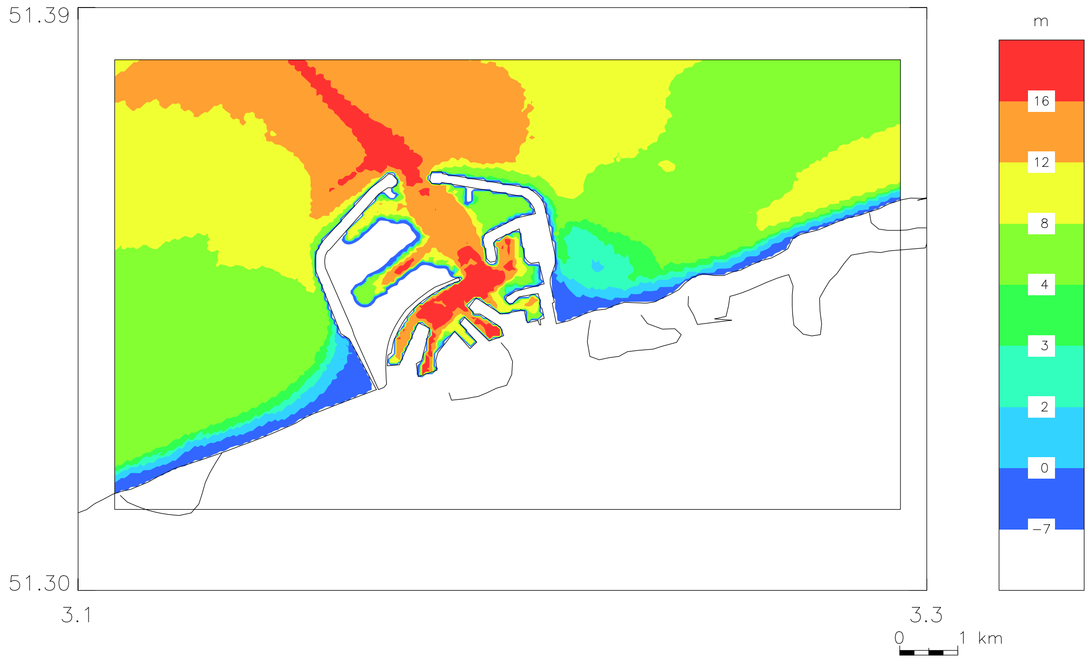
BEHEERSEENHEID VAN HET
MATHEMATISCH MODEL VAN DE NOORDZEE
SUMO GROEP

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 (1 april 2006 - 30 september 2006)

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MOMO/3/MF/200612/NL/AR/1

Voorbereid voor Afdeling Maritieme Toegang, Departement Mobiliteit en Openbare Werken, Ministerie van de Vlaamse Gemeenschap, contract MOMO

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Appendix 2: Fettweis M. & Van den Eynde, D. 2006. Dumping of dredged material in sea: towards operational use of sediment transport models. International Hydrographic Conference 2006, Evolutions in Hydrography, 6-9 November 2006, Antwerp, Belgium

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1. Inleiding

1.1. Voorwerp van deze opdracht

MOMO staat voor 'monitoring en modellering van het cohesieve sedimenttransport en de evaluatie van de effecten op het mariene ecosysteem ten gevolge van bagger- en stortoperatie'. Het MOMO-project 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 overeenkomstig het Verdrag inzake de bescherming van het mariene milieu van de noordoostelijke Atlantische Oceaan (1992, OSPAR-Verdrag). De OSPAR Commissie heeft de objectieven van haar huidig "Joint Assessment and Monitoring Programme" (JAMP) gedefinieerd tot 2010 met de publicatie van een holistisch "quality status report" 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 habitats, 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 perioden (2002-2004 en 2004-2006) kan gevonden in het "Syntheserapport over de effecten op het mariene milieu van baggerspeciestortingen" (Lauwaert et al., 2004; 2006) 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. Voor een uitgebreide beschrijving wordt verwezen naar de halfjaarlijkse rapporten.

1.2. Algemene Doelstellingen *(2006-2011-2016)*

Het onderzoek uitgevoerd in het MOMO project kadert in de algemene doelstelling om de baggerwerken op het BCP en in de kusthavens te verminderen, door enerzijds de sedimentatie te verminderen in de baggerplaatsen en anderzijds efficiënter te storten. Een nauwe samenwerking tussen de BMM en het WLH is één van de vereisten om de doelstelling te kunnen realiseren.

1.2.1. *Verminderen van de sedimentatie*

Vermindering van de sedimentatie zal kunnen bereikt worden door:

- een optimalisering van de vorm van de buitenmuur of een Current Deflecting Wall, zodat de wateruitwisseling tussen haven en zee vermindert.
- een aanpassing van de vorm van de toegangsgeul (bv verbreding, zachtere helling…).

1.2.2. *Efficiënter storten*

De efficiëntie van een stortplaats wordt bepaald door fysische (sedimenttransport i.f.v. getij, doodtij-springtij, wind, golven), economische en ecologische aspecten. Bij een efficiënte stortplaats is de recirculatie van het gestorte materiaal naar de baggerplaatsen zo klein mogelijk, is de afstand tussen bagger- en stortplaats minimaal en is de verstoring van het milieu verwaarloosbaar. Hieruit volgt dat er geen stortplaats kan bestaan die onder alle omstandigheden efficiënt is. Efficiënt storten zal kunnen betekenen dat in functie van de voorspelde fysische (wind, stroming, golven, sedimenttransport, recirculatie), economische (afstand, grootte baggerschip) en ecologische aspecten op korte termijn een stortlocatie zal worden gekozen. Om dit te bereiken is het volgende nodig:

- <u>definiëren van een 'goede' stortzones</u> i.f.v. sedimenttransport, recirculatie baggerspecie, ecologie, economie, bathymetrie van de baggerplaatsen
- <u>operationele voorspelling van de recirculatie van het gestorte materiaal</u> door de operationele data uit hydrodynamische en sedimenttransportmodellen, real time meetstations, satellietbeelden, bathymetrie van de baggerplaatsen te integreren zodat een efficiënte stortlocatie kan bepaald worden.

1.3. Doel van het MOMO project (april 2006 - maart 2008)

Taak 1: Monitoring

<u>Taak 1.1: Slibconcentratie metingen: getijcyclus en langdurig</u>

Er worden 4 meetcampagnes per jaar met de R/V Belgica voorzien om 13-uursmetingen uit te voeren. De metingen vinden plaats in het kustgebied van het BCP. Tijdens de metingen zullen tijdsreeksen worden verzameld van de stromingen, de concentratie aan en de korrelgrootteverdeling van het suspensiemateriaal, de temperatuur en de saliniteit.

Een tripode zal ingezet worden om stromingen, slibconcentratie, korrelgrootteverdeling van het suspensiemateriaal, saliniteit en temperatuur te meten gedurende een langere periode (>10 dagen). Langdurige metingen laten toe om de slibconcentratievariaties te kwantificeren die zich voordoen tijdens een doodtij-springtij cyclus en gedurende eventuele stormen. Tijdens de onderzoeksperiode zullen langdurige metingen worden uitgevoerd van minimum 1 maand. Hierdoor zal de gevoeligheid van de instrumentatie bij langdurige metingen kunnen worden gekwantificeerd. Dit kadert in de algemene doelstelling om te komen tot real time meetstations.

Taak 1.2: Slibverdeling op de bodem

Per jaar zullen een vijftigtal bodemstalen geanalyseerd worden om de korrelgrootte, het kalkgehalte en de organische fractie te bepalen. Bij de box cores zal ook de densiteit bepaald worden. Met deze data kan de slibverdeling in de kustzone verfijnd worden en zal onderscheid gemaakt kunnen worden tussen 'actief' slib (i.e. slib dat in de cyclus van afzetting en resuspensie is betrokken) en 'inactieve' slib (oude lagen die dagzomen en enkel eroderen tijdens extreme situaties). Een gedetailleerde kennis van de samenstelling van de zeebodem is belangrijk voor een nauwkeurige kwantificering van de erosiefluxen in sedimenttransportmodellen.

Taak 1.3: Analyse en interpretatie van de metingen

Sinds er in het MOMO project begonnen werd met het uitvoeren van langdurige metingen met een tripode (zomer 2003) werden meer dan 70 dagen aan data verzameld. Samen met de 13 uursmetingen (4-6 per jaar) en de satellietbeelden (>370) is er een hele reeks aan data beschikbaar die nog maar deels geanalyseerd en geïnterpreteerd werd. Metingen op het BCP werden ook uitgevoerd door het WLH (Nieuwpoort, Zeebrugge) en de KUL – Labo voor Hydraulica (Nieuwpoort). Een globale interpretatie van deze data zal worden uitgevoerd met als voornaamste doelstelling het analyseren van doodtij/springtij variaties, storminvloeden, seizoens effecten en locale verschillen tussen meetstations.

Taak 2: Modellering

Sub-taak 2.1: Verfijnen slibtransportmodel

Het gebruik van een numeriek sedimenttransportmodel vereist een regelmatige validatie van de modelresultaten met meetgegevens en eventueel aanpassing van parameterwaarden. Het gevalideerde model zal gebruikt worden om de verspreiding van het gestorte slib te Nieuwpoort en Blankenberge te bestuderen.

Sub-taak 2.2: Sedimentbalans

Een numeriek slibtransportmodel zal worden gebruikt om de hoeveelheid slib in suspensie op het BCP te bepalen en dit voor de verschillende fazen van het getij, gedurende een springtij/doodtij en voor de verschillende seizoenen. Door deze waarden te vergelijken met de totale flux aan SPM die per jaar het BCP binnenstroomt kan de gemiddelde verblijfstijd van het slib op het BCP bepaald worden. Deze berekeningen zullen in samenspraak met het WLH worden uitgevoerd. De zo bekomen informatie is ook belangrijk bij het bepalen van de efficiëntie van stortplaatsen.

In het kader van het project Mocha (Wetenschapsbeleid) werd de herkomst van het slib op het BCP bestudeerd. De resultaten van dit onderzoek zullen gebruikt worden om de invloed van het fijnkorrelige sedimentransport in de Westerschelde op de slibverdeling in de kustzone te bestuderen. Tot op heden is dit niet duidelijk gekwantificeerd.

Sub-taak 2.3: Alternatieve stortschema's i.f.v. omgevingsfactoren

Onderzoek naar alternatieve stortschema's (getijgebonden, enkel bij bepaalde windrichting,…) zal uitgebreid worden naar alle stortplaatsen. Het doel is om het effect van het getij (meteo) op de retourstroom naar de baggerplaatsen te bepalen. Er zal onderzocht worden of er een 'best dumping time' bestaat. De taak kan als volgt worden onderverdeeld:

- 2D langdurige simulaties. Deze simulaties gebeuren met het 2D hydrodynamisch en sedimenttransportmodel van het BCP en kunnen toelaten om eventuele effecten op de slibhuishouding ter hoogte van de Belgische kust tengevolge van een consequent getijgebonden storten gedurende een langere periode (1 jaar) te analyseren.
- 3D korte termijn simulaties. Simulaties van getijgebonden storten met behulp van een gedetailleerd 3D sedimenttransportmodel. De simulaties zullen uitgevoerd worden voor een normaal en extreem getij en tijdens verschillende meteorologische situaties.

1.4. Publicaties binnen het MOMO project (april 2006 – maart 2008)

Er werden volgende rapporten en publicaties opgesteld:

Halfjaarlijkse rapporten

Fettweis, M., Pison, V. & Van den Eynde, D. 2006. MOMO activiteitsrapport (april 2006 – september 2006). BMM-rapport MOMO/3/MF/200612/NL /AR/1, 14pp + app.

Conferenties/Workshops:

Fettweis, M., Van den Eynde, D. & Francken, F. 2006. Suspended particulate matter dynamics and aggregate sizes in a coastal turbidity maximum (southern North Sea, B-Nl coastal zone). Workshop on Physical Processes in Estuaries: Observations and Model Approaches, 4 April 2006, Waterbouwkundig Laboratorium Borgerhout.

Fettweis, Houziaux, J.-S., Francken, F. & Van den Eynde, D. 2006. 100 years of anthropogenic influence on the cohesive sediment distribution in the Belgian North Sea coastal zone as determined by numerical modelling and comparison of historical and recent field data. 17th Int. Sedimentological Congress, 27 August – 1 September 2006, Fukuoka. (zie appendix 1)

Van den Eynde, D. & Fettweis, M. 2006. Dumping of dredged material in sea: towards operational use of sediment transport models. International Hydrographic Conference 2006, Evolutions in Hydrography, 6-9 November 2006, Antwerp, Belgium. (zie appendix 2)

Publicaties (tijdschriften, boeken)

Fettweis, Houziaux, J.-S., Du Four, I., Baeteman, C., Wartel, S., Van Lancker, V., Francken, F., Thiry, Y. 100 years of anthropogenic influence on the cohesive sediment distribution in the Belgian coastal zone. Submitted to Marine Geology (zie appendix 3).

2. Verfijning 3D hydrodynamisch model

2.1. Inleiding

Voor de berekening van het fijnkorrelig sedimenttransport in het kustgebied en ter hoogte van de haven van Zeebrugge is een fijnmazig model nodig dat ook rekening kan houden met zones die tijdens laagwater droog komen te liggen. Toepassingen van het model, dat gebaseerd is op MU-BCS, zijn bijvoorbeeld het onderzoek naar een optimale storttijd of –plaats. Voor deze toepassing zijn verschillende aanpassingen nodig.

Ten eerste was een implementatie van een wetting-drying schema in het hydrodynamische model nodig. Verder was een verfijning van het modelrooster nodig, om enigszins nauwkeurige berekening te kunnen doen van de stromingen rond en in de haven van Zeebrugge. Er werd daarom een nieuw model geïmplementeerd dat gekoppeld werd aan het bestaande MU-BCSFIN model. Dit laatste heeft een maaswijdte van ongeveer 250 m × 250 m. Deze aanpassingen worden hieronder kort besproken.

2.2. Ontwikkeling wetting-drying

Het driedimensionale hydrodynamische COHERENS model (Luyten et al., 1999) werd aangepast zodat de totale diepte nooit onder een bepaalde waarde gaat gedurende de simulatie. Deze aanpassing laat een nauwkeurige simulatie toe van de stromingen in ondiepe gebieden en verhindert dat een minimum diepte moet worden opgelegd om numerieke redenen.

Het schema dat werd geïmplementeerd, is gebaseerd op datgene dat in het GETM model (Burchard et al., 2002) werd toegepast. Het princiep is als volgt: indien de waterstand een kritische waarde onderschrijdt, worden de termen uit de momentumvergelijkingen vermenigvuldigd met een factor alfa, die 0 bereikt, indien de totale diepte de minimale waarde benadert; enkel de drukgradient en de bodemschuifspanning behouden hun oorspronkelijke waarde. De kritische en minimale waarde moeten in functie van het bestudeerde gebied worden vastgelegd. Een aanpassing van de berekening van de drukgradiënt en van de evaluatie van de totale waterdiepte aan de grenzen van twee cellen (d.i. op de plaatsen waar de snelheidvectoren worden berekend) is eveneens nodig.

