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SAND NOURISHMENT

ECOLOGICAL AND MORPHOLOGICAL DEVELOPMENT OF A LOCAL SAND NOURISHMENT

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OESTERDAM ZANDSUPPLETIE – SAMENVATTING (EXTENDED SUMMARY IN DUTCH)

ACHTERGROND

In de Oosterschelde is door de aanleg van de stormvloedkering (1986) sprake van 'zandhonger'. Het getij is verminderd, waardoor het evenwicht tussen erosie en sedimentatie is verstoord. Bij rustig weer bouwt het intergetijdengebied zich niet meer voldoende op, terwijl er wel afbraak optreedt tijdens stormen. Dit sediment verdwijnt in de geulen.

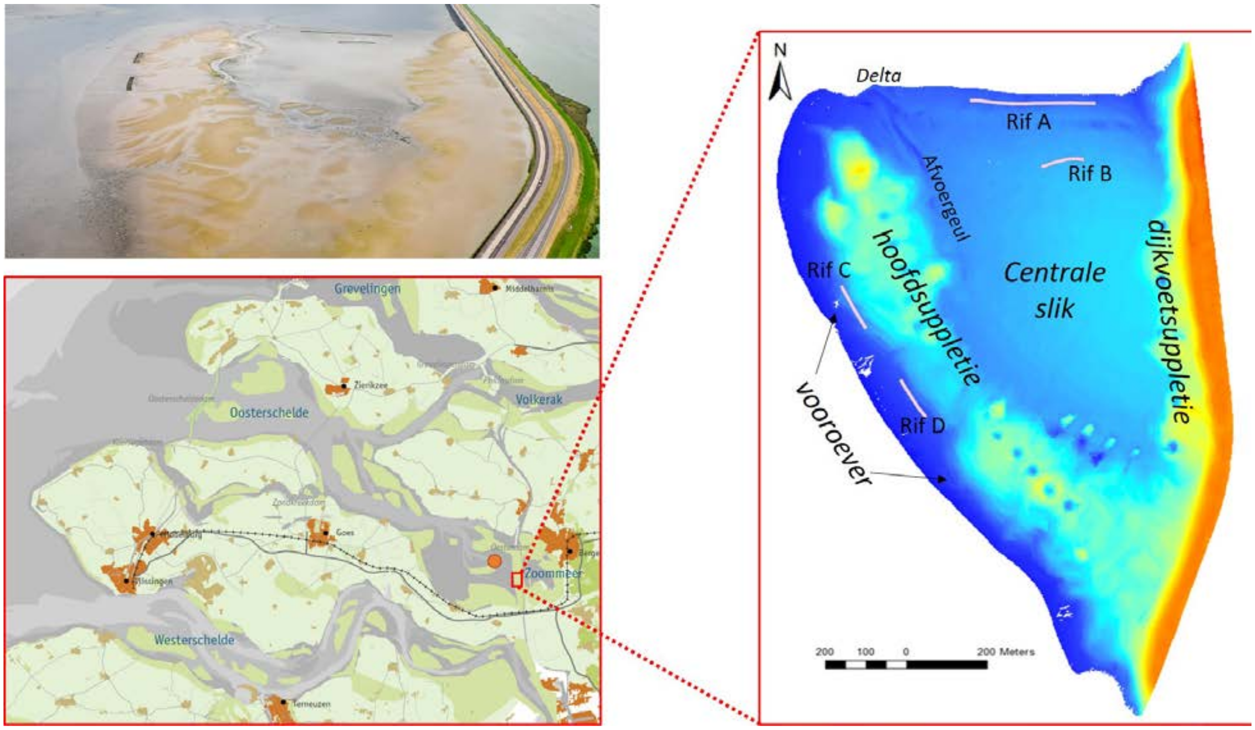
Door de zandhonger neemt het areaal en de droogvalduur van het intergetijdengebied af, dit heeft negatieve effecten voor de ecologie: het areaal droogvallende platen en slikken neemt af, alsmede de duur dat deze platen droogvallen tijdens laagwater. Hierdoor hebben vogels die voor hun voedsel van deze gebieden afhankelijk zijn steeds minder foerageerareaal ter beschikking en wordt ook de tijd dat hun voedsel, de bodemdieren, bereikbaar zijn steeds kleiner. Daarnaast zorgen zandplaten, slikken en schorren voor een natuurlijke demping tegen golven. Dijken met een voorland (slikken en platen) worden minder belast. Door de erosie van de slikken en platen, wordt de levensduur van dijken verkort of moeten dijken zwaarder worden aangelegd. Naast de gevolgen voor natuur en veiligheid, heeft de zandhonger ook een negatieve invloed op de landschappelijke waarden en sociaaleconomische belangen in het gebied.

De Oosterschelde is een Natura-2000 gebied en in dit verband heeft de overheid de verantwoordelijkheid om de natuurdoelen te behouden, te herstellen en eventueel te verbeteren. Voor elk Natura-2000 gebied gelden instandhoudingsdoelen, die aangeven welke leefgebieden en welke soorten (planten en dieren) behouden of hersteld moeten worden. De maatregelen die nodig zijn om de instandhoudingsdoelen te realiseren worden opgenomen in het Beheerplan Deltawateren. Voor het formuleren van deze maatregelen is kennis nodig.

VERKENNING ZANDHONGER

Om na te gaan of de bovengenoemde negatieve effecten van de zandhonger zijn af te remmen of te stoppen heeft Rijkswaterstaat in 2007 een MIRT-verkenning uitgevoerd (zogenaamd: *Verkenning Zandhonger*, Witteveen+Bos, & Bureau Waardenburg, 2013). Het doel van de verkenning is het formuleren van een voorkeursaanpak. Om kennis op te bouwen voor deze voorkeursaanpak is Rijkswaterstaat in de periode 2009-2013 gestart met een vijftal pilots, waar een combinatie tussen de verbetering van de natuurwaarden en verbetering van het veiligheidsniveau is gerealiseerd middels suppleties en/of kunstmatige oesterriffen. Het betreft de proefsuppletie Galgenplaat, Cascadeproef Schelphoek, Oesterriffen bij Viane en de Val (onderdeel van het Building with Nature onderzoeksprogramma), de duinvoetsuppletie Sophiastrand en de zandsuppletie Oesterdam (Schaap, 2012).

