entrance of Zeebrugge which shows that water exchange due to density currents is small compared with the total exchange flow (Vanlede and Dujardin 2014).

The direct import of sediment in suspension via the Leopoldkanaal and the Schipdonkkanaal is negligible. If we assume an average SPM concentration of 50 mg/l in the canals and a median freshwater discharge of 1.1 m^3/s, then the import of sediments by the canals represents only 0.05% of the total sediment import.

We therefore reject the hypothesis that freshwater inflow into the harbor influences sediment import (either through a density current or through a sediment load in suspension). This is confirmed by the fact that no correlation is found between the natural depth change of the mud-water interface (see Section 3.2) and the freshwater discharge (Dujardin et al. 2016).

4.2 Influence of wind and wave climate on sedimentation

The natural depth change of the mud-water interface (see Section 3.2) is binned according to the mean wave direction and the peak wave height at station Bol van Heist. The P95 significant wave height is used as a proxy for peak wave height.

In Fig. 6, we only find a weak positive correlation ($R^2 = 0.35$) between the peak wave height and the natural depth change of the mud-water interface (calculated with the method described in Section 3.2). The mud-water interface rises between 1 and 3 cm/day if the P95 significant wave height is larger than 1.19 m. Note that our results are in contrast to Lanckneus and Van Lancker (2001), who found higher siltation during periods of lower wave heights. The difference between both findings can be related to the low correlation between depth change and wave conditions, which can make the sign of the (weak) correlation dependent on the period that is analyzed.

Following a similar methodology, we also investigated the influence of wind climate on sedimentation, but found no meaningful correlation.

4.3 Intratidal variation

4.3.1 Intratidal variation of SPM concentration at fixed stations

Figure 7 shows the ensemble analysis of both SPM concentration and current velocity, measured with the lower sensors at stations Stern and Albert II during spring tide (ensembles for neap and mean tide show the same phasing). SPM concentration peaks 1 h before HW at station Stern and 50 min later at Albert II. A cross-correlation analysis of the complete time series at Stern and Albert II confirms that the SPM concentration signal at Albert II is 50 min delayed from the signal at Stern. This delay is explained in terms of the time of advection of SPM from station Stern to station Albert II by the primary gyre in the harbor basin.

A 50-min travel time over a 1000-m trajectory corresponds to an average advection velocity of 0.33 m/s. The peak SPM concentration near the bottom is higher deeper inside the harbor basin at Albert II (900 mg/l) than at Stern (600 mg/l), even though the velocity at that time is lower at Albert II. This result can be understood in terms of vertical settling during advection between stations Stern and Albert II. This also suggests that local resuspension is not the dominant process that determines sediment concentration in the Albert II dock.