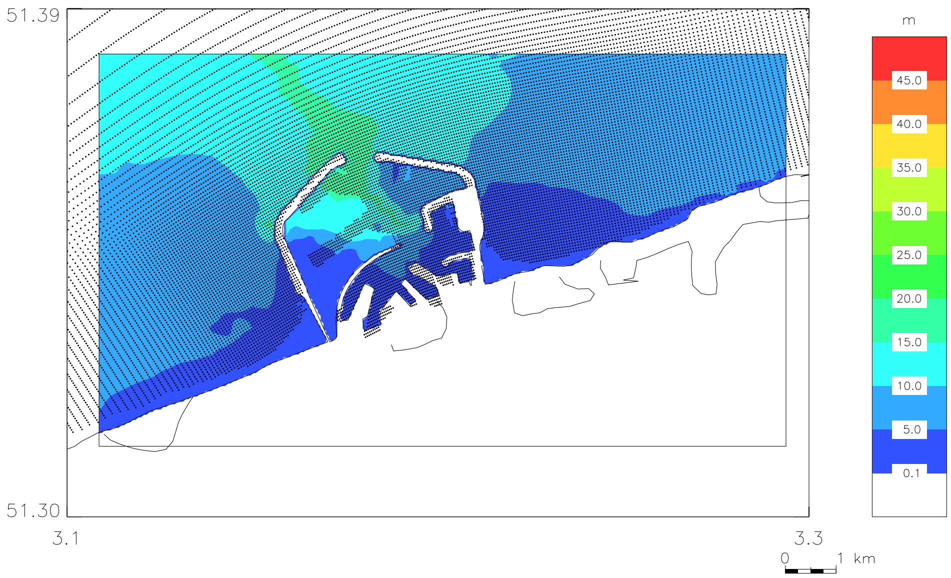
Het schema is geïmplementeerd in het COHERENS model en werd in verschillende situaties uitgetest. Zowel de 2D toepassing als de 3D toepassing werken op het ogenblik naar behoren. Het schema werd onder andere uitgetest en gecontroleerd in het Schelde-estuarium tussen Vlissingen en Antwerpen, waar zich veel "intergetijde" zones bevinden.

2.3. Ontwikkeling nieuw rooster

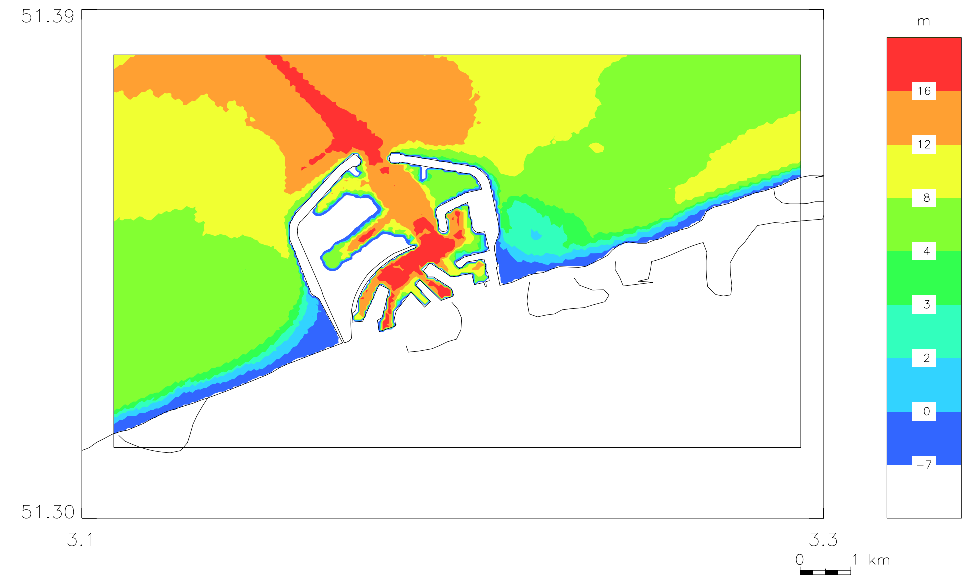
Voor de ontwikkeling van het nieuwe rooster werden contacten gelegd met de Ministerie van de Vlaamse Gemeenschap, Afdeling Waterwegen Kust (AWK). De lodingen die in de loop van 2005 werden uitgevoerd, werden reeds gebruikt door Ministerie van de Vlaamse Gemeenschap, Afdeling Waterbouwkundig Laboratorium en Hydrologisch Onderzoek (WLH), die de gegevens gebruikten voor het opstellen van een rooster voor de haven van Zeebrugge. De implementatie van dit model wordt uitgebreid beschreven in De Mulder (2006) en kon door ons worden gebruikt om het nieuwe rooster te ontwikkelen. De bathymetrie heeft een resolutie van ongeveer 50 m × 50 m en is gebaseerd op het curvilineair rooster van het WLH, zie figuur 2.1.

Uitgaande van deze bathymetrie werd een nieuwe modelrooster opgesteld voor het COHERENS model. Het nieuwe MU-HEIST model heeft een geografisch rooster en heeft een resolutie van 1.667″ x 2.8571″, wat ongeveer overeenkomt met een resolutie van 50 m x 50 m. Dit nieuwe model heeft dus een resolutie die 5 maal kleiner is dan de resolutie van het MU-BCZFIN model, waarmee het gekoppeld is. Het model heeft in het totaal 246 x 151 roostercellen. De tijdstap van het model is 2 seconden.

De bathymetrie wordt voorgesteld in Figuur 2.2. Er kan worden opgemerkt dat een deel van de bathymetrie een waterdiepte heeft van minder dan 4 m, de minimumdiepte die gebruikt wordt in modellen die niet zijn uitgerust met een "wetting-drying" module.

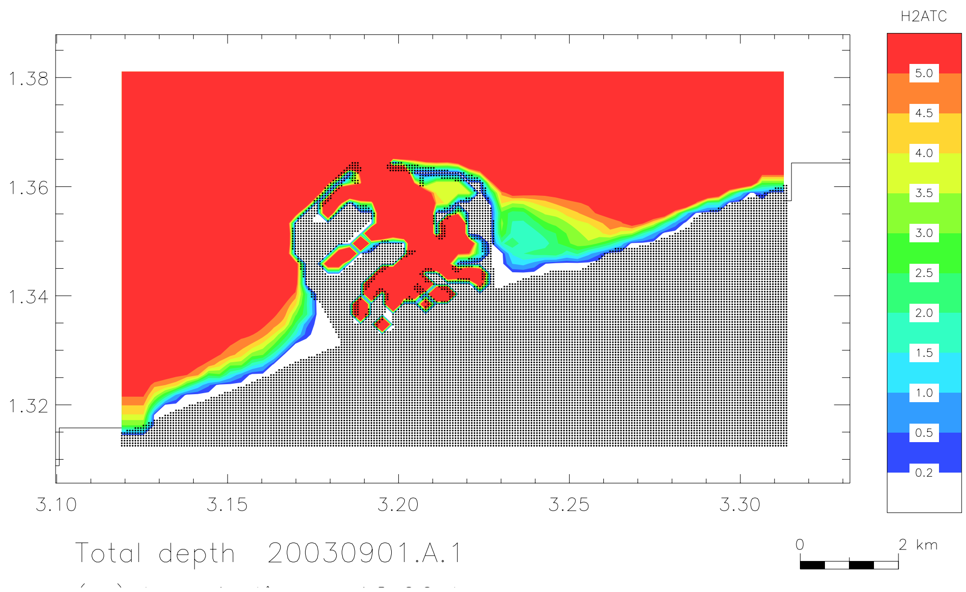


Figuur 2.1: De curvilineaire roosterpunten uit het WLH model ter hoogte van Zeebrugge, de waterdiepte is t.o.v het gemiddeld zeeniveau (MSL) weergegeven.

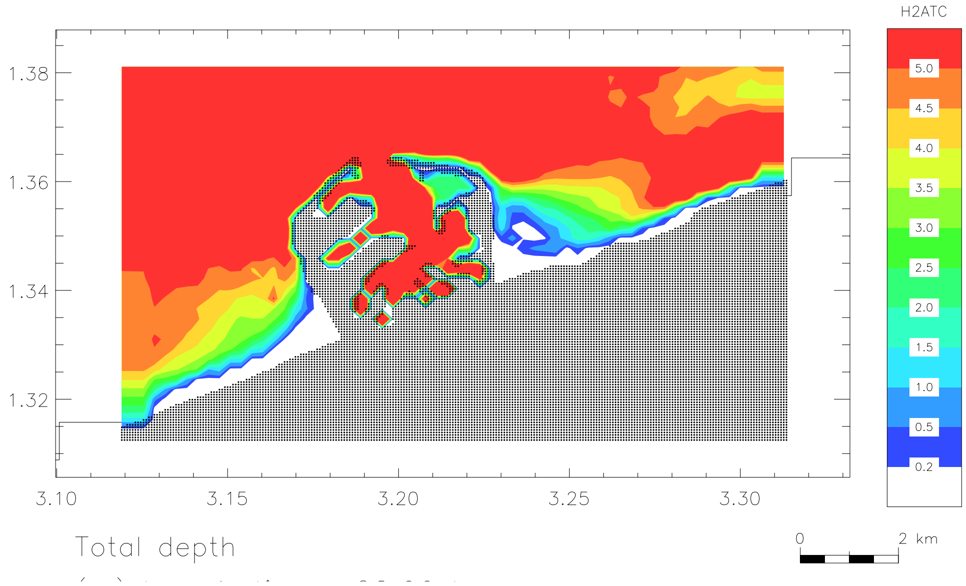


Figuur 2.2: Bathymetrie van het nieuwe 3D hydrodynamische model ter hoogte van Zeebrugge (MU-HEIST).

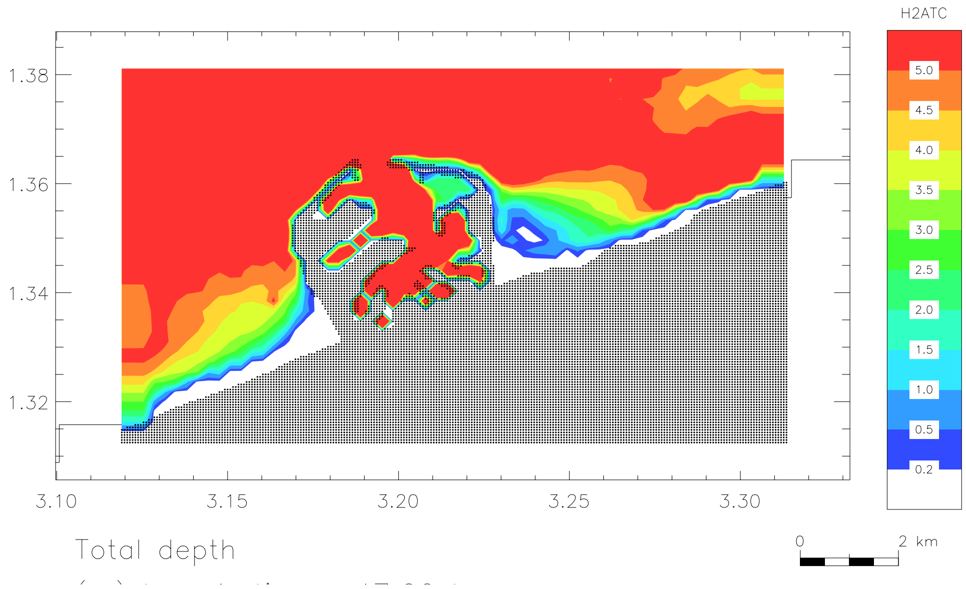
Enkele eerste resultaten worden voorgesteld in Figuur 2.3 tot Figuur 2.5. In de twee laatste figuren kan duidelijk worden vastgesteld dat het model in staat is het droog komen te staan van gebieden bij laagwaterstanden goed te simuleren.



Figuur 2.3: Totale waterhoogte berekend met het MU-HEIST model en weergegeven voor 1 september 2003 12h00.



Figuur 2.4: Totale waterhoogte berekend met het MU-HEIST model en weergegeven voor 1 september 2003 22h00.



Figuur 2.5: Totale waterhoogte berekend met het MU-HEIST model en weergegeven voor 2 september 2003 23h00.

3. 100 jaar menselijke invloed op de slibverdeling

In de Belgische kustzone worden verschillende types cohesieve sedimenten aangetroffen, zij verschillen in ouderdom gaande van recente afzettingen tot tertiaire klei. De invloed van menselijke ingrepen en natuurlijke processen op de verdeling of erosie van de cohesieve sedimenten werd bestudeerd in het Mocha project (PODO II, Federaal Wetenschapsbeleid). Dit project kon succesvol worden beëindigd dankzij data die tijdens het MOMO project werden verzameld. Een korte samenvatting van de resultaten over de menselijke ingrepen en hun effect op de slibverdeling wordt hieronder gegeven, een uitgebreid verslag is te vinden in Fettweis et al (submitted), zie ook appendix 2, en het Mocha eindrapport (Fettweis et al., 2007).

De effecten van grote werken en natuurlijke processen op erosie/depositie van cohesieve sedimenten werden bestudeerd met behulp van recente en historische (100 jaar oud) data. De kwaliteit van de historische data is hoog en kon daarom gebruikt worden als de belangrijkste .databron om de evolutie van de verdeling van cohesieve sedimenten tijdens de laatste eeuw te reconstrueren. De verwerking van de historische en recente data werd vooral gebaseerd op 'velddata' (beschrijvingen van de consolidatie, dikte van de lagen), op morfologische evolutie en – voor wat betreft de recente stalen – ook op radioactieviteitsmetingen en gamma densitometrie. Nadruk werd gelegd op het voorkomen van dikke lagen (>30 cm) van vers afgezet tot zeer zacht geconsolideerd slib. Dit soort sliblagen werd aan het begin van de twintigste eeuw vooral afgezet in een smalle band langsheen de kust tussen ongeveer Nieuwpoort en de monding van de Westerschelde. Deze afzettingen waren vooral het gevolg van natuurlijke processen. Tegenwoordig zijn de afzettingen van de meeste dikke sliblagen het gevolg van menselijke ingrepen in het systeem, zoals het storten van baggerspecie, het verdiepen van vaargeulen en de bouw en uitbreiding van (vooral) de haven van Zeebrugge. Uit een vergelijking tussen de huidige en de situatie van 100 jaar geleden blijkt dat tegenwoordig – met uitzondering van de slibafzettingen op de baggerplaatsen – dikke lagen van vers tot zeer zacht geconsolideerd slib verder in zee worden afgezet.

Zowel de historische als de recente data tonen aan dat het gebied ten oosten van Oostende van nature uit gekenmerkt wordt door hoge slibafzettingen. Hieronder vallen ook de tijdelijke afzettingen van enkele cm dikte (de zogenoemde 'fluffy layers'), die in het gebied dat overeenkomt met het turbiditeitsmaximum worden teruggevonden. De effecten van veranderingen in suspensieconcentratie en in de verdeling van de cohesieve sedimenten gedurende de laatste 100 jaar op het habitat van de benthische invertebraten is waarschijnlijk van minder belang en geen sleutelelement om de tijdelijke veranderingen in benthische gemeenschappen te verklaren sinds het begin van de twintigste eeuw.

4. Conclusies

In dit rapport worden twee onderwerpen voorgesteld, deze zijn:

(1) eerste stappen om het numerieke hydrodynamisch model ter hoogte van Zeebrugge te verfijnen door een fijner rooster en een 'wetting-drying' schema te implementeren.