De grootste pilot is de zandsuppletie bij de Oesterdam, ook wel Veiligheidsbuffer Oesterdam genoemd, waar in november 2013 350.000 kuub zand is aangebracht binnen het intergetijdengebied, bestaande uit een hoofdsuppletie en een dijkvoetsuppletie; dit in combinatie met vier kunstmatige oesterriffen (Figuur 1), die moeten bijdragen aan een vertraging van het erosieproces. Deze oesterriffen bestaan uit kooien (gabions) gevuld met oesterschelpen en hebben een breedte van 8 m en variërende lengte (100 tot 250 m). Tussen de twee suppleties bevindt zich een ongestoord deel van het slik (centrale slik; Figuur 1). Het doel is dat dit centrale slik wordt beschermd door de hoofdsuppletie en langzaam gevoed wordt met sediment vanuit de hoofdsuppletie.



Figuur 1. Zandsuppletie Oesterdam in september 2016 (linksboven, foto: Edwin Paree). Locatie van de Oesterdam in de Oosterschelde (rechtsonder). Naamgeving van suppletie onderdelen en riffen (links).

Binnen de pilotstudies die door Rijkswaterstaat Zee en Delta zijn geïmplementeerd zijn tal van onderzoeksvragen te stellen die bijdragen aan de nodige kennisontwikkeling met betrekking tot de bestrijding van de zandhonger. Rijkswaterstaat heeft zich in eerste instantie gefocust op de meest essentiële vragen, samengevat in een monitoringsplan (Schaap, 2012). Voor de monitoring en onderzoek van de Oesterdam suppletie heeft Rijkswaterstaat contact gezocht met het Centre of Expertise Delta Technology (CoE-DT), waardoor meer middelen en menskracht beschikbaar kwamen om het onderzoeksproject met een bredere doelstelling uit te kunnen voeren.

DOELSTELLING

De algemene doelstellingen van het overkoepelende project *Veiligheidsbuffer Oesterdam* zijn:

1. Ontwikkelen van een duurzame en veilige oplossing voor de Oesterdam zodanig, dat de Oesterdam gevrijwaard is van te hoge golfaanval, waardoor grote investeringen in versterking van de steenbekleding, als gevolg van de zandhonger met minimaal 25 jaar kunnen worden uitgesteld;
2. Ontwikkelen van een oplossing om het zandhongerprobleem ter plaatse van de Oesterdam aan te pakken zodanig, dat het waardevolle slikkenlandschap en de ecologische functies daarvan de komende vijftig jaar behouden kan blijven;

Het hieraan gekoppelde monitoringsprogramma- en onderzoeksprogramma is onderwerp van dit rapport en heeft de volgende doelstellingen:

3. Bijdragen aan kennisontwikkeling over de processen rond zandhonger en een bijdrage aan de ontwikkeling van flexibel, klimaatbestendig en kosteneffectief kustmanagement door middel van een proefproject op ware schaal;

4. Het onderwijs voorzien van een kwaliteitsimpuls die aansluit bij de behoeften van watersector door studenten te betrekken bij het onderzoek en docent-onderzoekers de kans te geven zich op dit onderzoeksgebied te ontwikkelen;
5. Opzetten van een structureel samenwerkingsverband waarin alle partijen willen investeren. Dit moet bijdragen aan een Centre of Expertise Delta Technology waarin de partners zich herkennen.

ONDERZOEKSMETHODEN

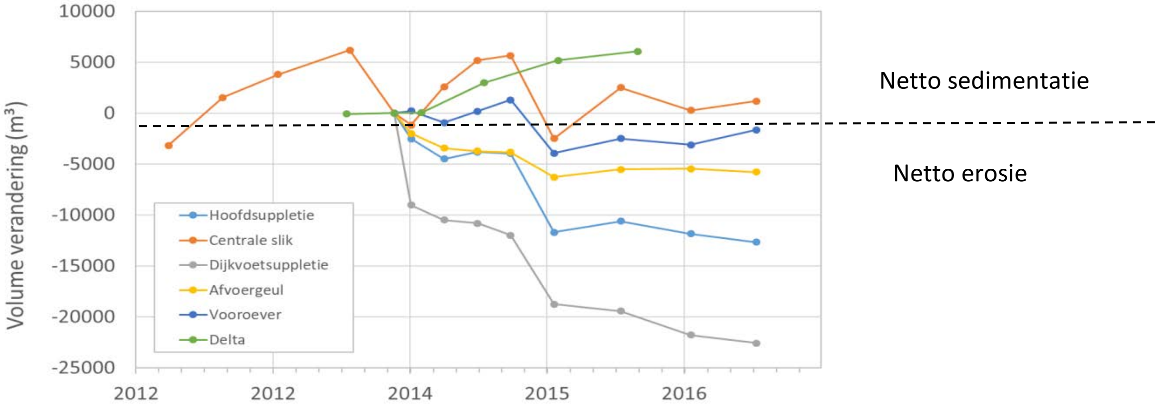
Het monitoring- en onderzoeksproject richt zich op verschillende aspecten: de golfbelasting, stroming en morfodynamiek op basis van de meetgegevens en numerieke modellering (Deltares); de morfologische ontwikkeling van de suppleties en de effecten van de oesterriffen hierop (HZ); de ecologische ontwikkeling en functioneren van suppleties en centrale slik (WMR); toegepast onderzoek naar biofysische interacties tussen bodem en bodemdieren (NIOZ); de biodiversiteit op de oesterriffen (HZ). De methoden zijn in meer detail beschreven in het projectplan (Boersema, et al., 2013).

RESULTATEN EN DISCUSSIE

Morfologie

De morfologische veranderingen op de suppleties worden gedomineerd door golfwerking, dit blijkt uit veldmetingen met mini-zandsuppleties (Ikeya, 2014) en de Delft3D studie van Pezij (2015). Dit is ook in lijn met de bevindingen van eerdere onderzoeken gericht op de veranderingen in de Oosterschelde na het gereedkomen van de Deltawerken. Door de aanleg van de stormvloedkering is de vraag naar zand in de geulen enorm toegenomen en heeft het morfologisch evenwicht tussen golven en het horizontale getij plaatsgemaakt voor een meer golf-gedomineerd systeem.