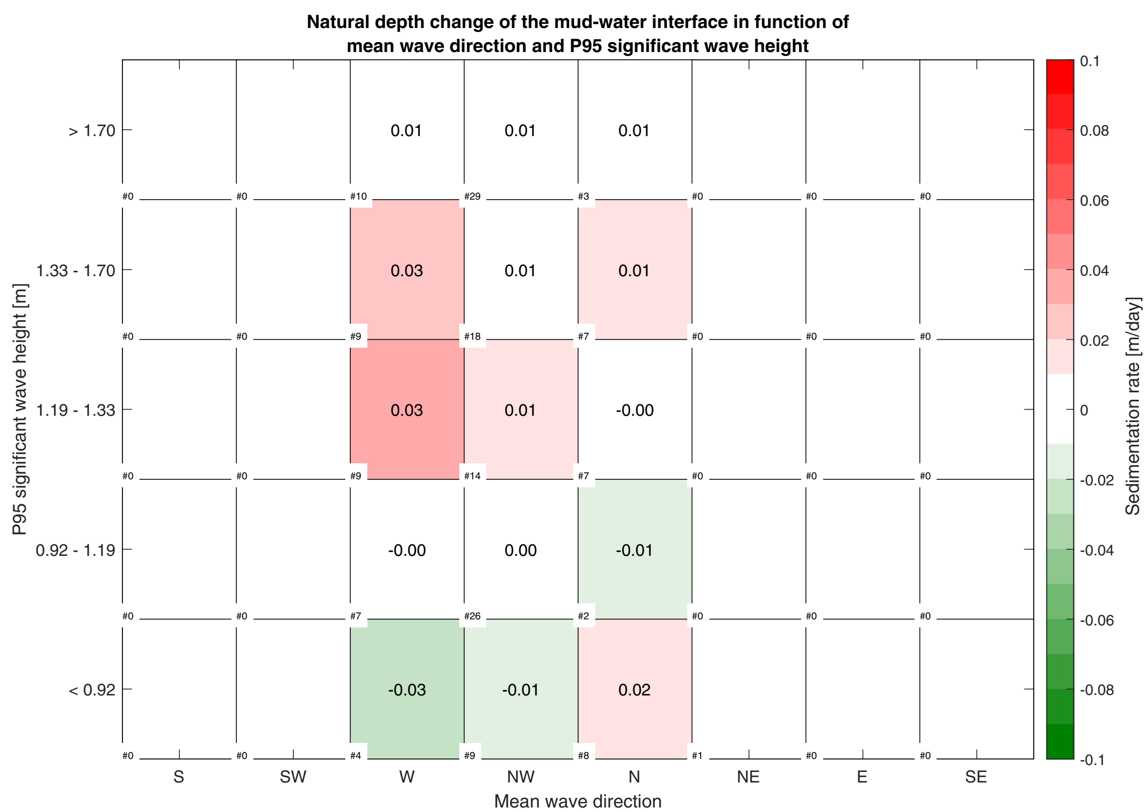


Fig. 6 Natural depth change of the mud-water interface [m/day] classified according to mean wave direction and P95 significant wave height. The number of datapoints is shown in the lower left corner of each cell. Bins of less than three datapoints are represented by empty cells

