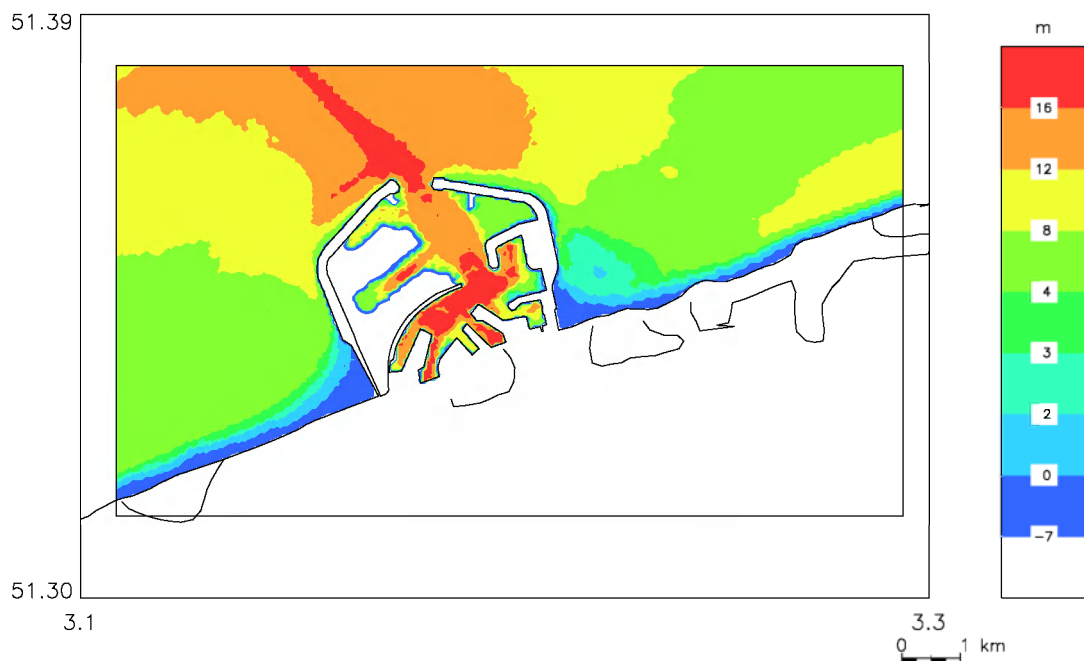




MOnitoring en **MO**delling van het cohesieve sedimenttransport en evaluatie van de effecten op het mariene ecosysteem ten gevolge van bagger- en stortoperatie (**MOMO**)



Activiteitsrapport 1 (1 april 2006 - 30 september 2006)

Michael Fettweis, Virginie Pison & Dries Van den Eynde

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

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

BMM
100 Gulledelle
B-1200 Brussel
België

Inhoudstafel

| | | |
|-----------|---|-----------|
| 1. | Inleiding | 3 |
| 1.1. | Voorwerp van deze opdracht | 3 |
| 1.2. | Algemene Doelstellingen (2006-2011-2016) | 3 |
| 1.2.1. | Verminderen van de sedimentatie | 4 |
| 1.2.2. | Efficiënter storten | 4 |
| 1.3. | Doel van het MOMO project (april 2006 - maart 2008) | 4 |
| 1.4. | Publicaties binnen het MOMO project (april 2006 – maart 2008) | 6 |
| 2. | Verfijning 3D hydrodynamisch model | 7 |
| 2.1. | Inleiding | 7 |
| 2.2. | Ontwikkeling wetting-drying | 7 |
| 2.3. | Ontwikkeling nieuw rooster | 7 |
| 3. | 100 jaar menselijke invloed op de slibverdeling | 11 |
| 4. | Conclusies | 12 |
| 5. | Referenties | 13 |

Appendix 1: 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 (Japan).

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

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).

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 baggerspeciéstortingen" (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 toegangseul (bv verbreding, zachtere helling...).

1.2.2. Efficiënter storten

De efficiëntie van een stortplaats wordt bepaald door fysische (sedimenttransport i.f.v. getij, dootij-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:

- definiëren van een 'goede' stortzones i.f.v. sedimenttransport, recirculatie baggerspecie, ecologie, economie, bathymetrie van de baggerplaatsen
- operationele voorspelling van de recirculatie van het gestorte materiaal 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

Taak 1.1: Slibconcentratie metingen: getijcyclus en langdurig

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 slibconcentratievariëaties te kwantificeren die zich voordoen tijdens een dootij-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 lokale verschillen tussen meetstations.

Taak 2: Modellerings

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 fasen 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 sedimenttransport 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-NI 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 $250 \text{ m} \times 250 \text{ m}$. 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 principe is als volgt: indien de waterstand een kritische waarde onderschrijft, worden de termen uit de momentumvergelijkingen vermenigvuldigd met een factor α , die 0 bereikt, indien de totale diepte de minimale waarde benadert; enkel de drukgradiënt 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 snelheidsvectoren 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.

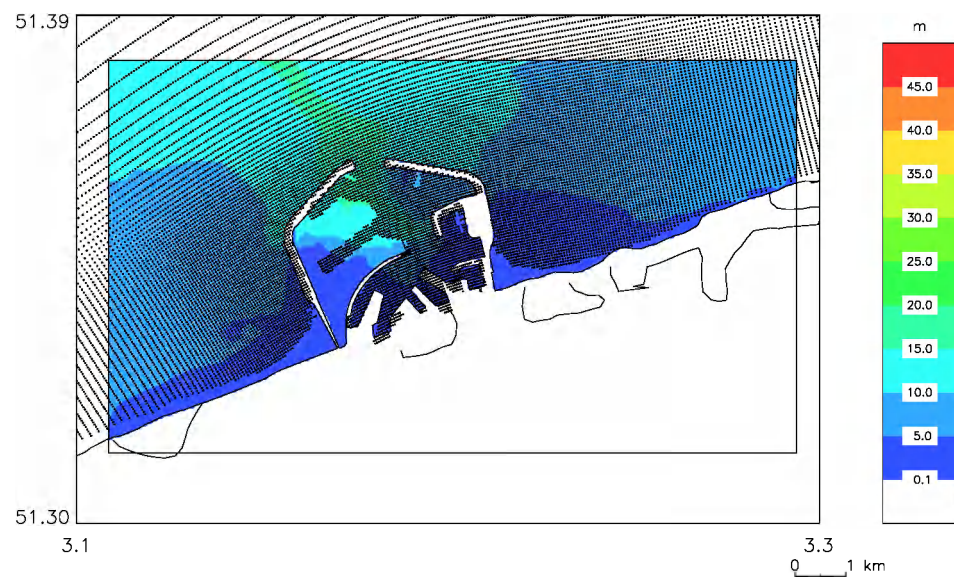
2.3. Ontwikkeling nieuw rooster

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

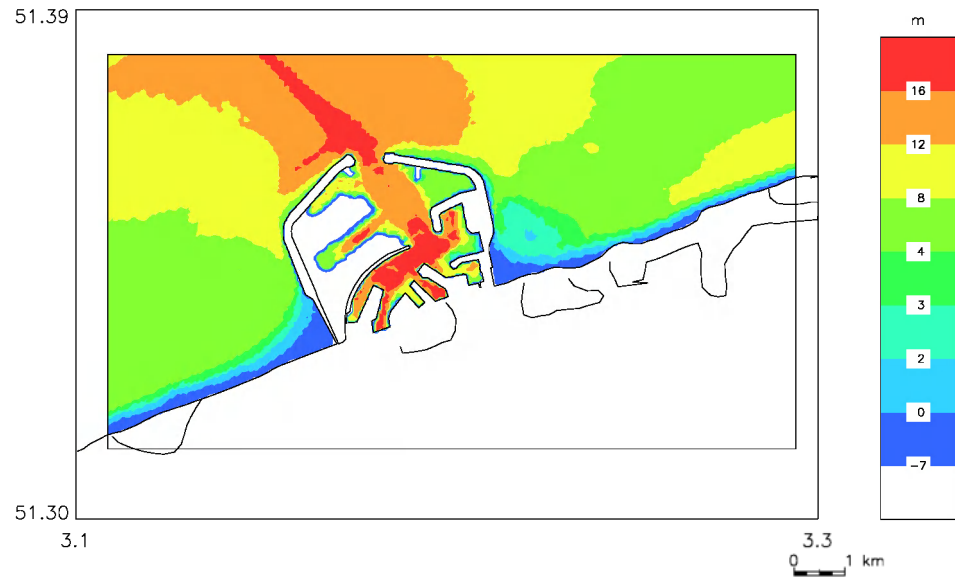
voor het opstellen van een rooster voor de haven van Zeebrugge. De implementatie van dit model wordt uitgebreid beschreven in De Mulder (2006) en kon door ons worden gebruikt om het nieuwe rooster te ontwikkelen. De bathymetrie heeft een resolutie van ongeveer $50\text{ m} \times 50\text{ m}$ en is gebaseerd 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 $1.667'' \times 2.8571''$, wat ongeveer overeenkomt met een resolutie van $50\text{ m} \times 50\text{ m}$. 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 246×151 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.

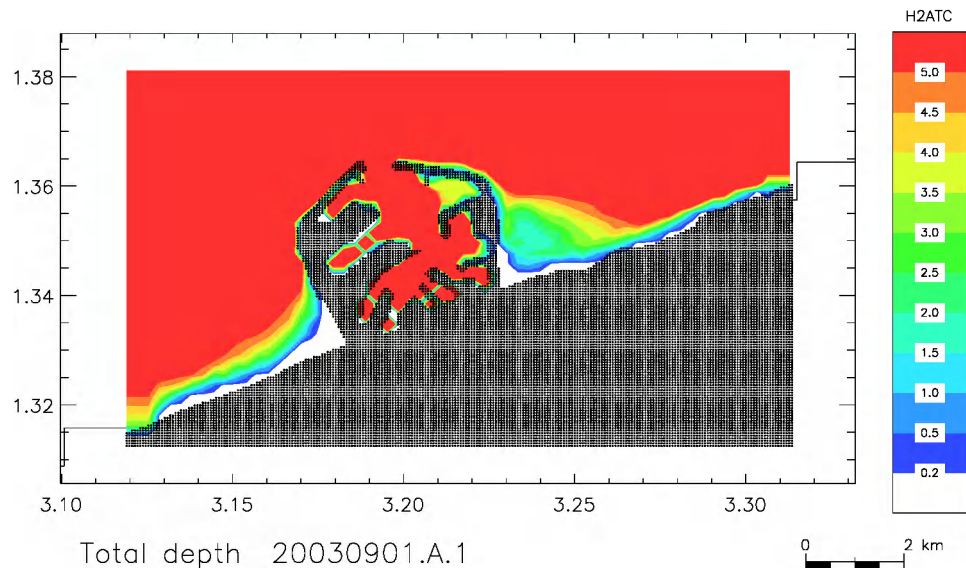


Figuur 2.1: De curvilineaire roosterpunten uit het WLH model ter hoogte van Zeebrugge, de waterdiepte is t.o.v het gemiddeld zeeniveau (MSL) weergegeven.