Na een initiële aanpassing van de hogere delen van de suppletie bij de Oesterdam, versterkt door zetting van het suppletiezand, gaan de ontwikkelingen op de hoofdsuppletie (haakvorm) en de dijkvoetsuppletie geleidelijk. In de meetperiode (11/2013 tot 10/2016) daalt de gemiddelde hoogte van de hoofdsuppletie van -0,28 m NAP naar -0,34 m NAP; dit komt neer op een erosiesnelheid van ongeveer 2 cm/jaar, een verlies van ≈13.000 m^3 over de meetperiode van drie jaar (Figuur 2) of 4.300 m^3/jaar. De dijkvoetsuppletie ligt aanzienlijk hoger en de verwachting was dat dit tot meer erosie zou leiden, vanwege de hogere golfenergie. Dit is ook te zien in de resultaten, de dijkvoetsuppletie erodeerde van 0,78 m NAP naar 0,61 m NAP, een erosiesnelheid van ongeveer 5 cm/jaar en een volume verlies van ≈23.000 m^3 (7.500 m^3/jaar). In totaal verdween in de studieperiode ruim 10% van het gesuppleerd zand uit het studiegebied.



Figuur 2. Erosie en sedimentatie van de verschillende morfologische eenheden op de studielocatie

De centrale getijdenplaat (26 ha) laat in de periode voor de suppletie (2012-2013) een lichte aanzanding zien, na het suppleren in november 2013 is er sprake van zowel erosie als sedimentatie. Er is geen verband zichtbaar tussen de aanwezigheid van de suppleties en de hoogte van de centrale getijdenplaat. Wel neemt de mediane korrelgrootte van de getijdenplaat toe en daarnaast is op orthogonale foto's een kleurverandering zichtbaar die identiek is aan de suppleties. Beide verschijnselen zijn bevestigingen dat er zandtransport mogelijk is van de suppletie naar de getijdenplaat, echter van een substantiële aanzanding is geen sprake. De meetperiode is te kort om te kunnen concluderen dat de aanwezigheid van de suppletie leidt tot een trendbreuk met de periode vooraf gaande aan het suppleren.

Kort na de aanleg van de suppletie ontwikkelt zich een drainagegeul die direct ten oosten ligt van de hoofdsuppletie (Figuur 1). De geul ligt ingeklemd tussen het aflopende centrale slik en de hoofdsuppletie. Hoogtemetingen door de tijd laten zien dat de geulmeanders migreren in noordelijke richting, wat wijst op een eb-dominantie in de stroomsnelheid, wat overeenkomt met de stroomsnelheidsmetingen. De geul erodeert gedurende de meetperiode ongeveer 5000 m^3 (Figuur 1) van het centrale slik en het doorstroomoppervlak bereikt na ongeveer twee jaar een evenwicht met het debiet. Het geërodeerde materiaal komt terecht in een delta. De geul wordt niet groter en lijkt geen bedreiging te vormen voor de hoofdsuppletie.

Uit het numerieke modelonderzoek (Delft3D) blijkt dat de morfologische ontwikkeling van de Oesterdamsuppletie voornamelijk bepaald wordt door de gecombineerde werking van getij en golven. Golven zorgen voor sedimentopwoeling en het sediment wordt vervolgens door de getij- en golf gedreven stroming getransporteerd.

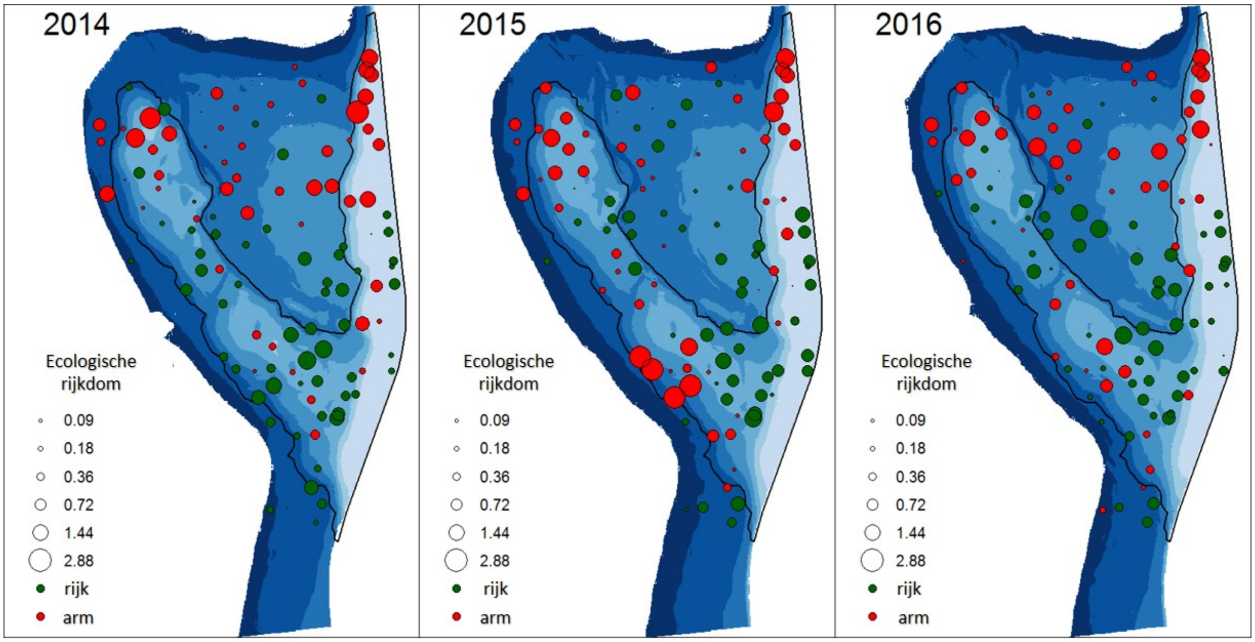
Golfbelasting gedurende maatgevende stormcondities