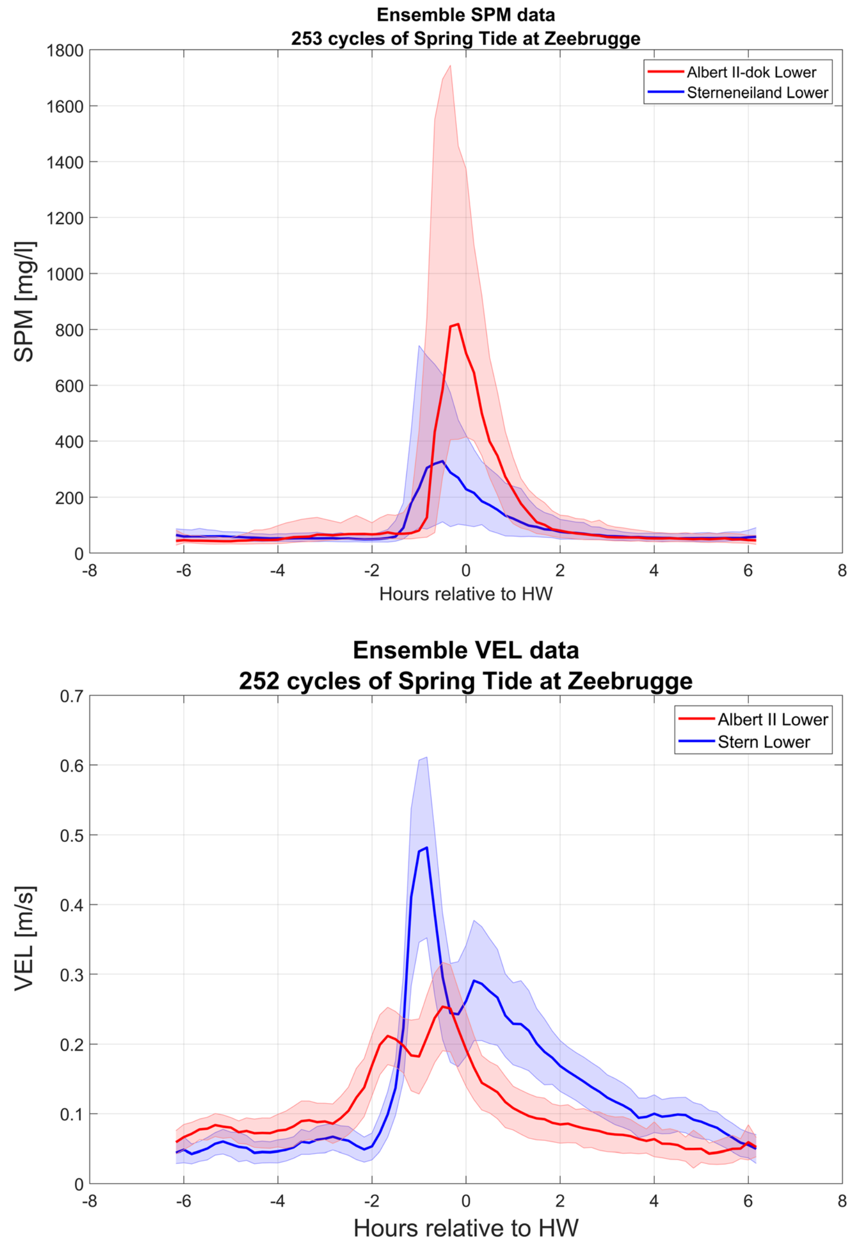


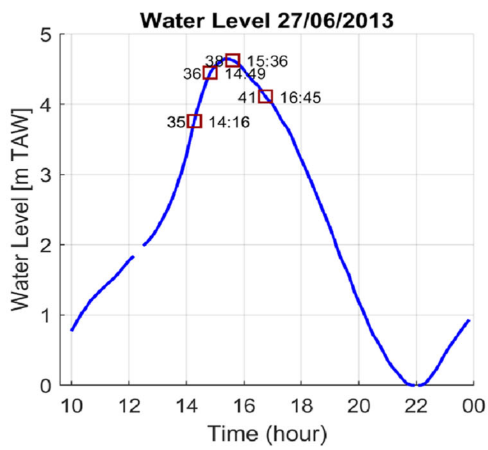
Fig. 7 Ensemble analysis for SPM (top) and velocity (bottom) measured during spring tide conditions with the lower sensors of stations Albert II (in red) and Stern (in blue). The full line is the median; the shaded area lies between the 20th and 80th percentile

The peak SPM concentration at the upper sensor, however, is similar at both stations (350 mg/l). This suggests that a slower settling fraction determines the sediment concentrations in the upper part of the water column.

These results are consistent with the analysis of the flow exchange mechanisms between a harbor basin and the open sea, applied to Zeebrugge by Vanlede and Dujardin (2014). They concluded that horizontal exchange is the most important component of the sediment import at the harbor mouth of Zeebrugge and that most of the sediment import occurs from 2 h before high water to high water. In that timeframe, flood currents in the North Sea (directed northeastward along the Belgian coast) drive the primary gyre in the harbor mouth, which is advected into the basin during rising tide. This results in water inflow near the eastern breakwater (close to the measurement station Stern; see Fig. 4) and outflow near the western breakwater. Because of sediment settling in the harbor, the sediment concentration in the outflowing water is lower than that in the inflowing water, which results in a net import of SPM.

4.3.2 Intratidal variation of SPM concentration from ADCP transects

Figure 8 shows four vertical profiles of SPM concentration, measured during one tidal cycle in June 2013 (see