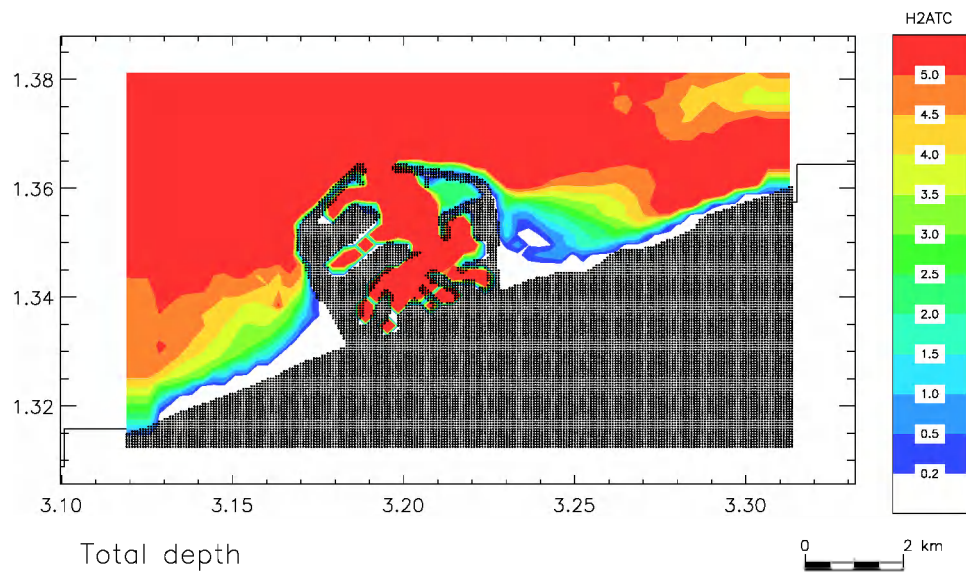


Figuur 2.2: Bathymetrie van het nieuwe 3D hydrodynamische model ter hoogte van Zeebrugge (MU-HEIST).

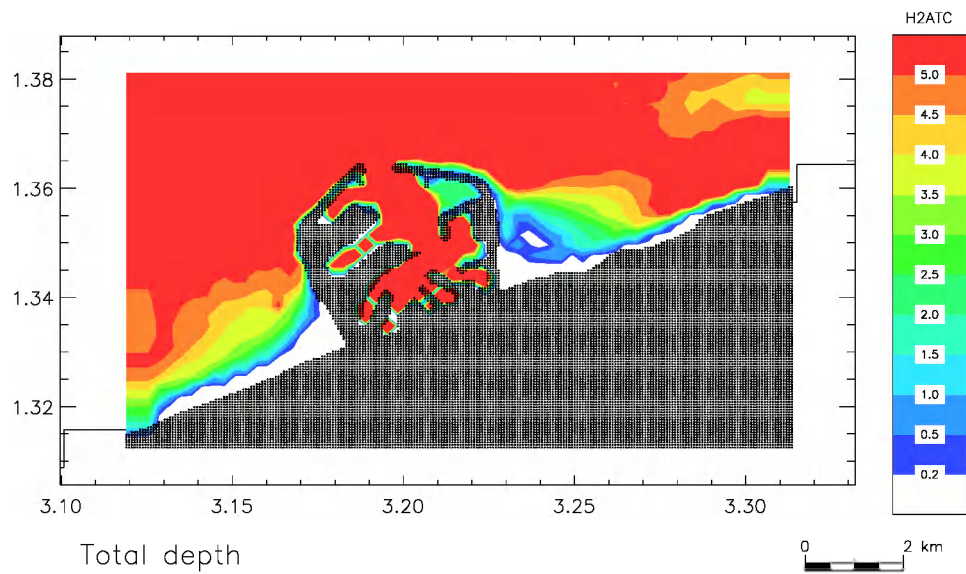
Enkele eerste resultaten worden voorgesteld in Figuur 2.3 tot Figuur 2.5. In de twee laatste figuren kan duidelijk worden vastgesteld dat het model in staat is het droog komen te staan van gebieden bij laagwaterstanden goed te simuleren.



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 'veld-data' (beschrijvingen van de consolidatie, dikte van de lagen), op morfologische evolutie en – voor wat betreft de recente stalen – ook op radioactiviteitsmetingen 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 sleutelement 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

- Burchard, H. & Bolding, K. 2002. GETM, a general estuarine model. Scientific documentation, European Commission, Report EUR 20253, 157pp.
- 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.
- Fettweis, M., Houziaux, J.-S., Du Four, I., Baeteman, C., Wartel, S., Van Lancker, V., Mathys, M., 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 2).
- Fettweis, M., Houziaux, J.-S., Du Four, I., Van Lancker, V., Vandenberghe N., Zeelmaeker, E., Nechad, B., Francken, F., Wartel, S., Pison, V., Van den Eynde, D., Baeteman, C., Mathys, M. 2007. Mud Origin, Characterisation and Human Activities (MOCHA). Final Scientific Report. Belgian Science Policy Office.
- Lauwaert, B., Fettweis, M., Cooreman, K., Hillewaert, H., Moulaert, I., Raemaekers, M., Mergaert, K. & De Brauwer, D. 2004. Syntheserapport over de effecten op het mariene milieu van baggerspeciestorringen. BMM, DVZ & AMT rapport, BL/2004/01, 52pp.
- Lauwaert, B., De Brauwer, D., Fettweis, M., Hillewaert, H., Hostens, K., Mergaert, K., Moulaert, I., Parmentier, K. & Verstraeten, J. 2006. Syntheserapport over de effecten op het mariene milieu van baggerspeciestorringen (vergunningperiode 2004-'06). BMM, ILVO & AMT rapport, BL/2006/01, 87pp+ app.
- Luyten, P.J., J.E. Jones, R. Proctor, A. Tabor, P. Tett and K. Wild-Allen, 1999. COHERENS – A Coupled Hydrodynamical-Ecological Model for Regional and Shelf Seas: User Documentation. MUMM Report, Management Unit of the Mathematical Models of the North Sea, 914 pp.

COLOPHON

Dit rapport werd voorbereid door de BMM in december 2006
Zijn referentiecode is MOMO/3/MF/200612/NL/AR/1.

Status draft
 finale versie
 herziene versie
 vertrouwelijk

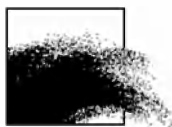
Beschikbaar in het Engels
 Nederlands
 Frans

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

BMM
100 Gulledele
B-1200 Brussel
België
Tel: +32 2 773 2111
Fax: +32 2 770 6972
<http://www.mumm.ac.be/>

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

M. FETTWEIS¹, J.-S. HOUZIAUX², F. FRANCKEN¹, D. VAN DEN EYNDE¹

¹Royal Belgian Institute of Natural Science (RBINS), Management Unit of the North Sea Mathematical Models (MUMM), Gulledele 100, 1200 Brussels, Belgium (m.fettweis@mumm.ac.be)

²RBINS, Invertebrates Department, rue Vautier 29, 1000 Brussels, Belgium

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, $\rho > 1800 \text{ kg m}^{-3}$), soft to medium consolidated (Holocene mud, $\rho = 1500\text{-}1800 \text{ kg m}^{-3}$), freshly deposited mud ($\rho = 1300\text{-}1500 \text{ kg m}^{-3}$) 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 whether the distribution 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.

REFERENCES

- [1] 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 Research*, **23**, 669-691.
- [2] van Loen, H., Houziaux, J.-S., Van Goethem, J. 2002. The collection Gilson as a reference framework for the Belgian marine fauna: a feasibility study. Belgian Science Policy Final Report MN/36/94, 41pp.
- [3] Van Mierlo, C.-J., 1897. Quelques mots sur le régime de la côte devant Heyst. *Annales de l'association des ingénieurs sortis des écoles spéciales de Gand*, tome XX, 4^e livraison.

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

Michael Fettweis, Dries Van den Eynde

Management Unit of the North Sea Mathematical Models (MUMM), Royal Belgian Institute of Natural Sciences, Gulledele 100, 1200 Brussels, Belgium

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.

References

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).**

1 **100 years of anthropogenic influence on the cohesive sediment**
2 **distribution in the Belgian coastal zone**

3
4 Michael Fettweis¹ (*), Jean-Sébastien Houziaux², Isabelle Du Four³, Cecile Baeteman⁴,
5 Stanislas Wartel¹, Mieke Mathys³, Vera Van Lancker³, Frederic Francken¹

6
7 ¹Royal Belgian Institute of Natural Science (RBINS), Management Unit of the North Sea
8 Mathematical Models (MUMM), Gulledele 100, 1200 Brussels, Belgium

9 ²RBINS, Invertebrates Department, rue Vautier 29, 1000 Brussels, Belgium

10 ³Ghent University, Renard Centre of Marine Geology (RCMG), Krijgslaan 281, S8, 9000 Gent,
11 Belgium

12 ^(*)corresponding author

13 tel. +32 2 7732132, fax. + 32 2 7706972, email: m.fettweis@mumm.ac.be

14
15 **Abstract**

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

29 Thick layers of fresh mud were deposited in the beginning of the 20th century mainly in a
30 narrow band along the coast from about Nieuwpoort up to the mouth of the Westerschelde.
31 These deposits were mainly the result of natural morphological changes. Today, most of the
32 depositions of thick layers of fresh mud have been induced by anthropogenic operations,
33 such as dumping, deepening of the navigation channels and construction and extension of
34 the port of Zeebrugge. Comparing the actual situation with the situation 100 years ago

35 reveals that the area around Zeebrugge where fresh mud is deposited extends more offshore
36 today.

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

43 **Keywords**

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

45

46

47 **1. Introduction**

48 The Belgian-Dutch nearshore zone is naturally a very dynamic area as can be seen e.g. from
49 bathymetrical differences in nautical charts from 1866 on. The construction of the port of
50 Zeebrugge in the 20th century and the dredging or deepening of navigation channels
51 represent the most conspicuous anthropogenic impact in the Belgian coastal zone. The
52 construction of the port started at the end of the nineteenth century when the Belgian
53 government decided to build a new outer port on a location where there was little more than
54 a beach and a row of dunes. Van Mierlo (1897) predicted already from the beginnings a fast
55 siltation of the port. The first port was constructed between 1899 and 1903 and was modest
56 in size; the embankment had a length of 1.7 km and a maximum distance from the coast of
57 1.1 km (Fig. 1). The navigation channel 'Pas van het Zand' was dredged in 1903 through a
58 recently and naturally formed sand bank (Van Mierlo, 1897); the channel had a length of
59 2.8 km, a width of 0.3 km and a depth of 9 m below Mean Low Low Water Spring
60 (MLLWS). Since then many adjustments were carried out in order to deepen the access
61 channels and finally to extend the outer port (photos of the port of Zeebrugge:
62 www.portofzeebrugge.be). Significant expansion works were carried out between 1980 and
63 1985 with the construction of two longitudinal breakwaters with a length of 4 km and
64 extension of about 3 km in sea. The outer port has a depth up to 16 m below MLLWS and its
65 connection towards the open sea ('Pas van het Zand') of 14 m below MLLWS; they are
66 significantly deeper than the foreshore/offshore area, which has a water depth of less than
67 10 m below MLLWS. Harbour extensions, deepening of navigation channels and construction
68 of other large scale projects (e.g. windmill farms) will continue in the future and knowledge

69 of the impact of such activities on the fine-grained sediment dynamics and on the dredging
70 and dumping activities is necessary for a sustainable development of the area.