(2) een studie - die in het kader van het Mocha project werd uitgevoerd met behulp van data uit het Momo project – over de invloed van menselijke ingrepen op de slibverdeling in de kustzone.

5. Referenties

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De Mulder, T., 2006. Numeriek model voor de haven van Zeebrugge, Deelrapport 1: Opmaak en eerste afregeling van een tweedimensionaal model zonder zout. Waterbouwkundig Laboratorium Borgerhout, Model 643/7, 32+14pp.

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COLOPHON

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BEHEERSEENHEID VAN HET
MATHEMATISCH MODEL VAN DE NOORDZEE

SUMO GROEP

De lettertypes gebruikt in dit zijn Gudrun Zapf-von Hesse's *Carmina Medium* 10/14 voor de tekst en Frederic Goudy's *Goudy Sans Medium* voor titels en onderschriften.

APPENDIX 1

17th International Sedimentological Congress, 27 August – 1 September 2006, Fukuoka (Japan)

Abstract

100 years of anthropogenic influence on the cohesive sediment distribution in the Belgian North Sea coastal zone as determined by numerical modelling and comparison of historical and recent field data

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In the Belgian coastal area of the southern North Sea different cohesive sediment facies can be identified. These sediments consist of a mixture of water, clay minerals, silt, carbonates, organic matter and sand and may be classified following their bulk density (ρ) as stiff to very stiff consolidated (Paleogene clay, ρ>1800 kg m^{-3}), soft to medium consolidated (Holocene mud, ρ = 1500-1800 kg m^{-3}), freshly deposited mud (ρ = 1300-1500 kg m^{-3}) and fluid mud. Variation in bulk density of the consolidated mud may point to different sand content but is also typical for softening of the surface layer by rewetting. The freshly deposited mud may occur as thin (<2 cm) fluffy surface layers or thick packages (> 0.5 m); the Holocene mud as layered sediments with intercalation of sandy horizons; erosion remains of the clay occur locally as pebbles.

The occurrence of a coastal turbidity maximum makes the area one of the most turbid in the North Sea (values >500 mg/l are common) and is responsible for the continuous dredging works carried out to maintain the accessibility of the ports. The port of Zeebrugge and its connection to the open sea ('Pas van het Zand') as well as the navigation channels towards the Westerschelde estuary are efficient sinks. Dredging and dumping amounts up to 11 millions tons of dry matter yearly, from which more than 70% is mud. 10% of the total dredged matter is extracted in the 'Pas van het Zand' and 62% in the port of Zeebrugge. The dredged matter is dumped in the coastal area. Comparison between the natural input of fine grained sediments into the coastal zone through (mainly) the Strait of Dover and the quantities dredged and dumped at sea shows that an important part of the suspended sediments is involved in the dredging/dumping cycle [1].

The construction of the port of Zeebrugge started at the end of the nineteenth century when the Belgian government decided to build a new outer port on a location where there was little more than a beach and a row of dunes; the works were completed in 1905. Interesting is the fact that Van Mierlo [3] has predicted a fast siltation of the harbour and changes in local sand transport patterns before its construction, which led him to fight against this project. This first port was modest in size, but since then many adjustments have been carried out in order to deepen and widen the access channels and finally to extend the outer port.

We question wether the distrubtion of surficial cohesive sediments has changed in the coastal area as a result of human pressure, e.g. locally increased erosion or mud deposition due to hydrodynamic changes. This is to be expected, because the changes (port extension and deep navigation channels) have resulted in hydrodynamic conditions, which are not in equilibrium with the present bathymetrical situation. During the presentation evidence of the influence of the major engineering works that were carried out during the last century on the cohesive sediment distribution will be provided using a qualitative and quantitative comparison of the recent and the historical situation.

The qualitative comparison is based on description and analysis of recent and historical bed samples and maps of cohesive sediment distribution. The historical samples (mainly from 1899-1911) originate from the collection of G. Gilson kept until nowadays in the RBINS repositories [2]. Gilson, a pioneer in marine ecology aimed at understanding how environmental parameters influence the distribution of marine species in front of the Belgian coast, which led him to thoroughly sample bed sediments. Sampling information was generally well documented, which allows drawing a reference situation at small scale. The recent bulk density measurements give an indication of the consolidation and thus of the geological age of the cohesive sediments.

The quantitative comparison between historic and modern situations is carried out using numerical models (hydrodynamic and sediment transport), which take into account physical changes of the environment (such as bathymetric changes associated with emergence of ports and navigation channels). The models allow to simulate mud deposition and erosion today and as they were before the major anthropogenic changes and allow to quantify differences.

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APPENDIX 2

Presentatie op de International Hydrographic Conference, Evolutions in Hydrography, 6-9 November 2006, Antwerp Abstract

Dumping of dredged matter in sea : towards operational sediment transport models

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The Belgian-Dutch coastal area is shallow (depth between 5-35 m) and major navigation channels connect the open sea to the harbour of Zeebrugge and the Westerschelde. The coastal turbidity maximum, which is situated between about Oostende and the Westerschelde estuary, makes the Belgian coastal waters one of the most turbid in the North Sea (values of a few hundreds mg/l are common) and is responsible for the continuous dredging works carried out to maintain the accessibility to the harbours. The Zeebrugge harbour and its connection to the open sea as well as the navigation channels towards the Westerschelde estuary are efficient sinks. Dredging and dumping amounts to about 11 millions tons of dry matter yearly, from which more than 70% is silt and clay. 10% of the total dredged quantity is dredged in the 'Pas van het Zand', the navigation channel connecting the port of Zeebrugge with the open sea and 62% in the port of Zeebrugge. The rest is extracted from the navigation channel towards the Westerschelde (22%) and the harbour of Oostende (5%). Comparison between the natural input of SPM in the coastal zone through (mainly) the Strait of Dover and the quantities dredged and dumped at sea shows that an important part of the SPM is involved in the dredging/dumping cycle (Fettweis and Van den Eynde, 2003).

Dredging works may be limited by reducing the sedimentation in harbours (transformation of the harbour entrance or current deflecting wall) or by applying a more efficient dumping scheme.

The efficiency of a dumping place is determined by physical (sediment transport, hydrodynamics), economical and ecological aspects. An efficient dumping place has a minimal recirculation of dumped matter back to the dredging places, has a minimal distance between dumping place and dredging area and has a minimal influence on the environment. A dumping place, which is always efficient, does thus not exist. Efficient dumping could mean that the predicted physical, economical and ecological aspects of a dumping place will determine on short term where the matter is dumped. In order to achieve this following is necessary:

- Definition of 'good' dumping places as a function of sediment transport, recirculation of dumped matter, ecology, economy and bathymetry of dumping places.
- Operational forecast of the recirculation of dumped matter based on operational data from hydrodynamic and sediment transport models.

In the presentation results from the MOMO project (financed by the Ministry of the Flemish Community) are presented. As example different dumping schemes (east, west or as a function of tide) for the dumping place Zeebrugge will be presented.

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Fettweis, M., Van den Eynde, D. 2003. The mud deposits and the high turbidity in the Belgian-Dutch coastal zone, Southern bight of the North Sea. Continental Shelf Res. 23, 669-691.

APPENDIX 3

Fettweis, Houziaux, J.-S., Du Four, I., Baeteman, C., Wartel, S., Mathys, M., Van Lancker, V., Francken, F. 100 years of anthropogenic influence on the cohesive sediment distribution in the Belgian coastal zone.
Marine Geology. (submitted).

100 years of anthropogenic influence on the cohesive sediment distribution in the Belgian coastal zone

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Abstract

The cohesive sediments, which are frequently found in the Belgian nearshore zone (southern North Sea), are of different age such as tertiary clays, Holocene muds and recently deposited muds. The area is characterised by the occurrence of a turbidity maximum. The effect of human impact vs. natural processes on the distribution or erosion of these sediments has been investigated using historic and recent field data. The historic data have been collected in the beginning of the 20th century, the quality of these samples and the meta-information is very high and they have proven to be a major reference to understand the evolution of the cohesive sediment distribution. The processing of the historic and recent data on cohesive sediments was mainly based on field descriptions of the samples (consolidation, thickness), on morphological evolution and on radioactive measurements and gamma densitometry of some of the recent samples. During the processing the emphasis was put on the occurrence of thick layers (>30cm) of freshly deposited to very soft consolidated mud and of clay and mud pebbles, because these sediments are witnesses of changes.

Thick layers of fresh mud were deposited in the beginning of the 20th century mainly in a narrow band along the coast from about Nieuwpoort up to the mouth of the Westerschelde. These deposits were mainly the result of natural morphological changes. Today, most of the depositions of thick layers of fresh mud have been induced by anthropogenic operations, such as dumping, deepening of the navigation channels and construction and extension of the port of Zeebrugge. Comparing the actual situation with the situation 100 years ago reveals that the area around Zeebrugge where fresh mud is deposited extends more offshore today.

The Belgian coastal waters east of Oostende are naturally subject to high siltation rates, resulting in the deposition of tidal driven ephemeral fluffy layers of a few cm over the area covered by the turbidity maximum. The effects of variation in SPM concentration and cohesive sediment distribution through time on the habitat of benthic invertebrates are therefore probably minor and not a key to explain temporal changes in the composition of the benthic communities since the early 20th century.

Keywords

Cohesive sediments, anthropogenic impact, historic data, habitat, radioactive isotopes

1. Introduction

The Belgian-Dutch nearshore zone is naturally a very dynamic area as can be seen e.g. from bathymetrical differences in nautical charts from 1866 on. The construction of the port of Zeebrugge in the 20th century and the dredging or deepening of navigation channels represent the most conspicuous anthropogenic impact in the Belgian coastal zone. The construction of the port started at the end of the nineteenth century when the Belgian government decided to build a new outer port on a location where there was little more than a beach and a row of dunes. Van Mierlo (1897) predicted already from the beginnings a fast siltation of the port. The first port was constructed between 1899 and 1903 and was modest in size; the embankment had a length of 1.7 km and a maximum distance from the coast of 1.1 km (Fig. 1). The navigation channel 'Pas van het Zand' was dredged in 1903 through a recently and naturally formed sand bank (Van Mierlo, 1897); the channel had a length of 2.8 km, a width of 0.3 km and a depth of 9 m below Mean Low Low Water Spring (MLLWS). Since then many adjustments were carried out in order to deepen the access channels and finally to extend the outer port (photos of the port of Zeebrugge: www.portofzeebrugge.be). Significant expansion works were carried out between 1980 and 1985 with the construction of two longitudinal breakwaters with a length of 4 km and extension of about 3 km in sea. The outer port has a depth up to 16 m below MLLWS and its connection towards the open sea ('Pas van het Zand') of 14 m below MLLWS; they are significantly deeper than the foreshore/offshore area, which has a water depth of less than 10 m below MLLWS. Harbour extensions, deepening of navigation channels and construction of other large scale projects (e.g. windmill farms) will continue in the future and knowledge of the impact of such activities on the fine-grained sediment dynamics and on the dredging and dumping activities is necessary for a sustainable development of the area.

Despite the natural morphological evolution occurring in the nearshore and shoreface area, the major human impact poses the question how the distribution of cohesive sediments has changed due to this human impact, e.g. more intense erosion or higher deposition rates and thus also if the sediments have become more or less muddy?

Alterations in the cohesive sediment distribution are to be expected, since the engineering together with the dredging and dumping works have resulted in hydrodynamic conditions, which are not everywhere in equilibrium with the present bathymetrical situation. Therefore the aim of this paper is to present and obtain more evidence on the influence of the major engineering works that were carried out during the last 100 years on the cohesive sediment distribution. This will be achieved by comparing the present and a historical distribution of cohesive sediments. The comparison is based on a description and analysis of recent and historical (1900s) seabed samples and on the results of numerical model simulations (hydrodynamic and sediment transport), which take into account the bathymetric changes associated with the extension of the port and the navigation channels since the 1950ties.

The paper is structured as follows. In section 2 the study area is situated. The treatment and interpretation of the historical and recent field data is described in section 3. Gamma densitometry and radiometric analysis methods, which have been applied to some of the recent field samples, are presented followed by a description of the numerical models and the GIS methods. In section 4 results of historic and recent sediment distribution are presented. The comparison between the recent and the historic situation is presented and discussed in section 5. Some general conclusions are offered in section 6.

2. Regional settings

The study area is situated in the southern North Sea, more specifically in the Belgian nearshore zone, where the depth is generally between 0-15 m (MLLWS); except in the mouth of the Westerschelde estuary where the depth can reach more than 20 m below MLLWS (Fig. 1). The mean tidal range at Zeebrugge is 4.3 m and 2.8 m at spring and neap tide, respectively and the maximum current velocities are more than 1 m s^{-1}. The winds are dominantly from the southwest and the highest waves occur during north-western winds.

2.1. Geological setting

The Belgian coast is characterised by a straight and closed coastline with a general SW-NE direction. The geological setting shows a striking difference between the western and eastern part, a difference which is already expressed in the Tertiary subsoil. The western part is characterised by compact stiff clay. In the eastern part, a vertical and lateral succession of fine sand and silt, sand and sandy clay, and clay, belonging to the Lower Eocene, is forming the Tertiary subsoil (Marechal, 1993). The top of these deposits is located at depth increasing in an offshore direction and reaches about -30 m TAW (national reference level, 0 m TAW = 0.19 m below MLLWS at Zeebrugge) in the surroundings of Zeebrugge and about –20 m to -25 m TAW in the coastal plain.

Also in the Pleistocene, the western and eastern coastal area experienced a different evolution. Because of the presence of the IJzer, a major palaeovalley which morphology is already expressed in the top of the Tertiary subsoil (Baeteman, 2004), the western part of the plain shows a succession of fluvial and estuarine sediments formed during glacial and interglacial periods, respectively (Bogemans and Baeteman, 1993), while in the eastern part, cover sands from the Last Glacial overly coastal and open marine sediments from the Last Interglacial. In the offshore area, most of the Pleistocene deposits have been eroded during the Holocene.

The situation in the offshore zone is very much in relation with the development of the coastal plain during the Holocene. The coastal plain reaches its greatest width of about 20 km in the west, while in the east it is limited to about 10 km. Also the thickness of the Holocene deposits (exclusive the eolian deposits) at the present coastline varies in thickness between ±25 m in the west and not more than 10 m in the east, except for the young Holocene sand-filled tidal channels. The thickness and width are defined by the morphology of the pre-transgressive surface, *i.e.* the top of the Pleistocene deposits, and the occurrence of palaeovalleys (Baeteman, 1999; Beets and van der Spek, 2000). The western part is characterised by a major palaeovalley which was inundated by the tidal environment as from the beginning of the Holocene (Baeteman, 1999; Baeteman and Declercq, 2002). Although the Holocene deposits have not been mapped systematically in the eastern part, it is known from punctual data in literature and unpublished borehole data that the top of the Pleistocene is at an elevation of about -2 m TAW in the plain near Zeebrugge. Because of this high elevation of the Pleistocene deposits, the inundation started much later in the eastern part (at least in what is now the coastal plain).