Water levels in Zeebrugge during ADCP transects 27/06/2013

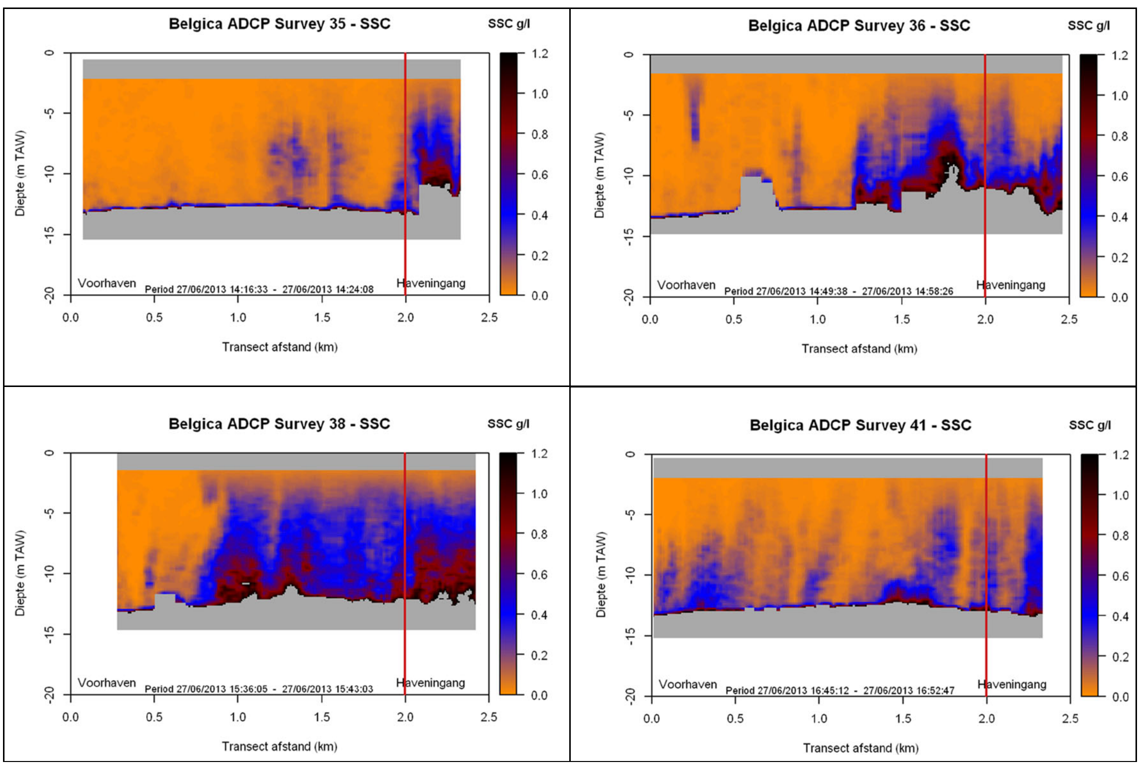


Fig. 8 SPM from ADCP backscatter, measured on 27 June 2013 on a longitudinal transect in the port. The port entrance (indicated with a red line) is to the right of each panel. Phase during the tidal cycle clockwise from top left: 1 h before HW (survey 35), 30 min before HW, 30 min after HW, 2 h after HW (survey 41)

Section 3.4 for a description of the dataset and Fig. 1 for the location of the transect). The four panels in the figure are arranged clockwise from the top left and show SPM being transported in suspension from the harbor entrance to deeper inside the harbor. At 1 h before HW (top left panel), the sediment in suspension is concentrated outside the harbor. At 30 min before HW (top right panel), the suspended sediment has been transported into the harbor along the eastern side of the harbor mouth. Thirty minutes after HW (bottom right panel), the SPM front is advected a further 500 m. Two hours after HW (bottom left panel), the SPM concentrations in the water column are lower, because of settling and deposition.

The intratidal phasing of the vertical SPM profile is consistent with the tidal modulation in SPM concentration measured at stations Albert II and Stern (see Section 4.3.1). The sequence of vertical profiles of SPM concentration in Fig. 8 confirms that the bulk of the SPM is transported into the harbor through advection around HW and that the most important transport occurs in the bottom half of the water column.

Table 1 Spring-neap variation in net sediment influx to the Port of Zeebrugge

Source	Net sediment influx-neap tide [TDM/day]	Net sediment influx-spring tide [TDM/day]	Ratio spring/neap
Claeys et al. (2001)	1590	6400	4.0
Dujardin et al. (2009)	3454	13,880	4.0
IMDC (2011)	834	1468	1.8
Average	1986	7357	3.0

4.4 Spring/neap cycle

4.4.1 Spring/neap variation in sediment import

The amount of sediment that enters the harbor in suspension have been estimated from ADCP measurements executed on a transect across the harbor entrance, e.g., Claeys et al. (2001). In IMDC (2010), two measurement campaigns are described that have been executed during spring and neap tide conditions. In the bottom blanking zone of the ADCP, IMDC (2010) extrapolated the vertical SPM profiles towards the bed. Dujardin et al. (2009) used the same ADCP dataset, but used concurrent turbidity measurements close to the bottom to derive the SPM concentrations close to the bed. The resulting estimates for the total sediment import are five to ten times higher than in IMDC (2010). This result underlines the importance of near-bed data for estimating total sediment fluxes.

Table 1 summarizes the different estimates of the spring-neap modulation in the net sediment influx into the harbor. On average, sediment import into the harbor during spring tide is two to four times higher than during neap tide.

This is consistent with the spring-neap variation of SPM concentrations outside the harbor, measured with a benthic lander at MOW1 (Fettweis and Baeye 2015). De Maerschalck et al. (2015) have shown that the peak SPM concentrations at 2.2 m above the bottom (mab) are up to be three times higher during spring than during neap tide.