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

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

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

92 **2. Regional settings**

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

99 **2.1. Geological setting**

100 The Belgian coast is characterised by a straight and closed coastline with a general SW-NE
101 direction. The geological setting shows a striking difference between the western and eastern
102 part, a difference which is already expressed in the Tertiary subsoil. The western part is
103 characterised by compact stiff clay. In the eastern part, a vertical and lateral succession of

104 fine sand and silt, sand and sandy clay, and clay, belonging to the Lower Eocene, is forming
105 the Tertiary subsoil (Marechal, 1993). The top of these deposits is located at depth increasing
106 in an offshore direction and reaches about -30 m TAW (national reference level, 0 m TAW =
107 0.19 m below MLLWS at Zeebrugge) in the surroundings of Zeebrugge and about -20 m to -
108 25 m TAW in the coastal plain.

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

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

132 The Holocene sequence in the plain consists mainly of alternations of intertidal mud and
133 peat beds. The uppermost intercalated peat bed (also called surface peat) developed at about
134 6300-5500 cal BP in the landward part of the plain, and ca. 4700 cal BP in the more seaward
135 areas. It accumulated almost uninterruptedly for a period of 2-3 ka years while the coast
136 was prograding. The surface peat is generally 1 to 2 m thick and occurs between -1 and +1
137 m TAW. The upper peat bed is covered by a 1 to 2 m thick deposit formed by a renewed
138 expansion of the tidal environment in the late Holocene. The expansion was associated with

139 the formation of tidal channels which eroded deeply into the early and mid Holocene
140 sediments, and sometimes into the underlying Pleistocene deposits. The renewed expansion
141 of the tidal flat was also associated with shoreface erosion and a landward shift of the
142 coastline in particular in the central and eastern part. Here, the Holocene sequence at the
143 present shoreline consists of mud and peat beds (unpublished borehole data), which continue
144 towards offshore. Holocene muds have often been found in the eastern nearshore area, see
145 Fig.2. This is in contrast with the west where in a wide area in the seaward region, the
146 Holocene sequence consists of a ca. 25 m thick sand body deposited in a coastal barrier and
147 tidal inlet (Fig. 2). Such a situation with a transition from barrier to back-barrier deposits
148 (peat and mud) is the typical situation. The absence of barrier deposits in the central and
149 eastern part of the plain indicates severe shoreface erosion and a significant landward shift of
150 the coastline. The timing of the onset of this erosion still remains questionable, but it appears
151 that it coincides with the period of Roman occupation (Baeteman, 2007).

152 **2.2 Cohesive sediments**

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

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

174 **3. Materials and Methods**

175 **3.1 Mapping of historic and recent cohesive sediments**

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

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

198 The historical sedimentary situation was drawn based on sediment samples collected by
199 G. Gilson in the early 20th century. Gilson established an ambitious sampling programme
200 aiming to understand how environmental parameters influence the distribution of marine
201 invertebrates (Gilson, 1900). He therefore included an exhaustive sediment sampling scheme
202 to complement benthos sampling, but these data were never analyzed as a whole. The
203 archived inventory of Gilson's sediment samples contains a list of 2979 sampling events
204 between 1899 and 1939, from which 90% occurred before 1911. Gilson's cup-shaped
205 instrument ('ground collector') was able to sample the first 10-20 cm of soft bottoms and
206 allowed for good conservation of sediment layers in the sample, see Gilson (1901) and Van
207 Loen et al. (2002). Gilson performed only several grain-size analyses and only 700 sub-
208 samples are still preserved today. However, detailed field descriptions of the sediment

209 samples were written onboard, which enable a standardized approach to investigate
210 sediment parameters such as mud content, sand grain-size, shell content, gravel content and
211 others (Houziaux et al, in prep). For part of the dataset, the original field description could
212 not be recovered, but a summarized or truncated version still exists. Where both versions are
213 available, the summarized one is clearly less detailed, but it provides elementary information
214 on mud content or sand grain size. In the nearshore area 1956 sediment samples are
215 considered valid in terms of sedimentological information content and geo-referencing
216 accuracy.

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

238 **3.2 Radioactivity and density measurements**

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

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

247 The method used to infer the density of the non-disturbed core sediments is based on the
248 transmission of gamma-ray photons through the core (Preiss, 1968). The source of gamma
249 rays used is ^{241}Am , with a principal energy level at 60 KeV. Photons emitted at this energy
250 level are absorbed by the sediment rather than scattered. It is also very sensitive to small
251 contrasts in densities, though also to chemical composition (called the soil-type effect) as can
252 be foreseen from its very low energy level (Caillot and Courtois, 1969; Bouron-Bougé, 1972).
253 To reduce the soil-type effect calibration standards were made of sediment from the Belgian
254 continental shelf. Two types of sediment were used: a mud and a well-sorted medium-fine
255 sand sample. The water of the mud was slowly evaporated while stirring the mud in order
256 to obtain a homogenous mass that was transferred to a 12 cm long PVC tube of the same
257 composition as used for the cores to be analysed. The radiation passing the tube was
258 measured over the whole length in steps of 2 mm to ensure the homogeneity of the sample.
259 After measuring the density small aliquots of mud were sampled and transferred to pre-
260 weighed aluminium moisture cans and the water content was determined from the loss
261 weight after evaporation at 105°C for 12 hours. The bulk density, ρ_b , was then calculated
262 using 2600 kg/m³ for sand and 2000 kg/m³ for mud particle density (Bennett and Lambert,
263 1971).

264 3.3 Numerical model descriptions

265 3.3.1 Hydrodynamic model

266 The hydrodynamics has been modelled using the public domain 3D hydrodynamic
267 COHERENS model (Luyten et al., 1999). This model has been developed between 1990 and
268 1998 in the framework of the EU-MAST projects PROFILE, NOMADS and COHERENS. The
269 hydrodynamic model solves the momentum equation, the continuity equation and the
270 equations of temperature and salinity. The equations of momentum and continuity are
271 solved using the ‘mode-splitting’ technique. COHERENS disposes of different turbulence
272 schemes, including the two equations k - ε turbulence model.

273 For this application 2D currents from a 3D implementation of the COHERENS model to
274 the Belgian Continental Shelf (BCS) were used. The OPTOS-BCS model covers an area
275 between 51°N and 51.92° N in latitude and between 2.08° E and 4.2° E in longitude. The
276 horizontal resolution is 0.01183° (longitude) and 0.007° (latitude), corresponding both to

277 about 800 m. Boundary conditions are water elevation and depth-averaged currents, these
278 are provided by OPTOS-NOS, which is also based on the COHERENS code, but covering the
279 whole of the North Sea and part of the English Channel. The OPTOS-NOS model is receiving
280 boundary conditions from the OPTOS-CSM model, which covers the North-West European
281 Continental Shelf. Four semi-diurnal tidal components (M_2 , S_2 , N_2 , K_2) and four diurnal tidal
282 components (O_1 , K_1 , P_1 , Q_1) are used to force the tidal elevation on the open boundaries of the
283 Continental Shelf Model. The current velocities of OPTOS-BCS have been validated using
284 ADCP measurements (Pison and Ozer, 2003).

285 3.3.2 Cohesive sediment transport model

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

298 The values used in the model for the critical shear stress for erosion τ_{ce} have been set to
299 0.5 Pa for freshly deposited mud and 2.0 Pa for the soft to medium consolidated mud of the
300 parent bed (Fettweis and Van den Eynde, 2003). The erosion constant for 100% mud content
301 was set to $0.12 \times 10^{-3} \text{ kg/m}^2\text{s}$. In sediments with lower mud content, which can only occur in
302 the parent bed, the erosion rate is multiplied by the mud fraction. In the model a constant
303 fall velocity of 0.001 m/s has been used. The critical shear stress for deposition τ_{cd} has been
304 set to 0.5 Pa. The SPM concentration condition along the open boundaries of the mud
305 transport model has been constructed using in situ measurements and satellite images
306 (Fettweis et al., 2007).

307 4. Results

308 4.1 Actual cohesive sediment distribution

309 The map in Fig. 3a is based on sediment samples, which have been collected between 2000
310 and 2004, and shows the mud content and the distribution of four major cohesive sediment

311 facies as they emerge from the sample descriptions and the wet bulk density measurements;
312 the consolidation terminology is from the Coastal Engineering Manual (2002) classification.
313 This classification is based on bulk densities for pure cohesive sediments and should be used
314 therefore as an indication; small amounts of sand, which often occur in the mud, may
315 increase the bulk density. The four main facies are:

- 316 1. Clay or mud pebbles, which occur in a sand matrix or on top of mud layers and may
317 indicate eroded (naturally or due to deepening dredging works) and transported tertiary
318 clays or consolidated mud layers (Fig 4a).
- 319 2. Soft to medium consolidated cohesive sediments, which have a wet bulk density (ρ_b) of
320 1500-1800 kg/m³) and indicate Holocene (Fig. 4b) or possibly younger sediments (Fig.
321 4e). Based on the consolidation of the sediment sample it is not always possible to clearly
322 identify the age of the sediment. Holocene mud has typically a layered structure with
323 intercalation of thin sandy layers. Other types of consolidated mud, such as the lower
324 layer in Fig. 4e, are sticky and no clear layering can be visually identified; it corresponds
325 not with the Holocene mud and it is assumed therefore to be of more recent age (up to a
326 few centuries), it is called 'modern mud'. In Fig. 3 no difference between the different
327 types of soft to medium consolidated cohesive sediments is made.
- 328 3. Freshly deposited to very soft consolidated cohesive sediments ($\rho_b = 1300-1500$ kg/m³),
329 which may indicate recent deposits of thick mud layers (Fig. 4c, 4e) or rewetted older and
330 more consolidated mud. Freshly deposited mud occurs typically in the ports below fluid
331 mud layers (Fig. 4f).
- 332 4. Fluid mud ($\rho_b = \pm 1100-1200$ kg/m³), which flows through fingers and occurs as thin
333 surface layers of a few cm (fluffy layers, see Fig. 4d) or thick layers in navigation
334 channels and ports (Fig. 4f).

335 The wet bulk density of box core samples from the nearshore area near Oostende and
336 Zeebrugge ranges between 1088 kg/m³ and 2300 kg/m³, two examples are shown in Fig. 5.
337 A clear distinction can be made in ZB6 core between the very soft layer (<1300 kg/m³) on
338 top, the freshly deposited to very soft consolidated mud (± 1500 kg/m³) between 2 cm and
339 26 cm and the very sticky soft to medium consolidated mud below 26 cm (± 1600 kg/m³)
340 (Fig. 5a). The organic matter content is about 5% in the lower part and 10-20% in the upper
341 part of the ZB6 core; these differences points to a different age of both sediments. The upper
342 part of the density profile is very irregular. These variations in wet bulk density are an
343 indication of tidal deposits and represent an alternation of more and less muddy layers
344 formed in sheltered areas; it is typical that these structures cannot be seen from a visual

345 inspection of the sample. Two radiographies of Reineck core samples taken very close to the
346 ZB6 and ZB2 box core samples show clearly these tidalites (Fig. 6).

347 The wet bulk density of the upper 30 cm of the OE14 core (Fig. 5b), which has been
348 sampled near the old dumping site of Oostende (B&W-O in Fig. 1b) is very low (1200-1400
349 kg/m³). The fact that a thick layer of freshly deposited mud can be deposited points to a
350 protected hydrodynamic environment.