Uit het modelonderzoek blijkt dat onder alledaagse windcondities, golven maar beperkt energie verliezen door golfbreking op de hoofdsuppletie. Golven worden vooral kleiner door bodemwrijving en brekende golven ("white capping"). Gedurende hoogwater kunnen de golven weer groeien op het centrale slik. Gedurende maatgevende stormcondities met een waterstand van 4 m NAP heeft de hoofdsuppletie een zeer klein effect op de golfhoogtes. Het is dan met name de dijkvoetsuppletie die een reducerend effect heeft. Een doorgaande erosietrend van de suppletie resulteert naar verwachting in een sterke toename van het berekende debiet dat over de Oesterdam stroomt tijdens maatgevende condities. De suppleties zorgen voor ca. 50% afname van de berekende golfbelasting tijdens maatgevende condities en heeft hiermee ook een sterk reducerend effect op de overslagdebieten.

Ecologie

De Oesterdam suppleties laten een snelle rekolonisatie zien van de benthische macrofauna (bodemdieren > 1 mm). Na één jaar (2014) is de soortenrijkdom op de suppleties al grotendeels hersteld en zijn de aantallen gelijk of zelfs groter in vergelijking met het centrale slik. De biomassa blijft in dat jaar echter nog achter op de suppleties omdat het voor een deel gaat om jonge individuen van bv schelpdieren en/of kleine soorten als wadslakjes. In 2015 en 2016 herstelt de soortenrijkdom verder en is de biomassa gelijkaardig als op het centrale slik, maar de gemeenschappen zijn nog steeds verschillend tussen de suppleties en het centrale slik. Een verschil in sedimentsamenstelling (mediane korrelgrootte op respectievelijk centraal slik, hoofdsuppletie en dijkvoetsuppletie 185-192 μm, 275-296 μm, en 287-307 μm) en droogvalduur (29%, 43%, en 64% op respectievelijk centraal slik, hoofdsuppletie en dijkvoetsuppletie) verklaren mogelijks deels het verschil in gemeenschapsstructuur.

De kolonisatie van de suppleties verloopt niet homogeen, sommige delen laten een hogere soortenrijkdom, aantallen en biomassa zien dan andere delen; er is sprake van een sterke ruimtelijke variatie. Sommige gebieden zijn aan te duiden als ecologische 'hotspots'; deze gebieden liggen aan de lijzijde (of oostzijde) van de hoofdsuppletie meer beschut. Andere gebieden zijn aan te duiden als ecologische 'coldspots', gekenmerkt door minder hydrodynamische beschutting en meer dynamiek in de sedimentatie en erosie. Hier zijn aantal soorten, aantallen en biomassa's significant lager. Over de periode 2014, 2015 en 2016 gaat het om respectievelijk 53, 54 en 53 soorten op de zandsuppleties.



Figuur 3. Verspreidingskaart van de ecologische rijkdom op de Oesterdam in 2014, 2015 en 2016. Ecologische rijkdom is een gecombineerde maat op basis van soortenrijkdom, aantallen en biomassa. Een positieve ecologische rijkdom (groene kleur) wijst op een relatief rijk bodemleven, een negatieve ecologische rijkdom (rode kleur) op een relatief arm bodemleven.

Tijdens de onderzoeksperiode (2014-2016) lieten de kokkel, tapijtschelp en het nonnetje een succesvolle broedval zien op de suppleties, wat heeft bijgedragen aan een snelle kolonisatie van de suppleties. De kokkelbestandsopname laten ook zien dat 2014 en 2016 succesvolle broedval jaren waren (Troost *et al.* 2017). De kokkel liet ook een goede broedval zien op het centrale slik, terwijl dit in mindere mate is waargenomen voor de andere twee soorten. In 2015 en vooral 2016 zijn er zeer hoge dichtheden van de kokkel waargenomen (lokaal meer dan 2000 individuen per m^2). De kokkel is dan ook met afstand de soort die het meeste bijdraagt aan de biomassa. Qua aantallen domineert het wadslakje in het gebied. De wadpier is in aantallen afgenomen op de suppletie, maar ook op het centrale deel. De oorzaak hiervan is onbekend. In 2017 is er in de oksel tussen de hoofdsuppletie en de damvoetsuppletie én op de damvoetsuppletie klein zeegras aangetroffen. Deze planten zijn waarschijnlijk afkomstig van de zich sterk uitbreidende klein zeegraspopulatie op het slik in de omgeving van Krabbendijke.

De scholekster en de wulp foerageren in het hele gebied, inclusief in de gesuppleerde gebieden (vooral de hoofdsuppletie). Andere soorten steltlopers werden maar zelden waargenomen, terwijl deze wel gebruik maken van de gebieden ten zuiden van het studiegebied. Door de snelle kolonisatie van benthische macrofauna, vooral de tweekleppige soorten, biedt het gebied potentieel foerageermogelijkheden voor de kanoet; maar ook andere soorten kunnen hier potentieel goed foerageren. De afwezigheid van andere soorten steltlopers in het gebied zou te maken kunnen hebben met de verstoring door mensen. Het gebied wordt frequent gebruikt door pierenspitters, wandelaars, vaak met loslopende honden, en kitesurfers. Voor deze laatste is de Oesterdam een belangrijk hotspot gebied geworden en bieden de suppleties, wegens hun zandige karakter, een ideale toegang tot het gebied. Deze vormen van recreatie hebben zondermeer een negatieve impact op de geschiktheid van het gebied als foerageergebied voor vogels.