This is also consistent with the spring-neap variation of peak SPM concentrations observed near the entrance of the harbor. An ensemble analysis of the spring-neap variation of SPM at station Stern (Fig. 9) shows peak SPM concentrations prior to high water, i.e., at the moment of highest sediment import, that are four times higher during spring tide than during neap tide. The intratidal phasing of the SPM peak does not change over the spring-neap cycle. No significant spring-neap variation was found however at stations deeper inside the harbor (LNG and Hermes).

Based on the flow atlas (Flemish Government 2011), we can determine that the maximum velocity near the eastern breakwater during inflow is about two times higher during spring than during neap tide. The spring/neap variation in sediment import is therefore a combination of higher SPM concentrations and higher velocities during spring tide.

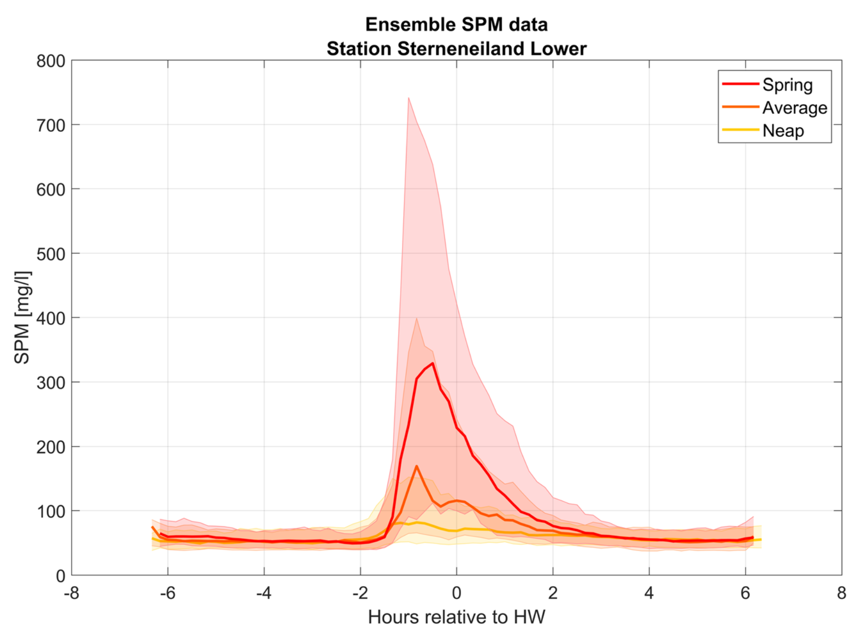


Fig. 9 Spring (red) to neap (in yellow) variation of SPM during a tidal cycle at station Stern. The full line is the median; the shaded area lies between the 20th and 80th percentile

Sediment import, SPM concentrations in the Belgian nearshore, and SPM concentrations inside the harbor close to the entrance all co-vary over a spring-neap cycle with similar relative amplitude and phasing. This supports the hypothesis of sediment import through advection. The SPM concentrations at the landward end of the harbor do not show this spring/neap variation however, which suggests that they are governed by different processes, such as resuspension (due to ship movements or dredging activity) or gravitational flow of mud layers inside the harbor.

4.4.2 Influence on the mud-water interface

Averaged over 1 month, the total mass dredged is equal to the sediment import. There is, however, no spring-neap variation in the daily dredging amounts (Dujardin et al. 2016), which means that the sediment extraction from the port does not follow the modulation in sediment import. As a result, the level of the mud-water interface in Albert II dock typically rises up to 15 cm/day during spring tide conditions and falls 5 to 10 cm/day during neap and mean tide conditions.

4.5 Seasonal variation

SPM concentrations inside the harbor have a significant seasonal variation in all fixed measurement stations, with lower SPM concentrations in spring and summer and higher in autumn and winter (Dujardin et al. 2016). Figure 10 shows the relative frequency distribution of SPM values in station Albert II in summer and winter conditions. This figure illustrates how the median SPM is higher in winter than in summer, both for the top and the bottom sensor. There is also a higher probability of higher SPM values (> 100 mg/l) in winter in the bottom sensor.

The seasonality inside the harbor is consistent with the seasonality in SPM concentration at the surface and in the water column that is observed in the Belgian nearshore area (Fettweis et al. 2007; Fettweis and Baeye 2015). Seasonality of surface SPM in the North Sea at stations MOW0 (Wandelaar) and Vlakte van de Raan was quantified from satellite imagery. Surface SPM concentration at these stations is about half the yearly average for spring and summer and 70% higher in winter. The bottom SPM concentration from the benthic lander located at MOW1 shows a comparable seasonal variation, with peak SPM concentrations at 2.2 mab about twice as high in autumn-winter than in spring-summer (De Maerschalck et al. 2015).