351 **4.2 Age and accumulation rates based on radio-isotopes of recent samples**

352 The radioactivity of ²¹⁰Pb, ²²⁶Ra and ¹³⁷Cs has been measured to determine the age and the
353 accumulation rate of the sediments in two box-core samples. The OE11 core has been taken
354 in March 2004 near the old dumping place of Oostende and consists (B&W-O in Fig. 1b) of
355 43 cm of freshly deposited to soft consolidated mud (similar as Fig 4c). In the ZB6 core,
356 which has been sampled in November 2002 northeast of the port of Zeebrugge (see Fig. 1b),
357 two clearly different parts have been distinguished: the upper 19 cm consist of freshly
358 deposited to soft consolidated mud (1400-1500 kg/m³) intercalated with thin more sandy
359 layers and the lower 29 cm of medium consolidated mud (similar as Fig. 4e and 5a). On top
360 is a thin layer of freshly deposited mud (\pm 1300 kg/m³). The radio-isotope profiles in both
361 box cores are irregular as can be seen from Fig. 7 and 8.

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

377 • The peak in ¹³⁷Cs activity between 17 cm and 33 cm below the surface in the
378 OE11 core has been ascribed to the peak in fall out of atmospheric nuclear bomb tests
379 during the sixties. The apparent accumulation rate for the upper part of the core is

380 then about 0.6 cm yr⁻¹. The lower ¹³⁷Cs peak in this core (37–41 cm) indicates that
381 these sediments are at least younger than 1950 when the significant releases of ¹³⁷Cs
382 into the environment started.

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

392 **4.3 Historical cohesive sediment distribution**

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

406 Areas where an accumulation of sediment is observed are found in a parallel band of 5
407 km width along the coast line (Fig. 9). The highest accumulation (± 3 m) occurs between
408 Oostende and Zeebrugge, an area which corresponds with high mud contents at the end of
409 the 19th and the beginning of the 20th century (see Fig. 3b) just before and during the
410 construction works. The hydrographic chart of Stessels (1866) shows the occurrence of pure
411 mud at the same location. East of the port near-field accretion of mainly sand occurred (not
412 shown in Fig. 3); important morphological changes in the area continue until today.
413 Comparison between the hydrographical maps of 1866 and 1911 (Fig. 9) indicates that these
414 changes have started before the construction of the port of Zeebrugge and could thus be the

415 result of a natural morphological evolution. However, human influences such as the
416 construction of coastal defence structures in the 19th century along the eastern Belgian coast
417 cannot totally be excluded to explain at least partly these morphological changes. These
418 changes resulted in the formation of a sand bank (called “Het Zand”) at the place where the
419 port is situated nowadays (Van Mierlo, 1899). The most direct impact of the first
420 infrastructure has possibly been to locally reinforce natural morphological trends in
421 decreasing depth, as predicted by Van Mierlo (1897).

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

430 **4.4 Numerical model results**

431 The aim of the model simulations was to simulate the transport and deposition of fine
432 grained sediments using a bathymetry before (i.c. bathymetry of 1959, without port of
433 Zeebrugge) and after the major engineering works have been carried out (bathymetry of
434 2003, with port of Zeebrugge). The bathymetries used to simulate the hydrodynamics and
435 the sediment transport are shown in Fig. 10. The simulations have been carried out during
436 calm weather and lasted one spring-neap tidal cycle. It is assumed that the SPM
437 concentration along the open boundaries of the OPTOS-BCS model is the same for the recent
438 and historic situation. The results are presented in Fig. 11 (2003 situation) and Fig. 12 (1959
439 situation, without Zeebrugge). The figures show that the Belgian and southern Dutch
440 coastal waters are an effective trap for suspended sediments, resulting in the formation of an
441 area of high SPM concentration. During spring tide the SPM concentration reaches a
442 maximum, whereas during neap tide the mud deposition is highest.

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

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

452 **5. Discussion**

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

461 **5.1 Deposition of fine grained sediments**

462 The coastal turbidity maximum is responsible for the availability of fine grained sediments
463 and thus also for the deposition of fresh mud. On most places in the nearshore zone the
464 occurrence of fresh mud is limited to thin layers of maximum a few cm on top of the
465 sediment bed (liquid layer or fluffy layer). The erosion resistance is small and they are
466 resuspended during high currents. The occurrence of fluffy layers cannot be used as
467 indication of variation in cohesive sediment distribution between the past (100 years ago)
468 and today. Thick layers (± 0.5 m) of freshly deposited to very soft consolidated mud (Fig. 4c)
469 however are a good indicator of changes. They occur today in environments which are or
470 have been strongly influenced by human activities such as near dumping places (B&W-O in
471 Fig.1), navigation channels, inside harbours, and in the area around the port of Zeebrugge,
472 see Fig. 3a. These mud layers can easily be distinguished from the older more consolidated
473 cohesive sediments (Fig. 4b and 4e) or the fluffy layers (Fig. 4d). The fact that Gilson did not
474 mentioned the occurrence of thick freshly deposited to very soft mud layers could indicate
475 that they did not occur 100 years ago and that they are a result of human impact into the
476 system. This reasoning is however unbalanced. First, the functioning of Gilson's ground
477 sampler could lead to a washing out of the fresh mud. The sampler is able to penetrate the
478 substratum to about 20 cm when it lies on its side, but its vertical height is limited to about
479 10 cm so that when hauled back, the heavy closing lid may have expelled a more or less
480 large part of the soft to fluid matter; this has been reported once. Second, field description of
481 the samples does often not encompass details on compaction of the sample. Occurrence of
482 thick layers of freshly deposited to very soft consolidated mud have probably occurred in the

483 eastern nearshore area where the sediments consist of mud and the depth soundings indicate
484 “soft” and/or “sticky” bottoms.

485 From a combination of the mud content derived from Gilson’s meta-information (Fig. 3b)
486 and the morphological changes between 1866 and 1911 (Fig. 9) it can be seen that the
487 surface layer consists of mainly mud, which is found in a narrow band along the coastline
488 and corresponds most probably with the freshly deposited to very soft consolidated mud of §
489 4.1. No information is available on the thickness of these layers, but the fact that Gilson
490 sampled the area on several occasions and that he found most of the time muddy sediments
491 leads to the conclusions that the deposits were permanent during the considered interval and
492 could resist the strong currents during spring-tide. Furthermore the metadata of several
493 sampling occasions clearly mentions ‘very soft’ bottom in the area, possibly indicating
494 freshly deposited mud on top; it is however not possible to give a thickness to these deposits,
495 thus it could also indicate a fluffy layer of a few cm or more. Van Mierlo (1908) wrote that
496 after the construction of the first port of Zeebrugge the water depth west of the harbour
497 mole decreased by 2 m due to the deposition of cohesive sediments. The same author wrote
498 that before the port construction, a layer of 60 cm of mud was deposited in the same area
499 over a period of 10 years, this corresponds with a accumulation rate of 6 cm/yr. If these
500 sediments still exist today, then it is expected that they fit the class ‘soft to medium
501 consolidated’ and correspond thus with modern mud. Although the recent sampling
502 resolution is generally lower than Gilson’s one, freshly deposited to very soft consolidated
503 thick mud layers (>30 cm) in this narrow coastal band have only been found today near the
504 old dumping place of Oostende (B&W-O). In some samples this mud is deposited on soft to
505 medium consolidated mud (see box core OE14 in Fig. 5), the latter corresponds possibly with
506 the freshly deposited mud layers of the beginning of the 20th century. The deposition of the
507 freshly to very soft consolidated mud near B&W-O started after the 1950ties as was detected
508 from the radiometric measurements of the OE11 box core (see § 4.2) and was only possible
509 because the modification of the bathymetry created a hydrodynamic protected area. Van
510 Lancker et al. (2004) have studied using different bathymetrical maps from 1955 up to 1997
511 the morphological evolution of the area around B&W-O. They conclude that the water depth
512 decreased on the dumping place and that north and south of the dumping place two
513 channels were formed. The decrease in water depth was initiated by the dumping activities
514 and was followed by morphological changes.

515 Other areas today with important depositions of fresh mud are the navigation channels,
516 the harbours and – more interesting – the area situated a few km north of the port of
517 Zeebrugge (see Fig. 3a), such as the recent mud found at ZB6. This deposition is probably

518 related to the extension of port of Zeebrugge in the 1980ties, as was deduced from the
519 radiometric measurements (§ 4.2). The results of the numerical model simulations suggest
520 that solely the deepening of the bathymetry and the extension of the outer port of Zeebrugge
521 are responsible for a decrease in SPM concentration and an increase in mud deposition
522 between the 1959 and the 2003 situation in the area around Zeebrugge. Keeping in mind the
523 limitation of the model (resolution, 2D simulation) they also show that the extension of the
524 port of Zeebrugge results in mud deposition near the port; a feature not occurring in the
525 1959 model.

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

534 **5.2 Increased erosion of Holocene or tertiary mud**

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

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

544 On other places the occurrence of mud or clay pebbles may indicate erosion of old mud
545 (Holocene or modern) or tertiary clay. Near the sampling site MOW1 (Fig 1) Holocene mud is
546 outcropping; it is covered by an ephemeral fine sand layer of 1 to 10 cm. Mud lenses have
547 been observed in the sand indicating probably erosion of the underlying Holocene mud.
548 Interesting in the OE11 core is the lower ²¹⁰Pb activity in the surface layer (Fig. 8) than
549 between 23 cm and 27 cm below the surface where a maximum is found. The observed
550 profile could be explained by assuming a supply and deposition of mud with a low ²¹⁰Pb
551 content. Possible sources are from the erosion of the Holocene mud and from capital
552 dredging works, which may bring Holocene and Tertiary fine grained sediments in

553 suspension. Similar observations from elsewhere have been reported by Ten Brinke et al.
554 (1995) and Andersen et al. (2000). Variation in industrial ^{226}Ra discharges and the closing
555 down of the BASF–Antwerpen discharges in 2002 could also give an explanation for the
556 decreasing ^{210}Pb activity. Quantitative information on transport and diffusion of ^{226}Ra from
557 the Schelde estuary towards the southern North Sea is however not known to confirm this
558 explanation.

559 **5.3 Dredging and dumping effects**

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

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

577 The dumping of fine grained sediment increases temporarily the SPM concentration by
578 50–100 mg/l in a diameter of 20–40 km around dumping place B&W–S1 and increase the
579 deposition of mud north of the dumping place (Van den Eynde and Fettweis, 2004). The
580 seasonal averaged SPM concentration in this area as derived from satellite images and in situ
581 measurements amounts to 25 mg/l \pm 100% in summer up to 100 mg/l \pm 70% in winter
582 (Fettweis et al., 2007). If the assumption that the SPM transport has not changed globally in
583 the southern North Sea in the last 100 years is valid, then it can be concluded from these
584 results and from the model results of § 4.4 that the turbidity maximum area has shifted in
585 the last 100 years more offshore, because SPM concentration near the dredging areas has
586 slightly decreased due to deposition, while around the dumping places it has increased.

587 **5.4 Changes in storminess**

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

601 **6. Conclusion**

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

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

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

645 7. **Acknowledgements**

646 This study was partly funded by the Belgian Science Policy within the framework of the
647 MOCHA and HINDERS projects and partly by the Maritime Access Division of the Ministry of
648 the Flemish Community in the framework of the MOMO project. The measurements have
649 been collected onboard of the R/V Belgica. We wish to acknowledge Virginie Pison (MUMM),
650 Johan Paridaens (SCK-CEN) and Paul Fettweis who have greatly improved the paper during
651 the many discussions and helpful suggestions. The radioactive measurements have been
652 carried out at the cyclotron of the VUB, P. Van Winckel is greatly acknowledged.