Biofysische interacties tussen bodem en bodemdieren

Er is een aantal experimenten uitgevoerd, zowel in het veld als in het laboratorium. De veldexperimenten toonden dat het defauneren van een stuk getijdeplaat (d.w.z. test-plot van een paar vierkante meter ontdoen van alle bodemdieren) soms verrassend weinig effect had op de morfologische ontwikkeling van de test-plot. Dit was zeer opmerkelijk gezien de enorme effecten die waren gemeten in eerdere defaunatie experimenten bij Paulinapolder (Montserrat *et al.* 2008). De verklaring werd gevonden door het uitvoeren van stroomgootexperimenten. Samenvattend toonden deze experimenten het volgende:

- Bodemdieren hebben geen effect op de erodeerbaarheid van zandige substraten;
- Bodemdieren kunnen de erodeerbaarheid van slibrijke en cohesieve sedimenten sterk verhogen;
- De impact van de bodemdieren op de erodeerbaarheid is globaal gezien proportioneel aan de biomassa van de aanwezige dieren;
- Om de erosie van slibrijke en cohesieve sedimenten daadwerkelijkheid te verhogen, is zowel een hoge biomassa van het benthos als een hoge stroomsnelheid nodig;
- In veel gebieden lijkt het effect van benthos op de erodeerbaarheid beperkt, vanwege lage biomassa in geëxponeerde gebieden en hoge biomassa in gebieden met weinig hydrodynamische energie.

Daarnaast zijn experimenten uitgevoerd om te zien of “priming” (d.w.z., het aanbrengen van benthos op een gebied waar geen bodemdieren zitten) kan bijdragen aan een versneld herstel en de vestiging van invasieve soorten kan tegengaan. Deze experimenten leverden geen bruikbare resultaten op. We vermoeden dat dit komt doordat ze te kleinschalig zijn uitgevoerd (d.w.z., te groot rand effect t.o.v. het bestudeerde oppervlak). We adviseren daarom deze methode in de toekomst verder te evalueren in grootschaligere veld experimenten, voor te besluiten of dit een waardevolle/waardeloze toevoeging is.

Aangelegde oesterriffen

Kunstmatige oesterriffen blijken in staat te zijn om lokaal sediment vast te houden, echter de invloed op de schaal van de zandsuppleties is beperkt en de riffen hebben weinig invloed op het algemene erosie- en sedimentatiepatroon. Achter de riffen ontstaat meer luwte, waarvan de benthische fauna lijkt te profiteren. Op alle riffen komt een gelijke samenstelling van hardsubstraat organismen voor. Oesterbroed wordt ingevangen op alle riffen al zijn er wel verschillen over de periode 2013-2016. De riffen blijken in staat om een stevige structuur te ontwikkelen. De kooien die bij aanvang de oesterschelpen bijeenhielden blijken deels verroest en hebben hun constructieve kracht verloren, welke is overgenomen door de hechting tussen de oesters.

CONCLUSIES

1. Erosietrends tonen aan dat de dijkvoetsuppletie sneller in hoogte afneemt (5 cm/jaar) dan de hoofd-suppletie (2 cm/jaar). In totaal is ongeveer 10% van het zandvolume verloren gegaan in de periode 2013-2016;
2. De hoofdsuppletie lijkt te fungeren als zandbron voor het centrale slik, maar dit proces resulteert niet in een significante toename in de hoogte van het slik, de erosietrend lijkt wel te zijn gestagneerd;
3. De hoofdsuppleties zorgt voor extra beschutting van het centrale slik, dit heeft een positief effect op het bodemleven (soortenrijkdom en biomassa). De suppleties laten in het algemeen een snelle kolonisatie zien van bodemleven; dit is ook zichtbaar door de aanwezigheid van vogels, met name de scholekster en wulp. De potentie voor vogels qua voedsel is groter maar wordt niet waargenomen. Waarschijnlijk als gevolg van toegenomen verstoring;
4. De afname van de golfbelasting op de dijk komt vrijwel geheel door de aanwezigheid van de dijkvoet-suppletie; de bijdrage van de hoofdsuppletie is zeer beperkt;
5. Het op de oesterdam aanwezige bodemleven heeft slechts een zeer beperkte invloed op de erosie snelheid van de suppletie, door de zandige aard van de suppletie

6. De kunstmatige oesterriffen zorgen voor extra beschutting voor het bodemleven aan de lijzijde van het rif en zorgen voor een habitat voor hardsubstraat organismen. De morfologische invloed van de riffen is lokaal, de vier riffen hebben een beperkt invloed op de algehele morfologische gedrag binnen het studiegebied en de levensduur van de suppletie. De riffen ontwikkelen zich tot stevige structuren.

ONDERWIJS VERSTERKING

Dit project bleek een uitstekende case te zijn voor studenten om aan te werken. In totaal zijn er 28 studentenprojecten gerealiseerd (Appendix 3) van tweedejaars HBO tot Universitair Master niveau. Daarnaast is er door de HZ-staf een benthosmodule ontwikkeld, waarmee in totaal 250 studenten (Appendix 4) tijdens de looptijd van dit project kennis hebben opgedaan over deze beheerstrategie, gericht op de combinatie van waterveiligheid en ecologisch herstel. Betrokken zijn bij dit toegepaste project bleek een waardevolle ervaring voor studenten die zich voorbereiden op de toekomst.

Docent-onderzoekers die hebben meegewerkt aan dit project zullen hun opgedane kennis binnen dit project verder verspreiden binnen de cursussen: Ecological Engineering en Coastal Zone Management. Bij het vergroten van de kennis van de docent-onderzoekers was de samenwerking met de kennisinstellingen en Rijkswaterstaat van grote waarde.

TABLE OF CONTENT

1 INTRODUCTION

1.1 BACKGROUND

After the North Sea flood of 1953 the Dutch government initiated the Delta Works, an extensive project of constructing sea dykes, dams and barriers intended to protect the human population in the Netherlands from future flooding from the sea and the large rivers. As a part of this project the Oosterschelde (Figure 1-1), once an open estuary, changed into a coastal bay behind a semi-open storm surge barrier. Studies in the last 25 years Van Berchum & Wattel, 1997; Hesselink et al., 2003; Geurts van Kessel, 2004; Van Zanten & Adriaanse, 2008; De Ronde, et al., 2013) showed a strong decrease of the intertidal areas, due to an imbalance between the existing basin morphology and the tempered tide (reduction of tidal volume and current velocity), also known as the 'sand deficit problem'. This erosion of the intertidal areas is not a new phenomenon. Just after the decision by the Dutch government in 1976 to realize the semi-open barrier (Figure 1-1) instead of a closed dam, the first predictions where made concerning the loss of intertidal area. In a collaborative study, Kohsiek et al. (1987) concluded an average erosion by 2020 of 1500 ha, which is equal to 45 ha/year. Since the construction of the storm surge barrier in 1986, actual measurements showed that surface of the inter tidal areas decreased by an average of 50 ha/ year, reasonably well in accordance with the prediction (Van Berchum & Wattel, 1997; Hesselink et al., 2003; Geurts van Kessel, 2004; Van Zanten & Adriaanse, 2008; De Ronde, et al., 2013).