The Holocene sequence in the plain consists mainly of alternations of intertidal mud and peat beds. The uppermost intercalated peat bed (also called surface peat) developed at about 6300-5500 cal BP in the landward part of the plain, and ca. 4700 cal BP in the more seaward areas. It accumulated almost uninterruptedly for a period of 2-3 ka years while the coast was prograding. The surface peat is generally 1 to 2 m thick and occurs between –1 and +1 m TAW. The upper peat bed is covered by a 1 to 2 m thick deposit formed by a renewed expansion of the tidal environment in the late Holocene. The expansion was associated with the formation of tidal channels which eroded deeply into the early and mid Holocene sediments, and sometimes into the underlying Pleistocene deposits. The renewed expansion of the tidal flat was also associated with shoreface erosion and a landward shift of the coastline in particular in the central and eastern part. Here, the Holocene sequence at the present shoreline consists of mud and peat beds (unpublished borehole data), which continue towards offshore. Holocene muds have often been found in the eastern nearshore area, see Fig.2. This is in contrast with the west where in a wide area in the seaward region, the Holocene sequence consists of a ca. 25 m thick sand body deposited in a coastal barrier and tidal inlet (Fig. 2). Such a situation with a transition from barrier to back-barrier deposits (peat and mud) is the typical situation. The absence of barrier deposits in the central and eastern part of the plain indicates severe shoreface erosion and a significant landward shift of the coastline. The timing of the onset of this erosion still remains questionable, but it appears that it coincides with the period of Roman occupation (Baeteman, 2007).

2.2 Cohesive sediments

In the area different cohesive sediment types occur. These sediments are characterised by a particular rheological and/or consolidation state. The cohesive sediments have been classified as Eocene clay, consolidated mud from Holocene age, consolidated mud of modern age, freshly deposited mud and suspended particulate matter (SPM). The freshly deposited mud occurs generally as thin (<2 cm) fluffy layers or locally as gradually more consolidated thicker packages (±0.2-0.5 m). The Holocene deposits, which extends over most of the foreshore area, consists of medium consolidated mud with intercalation of more sandy horizons; they are often covered by sand layers of some cm to tenth of cm or fluffy layers of a few cm. The thickness of the Quaternary cover in the offshore is locally less than 2.5 m, in these areas tertiary outcrops (clay) are to be expected (Le Bot et al., 2003), see Fig. 3a.

SPM forms a turbidity maximum between Oostende and the mouth of the Westerschelde. Most of these suspended sediments originate from the English Channel and are transported into the North Sea through the Strait of Dover. The formation of a coastal turbidity maximum has been ascribed to the reduced residual water transport resulting in a congestion of the sediment transport in the area (Fettweis and Van den Eynde, 2003). SPM concentration measurements indicate variation in the coastal zone between minimum 20-70 mg/l and maximum 100-1000 mg/l; low values (<10 mg/l) have been measured in the offshore area (Fettweis et al., 2006, 2007). Near bed layers of SPM with concentrations of more than a few 10 g/l and a non-Newtonian behaviour (i.e. fluid mud) have been reported in the bottom layer of the 'Pas van het Zand', the navigation channel towards the port of Zeebrugge (Strubbe, 1987).

3. Materials and Methods

3.1 Mapping of historic and recent cohesive sediments

The coastal 'mud fields' have been mapped by Van Mierlo (1899), Bastin (1974), Missiaen et al. (2002) and Van Lancker et al. (2004). The techniques used are based on remote geophysical methods or on in situ sampling. Indications of muddy areas are also found on old hydrographical maps such as Stessels (1866). Bottom hardness as estimated by a hand-operated sounding weight is sometimes indicated on these maps and could constitute a hint to areas with freshly deposited mud. Bastin (1974) made a detailed sedimentological map using the natural radioactivity of sediments, but could not differentiate between the different cohesive sediment facies. Missiaen et al. (2002) used seismic techniques and described an area marked by poor seismic penetration due to gas formation in shallow peat layers, which corresponds with the extension of the Holocene mud. Geo-acoustical methods (multibeam, side scan sonar) have been applied by Van Lancker et al. (2004). They concluded that an acoustic seabed classification can be setup especially for very fine sand, mud and very coarse (shells) sediments, but holds many uncertainties because not only the grain size plays a role but also compactness, topography, the benthic fauna, shell cover, volume scattering and instrument settings influence the backscatter intensity.

Given the uncertainties of geophysical methods and the need of having a method enabling the comparison between historical and recent sediment samples, we decided to mainly base the mapping and the comparison on the detailed field description of the samples. Four items related to cohesive sediment consolidation and/or erosion/deposition processes have a priori been selected as they could be found in the historic and recent dataset: clay pebbles, hard mud, soft mud and liquid mud. This approach has the advantage that the historical and the recent data are treated similarly.

The historical sedimentary situation was drawn based on sediment samples collected by G. Gilson in the early 20th century. Gilson established an ambitious sampling programme aiming to understand how environmental parameters influence the distribution of marine invertebrates (Gilson, 1900). He therefore included an exhaustive sediment sampling scheme to complement benthos sampling, but these data were never analyzed as a whole. The archived inventory of Gilson's sediment samples contains a list of 2979 sampling events between 1899 and 1939, from which 90% occurred before 1911. Gilson's cup-shaped instrument ('ground collector') was able to sample the first 10-20 cm of soft bottoms and allowed for good conservation of sediment layers in the sample, see Gilson (1901) and Van Loen et al. (2002). Gilson performed only several grain-size analyses and only 700 sub-samples are still preserved today. However, detailed field descriptions of the sediment samples were written onboard, which enable a standardized approach to investigate sediment parameters such as mud content, sand grain-size, shell content, gravel content and others (Houziaux et al, in prep). For part of the dataset, the original field description could not be recovered, but a summarized or truncated version still exists. Where both versions are available, the summarized one is clearly less detailed, but it provides elementary information on mud content or sand grain size. In the nearshore area 1956 sediment samples are considered valid in terms of sedimentological information content and geo-referencing accuracy.

The level of detail of these sample descriptions is high and allowed a standardized aggregation of specific information to rank the samples within a mud to sand ratio scale. Other constituents like gravel or shell debris were not considered because semi-quantitative information is not always available. In a first step, mud and sand content were ranked accordingly to four basic categories: sand; muddy sand; sandy mud and mud. This basic mud/sand proportion scale was manually adjusted where possible using the additional semi-quantitative indications provided by Gilson (e.g. "mud, sand, approximately same quantity" is considered as 50% mud and sand). This adjustment is subjective and induces a bias in the ranking when semi-quantitative information is not available. Processing the data this way does not give any indication on the cohesive sediment facies, but it provides an opportunity to map relative mud content of these samples in a high resolution grid. Gilson indicated only on several occasions the vertical order of the observed layers, however, often additional information on mud appearance were often provided, such as "in pieces" or "in lumps", "hard", "liquid", "grey", "black" or "superficial", which provides clues on its age, consolidation or origin. Occasionally, additional indications on bottom hardness as recorded with a depth sounding weight are given at the sampling locations; a work commonly carried out by hydrographers by then. This information has been taken into account to identify areas with soft to medium consolidated cohesive sediments and to perform comparisons with contemporary mud samples. As aforementioned, only positive indications are considered as data, because it is not certain that such features were always appropriately recorded and their absence could thus also be due to misreporting.

3.2 Radioactivity and density measurements

As supplement to the recent sediment sample descriptions radiometric and bulk density measurements have been carried out on box core samples taken in the nearshore zone. The box core samples have a maximum length of 50 cm and have been kept in PVC tubes of 8 cm diameter and closed by rubber stoppers.

The radiometric measurements have been carried out with a Ge gamma detector connected to a multi-channel analyser (Canberra Series 35 Plus). Radiometric dating of sediment cores using ^{210}Pb, ^{226}Ra, ^{137}Cs and ^{241}Am activity is a widely used technique to estimate accumulation rates and age on a time scale of 10-100 years; see e.g.

The method used to infer the density of the non-disturbed core sediments is based on the transmission of gamma-ray photons through the core (Preiss, 1968). The source of gamma rays used is ^{241}Am, with a principal energy level at 60 KeV. Photons emitted at this energy level are absorbed by the sediment rather than scattered. It is also very sensitive to small contrasts in densities, though also to chemical composition (called the soil-type effect) as can be foreseen from its very low energy level (Caillot and Courtois, 1969; Bouron-Bougé, 1972). To reduce the soil-type effect calibration standards were made of sediment from the Belgian continental shelf. Two types of sediment were used: a mud and a well-sorted medium-fine sand sample. The water of the mud was slowly evaporated while stirring the mud in order to obtain a homogenous mass that was transferred to a 12 cm long PVC tube of the same composition as used for the cores to be analysed. The radiation passing the tube was measured over the whole length in steps of 2 mm to ensure the homogeneity of the sample. After measuring the density small aliquots of mud were sampled and transferred to pre-weighed aluminium moisture cans and the water content was determined from the loss weight after evaporation at 105°C for 12 hours. The bulk density, ρ_b, was then calculated using 2600 kg/m^3 for sand and 2000 kg/m^3 for mud particle density (Bennett and Lambert, 1971).

3.3 Numerical model descriptions

3.3.1 Hydrodynamic model

The hydrodynamics has been modelled using the public domain 3D hydrodynamic COHERENS model (Luyten et al., 1999). This model has been developed between 1990 and 1998 in the framework of the EU-MAST projects PROFILE, NOMADS and COHERENS. The hydrodynamic model solves the momentum equation, the continuity equation and the equations of temperature and salinity. The equations of momentum and continuity are solved using the 'mode-splitting' technique. COHERENS disposes of different turbulence schemes, including the two equations k-ε turbulence model.

For this application 2D currents from a 3D implementation of the COHERENS model to the Belgian Continental Shelf (BCS) were used. The OPTOS-BCS model covers an area between 51°N and 51.92° N in latitude and between 2.08° E and 4.2° E in longitude. The horizontal resolution is 0.01183° (longitude) and 0.007° (latitude), corresponding both to about 800 m. Boundary conditions are water elevation and depth-averaged currents, these are provided by OPTOS-NOS, which is also based on the COHERENS code, but covering the whole of the North Sea and part of the English Channel. The OPTOS-NOS model is receiving boundary conditions from the OPTOS-CSM model, which covers the North-West European Continental Shelf. Four semi-diurnal tidal components (M_2, S_2, N_2, K_2) and four diurnal tidal components (O_1, K_1, P_1, Q_1) are used to force the tidal elevation on the open boundaries of the Continental Shelf Model. The current velocities of OPTOS-BCS have been validated using ADCP measurements (Pison and Ozer, 2003).

3.3.2 Cohesive sediment transport model

Transport of mud is determined by the settling of mud particles under the influence of gravity and by erosion and sedimentation due to the local current velocity. The model solves the 2D depth-averaged advection-diffusion equation for cohesive sediment transport on the same grid as the OPTOS-BCS model. Erosion and deposition rates are calculated using the formulations of Ariathurai-Partheniades (Ariathurai, 1974) and Krone (1962), respectively. The model uses the semi-Lagrangian Second Moment Method (Egan and Mahoney, 1972; de Kok, 1994) for the advection of the material in suspension. In this method all material in each grid cell is represented by one rectangular mass, with sides parallel to the model grid, characterized by its zero order moment (total mass), first order moments (mass centre) and second order moments (extent). The diffusion of suspended matter is based on the work of Johnson et al. (1988) and calculates the enlargement of the rectangular mass assuming a Fickian diffusion.

The values used in the model for the critical shear stress for erosion τ_{ce} have been set to 0.5 Pa for freshly deposited mud and 2.0 Pa for the soft to medium consolidated mud of the parent bed (Fettweis and Van den Eynde, 2003). The erosion constant for 100% mud content was set to 0.12×10^{-3} kg/m^{2}s. In sediments with lower mud content, which can only occur in the parent bed, the erosion rate is multiplied by the mud fraction. In the model a constant fall velocity of 0.001 m/s has been used. The critical shear stress for deposition τ_{cd} has been set to 0.5 Pa. The SPM concentration condition along the open boundaries of the mud transport model has been constructed using in situ measurements and satellite images (Fettweis et al., 2007).

4. Results

4.1 Actual cohesive sediment distribution

The map in Fig. 3a is based on sediment samples, which have been collected between 2000 and 2004, and shows the mud content and the distribution of four major cohesive sediment facies as they emerge from the sample descriptions and the wet bulk density measurements; the consolidation terminology is from the Coastal Engineering Manual (2002) classification. This classification is based on bulk densities for pure cohesive sediments and should be used therefore as an indication; small amounts of sand, which often occur in the mud, may increase the bulk density. The four main facies are:

1. Clay or mud pebbles, which occur in a sand matrix or on top of mud layers and may indicate eroded (naturally or due to deepening dredging works) and transported tertiary clays or consolidated mud layers (Fig 4a).
2. Soft to medium consolidated cohesive sediments, which have a wet bulk density (ρ_b) of 1500-1800 kg/m^3) and indicate Holocene (Fig. 4b) or possibly younger sediments (Fig. 4e). Based on the consolidation of the sediment sample it is not always possible to clearly identify the age of the sediment. Holocene mud has typically a layered structure with intercalation of thin sandy layers. Other types of consolidated mud, such as the lower layer in Fig. 4e, are sticky and no clear layering can be visually identified; it corresponds not with the Holocene mud and it is assumed therefore to be of more recent age (up to a few centuries), it is called 'modern mud'. In Fig. 3 no difference between the different types of soft to medium consolidated cohesive sediments is made.
3. Freshly deposited to very soft consolidated cohesive sediments (ρ_b = 1300-1500 kg/m^3), which may indicate recent deposits of thick mud layers (Fig. 4c, 4e) or rewetted older and more consolidated mud. Freshly deposited mud occurs typically in the ports below fluid mud layers (Fig. 4f).
4. Fluid mud (ρ_b = ±1100-1200 kg/m^3), which flows through fingers and occurs as thin surface layers of a few cm (fluffy layers, see Fig. 4d) or thick layers in navigation channels and ports (Fig. 4f).

The wet bulk density of box core samples from the nearshore area near Oostende and Zeebrugge ranges between 1088 kg/m^3 and 2300 kg/m^3, two examples are shown in Fig. 5. A clear distinction can be made in ZB6 core between the very soft layer (<1300 kg/m^3) on top, the freshly deposited to very soft consolidated mud (±1500 kg/m^3) between 2 cm and 26 cm and the very sticky soft to medium consolidated mud below 26 cm (±1600 kg/m^3) (Fig. 5a). The organic matter content is about 5% in the lower part and 10-20% in the upper part of the ZB6 core; these differences points to a different age of both sediments. The upper part of the density profile is very irregular. These variations in wet bulk density are an indication of tidal deposits and represent an alternation of more and less muddy layers formed in sheltered areas; it is typical that these structures cannot be seen from a visual inspection of the sample. Two radiographies of Reineck core samples taken very close to the ZB6 and ZB2 box core samples show clearly these tidalites (Fig. 6).

The wet bulk density of the upper 30 cm of the OE14 core (Fig. 5b), which has been sampled near the old dumping site of Oostende (B&W-O in Fig. 1b) is very low (1200-1400 kg/m^3). The fact that a thick layer of freshly deposited mud can be deposited points to a protected hydrodynamic environment.

4.2 Age and accumulation rates based on radio-isotopes of recent samples

The radioactivity of ^{210}Pb, ^{226}Ra and ^{137}Cs has been measured to determine the age and the accumulation rate of the sediments in two box-core samples. The OE11 core has been taken in March 2004 near the old dumping place of Oostende and consists (B&W-O in Fig. 1b) of 43 cm of freshly deposited to soft consolidated mud (similar as Fig 4c). In the ZB6 core, which has been sampled in November 2002 northeast of the port of Zeebrugge (see Fig. 1b), two clearly different parts have been distinguished: the upper 19 cm consist of freshly deposited to soft consolidated mud (1400-1500 kg/m^3) intercalated with thin more sandy layers and the lower 29 cm of medium consolidated mud (similar as Fig. 4e and 5a). On top is a thin layer of freshly deposited mud (±1300 kg/m^3). The radio-isotope profiles in both box cores are irregular as can be seen from Fig. 7 and 8.