653 6. **References**

654 Ariathurai, C.R., 1974. A finite element model for sediment transport in estuaries. Ph.D.
655 Thesis, Univ. California, Davis, USA.

656 Andersen, T. J., Mikkelsen, O. A., Moller, A. L., Pejrup, M. 2000. Deposition and mixing
657 depths on some European intertidal mudflats based on Pb210 and Cs137 activities.
658 *Continental Shelf Res.*, 20, 1569-1591.

659 Baeteman, C. 1999. The Holocene depositional history of the IJzer palaeovalley (Western
660 Belgian coastal plain) with reference to the factors controlling the formation of
661 intercalated peat beds. In: *Quaternary of Belgium: new perspectives* (Baeteman, C., ed.),
662 *Geologica Belgica*, 2(1-2), 39-72.

663 Baeteman, C. 2004. The Holocene development of a tide-dominated coastal lowland. Western
664 coastal plain of Belgium. *Field Guide. The QRA Third Int. Postgraduate Symp. Fieldtrip,*
665 *September 17th 2004. Belgian Geological Survey, Brussels. 76pp.*

666 Baeteman, C. 2005. Geological map of Belgium. General Sequence map of the Holocene
667 coastal deposits (1/25.000). Map Nieuwpoort-Leke, Oostduinkerke-De Panne,
668 Middelkerke-Oostende. Belgian Geological Survey, Brussels.

669 Baeteman, C. 2007. Roman peat-extraction pits as possible evidence for the timing of coastal
670 changes: An example from the Belgian coastal plain. *Liber Amicorum Prof. Dr. G.J.*
671 *Borger, Uitgeverij Aksant, Amsterdam, in press.*

672 Baeteman, C., Declercq, P-Y. 2002. A synthesis of early and middle Holocene coastal changes
673 in the Belgian lowlands. *Belgeo*, 2, 77-107.

674 Bastin, A. 1974. Regionale sedimentologie en morfologie van de zuidelijke Noordzee en het
675 Schelde estuarium. PhD thesis, Geography-Geology department, Katholieke Univ. Leuven,
676 Belgium, 91pp.

677 Beets, J.D., van der Spek, A.J.F. 2000. The Holocene evolution of the barrier and the back-
678 barrier basins of Belgium and the Netherlands as a function of late Weichselian
679 morphology, relative sea-level rise and sediment supply. *Geologie en Mijnbouw /*
680 *Netherlands J. of Geosc.*, 79, 3-16.

681 Bogemans, F., Baeteman, C. 2003. Kaart en Toelichting bij de Quartairgeologische Kaart
682 Veurne-Roeselare 19-20 (1/50.000). Ministerie van de Vlaamse Gemeenschap, Afdeling
683 Natuurlijke Rijkdommen en Energie, Brussel. 38pp.

684 Bennet, R.H., Lambert, D.N. 1971. Rapid and reliable technique for determining unit weight
685 and porosity of deep-sea sediments. *Mar. Geol.* 11, 201-207.

686 Bouron-Bougé, A. 1972. Applications de la radiographie et de la gammadensimétrie à l'étude
687 des carottes de sédiments meubles, PhD Thesis, Univ. Nantes, France. 159pp.

688 Caillot, A., Courtois, G. 1969. Mesure de la densité d'échantillons de vase en cours de
689 tassement par absorption de rayons gamma. Choix d'un isotope. DR/SAR.S/69-2/AC-MB,
690 Centre d'Etudes Nucléaires de Saclay, France.

691 Coastal Engineering Manual. 2002. Erosion, transport and deposition of cohesive sediments.
692 EM 1110-2-1100 (part III-chapter5).

693 Dawson, A.G., Hickey, K., Holt, T., Elliott, L., Dawson, S., Foster, I.D.L., Wadhams, P.,
694 Jonsdottir, I., Wilkinson, J., McKenna, J., Davis, N.R., Smith, D.E. 2002. Complex North
695 Atlantic Oscillation (NAO) index signal of historic North Atlantic storm-track changes.
696 The Holocene. 12, 363-369.

697 De Jong, F., Bakker, J.F., van Berkel, C.J.M., Dankers, N.M.J.A., Dahl, K., Gätje, C.,
698 Marencic, H., Potel, P. 1999. Wadden Sea Quality Status Report. Wadden Sea Ecosystem
699 No. 9. Common Wadden Sea secretariat, Trilateral Monitoring and Assessment Group,
700 Quality Status Report Group. Wilhelmshaven, Germany.

701 de Kok, J.M., 1994. Numerical modelling of transport processes in coastal waters. Ph.D.
702 Thesis, Univ Utrecht, The Netherlands.

703 Egan, B.A., Mahoney, J.R., 1972. Numerical modeling of advection and diffusion of urban
704 area source pollutants. J. Appl. Meteorology, 11, 312-322.

705 Fettweis, M., Van den Eynde, D. 2003. The mud deposits and the high turbidity in the
706 Belgian-Dutch coastal zone, Southern bight of the North Sea. Continental Shelf Res., 23,
707 669-691.

708 Fettweis, M., Francken, F., Pison, V., Van den Eynde, D. 2006. Suspended particulate matter
709 dynamics and aggregate sizes in a high turbidity area. Mar. Geol., 235, 63-74.

710 Fettweis, M., Nechad, B., Van den Eynde, D. 2007. An estimate of the suspended particulate
711 matter (SPM) transport in the southern North Sea using SeaWiFS images, in-situ
712 measurements and numerical model results. Continental Shelf Res. (in revision)

713 Gilson, G. 1900. Exploration de la mer sur les côtes de la Belgique en 1899. Mémoires du
714 Musées Royal d'Histoire Naturelle de Belgique, I, 81pp.

715 Gilson, G. 1901. A new sounding and ground collecting apparatus. Report of the British
716 Association for the Advancement of Science, 71, 696-697.

717 Houziaux, J.-S. 2007. The Hinder banks: yet an important region for the Belgian marine
718 biodiversity? Final report, Belgian Science Policy Office, PADD II program. 80 pp.

719 Johnson, B., Trawle, M.J., Adamec, S., 1988. Dredged material disposal modelling in Puget
720 Sound. J. Waterway Port Coastal Ocean Eng., 114, 700-713.

721 Krone, R.B., 1962. Flume studies of the transport of sediment in estuarial shoaling processes,
722 Hydraulic and Sanitary Engineering Research Laboratory, Univ. California, Berkeley,
723 USA.

724 Le Bot, S., Van Lancker, V., Deleu S., De Batist M., Henriët J.P. 2003. Tertiary and
725 Quaternary geology of the Belgian Continental Shelf. Belgian Science Policy, Final report
726 D/2003/1191/12, 75pp.

727 Luyten, P. J., Jones, J. E., Proctor, R., Tabor, A., Tett, P., Wild-Allen, K. 1999. COHERENS A
728 Coupled Hydrodynamical-Ecological Model for Regional and Shelf Seas: User
729 Documentation. MUMM report, Brussels. 911pp. [Available on CD-ROM at
730 <http://www.mumm.ac.be/coherens>].

731 Maréchal, R. 1993. A new lithostratigraphic scale for the Palaeogene of Belgium. Bulletin van
732 de Belgische Vereniging voor Geologie, 102, 215-229.

733 Missiaen, T., Murphy, S., Loncke, L., Henriët, J.-P. 2002. Very high-resolution seismic
734 mapping of shallow gas in the Belgian coastal zone. Continental Shelf Res., 22, 2291-
735 2301.

736 Paridaens, J., Vanmarcke, H. 2000. Inventarisatie en karakterisatie van verhoogde
737 concentraties aan natuurlijke radionucliden van industriële oorsprong in Vlaanderen.
738 SCK-CEN Departement Stralingsbeschermingsonderzoek, Mol. BLG 884, 44pp.

739 Pison, V., Ozer, J. 2003. Operational products and services for the Belgian coastal waters. In:
740 Building the European capacity in operational modeling, Proc. 3rd Int. Conf. on EuroGOOS
741 (Dahlin, H., Flemming, N.C., Nittis, K., Petersson, S.E., eds.). Elsevier Oceanography Series
742 69, 503-509.

743 Preiss, K. 1968. Non-destructive laboratory measurement of marine sediment density in a
744 core barrel using gamma radiation. Deep-Sea Res., 15, 401-407.

745 Stessels, 1866. Carte générale des bancs de Flandre compris entre Gravelines et l'embouchure
746 de l'Escaut. Ministre des affaires étrangères, Anvers, Belgium.

747 Strubbe, J. 1987. De Belgische Zeehavens: erfgoed voor morgen. Lannoo, Belgium. 181 pp.

748 Ten Brinke, W. B. M., Augustinus, P. G. E. F., Berger, G. W. 1995. Fine-grained sediment
749 deposition on mussel beds in the Oosterschelde (The Netherlands), determined from
750 echosoundings, radio-isotopes and biodeposition field experiments. Estuarine Coastal Shelf
751 Sc., 40 (2), 195-217.

752 Urbain, 1909. Carte "Mer du Nord, Dunkerke - Flessingue". Royaume de Belgique, Service des
753 Ponts et Chaussées, report n 687. (including updates from 11/05/1911).

754 Van den Eynde, D. & Fettweis, M. 2004. Modelling of fine-grained sediment transport and
755 dredged material on the Belgian Continental Shelf. J Coastal Res., SI 39, (ICS 2004
756 Proceedings).

757 Van den Eynde, D., Nechad, B., Fettweis, M. & Francken, F. 2006. SPM dynamics in the
758 southern North Sea derived from SeaWifs imagery, in situ measurements and numerical

759 modelling. In: Estuarine and Coastal Fine Sediment Dynamics (Maa, J. P.-Y., Sanford, L.
760 P., Schoelhammer, D. H., eds.). Proc. Marine Sc., Vol. 8, Elsevier.

761 Van Lancker, V., Deleu, S., Bellec, V., Le Bot, S., Verfaillie, E., Fettweis, M., Van den Eynde,
762 D., Francken, F., Pison, V., Wartel, S., Monbaliu, J., Portilla, J., Lanckneus, J., Moerkerke,
763 G., Degraer, S. 2004. Management, research and budgeting of aggregates in shelf seas
764 related to end-users (Marebasse). Belgian Science Policy, Scientific report 2, 144pp.

765 van Loen, H., Houziaux, J.-S., Van Goethem, J. 2002. The collection Gilson as a reference
766 framework for the Belgian marine fauna: a feasibility study. Belgian Science Policy, Final
767 Report MN/36/94, 41pp.

768 Van Mierlo, C.-J., 1897. Quelques mots sur le régime de la côte devant Heyst. Annales de
769 l'association des ingénieurs sortis des écoles spéciales de Gand, tome XX, 4^e livraison.

770 Van Mierlo, C.-J., 1899. La carte lithologique de la partie méridionale de la mer du Nord.
771 Bulletin de la Société Belge de Géologie, Paléontologie et Hydrologie, XII, 2^{nde} série (III),
772 219–265.

773 Van Mierlo, C.-J., 1908. Le port de Heyst. Annales de l'association des ingénieurs sortis des
774 écoles spéciales de Gand, 4^e série (I, 3).

775 WASA Group, 1998. Changing waves and storms in the Northeast Atlantic? Bull. American
776 Meteorological Soc., 79, 741–760

777 Weisse, R., van Storch, H., Feser, F. 2005. Northeast Atlantic Storminess as simulated by a
778 regional climate model during 1958–2001 and compared with observations. J. Climate,
779 18, 465–479.