This strong decrease of intertidal area has led to habitat loss (De Ronde, et al. 2013), and increasing wave loads on the dykes (Witteveen+Bos & Bureau Waardenburg, 2013). To mitigate the impact on nature values, and the dykes, Rijkswaterstaat[1] adopted a learning-by-doing approach, and started with the project *Verkenning Zandhonger* (English: 'Investigation Sand Demand') in 2007. The main goals of this project were the development of knowledge how to mitigate the negative effects of the sand deficit in the Oosterschelde with sand nourishments (Witteveen+Bos, 2011). Pilot studies with local sand nourishments and constructed oyster reefs were launched at five locations: sand nourishment *Galgenplaat*, cascade *Schelphoek*, constructed oyster reefs *Vianen* and *De Val* (part of the innovation programme Building with Nature), a dune foot nourishment at *Sophiastrand and* sand nourishment *Oesterdam* (Schaap, 2012). The largest of these pilots is the Oesterdam sand nourishment, where in November of 2013 a total of 350.000 m³ of sand was placed at the tidal flat, and artificial oyster reefs were constructed to slow down the erosion process (Figure 1-1).

In this interdisciplinary study the effectiveness of the sand nourishment approach was investigated with respect to morphology, wave load on dykes, biodiversity, ecosystem functionality, and how the latter is affected by biophysical interactions, at the Oesterdam sand nourishment.

1.2 CENTRE OF EXPERTISE DELTA TECHNOLOGY

This research started in 2013 and is executed by the Centre of Expertise Delta Technology (CoE-DT), a cooperation between Rijkswaterstaat, Deltares, Wageningen Marine Research, NIOZ and the HZ University of Applied Sciences. The collaboration focusses on knowledge development, knowledge distribution and the improvement of education in the field of delta technology. The CoE-DT is contributing to the focus area 'water' (Dutch: Topsector Water) of the Dutch government. Students are actively involved in this research since the CoE-DT is getting financial support of the Ministry of Education.

1.3 STUDY LOCATION

The Oesterdam nourishment is located in the south-eastern part of the Oosterschelde, and constructed in October till November 2013 (see also Chapter 2). In this part of the Oosterschelde the mean low tide is -1.56 m NAP, and the

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[1] Rijkswaterstaat is an agency within the Ministry of Infrastructure and Environment dealing with the execution of public works.

mean high-tide is 1.81 m NAP, and the springtides are: -1.67 m NAP and + 2.04 m NAP (gauge station Bergsediepsluis West). This means that the study location has a meso-tidal regime (tidal range 2 to 4 m; Davies, 1964), and at natural conditions without human interference the area will be characterized as a mixed energy tidal bay. But since the realisation of the Oesterdam in 1986 (Figure 1-1) this part of the Oosterschelde became cut off from the Markiezaat, an area of 1000 ha. This had a strong influence on the horizontal tide (flow velocity), because the exchange of water between the basin west from the Oesterdam and the Markiezaat stopped. Due to the construction of the storm surge barrier and compartment dams, like the Oesterdam, the Oosterschelde transformed to a so-called wave-dominated (unfilled) tidal bay (Martinius & Van den Berg, 2011). This is also the case in the study area: morphological processes are strongly dominated by wave action (generated by wind), and wave related currents.

To get an indication of the environmental conditions and benthic community composition at the Oesterdam prior to the nourishment, the Oesterdam tidal flat was sampled on three occasions (May 2012, October 2012, May 2013) (Ysebaert et al. 2017). The sediment on the Oesterdam was characterized as fine sand (median grain size 173-179 µm). In the southern part a small area with finer, more silty sediment was present. Over the three periods considered, a total of 41 macrobenthic taxa were observed, on average 30 taxa per sampling period (based on 20 sampling stations each period). Species richness per sampling location on average varied between 8.7 and 11.4 taxa, the density was on average 3900 ind/m^2 showing little variation among periods. The benthic community on the Oesterdam tidal flat typically consisted of a fine sand community with the bristle worm *Scoloplos armiger,* the lugworm *Arenicola marina*, and the amphipod *Urothoe poseidonis* as the most dominant species. The most common bivalves were the cockle *Cerastoderma edule* and the sand gaper *Mya arenaria*, the most common gastropod was the mud snail *Peringia ulvae*. Low tide bird counts were not performed prior to the nourishment.