The major source of ^{226}Ra is probably mostly associated with the discharges of phosphate gypsum at BASF-Antwerpen between 1968 and 2002 and the ^{226}Ra discharges from 1920 on by Tessenderlo Chemie in the Grote Nete (Schelde basin), see on this subject Paridaens and Vanmarcke (2000). Pb-210, which is a daughter isotope of ^{226}Ra, is formed by the decay of the industrial ^{226}Ra and thus cannot be used for dating with excess ^{210}Pb models. The sediments of the upper ZB6 and of whole the OE11 core can therefore be supposed to have been deposited recently (1920 – today). The study of the morphological evolution allowed to refine the age of deposition of the OE11 sediments as after 1960 (see § 5.1). In the beginning of the eighties large engineering works occurred in the area (extension of the port of Zeebrugge, deepening of navigation channels). The (surface) mud northeast of Zeebrugge has probably been deposited after (during) and due to these works and is thus younger than ±1980. The apparent accumulation rate of the upper 19 cm of ZB6 has been estimated as about 0.86 cm/yr. The lower part of the ZB6 core can be clearly distinguished from the upper part. It has been interpreted - based on field description – as modern mud; deposition has probably occurred after 1920 and significantly before 1980.

- The peak in ^{137}Cs activity between 17 cm and 33 cm below the surface in the OE11 core has been ascribed to the peak in fall out of atmospheric nuclear bomb tests during the sixties. The apparent accumulation rate for the upper part of the core is then about 0.6 cm yr^{-1}. The lower ^{137}Cs peak in this core (37-41 cm) indicates that these sediments are at least younger than 1950 when the significant releases of ^{137}Cs into the environment started.

It is clear that two samples cannot describe the complex accumulation pattern in whole the area. The measurements have however shown different isotope activity and distribution between the Oostende and Zeebrugge core, which can be explained by the recent morphological evolutions and anthropogenic influences at both sites and the age of the layers. The higher influence of the Westerschelde at Zeebrugge and thus a partially different origin of the mud could perhaps also explain the differences between the samples. The influence of the Westerschelde on the SPM concentration is for example visible in the two statistically different high turbidity zones in the nearshore area (i.c. Oostende and Zeebrugge), as is explained by Van den Eynde et al. (2006).

4.3 Historical cohesive sediment distribution

Despite initial doubts on the accuracy of the method used to reconstruct historical mud content, the developed approach provides a coherent historic map of mud content along the Belgian coast and the Westerschelde estuary (Fig. 3b). It was not possible to unambiguously link the descriptions of Gilson's samples to one of the four mud facies used in § 4.1, because only positive indications are considered as "data". A morphological analysis has therefore been carried out comparing the bathymetrical maps of Stessels (1866) and Urbain (1909) in order to link the occurrence of cohesive sediments with an increase (erosion) or a decrease (accumulation) in bathymetry. If Gilson's sample is situated in an area where the depth has decreased, then the mud has been deposited recently (maximum 35 years before sampling). If the sample is situated in an eroded or stable area then the surface mud is most probably old (Holocene of modern). Fresh mud may however occur in all areas (usually thin surface layers) through tidal and spring-neap tidal driven deposition such as described in the metadata.

Areas where an accumulation of sediment is observed are found in a parallel band of 5 km width along the coast line (Fig. 9). The highest accumulation (±3 m) occurs between Oostende and Zeebrugge, an area which corresponds with high mud contents at the end of the 19th and the beginning of the 20th century (see Fig. 3b) just before and during the construction works. The hydrographic chart of Stessels (1866) shows the occurrence of pure mud at the same location. East of the port near-field accretion of mainly sand occurred (not shown in Fig. 3); important morphological changes in the area continue until today. Comparison between the hydrographical maps of 1866 and 1911 (Fig. 9) indicates that these changes have started before the construction of the port of Zeebrugge and could thus be the result of a natural morphological evolution. However, human influences such as the construction of coastal defence structures in the 19th century along the eastern Belgian coast cannot totally be excluded to explain at least partly these morphological changes. These changes resulted in the formation of a sand bank (called "Het Zand") at the place where the port is situated nowadays (Van Mierlo, 1899). The most direct impact of the first infrastructure has possibly been to locally reinforce natural morphological trends in decreasing depth, as predicted by Van Mierlo (1897).

Areas where the seafloor has deepened (>1m) are partly artificial, such is the case in the 'Pas van het Zand' and the navigation channel towards the Westerschelde ('Scheur'). In these areas freshly deposited mud is expected to be found, as these environments are artificial sinks for fine-grained sediments. Further offshore, deepening is probably natural and must correspond with erosion processes. It is thus most likely that the mud observed in these areas coincide with outcropping of ancient mud (Holocene). The cohesive sediments in the offshore zone (> 10 m MLLWS) where the bathymetry has not changed are most probably also of ancient age (Holocene).

4.4 Numerical model results

The aim of the model simulations was to simulate the transport and deposition of fine grained sediments using a bathymetry before (i.c. bathymetry of 1959, without port of Zeebrugge) and after the major engineering works have been carried out (bathymetry of 2003, with port of Zeebrugge). The bathymetries used to simulate the hydrodynamics and the sediment transport are shown in Fig. 10. The simulations have been carried out during calm weather and lasted one spring-neap tidal cycle. It is assumed that the SPM concentration along the open boundaries of the OPTOS-BCS model is the same for the recent and historic situation. The results are presented in Fig. 11 (2003 situation) and Fig. 12 (1959 situation, without Zeebrugge). The figures show that the Belgian and southern Dutch coastal waters are an effective trap for suspended sediments, resulting in the formation of an area of high SPM concentration. During spring tide the SPM concentration reaches a maximum, whereas during neap tide the mud deposition is highest.

Permanent mud deposits are those, which are not eroded during spring tide; they are situated in the navigation channels and – for the recent situation – around Zeebrugge. Nevertheless the limitations of the model, the results indicate that despite the occurrence of a turbidity maximum in the nearshore zone only few permanent deposits of cohesive sediments exist and that most of them are situated in areas with a high anthropogenic impact.

The model results show further – as a consequence of mass conservation in the model and without taking into account dredging and dumping – that SPM concentration is on average lower and mud deposition higher today than in 1959.

5. Discussion

The construction and extension of the port of Zeebrugge and its connections to the open sea, the dumping of dredged matter and the morphological evolutions induced by these operations have had and still have an influence on the fine grained sediment system. The comparison between the recent data and the Gilson field data (Fig. 3, Fig. 9) shows that the distribution of freshly deposited to very soft consolidated mud and the clay pebbles has changed. The possible explanations such as natural or human induced morphological changes, dredging and dumping, increased erosion of clayey sediments and changes in storminess are discussed below.

5.1 Deposition of fine grained sediments

The coastal turbidity maximum is responsible for the availability of fine grained sediments and thus also for the deposition of fresh mud. On most places in the nearshore zone the occurrence of fresh mud is limited to thin layers of maximum a few cm on top of the sediment bed (liquid layer or fluffy layer). The erosion resistance is small and they are resuspended during high currents. The occurrence of fluffy layers cannot be used as indication of variation in cohesive sediment distribution between the past (100 years ago) and today. Thick layers (±0.5 m) of freshly deposited to very soft consolidated mud (Fig. 4c) however are a good indicator of changes. They occur today in environments which are or have been strongly influenced by human activities such as near dumping places (B&W-O in Fig.1), navigation channels, inside harbours, and in the area around the port of Zeebrugge, see Fig. 3a. These mud layers can easily be distinguished from the older more consolidated cohesive sediments (Fig. 4b and 4e) or the fluffy layers (Fig. 4d). The fact that Gilson did not mentioned the occurrence of thick freshly deposited to very soft mud layers could indicate that they did not occur 100 years ago and that they are a result of human impact into the system. This reasoning is however unbalanced. First, the functioning of Gilson's ground sampler could lead to a washing out of the fresh mud. The sampler is able to penetrate the substratum to about 20 cm when it lies on its side, but its vertical height is limited to about 10 cm so that when hauled back, the heavy closing lid may have expelled a more or less large part of the soft to fluid matter; this has been reported once. Second, field description of the samples does often not encompass details on compaction of the sample. Occurrence of thick layers of freshly deposited to very soft consolidated mud have probably occurred in the eastern nearshore area where the sediments consist of mud and the depth soundings indicate "soft" and/or "sticky" bottoms.

From a combination of the mud content derived from Gilson's meta-information (Fig. 3b) and the morphological changes between 1866 and 1911 (Fig. 9) it can be seen that the surface layer consists of mainly mud, which is found in a narrow band along the coastline and corresponds most probably with the freshly deposited to very soft consolidated mud of § 4.1. No information is available on the thickness of these layers, but the fact that Gilson sampled the area on several occasions and that he found most of the time muddy sediments leads to the conclusions that the deposits were permanent during the considered interval and could resist the strong currents during spring-tide. Furthermore the metadata of several sampling occasions clearly mentions 'very soft' bottom in the area, possibly indicating freshly deposited mud on top; it is however not possible to give a thickness to these deposits, thus it could also indicate a fluffy layer of a few cm or more. Van Mierlo (1908) wrote that after the construction of the first port of Zeebrugge the water depth west of the harbour mole decreased by 2 m due to the deposition of cohesive sediments. The same author wrote that before the port construction, a layer of 60 cm of mud was deposited in the same area over a period of 10 years, this corresponds with a accumulation rate of 6 cm/yr. If these sediments still exist today, then it is expected that they fit the class 'soft to medium consolidated' and correspond thus with modern mud. Although the recent sampling resolution is generally lower than Gilson's one, freshly deposited to very soft consolidated thick mud layers (>30 cm) in this narrow coastal band have only been found today near the old dumping place of Oostende (B&W-O). In some samples this mud is deposited on soft to medium consolidated mud (see box core OE14 in Fig. 5), the latter corresponds possibly with the freshly deposited mud layers of the beginning of the 20th century. The deposition of the freshly to very soft consolidated mud near B&W-O started after the 1950ties as was detected from the radiometric measurements of the OE11 box core (see § 4.2) and was only possible because the modification of the bathymetry created a hydrodynamic protected area. Van Lancker et al. (2004) have studied using different bathymetrical maps from 1955 up to 1997 the morphological evolution of the area around B&W-O. They conclude that the water depth decreased on the dumping place and that north and south of the dumping place two channels were formed. The decrease in water depth was initiated by the dumping activities and was followed by morphological changes.

Other areas today with important depositions of fresh mud are the navigation channels, the harbours and – more interesting - the area situated a few km north of the port of Zeebrugge (see Fig. 3a), such as the recent mud found at ZB6. This deposition is probably related to the extension of port of Zeebrugge in the 1980ties, as was deduced from the radiometric measurements (§ 4.2). The results of the numerical model simulations suggest that solely the deepening of the bathymetry and the extension of the outer port of Zeebrugge are responsible for a decrease in SPM concentration and an increase in mud deposition between the 1959 and the 2003 situation in the area around Zeebrugge. Keeping in mind the limitation of the model (resolution, 2D simulation) they also show that the extension of the port of Zeebrugge results in mud deposition near the port; a feature not occurring in the 1959 model.

The results suggest that in the beginning of the 20th century permanent deposition of cohesive sediments occurred mainly in a narrow band along the coast from about Nieuwpoort up to the mouth of the Westerschelde. These depositions were mainly the result of natural occurring morphological changes. Today, permanent fresh mud deposits are found in the same area only near the dumping place B&W-O and in the outer port of Zeebrugge and the navigation channel 'Pas van het Zand'. Deposition of fresh mud seems to have shifted towards more offshore and occur today in the navigation channels 'Scheur' and 'Pas van het Zand' and in the area north of the port of Zeebrugge.

5.2 Increased erosion of Holocene or tertiary mud

Clay and mud pebbles of a few cm up to 10 cm in size and of different rounded shapes have been found regularly in sandy sediments 100 years ago and today. The rounded shape is an indication that these pebbles have been transported; the flattened shape may indicate that they originate from erosion of the layered Holocene mud. Fig. 3 shows that they are more frequently recorded today, despite the lower sampling resolution.

The higher frequency today of clay and mud pebbles in the vicinity of the dumping places B&W-S1 and B&W-O is probably a result of the dumping of dredged sediments from mainly deepening dredging works. Tertiary clay and Holocene mud are, e.g. outcropping in the navigation channel towards the Westerschelde and in the 'Pas van het Zand' (see Fig. 3a).

On other places the occurrence of mud or clay pebbles may indicate erosion of old mud (Holocene or modern) or tertiary clay. Near the sampling site MOW1 (Fig 1) Holocene mud is outcropping; it is covered by an ephemeral fine sand layer of 1 to 10 cm. Mud lenses have been observed in the sand indicating probably erosion of the underlying Holocene mud. Interesting in the OE11 core is the lower ^{210}Pb activity in the surface layer (Fig. 8) than between 23 cm and 27 cm below the surface where a maximum is found. The observed profile could be explained by assuming a supply and deposition of mud with a low ^{210}Pb content. Possible sources are from the erosion of the Holocene mud and from capital dredging works, which may bring Holocene and Tertiary fine grained sediments in suspension. Similar observations from elsewhere have been reported by Ten Brinke et al. (1995) and Andersen et al. (2000). Variation in industrial ^{226}Ra discharges and the closing down of the BASF-Antwerpen discharges in 2002 could also give an explanation for the decreasing ^{210}Pb activity. Quantitative information on transport and diffusion of ^{226}Ra from the Schelde estuary towards the southern North Sea is however not known to confirm this explanation.

5.3 Dredging and dumping effects

The port of Zeebrugge and its connection to the open sea as well as the navigation channels towards the Westerschelde estuary are efficient sinks for cohesive sediments. Maintenance dredging and dumping amount today to about 12 millions tons of dry matter yearly (average over the period 1999-2004), from which more than 70% is silt and clay. 48% of the total quantity is dredged in the navigation channels towards the Westerschelde and the port of Zeebrugge, 45% in the port itself and 7% in the smaller harbours (Oostende, Blankenberge and Nieuwpoort). 52% of the dredged matter is dumped on dumping place B&W-S1, 33% on B&W-ZO and 5% on B&W-O. Comparison between the SPM transport entering and leaving the BCS and the quantities dredged and dumped at sea shows that an important part of the SPM is involved in the dredging/dumping cycle (Fettweis and Van den Eynde, 2003).

The deposition of mud in the dredging areas should be seen as a temporarily storage and it does not affect the global sediment balance on a scale of the BCS. In these areas the human impact is however massive and the deposition is the results of the engineering works, which have been carried out (deepening, port construction). The fact that high amount of fine grained sediments are deposited and dredged shows that the nearshore zone has become more muddy since the beginning of the 20th century when dredging was significantly smaller.