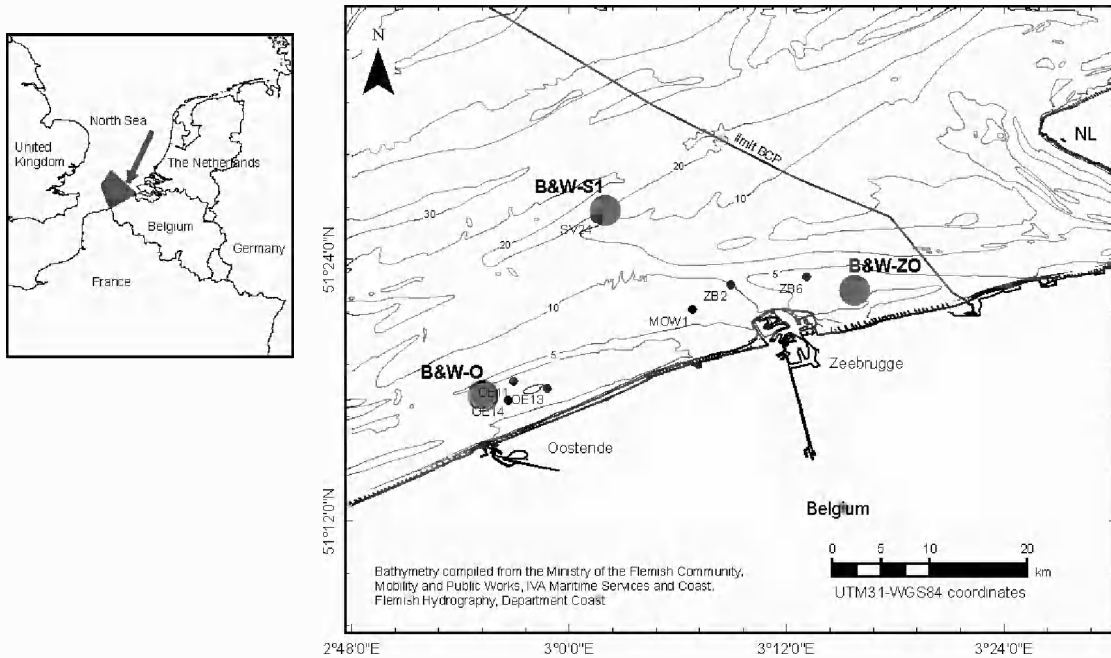


Figure 1: The Belgian-Dutch nearshore area between about Oostende and the mouth of the Westerschelde. The map shows the major dumping sites (B&W-S1; B&W-ZO, B&W-O). The dots on the map indicate the position of box core and Van Veen grab samples, which are discussed in the text.

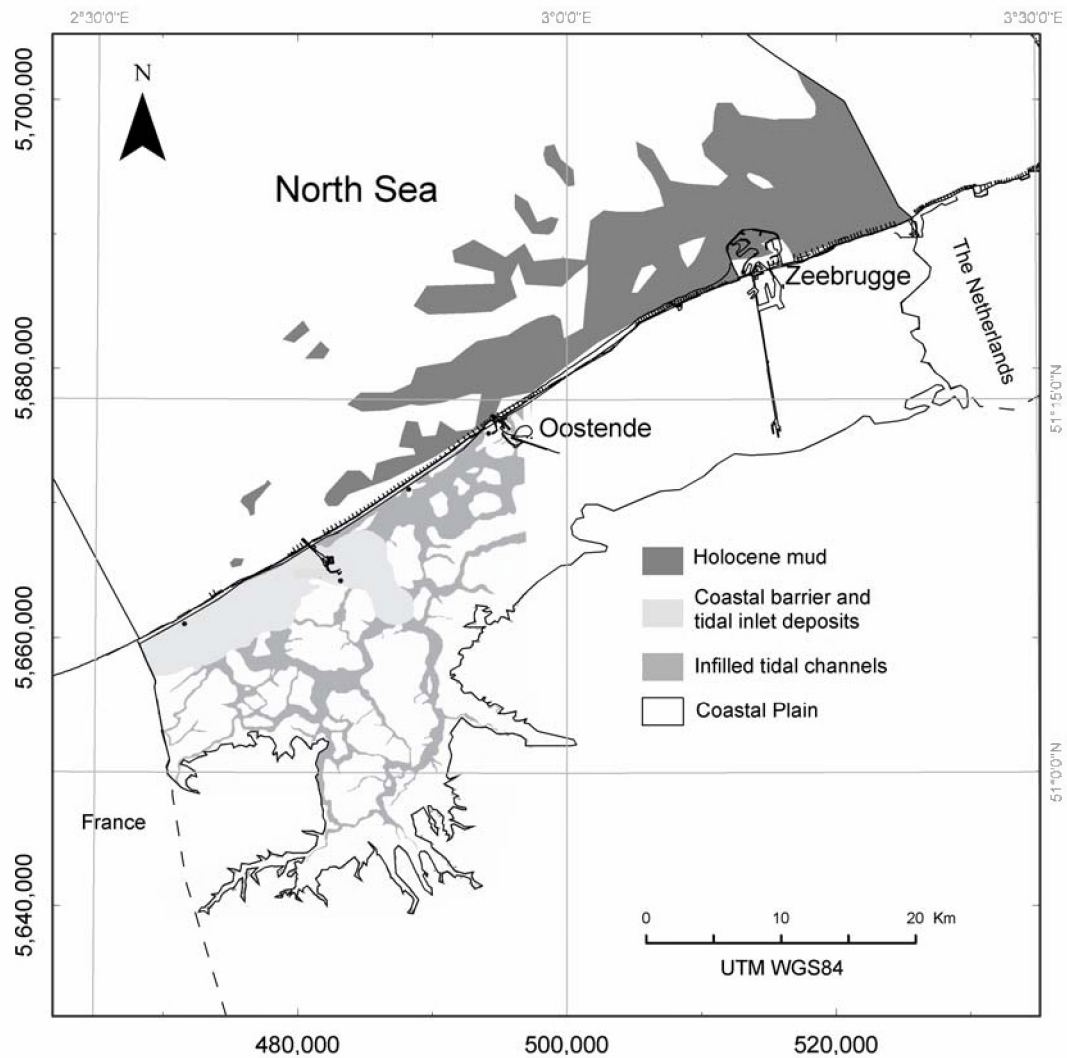


Figure 2: Holocene deposits of the Belgian nearshore zone and the coastal plain. The extension of the Holocene deposits in the coastal plain corresponds with the limits of the Polder. Only the Holocene deposits of the western coastal plain are shown in detail (from Baeteman, 2005).

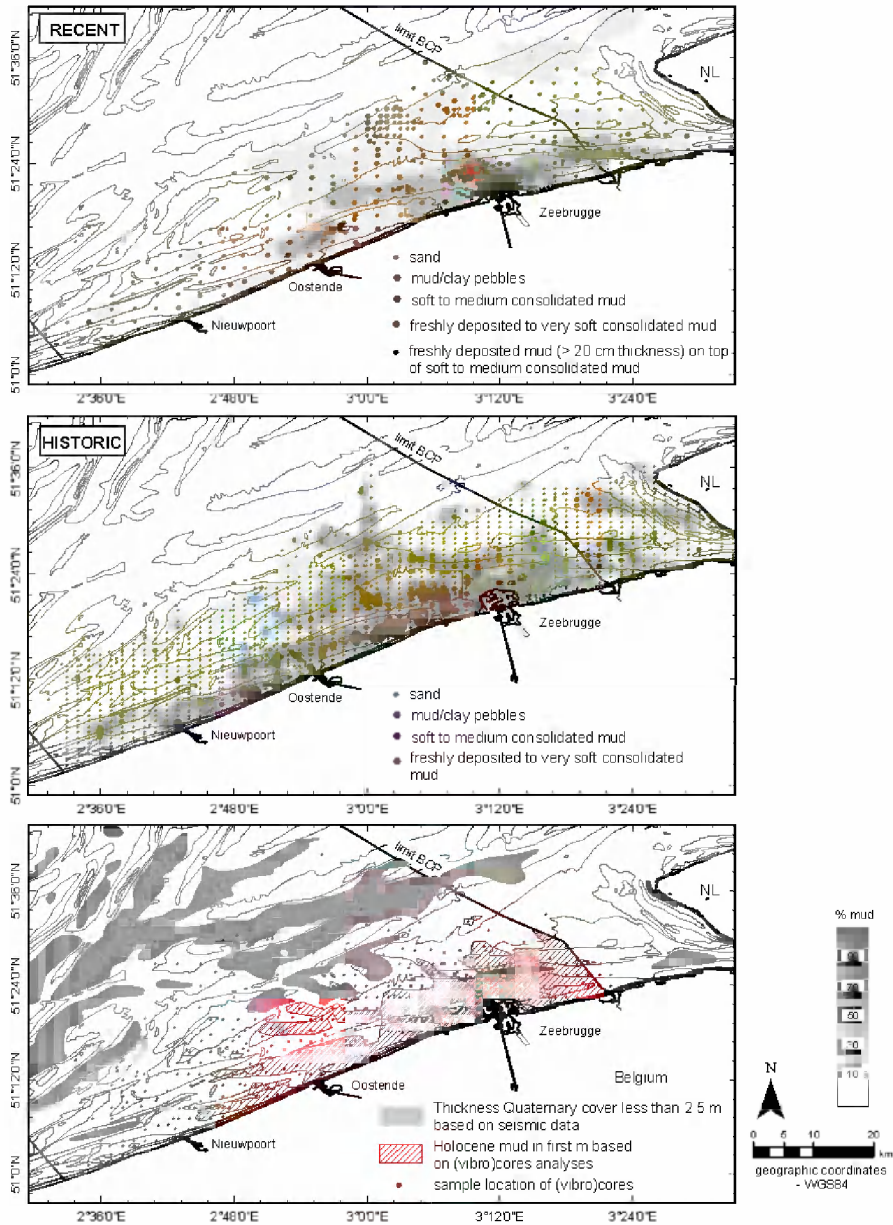


Figure 3: Cohesive sediment facies and mud content in the Belgian–Dutch coastal zone derived from recent (above) and historic (middle) sediment samples. The recent mud content is derived from grain size analysis, whereas the historic mud content distribution is based on metadata, see §3.1. Below is indicated 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).