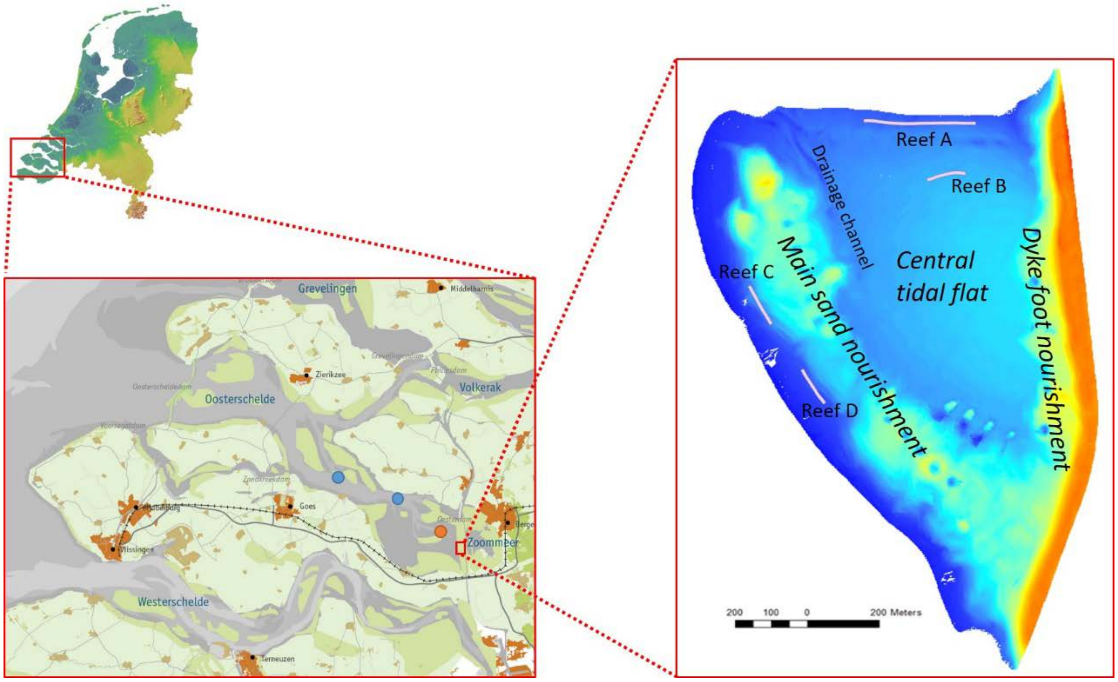

Figure 1-1. Location of the Oesterdam sand nourishment in the Oosterschelde (map on the left), including the borrow areas indicated with a blue dot (Wemeldinge left and Lodijksche Gat right), and the Rijkwaterstaat measurement pole "Marollegat" (orange). On the right the sand nourishment and locations of the constructed oyster reefs (Reef A, B, C and D).

1.4 PROJECT OBJECTIVES

The overall objective of the Oesterdam nourishment project is twofold:

WATER MANAGEMENT

1. Developing a sustainable and safe solution to protect the Oesterdam from high wave action and to postpone large investments in the reinforcement of the revetment for at least 25 years;
2. Contribute to the development of mitigations measures to decrease the negative effect of the sand deficit problem, at the Oesterdam, and the Oosterschelde as whole, to protect and sustain the valuable landscape with tidal flats for a period of fithy years.

The associated monitoring and research program, which is the subject of this report, aims at targeting the following objectives:

KNOWLEGDE DEVELOPMENT

3. Contributing to the development of knowledge related to the effectiveness of local sand nourishments to mitigate the negative effects of sand deficit in the Oosterschelde, and to flexible, climate-adaptable and cost effective coastal management;

EDUCATION ENHANCEMENT

4. Training of young professionals by improving the knowledge of teachers to be supported by state-of-the-art case studies; including interns and final thesis students in the development of the course modules;

NETWORK IMPROVEMENT AND KNOWLEDGE DISSEMINATION

5. Setting up a structural partnership between government, education and knowledge institutions, which will promote new collaborations and joint projects;
6. Promoting the circulation of knowledge within the field by combining all the knowledge within the *DeltaExpertise-site*.

1.5 MAIN RESEARCH QUESTIONS

1. Morphology:
    a. What is the sand balance in the study area?
    b. What is the erosion trend of Oesterdam sand nourishment over the period 2013-2016?
    c. Does the main sand nourishment influence the erosion rate of the central tidal flat?
    d. What is the morphological impact of the man-made oyster reefs on the main sand nourishment and tidal flat?
2. Wave load:
    a. What is the impact of the main sand nourishment and the dyke foot nourishment on the wave attenuation in normal-day and design wave conditions?
    b. What is the effect of the nourishment on the projected design storm wave loads from 2020 to 2080?
3. Ecology:
    a. How does benthic macrofauna develop over time (2014 – 2016) after the construction of the nourishment? Is the recolonization homogeneously distributed over the nourished areas? How does the communities on the nourished areas differ from the undisturbed, central tidal flat?
    b. Is the benthic macrofauna on the central, undisturbed tidal flat influenced by the construction of the nourishment?

   c. How do waders and other waterbirds use the Oesterdam mudflat after construction of the nourishment?
   d. Which macrofauna and algal species comprise the ecological community occupying the constructed oyster reefs? What proportion of the community on the reefs is composed of exotic species? Are there differences in the ecological community between reefs?
4. Biophysical interaction:
   a. What is the contribution of benthic organisms to the stability of a sand nourishment?
   b. What is the effect of benthic organisms on sediment erosion thresholds?
   c. How will different benthic species affect the sediment properties?

1.6 OUTLINE REPORT

This final report describes the development of the Oesterdam sand nourishment over the period November 2013 to December 2016. Chapter 2 shortly describes the design and realisation of the nourishment as background information. Chapter 3 gives an overview of the used research methods (for more detailed information please see the reports in Table 1). Chapter 4 describes hydrodynamic conditions based on field measurements and the wave loads on the dyke. The morphological development and the morphological response around the man-made oyster reefs are discussed in Chapter 5. This chapter also contains also morphological modelling study (Delft3D). Chapter 6 focusses on the development of the soft-sediment benthic macrofauna and the related bird species on the nourishment and the undisturbed central tidal flat. Secondly, the benthic organisms on the hard substrates (constructed oyster reefs) are investigated in Chapter 7. To get a better understanding of the physical processes and the influence of bio-physical interactions on the erosion rate of the nourishment, see Chapter 8. Chapter 9 focusses on the project’s impact on education at the HZ University of Applied Sciences. The discussion, conclusions and recommendations are presented in the last three chapters.

This integrated report is based on several underlying reports (Table 1), manuscripts and publications which are parts of the monitoring and research project at the Oesterdam sand nourishment executed by the CoE-DT. It is advised to look at the following reports for more details:

Table 1. Overview of all other reports part of this monitoring and research project.