The dumping of fine grained sediment increases temporarily the SPM concentration by 50-100 mg/l in a diameter of 20-40 km around dumping place B&W-S1 and increase the deposition of mud north of the dumping place (Van den Eynde and Fettweis, 2004). The seasonal averaged SPM concentration in this area as derived from satellite images and in situ measurements amounts to 25 mg/l ± 100% in summer up to 100 mg/l ± 70% in winter (Fettweis et al., 2007). If the assumption that the SPM transport has not changed globally in the southern North Sea in the last 100 years is valid, then it can be concluded from these results and from the model results of § 4.4 that the turbidity maximum area has shifted in the last 100 years more offshore, because SPM concentration near the dredging areas has slightly decreased due to deposition, while around the dumping places it has increased.

5.4 Changes in storminess

The occurrence and frequency of storms are important for the distribution of cohesive sediments. Indications of changing storminess in the North Sea have been frequently reported, see e.g. Wasa Group (1998) and Weisse et al. (2005). The Wasa Group (1998) mentions that the storm- and wave climate in most of the North Sea has undergone variations on time scales of decades; these variations are related to variations in the North Atlantic Oscillation index.. Interesting to note is that the intensity of the storm- and wave-climate in the 1990ties seems to compare with the intensity at the beginning of the twentieth century (WASA Group, 1998; Dawson et al., 2002). Nevertheless the decadal variation in storminess no statistical significant long-term trends (>100 years) could have been found, see the findings of De Jong et al. (1999) for the German Bight and of Verwaest (pers comm.) for the Belgian part of the North Sea. It is therefore concluded that variations in meteorological conditions cannot explain at least partly the differences in cohesive sediment distribution today and 100 years ago.

6. Conclusion

In the study area cohesive sediments of different age occur, ranging from tertiary clays up to freshly deposited mud. Based on recent field data the distribution of these sediments has been determined. The effects of engineering works or natural processes have been investigated by comparing the distribution of freshly deposited to very soft consolidated mud and mud and clay pebbles 100 years ago and today. The historic data of Gilson have been used to describe the cohesive sediment distribution as it occurred in the beginning of the 20th century in the Belgian nearshore area. The quality of these samples is very high regarding the available metadata and the data have proven to be a major reference to understand the evolution of the local cohesive sediment distributions. The processing of the historic and recent data was mainly based on field descriptions of the samples (consolidation, thickness) and on morphological evolution; emphasis was put on the occurrence of thick layers (>30cm) of freshly deposited to very soft consolidated mud and on the distribution of clay and mud pebbles. The major conclusions of the study are:

1. Thick layers of fresh mud (>30 cm) were deposited in the beginning of the 20th century mainly in a narrow band along the coast from about Nieuwpoort up to the mouth of the Westerschelde. These deposits were mainly the result of natural morphological changes. Today, permanent layers of fresh mud are concentrated around the old dumping site of Oostende, in the outer port of Zeebrugge, in the navigation channels 'Scheur' and 'Pas van het Zand' and in the area north to northeast of the port of Zeebrugge. Comparing the actual situation with the situation 100 years ago it seems that around Zeebrugge the area with fresh mud extends more towards offshore.

2. Most of the actual depositions of thick layers of fresh mud (>30 cm) have been induced by anthropogenic operations, such as dumping, deepening of the navigation channels and construction and extension of the port of Zeebrugge.
3. If the assumption that the SPM transport has not changed globally in the southern North Sea in the last 100 years is valid, then it can be concluded that the centre of the turbidity maximum area has probably shifted in the last 100 years more towards offshore. This is explained by the slight decrease in SPM concentration near the dredging areas due to high siltation rates and the increase in SPM concentration on the offshore dumping places (such as B&W-S1).
4. The higher frequency of clay and mud pebbles today compared with 100 years ago is probably mainly related to deepening dredging works. Indications (radiometric measurements) have however been found that a higher erosion of the Holocene mud may occur today. Erosion of the Holocene mud may occur in flakes or pebbles due to its consistency.
5. Both, the historical and the recent dataset, show that the Belgian coastal waters east of Oostende are naturally subject to high siltation rates, resulting in the deposition of fresh to very soft consolidated mud layers of more than 30 cm, but also in the deposition of tidal driven ephemeral fluffy layers of a few cm over the area covered by the turbidity maximum. The effects of variation in SPM concentration and cohesive sediment distribution through time on the habitat of benthic invertebrates are therefore probably minor and not a key to explain temporal changes in the composition of the benthic communities since the early 20th century.

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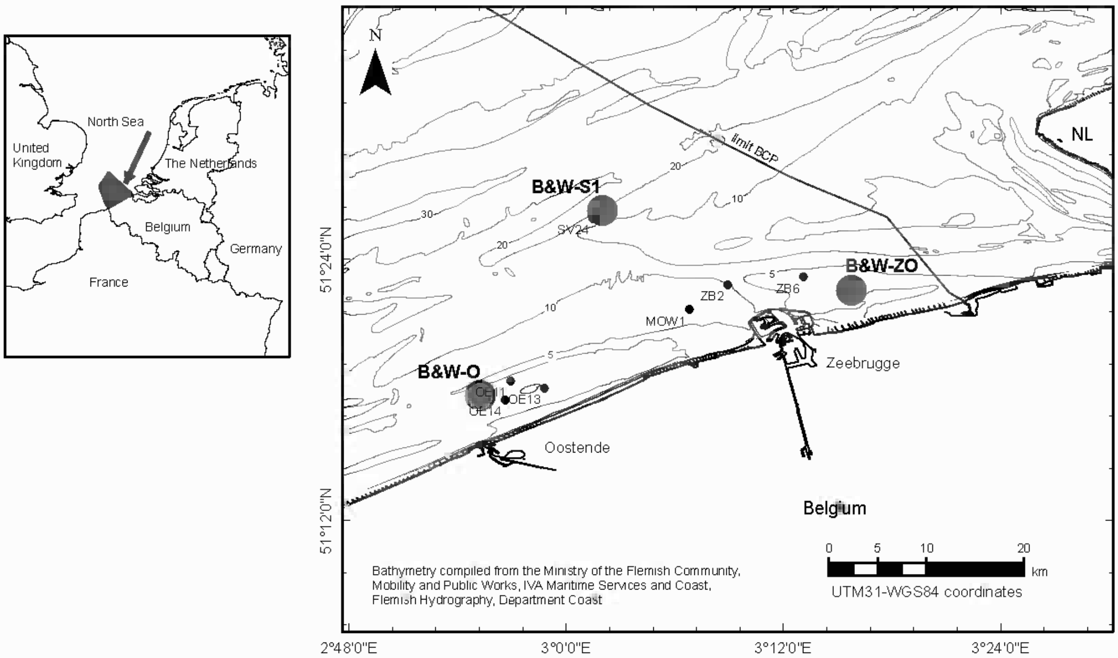


Figure 1: The Belgian-Dutch nearshore area between about Oostende and the mouth of the Westerschelde. The map shows the major dumping sites (B&W-S1; B&W-ZO, B&W-O). The dots on the map indicate the position of box core and Van Veen grab samples, which are discussed in the text.

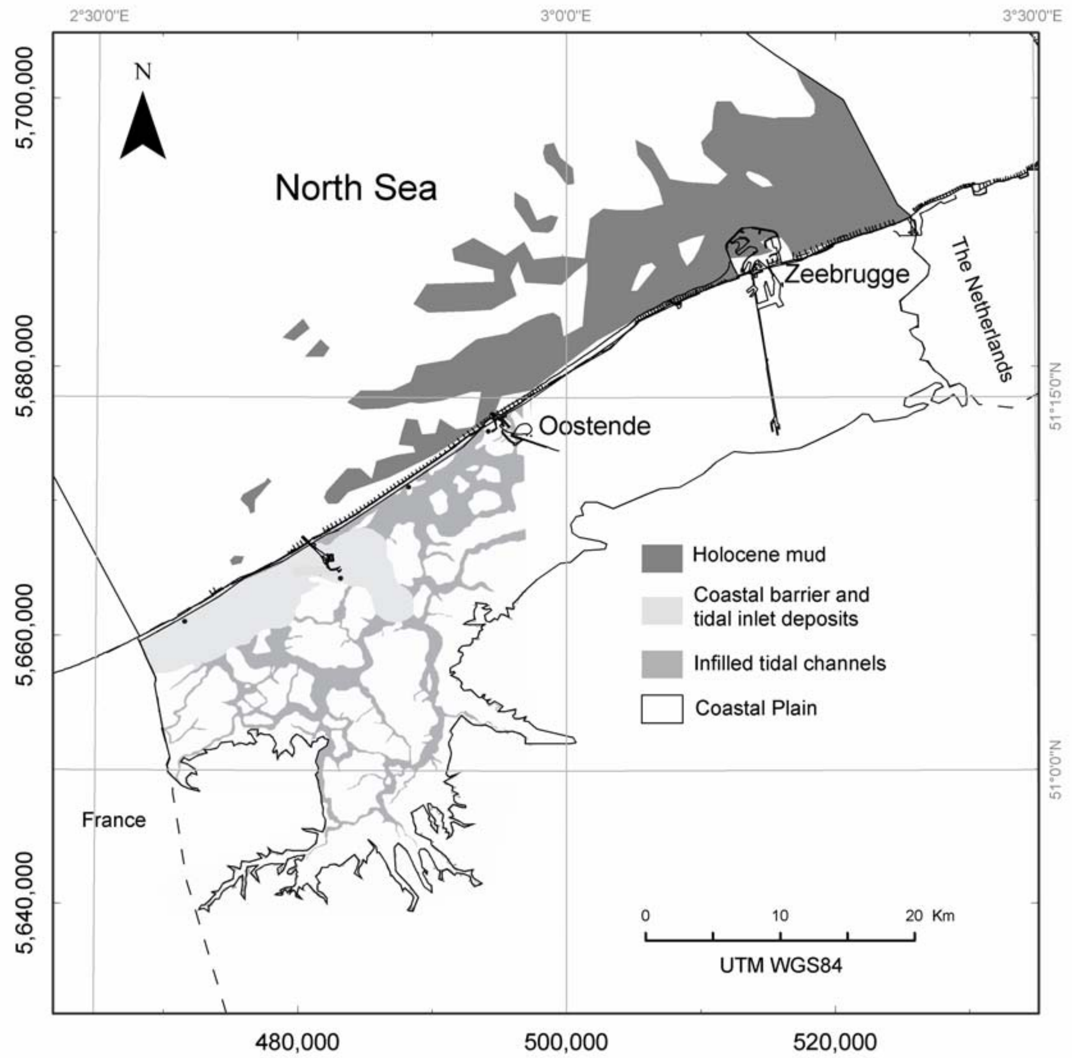


Figure 2: Holocene deposits of the Belgian nearshore zone and the coastal plain. The extension of the Holocene deposits in the coastal plain corresponds with the limits of the Polder. Only the Holocene deposits of the western coastal plain are shown in detail (from Baeteman, 2005).

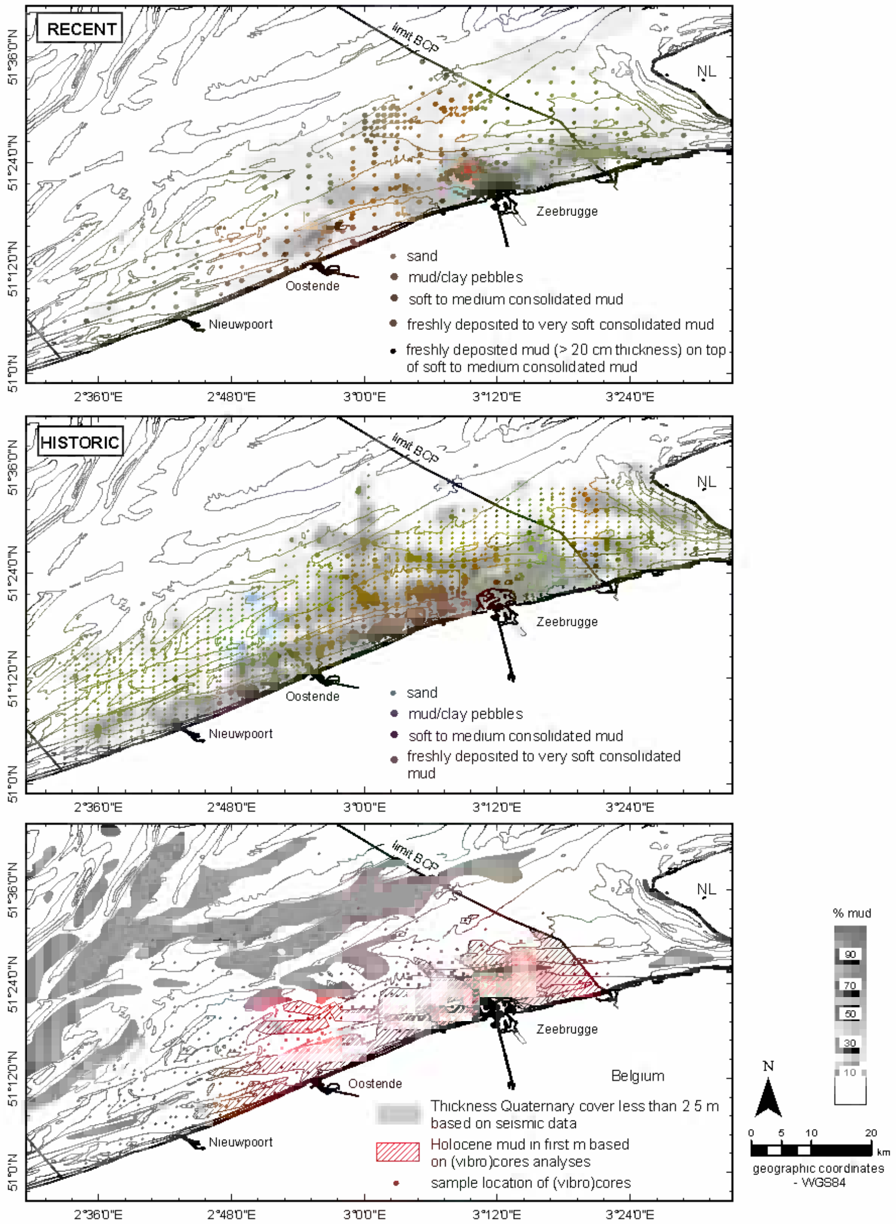
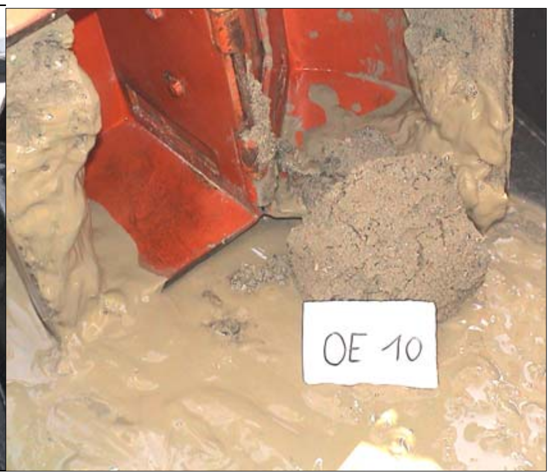


Figure 3: Cohesive sediment facies and mud content in the Belgian-Dutch coastal zone derived from recent (above) and historic (middle) sediment samples. The recent mud content is derived from grain size analysis, whereas the historic mud content distribution is based on metadata, see §3.1. Below is indicated the extension of Holocene mud on the Belgian continental shelf based on vibrocores and the areas where the Quaternary cover is less than 2.5 m thick.

a)

(b)

(c)



(d)

(e)

(f)

Figure 4: Photos of Van Veen (VV) grab (size of grab is 0.3 m × 0.2 m) and box core (BC) samples (height of core is 0.5 m), see Fig. 1 for geographical location.