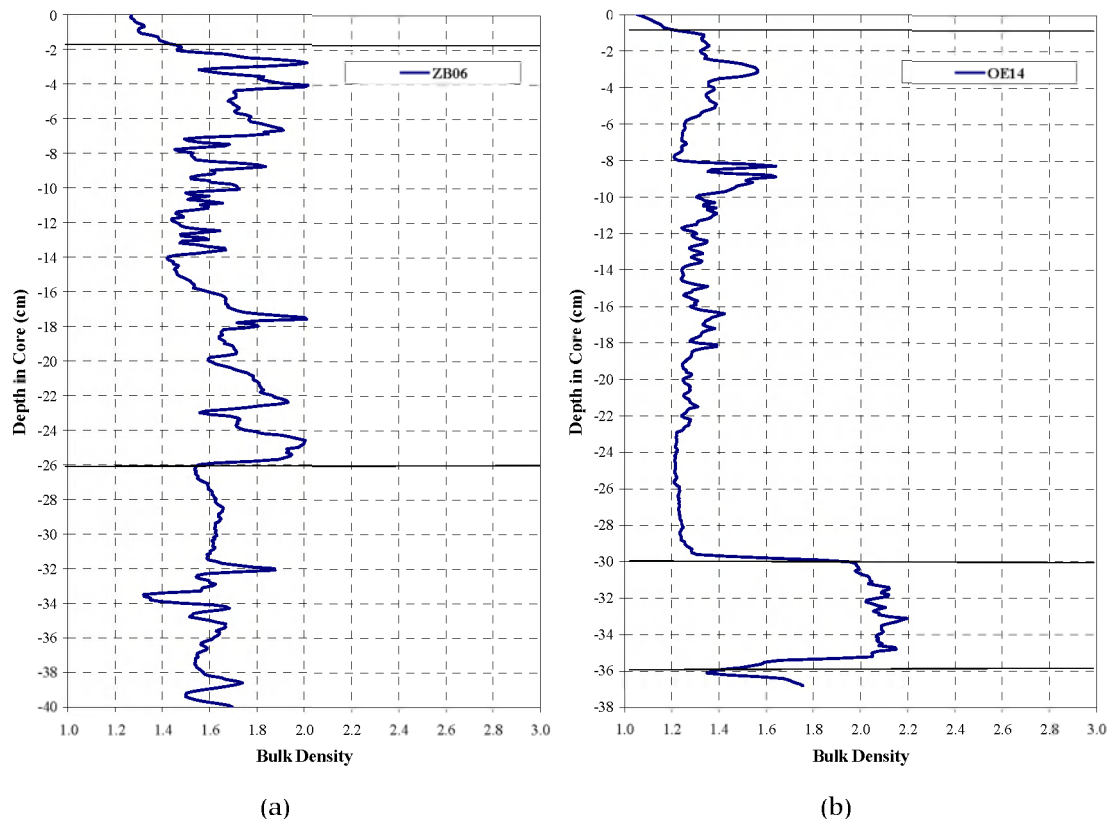


Figure 5: Wet bulk density profiles (kg l⁻¹) of selected box cores. (a) The ZB6 sample (27/11/2002) consist of 24 cm very soft consolidated mud (1.4-1.5 kg l⁻¹), which becomes more sandy in the lower part, above 29 cm of medium consolidated mud (>1.6 kg l⁻¹). On top is a thin layer of freshly deposited 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.

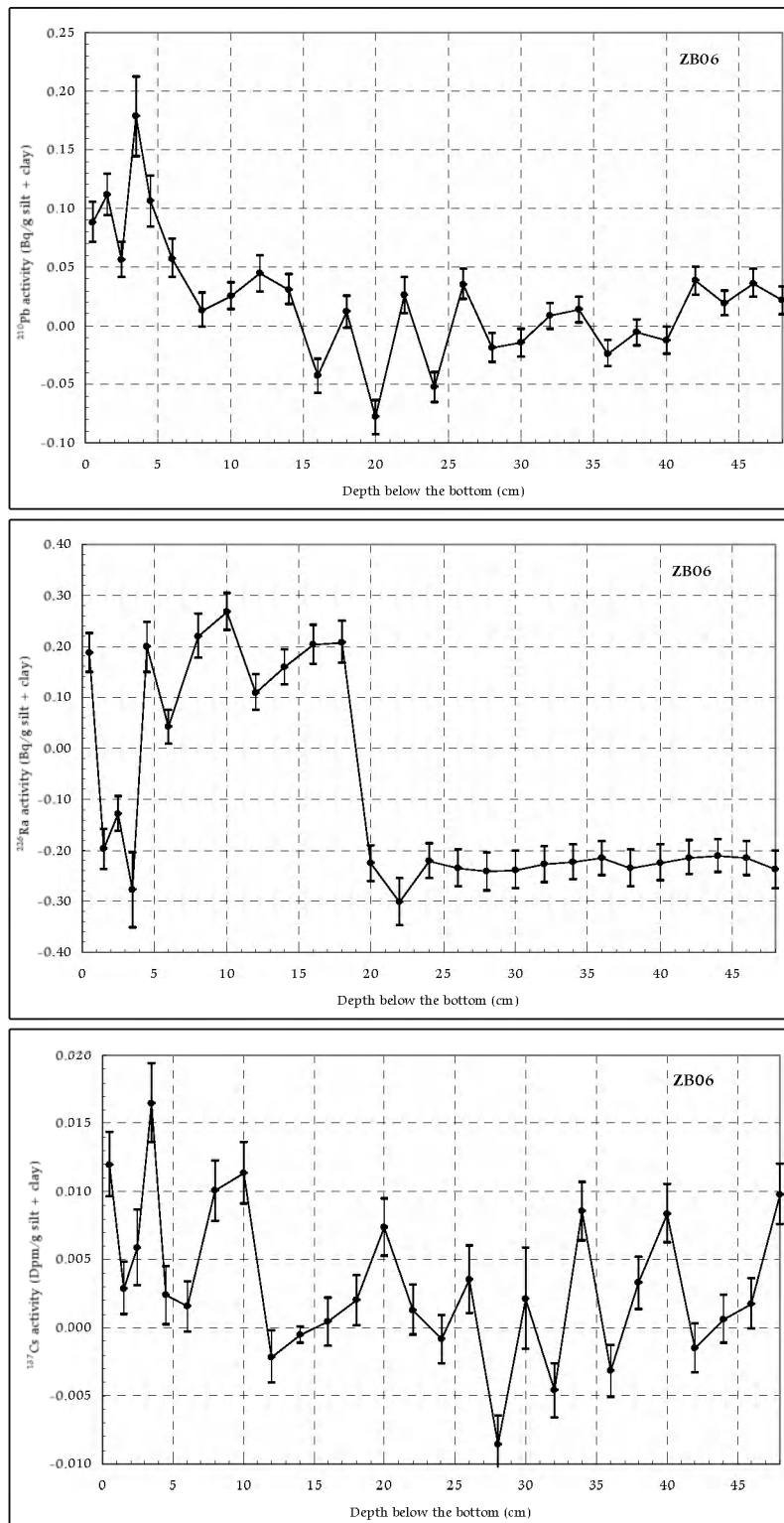


Figure 7: Total ^{210}Pb (above), ^{226}Ra (middle) and ^{137}Cs (below) activities in ZB6 core (27/11/2002). The bars indicate 2σ statistical error limits.

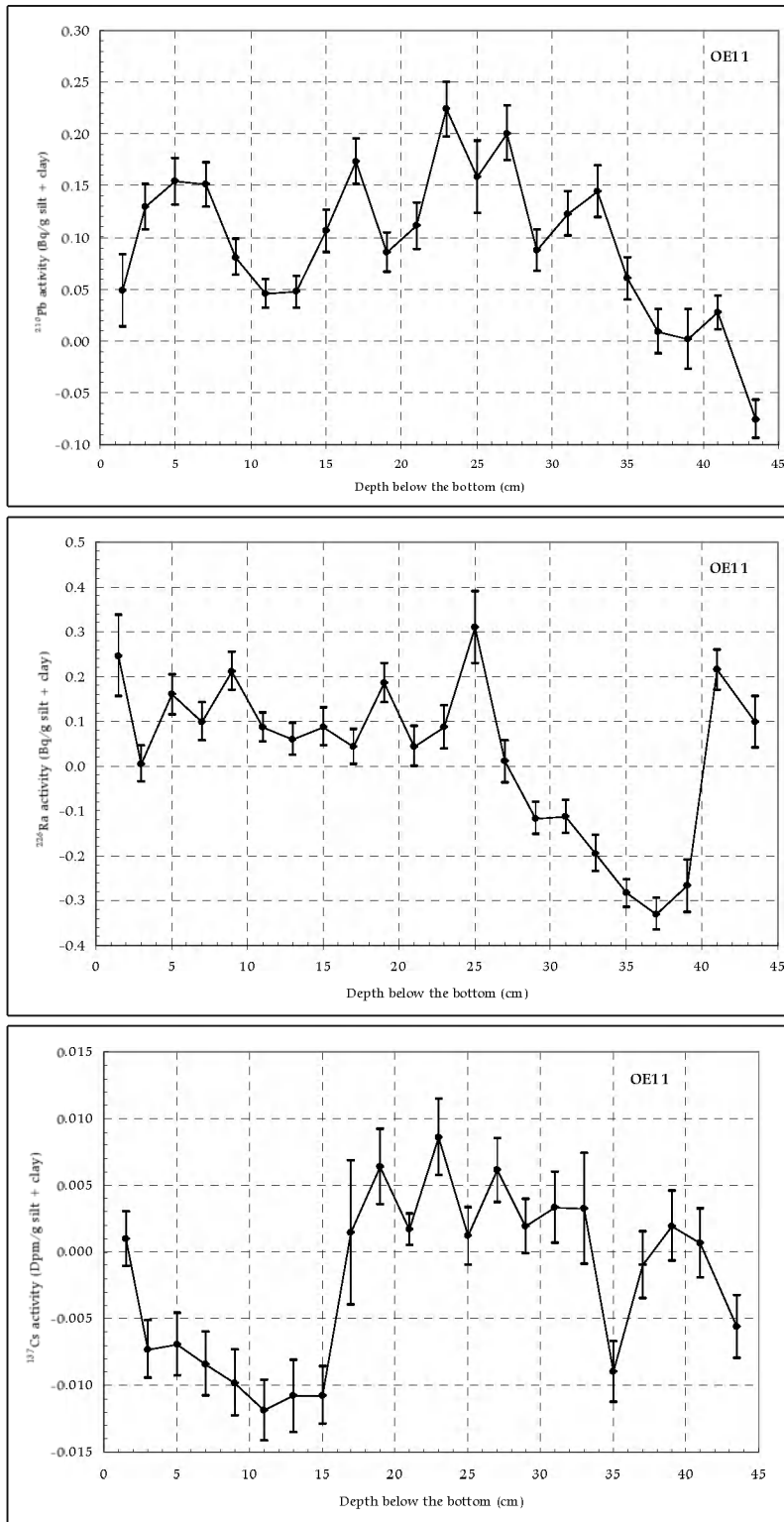


Figure 8: Total ^{210}Pb (above), ^{226}Ra (middle) and ^{137}Cs activities in OE11 core (08/03/2004). The bars indicate 2σ statistical error limits.