Figure 11 shows the seasonal variation of the most shallow point of the 210-kHz reflector along the leading light line (location in Fig. 1). As described Section 1, the height of the 210-kHz reflector is part of the local definition of the nautical bottom. The minimum height (or most shallow point) along the leading light line is thus an obvious statistic to monitor. If the 210-kHz reflector rises too high somewhere in the basin, nautical accessibility is hindered. Figure 11 clearly shows a seasonal variation in this statistic, with the top of the 210-kHz reflector being more shallow in winter.

Also, the density profiles show a lower density of the sediment layers in winter than in summer. In summer, 65% of sediment in between the 210-kHz and 33-kHz reflectors has a density below 1.18 g/l, whereas in winter, that number increases to 80% (Antea 2015b). The temperature of the pore water might play a role here. It affects the viscosity of the pore water, and the permeability is inversely proportional to viscosity (Merckelbach and Kranenburg 2004). For winter conditions, this means a higher viscosity, a lower permeability, and thus a slower consolidation in winter.

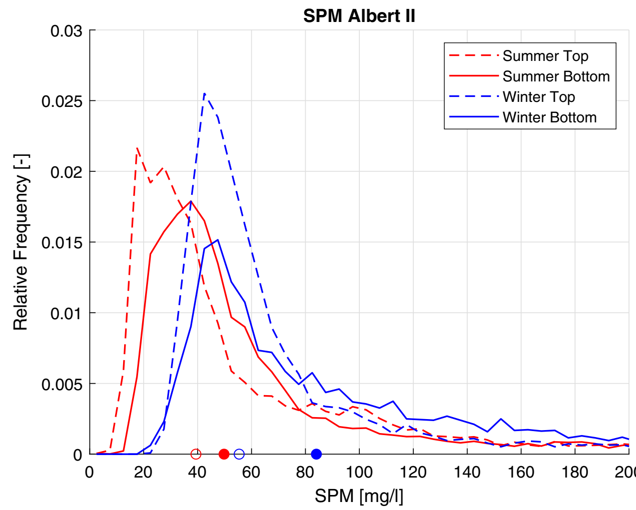


Fig. 10 Relative frequency distribution of SPM at station Albert II in winter (in blue) and summer (in red). Top sensor in dashed line, bottom sensor in solid line. Median values are indicated with a circle on the *x*-axis (a full circle for the bottom sensor and an outlined circle for the top sensor)

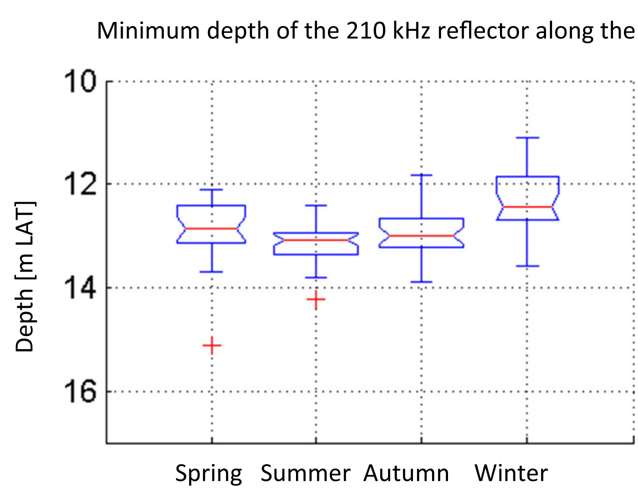


Fig. 11 Seasonal variation of the minimum depth along the leading light line of the 210-kHz reflector in CDNB. Data from 2007 to 2011