(a) BC sample showing mud pebbles on the surface (SV24, 19/02/2003), the core has been taken not far from the dumping place B&W-S1; the pebbles could have their origin in deepening dredging works.

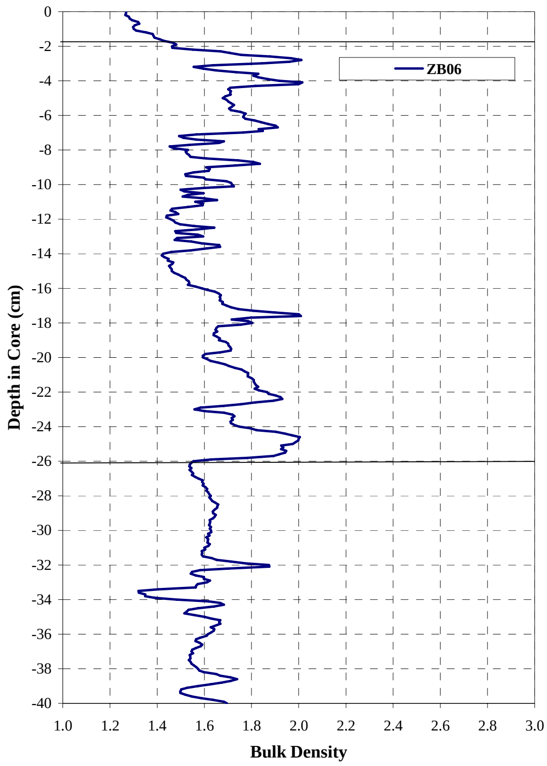
(b) VV sample of layered Holocene mud covered by a thin ephemeral sand layer (MOW1, 04/04/2005).

(c) VV of fluid mud on top of freshly deposited mud (port of Zeebrugge, 9/11/2006).

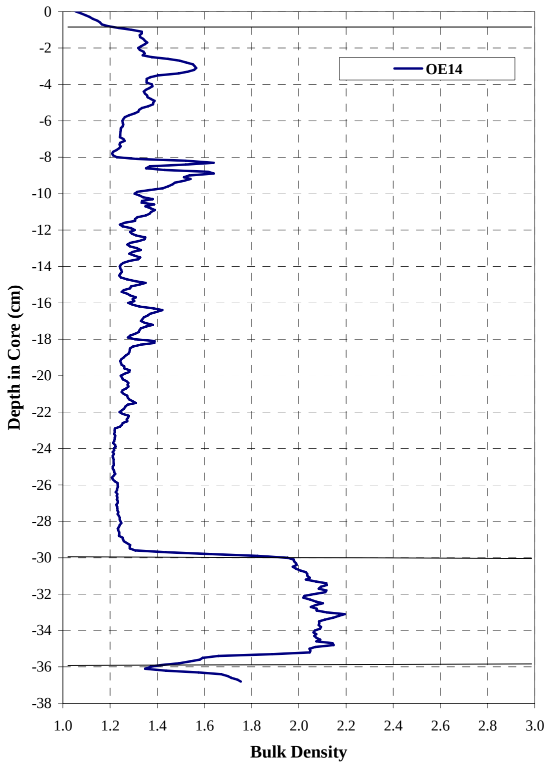
(d) VV of fine sand covered with a thin fluffy layer, (OE13, 21/02/2003).

(e) BC of freshly deposited mud above medium consolidated mud, (ZB2, 19/02/2003).

(f) BC (height ±45 cm) of freshly deposited to very soft mud, (OE14, 21/02/2003).

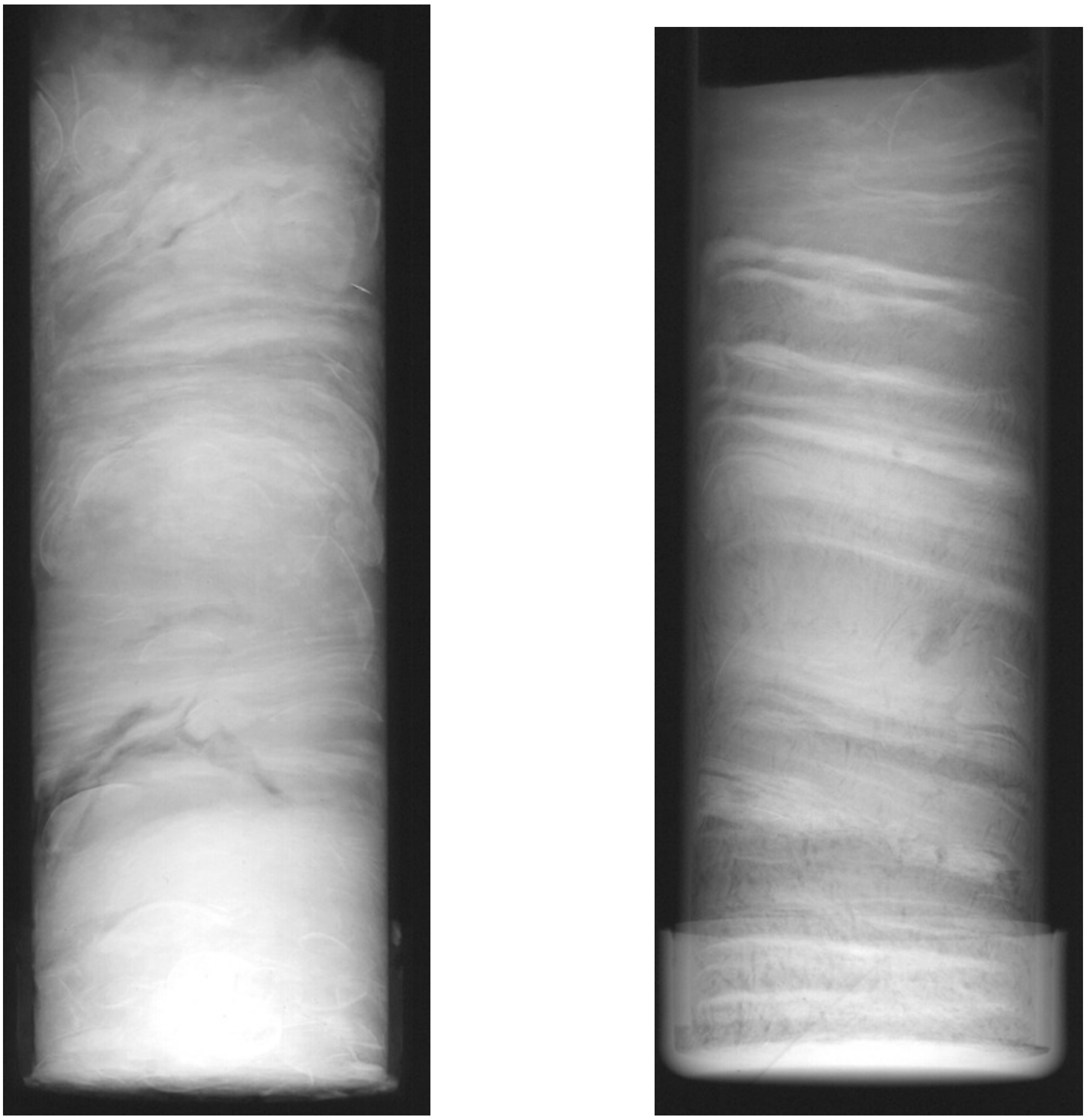


(a)



(b)

Figure 5: Wet bulk density profiles (kg l^{-1}) of selected box cores. (a) The ZB6 sample (27/11/2002) consist of 24 cm very soft consolidated mud (1.4-1.5 kg l^{-1}), which becomes more sandy in the lower part, above 29 cm of medium consolidated mud (>1.6 kg l^{-1}). On top is a thin layer of freshly deposited mud (±1.3 kg l^{-1}). (b) The OE14 sample (21/02/2003) consist of 1 cm fluffy layer on top of 29 cm of freshly deposited mud (1.2-1.4 kg l^{-1}); below is a layer of 5 cm muddy fine sand on top of medium consolidated mud. On top is a



(a) (b)

Figure 6: Radiography of selected box core (Reineck corer) near the harbour of Zeebrugge (width of the core is 5 cm). Both contain freshly deposited to soft consolidated mud with typical tidal deposition structure. (a) RK0026-04 (24/10/2000) sample has a length of 14 cm and been taken very close to ZB6 sample. (b) RK0124-14 (24/10/2000) sample has a length of 13.5 cm and has been taken in the navigation channel towards Zeebrugge near ZB2 sample.

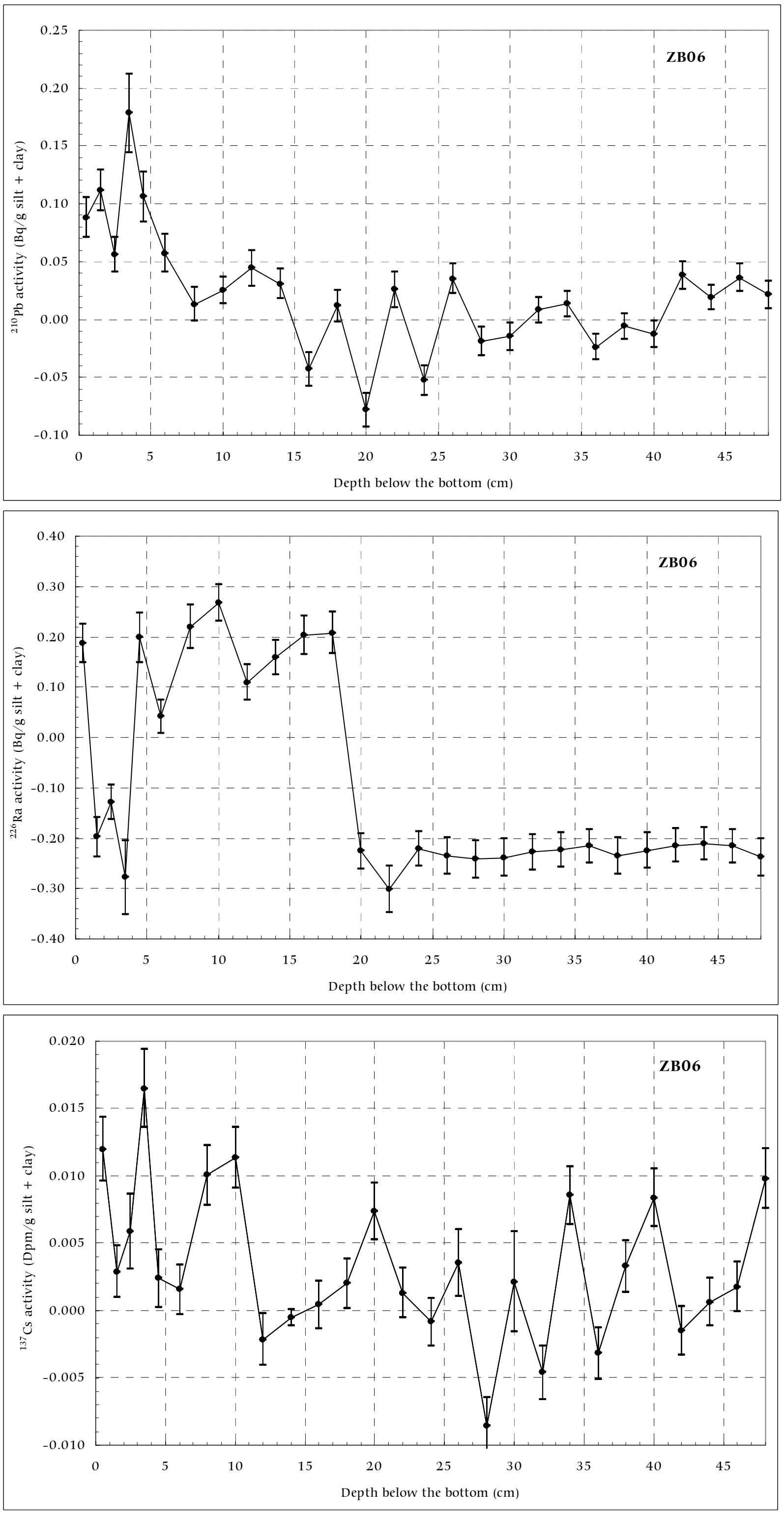


Figure 7: Total ^{210}Pb (above), ^{226}Ra (middle) and ^{137}Cs (below) activities in ZB6 core (27/11/2002). The bars indicate 2σ statistical error limits.

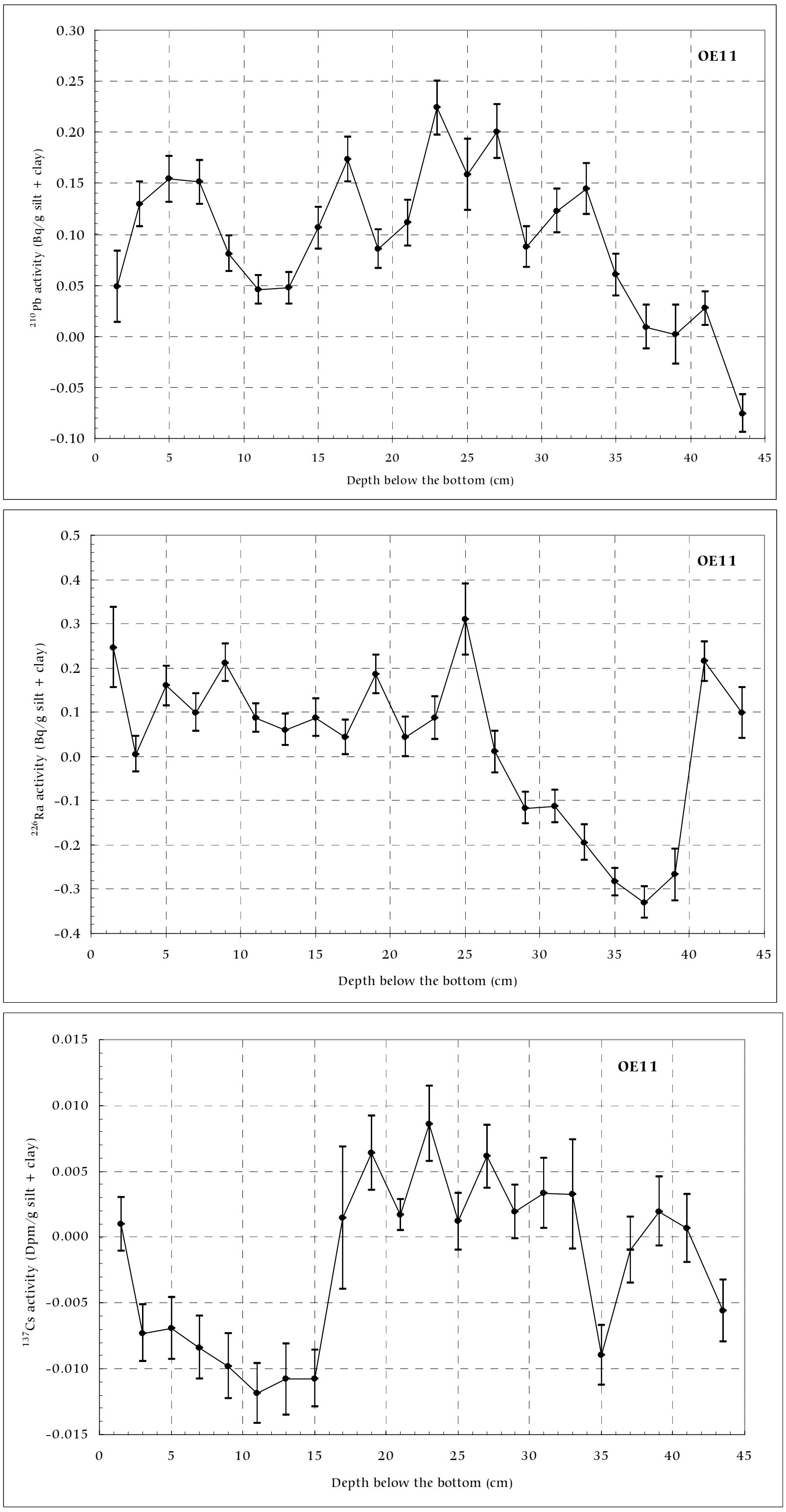


Figure 8: Total ^{210}Pb (above), ^{226}Ra (middle) and ^{137}Cs activities in OE11 core (08/03/2004). The bars indicate 2σ statistical error limits.