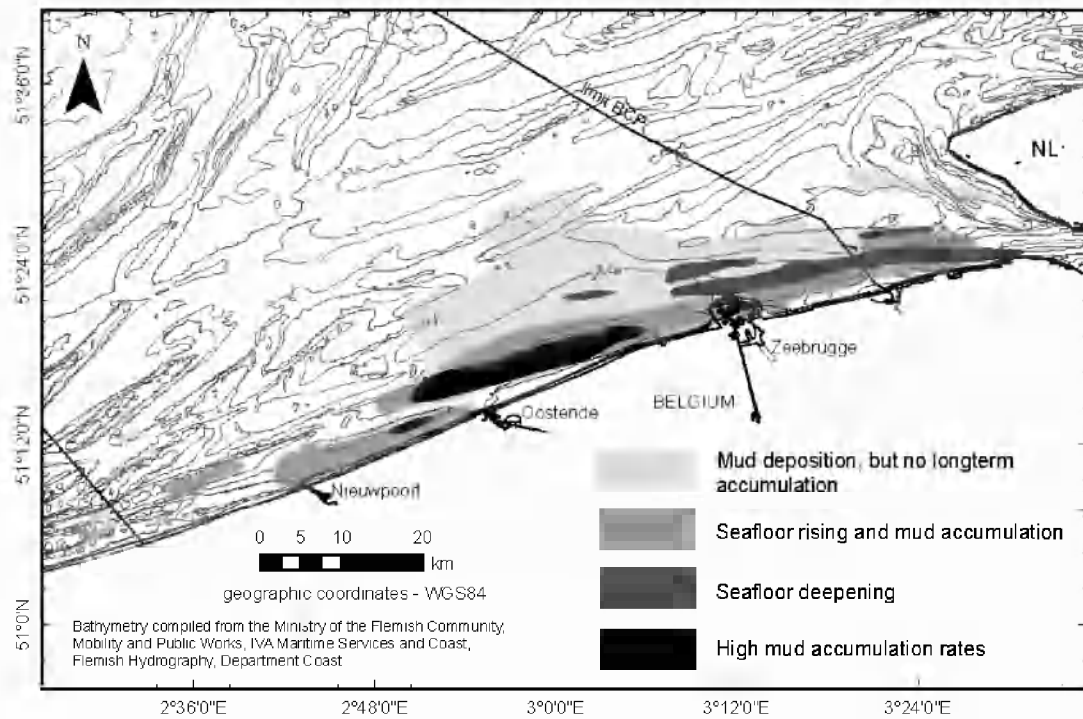


Figure 9: Aggregated trends in mud deposition and seafloor morphology inferred from detailed visual inspection of bathymetric changes (period 1866-1911) and mud content information derived from the historic sediment samples (see Fig. 3).

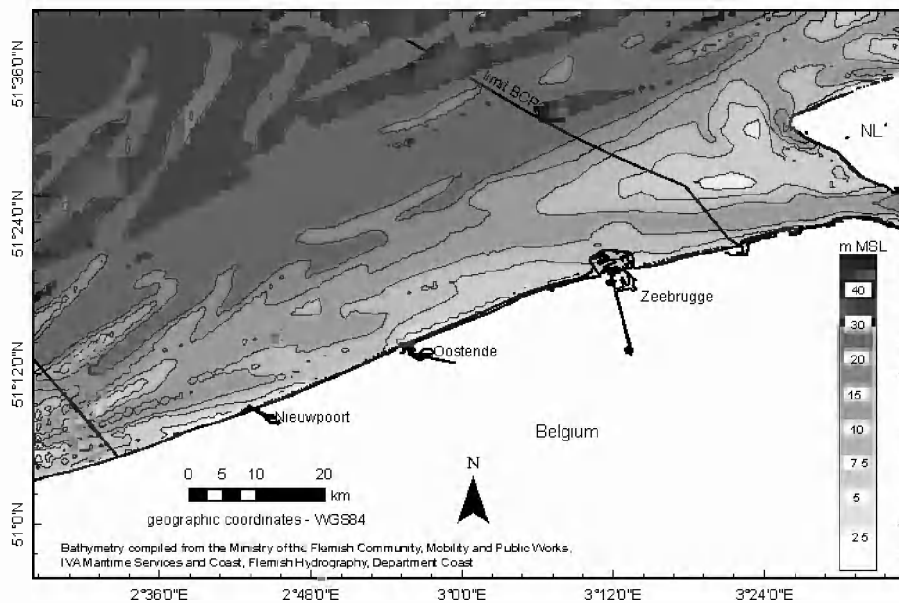
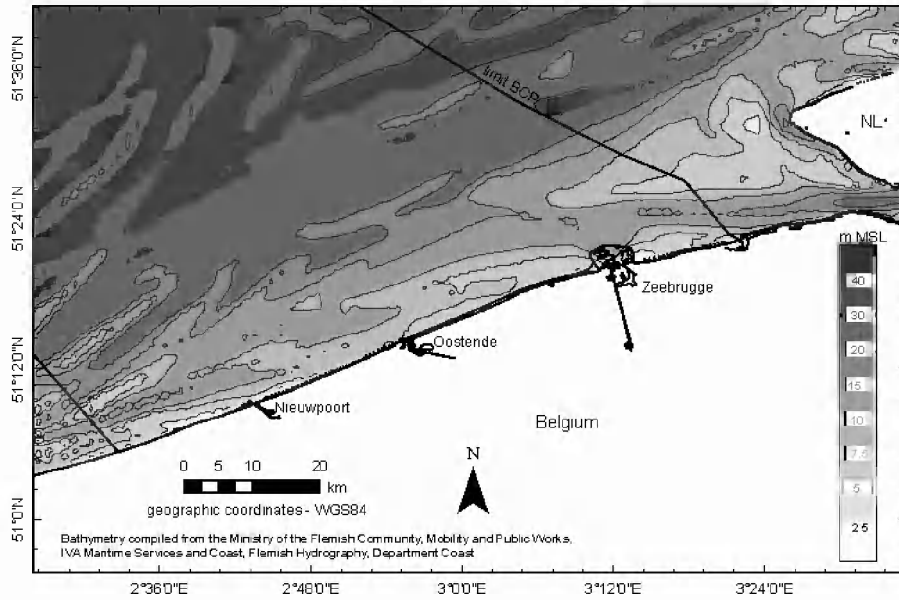


Figure 10: Bathymetry derived respectively from 2003 surveys (above) and from surveys before 1959 (below). Significant differences occur in the coastal zone and navigation channels.

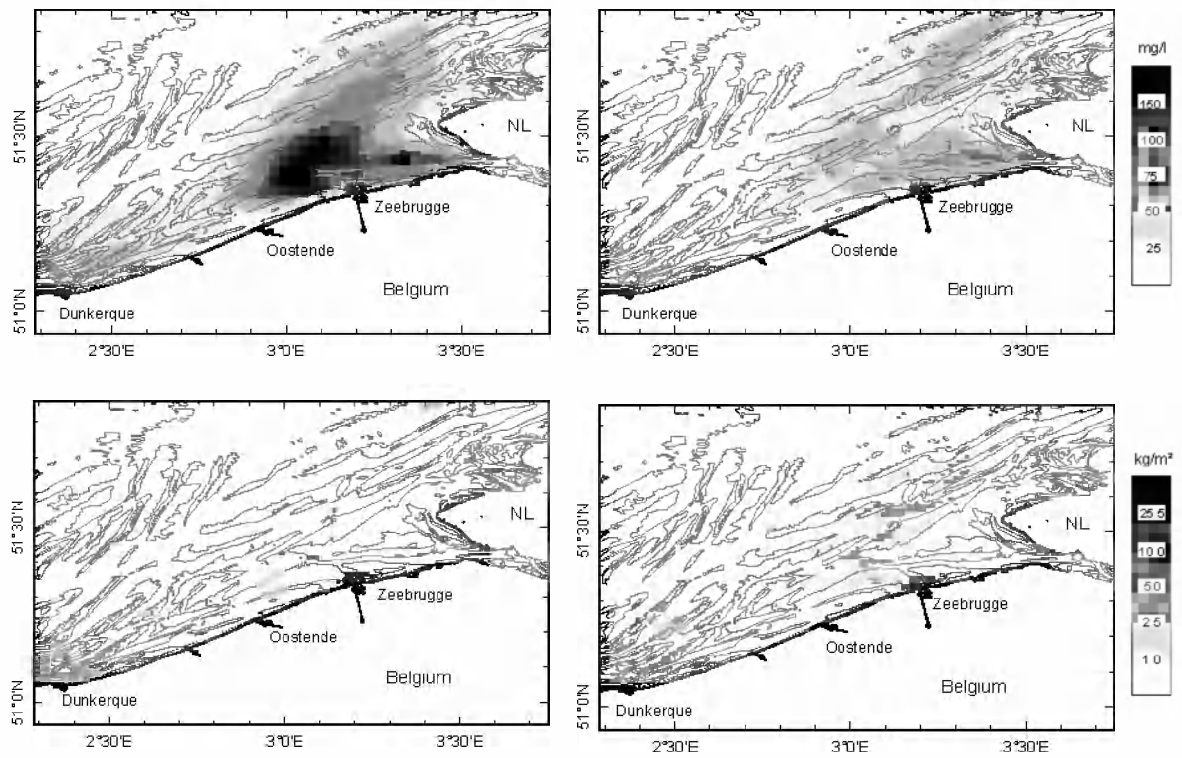


Figure 11: Tidal averaged SPM concentration (above) and mud deposition (below) during a spring tide (left) and a neap tide (right) for the present situation (2003).

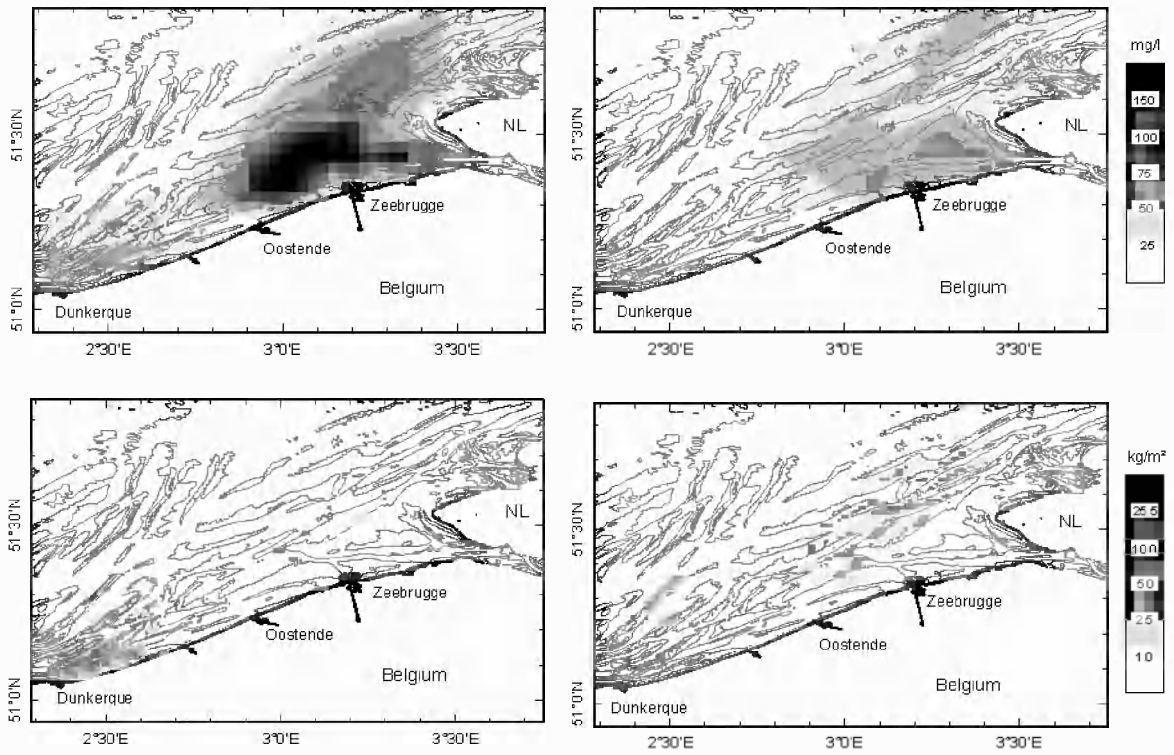


Figure 12: Tidal averaged SPM concentration (above) and mud deposition (below) during a spring tide (left) and a neap tide (right) for the pre-1959 situation.