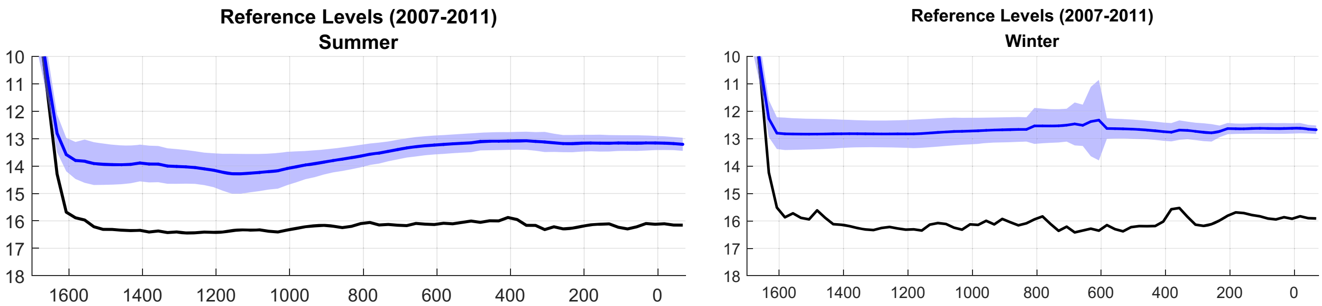


Fig. 12 Seasonal variation of levels in Albert II dock. Mean 210-kHz level (± 1 standard deviation) in blue for summer (left) and winter (right), 33 kHz in black. Values on *x*-axis correspond to the distance along the leading light line (indicated on Fig. 1)

Figure 12 shows the seasonal pattern in the shape of the mud layer in the Albert II dock. Where the mud-water interface is flat in winter, it shows a height variation of 1 m (max. slope 1/400) in summer. Seasonal modulation of the strength properties is a possible explanation for this pattern.

Fettweis and Baeye (2015) argue that microbial activity is the main driver of the seasonality in floc size yielding larger flocs in summer than in winter, rather than the seasonality in wind strength and thus wave climate. Further research is needed, however, to investigate the seasonal variations in floc properties inside the harbor (e.g., size and fractal dimension) and to link the floc properties with seasonal variations in settling velocity, sediment input rate, consolidation rate, and strength properties of the bed.

5 Conclusions

Data on the vertical position of the mud-water interface was combined with dredging data to calculate the natural depth change of the mud-water interface (Section 3.2). This natural depth change was cross-referenced with data on meteo conditions (waves and freshwater inflow) to study influencing factors. The effect of freshwater inflow on sediment import into the harbor is negligible, and only a slight positive correlation was found between the peak significant wave height and the natural depth change of the mud-water interface.

The data support the hypothesis that mud is transported into the harbor of Zeebrugge through advection of suspended sediment. Most of the sediment import occurs from 2 h before high water to high water. Sediment import through advection is apparent both in the ADCP backscatter dataset (Section 4.3.2) as in the ensembles based on the OBS dataset (Section 4.3.1). This hypothesis is consistent with the analysis of the sediment exchange mechanisms between the harbor of Zeebrugge and the North Sea presented by Vanlede and Dujardin (2014).

Another siltation mechanism where large quantities of mud are entrained and flow into the harbor as high concentration benthic suspensions (HCBS) has been previously reported for the Port of Rotterdam during storms (Kirby 1988; Winterwerp 1999). However, in our data, we found no evidence of this siltation mechanism transporting mud from the North Sea into the harbor basin, which is consistent with the conclusions of the HCBS measurement program that was executed in the harbor in 2006–2007 (IMDC et al. 2010). It is possible however that gravitational flow of mud layers plays a role in redistributing sediment inside the harbor basin, e.g., sediment flowing gravitationally from CDNB into Albert II dock.

The SPM concentration in the North Sea and in the port close to the entrance is three times higher during spring tide than during neap tide. The same spring-to-neap ratio is also found in the sediment influx per tide. Because there is no apparent spring-neap modulation in dredging works, the level of the mud-water interface in Albert II dock typically rises 15 cm/day during spring tide conditions and falls 5 to 10 cm/day during neap and average tide conditions.

The seasonality of SPM concentration in the port is consistent with the seasonality observed in the North Sea, with higher SPM concentrations during autumn-winter and lower SPM concentrations during spring-summer. The question to what degree the thickness and density variation of the fluid mud layer are related to differences in the suspended sediment input, to differences in the settling rates of suspended flocs, or to the mud consolidation rate remains open however.

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Daily values of freshwater inflow into the port through the Leopoldkanaal and the Schipdonkkanaal were made available by the "Hydrologisch Informatie Centrum" (HIC) of the Ministry of Public Works.

In situ (ADCP and frame) and remote sensing (satellite) data have been collected by the RBINS–OD Nature. The ship time of the RV Belgica was provided by BELSPO and RBINS–OD Nature.

The first author worked on this paper while affiliated as a guest to Delft University of Technology in the Faculty of Civil Engineering and Geosciences.

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