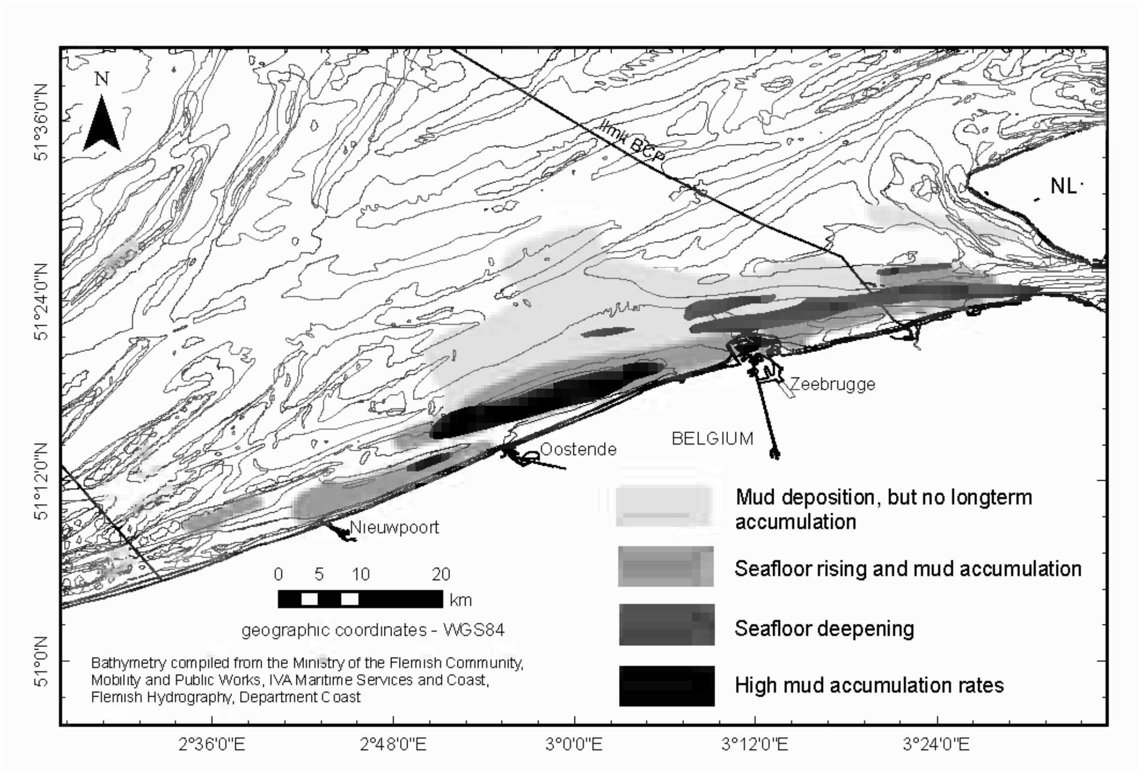


Figure 9: Aggregated trends in mud deposition and seafloor morphology inferred from detailed visual inspection of bathymetric changes (period 1866-1911) and mud content information derived from the historic sediment samples (see Fig. 3).

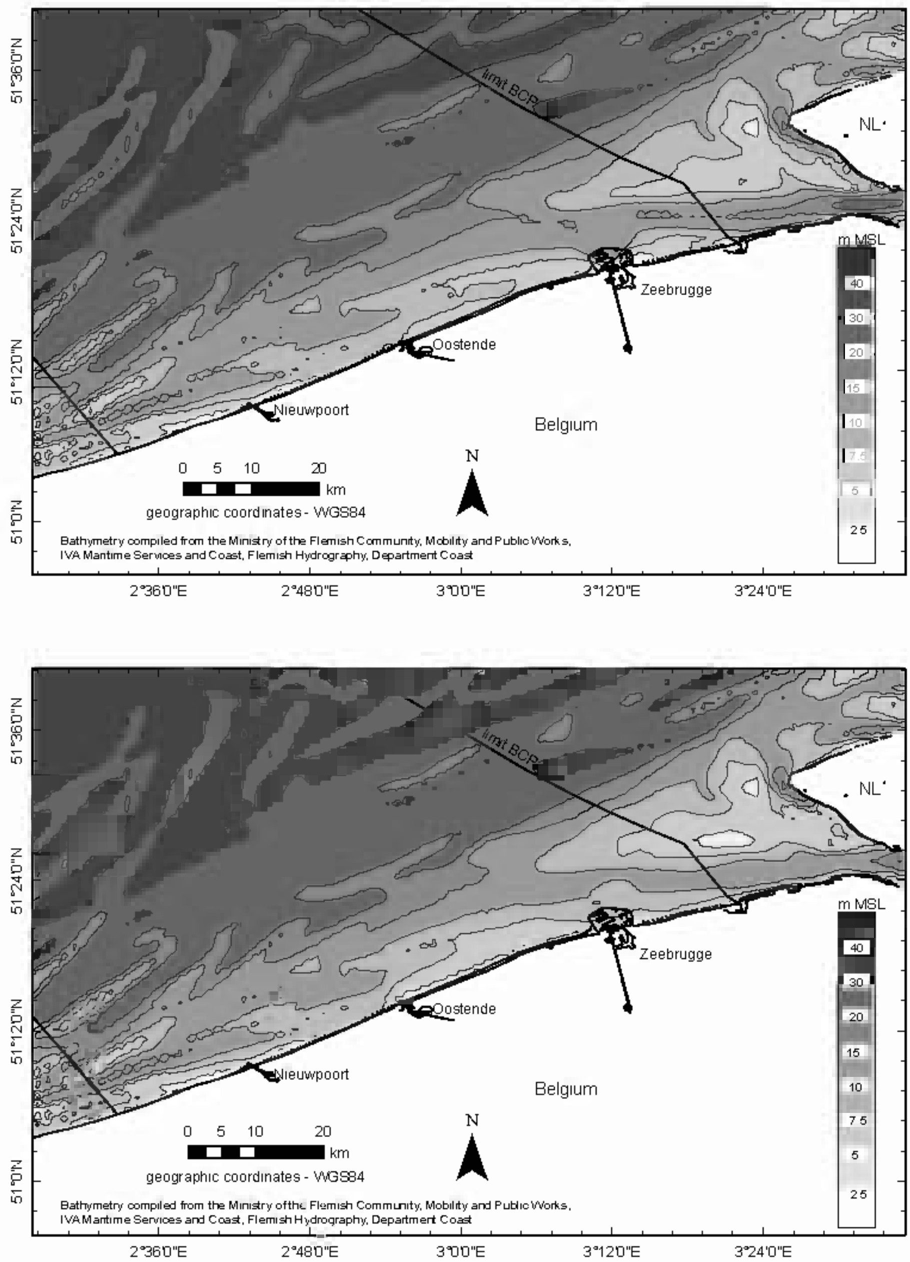


Figure 10: Bathymetry derived respectively from 2003 surveys (above) and from surveys before 1959 (below). Significant differences occur in the coastal zone and navigation channels.

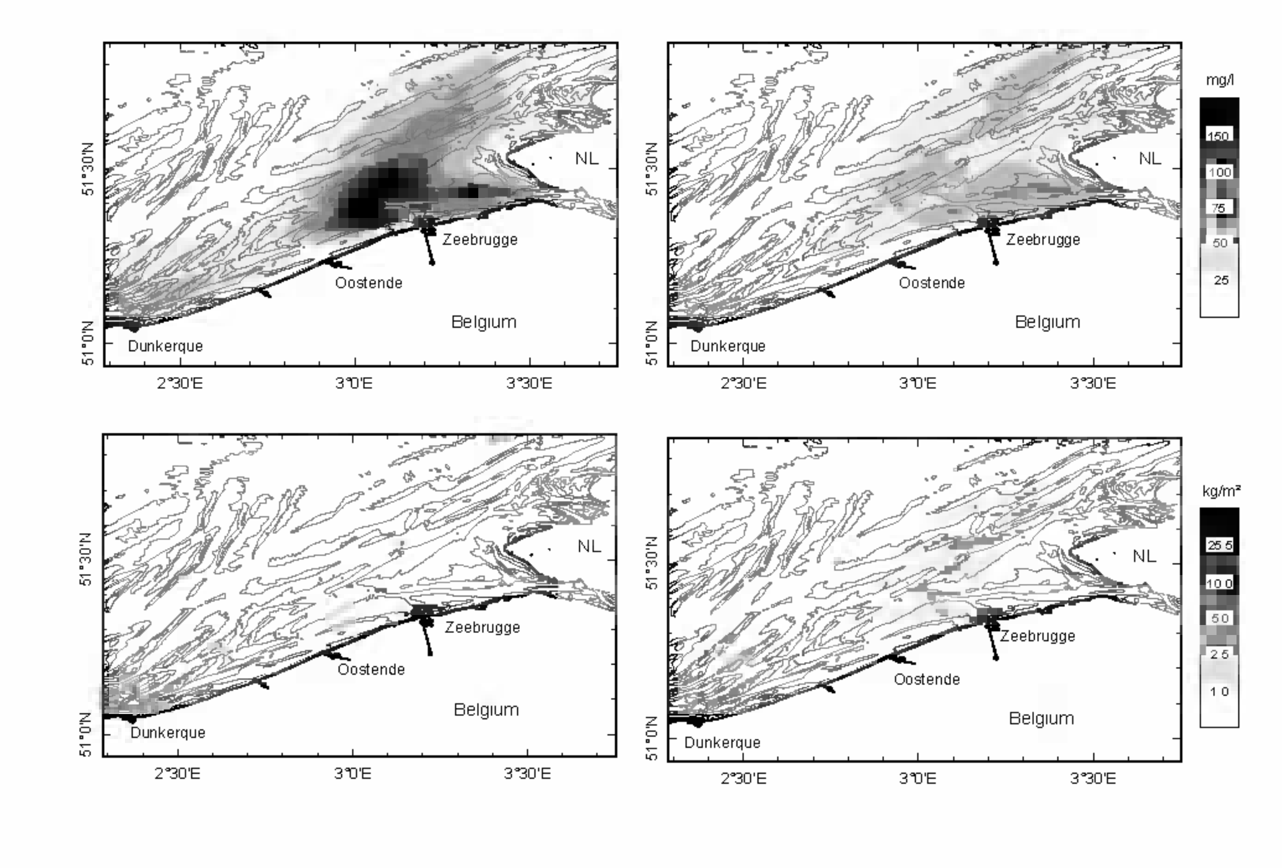


Figure 11: Tidal averaged SPM concentration (above) and mud deposition (below) during a spring tide (left) and a neap tide (right) for the present situation (2003).

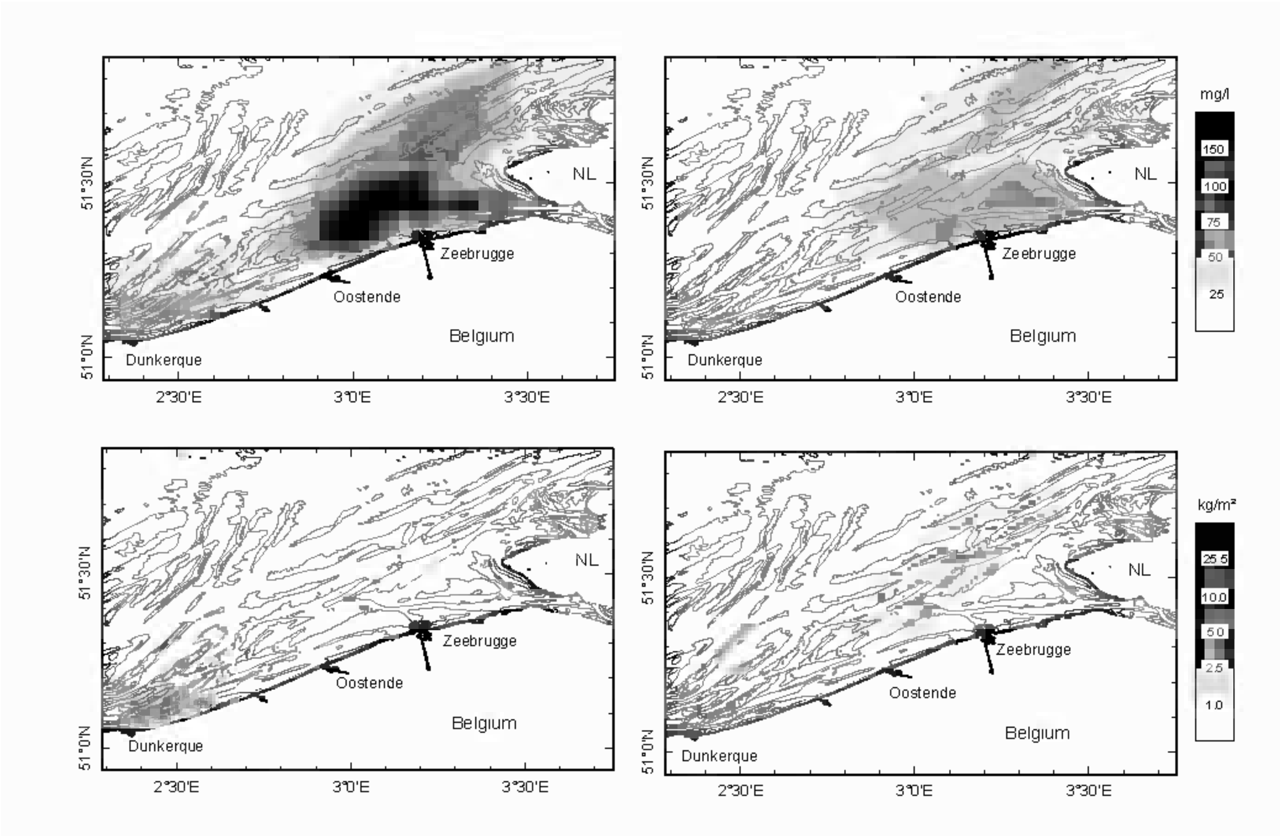


Figure 12: Tidal averaged SPM concentration (above) and mud deposition (below) during a spring tide (left) and a neap tide (right) for the pre-1959 situation.