Title	Authors	Publication
The conservation of eroding intertidal flats through nourishments: Ecological development on the Oesterdam tidal flat (Oosterschelde, the Netherlands)	Tom Ysebaert (WMR/NIOZ) Emiel Brummelhuis , Douwe van den Ende (WMR), Lennart van IJzerloo, Jeroen van Dalen (NIOZ), Brenda Walles (WMR)	Wageningen Marine Research – report (2017)
Effects of bioturbation on the erodibility of cohesive versus non-cohesive sediments along a current-velocity gradient: A case study on cockles	Baqauan Li, Francesco Cozzoli, Laura Soissons (NIOZ), Tjeerd Bouma (NIOZ/HZ), Linlin Chen (NIOZ)	Journal of Experimental Marine Biology and Ecology 496 (2017) 84–90
The combined influence of body size and density on cohesive sediment resuspension by bioturbators	Francesco Cozzoli, Tjeerd Bouma, Pauline Ottolander, Maria Salvador Lluch (NIOZ), Tom Ysebaert (WMR/NIOZ), Peter Herman (Deltares)	submitted

Sandification vs. Muddification of tidal flats by benthic ecosystem engineers: a flume study	Laura Soissons, Tatiana Gomes da Conceiçâo John Bastiaan, Francesco Cozzoli, Jeroen van Dalen, Tjeerd Bouma (NIOZ)	In preparation
On the combined influence of influence of abiotic and biotic factors in sediment erodibility – An integrated study on Cersatoderma edule (Linnaeus, 1758)	Francesco Cozzoli et al. (in prep)	In preparation
Clash of the crabs: Interspecific, inter-cohort competition between the native European green crab, Carcinus maenas and the exotic brush clawed crab Hemigrapsus takanoi on artificial oyster reefs	Anneke van den Brink, Samara Hutting (HZ)	Journal of Sea Research 128 (2017) 41–51
Ecosystem services on constructed oyster reefs	Joao Salvador de Paiva, Anneke van den Brink (HZ)	CoE-report (2017)
Morphological effect of constructed oyster reefs at the Oesterdam sand nourishment	Joao Salvador de Paiva, Silvia Cilli, Matthijs Boersema (HZ), Tjeerd Bouma (NIOZ)	In preparation
Understanding the morphological development of the Oesterdam nourishment (Master thesis)	Michiel Pezij (supervisors: Jebbe van der Werf, Lodewijk de Vet)	University of Twente – Master Thesis report (2015)
Wave attenuation over the Oesterdam tidal flat nourishment. Wind-wave transformation in the intertidal zone (Master Thesis)	Yahia Kala (supervisors: Jebbe van der Werf, Lodewijk de Vet)	Deltares – Master Thesis report (2016)
Morphodynamics and sediment transport direction at the Oesterdam sand nourishment (Internship research)	Victor Kenji Ikeya (supervisors: João Salvador de Paiva, Matthijs Boersema)	HZ – internship report (2014)
The efficiency of oyster reefs on coastal protection in the foreshore areas: Oesterdam case (Master Thesis)	Silvia Cilli (supervisors: João Salvador de Paiva, Matthijs Boersema)	HZ – Master Thesis report (2015)
Tidal channel development at the Oesterdam sand nourishment (Minor research)	Mireille Martens (supervisor: Matthijs Boersema)	HZ – Minor report (2015)
Benthos Module	Anneke van den Brink, João Salvador de Paiva, Carla Pesh, Matthijs Boersema (HZ)	HZ – report (2017)
Veiligheidsbuffer Oesterdam versterkt veiligheid en natuur	Matthijs Boersema (HZ), Jebbe van der Werf (Deltares), Eric van Zanten (Rijkswatestaat) en Tom Ysebaert (WMR, NIOZ)	Land+Water nr. 12 – December 2017
Ecologische onwikkelingen op de Veiligheidsbuffer Oesterdam (werktitel)	Brenda Walles (WMR), Anneke van den Brink (HZ), Matthijs Boersema (HZ) en Tom Ysebaert (WMR/NIOZ)	Land+Water nr. 1 – Januari 2018

2 DESIGN AND CONSTRUCTION PHASE

The actual start of the Oesterdam sand nourishment project (project: *Veiligheidsbuffer Oesterdam*) was the signing of the cooperation agreement on 14 April 2011. In 2012 the Oesterdam revetment was reinforced by Rijkswaterstaat over a length of 4.65 km of the southern part of the Oesterdam. Early 2011 Rijkswaterstaat together with Wageningen Marine Research and the HZ University of Applied Sciences started a measurement campaign to monitor the situation prior to the nourishment. Research regarding the quality of sand at the borrow areas, the investigation of explosives and bird counting has been realised by private companies. The public participation discussion was organized by the project team. The final design of the sand nourishment in front of the Oesterdam was selected after different design sessions with stakeholders.

The technical conditions for the project were given in the tender specifications. After the closure, four entries were registered. On April 5, 2013 the tender committee selected dredging firm Van Oord to execute the work. The possible increase in turbidity around the sand mining sites was a big issue in the discussion with the representatives of the oyster and mussel fishery. To prevent a turbidity cloud from the borrow areas the sand mining was restricted to certain tidal phases, when the tidal flow was not directed tot the mussel farm plots, also monitoring stations for turbidity were installed during the work.

In the second half of August 2013 the contractor installed pressure pipe lines and a trailing suction hopper of Van Oord, started in week 38. The vessel has transported about 440.000 m^3 (hopper volume) of sand in five weeks from the borrow areas *Wemeldinge* and *Lodijksche Gat* (Figure 1-1). Additionally to the sand nourishment four artificial oyster reefs were also placed at the tidal flat, see Figure 1-1. Their functions were to stabilize the sand in the tidal flat (Reef A and B) and to reduce the wave energy on the main sand nourishment (Reef C and D). The Approximate dimensions of the reefs are 255 m by 7.8 m for reef A, 91 m by 7.5 m for reef B, 101 m by 7.5 m for reef C and 93 m by 7.7 m for reef D (Figure 1-1). All reef have a height of 0.5 m.

After the work was finished the dyke foot nourishment (Figure 1-1) became a source for aeolian transport, caused by the relative height (see the profile of 18-2-2014, Figure 2-1). Sand was transported over the dam hindering the road traffic. This stopped after the top layer of the dyke foot nourishment was moved towards the flat by a bulldozer so the sand had less time to dry-up, caused by the lower elevation. This resulted in a lower, but wider dyke foot nourishment (Figure 2-1). The work started at the end of March 2014. The difference between the situation before and after the measure can be seen in the height maps below (left) and profiles (right).

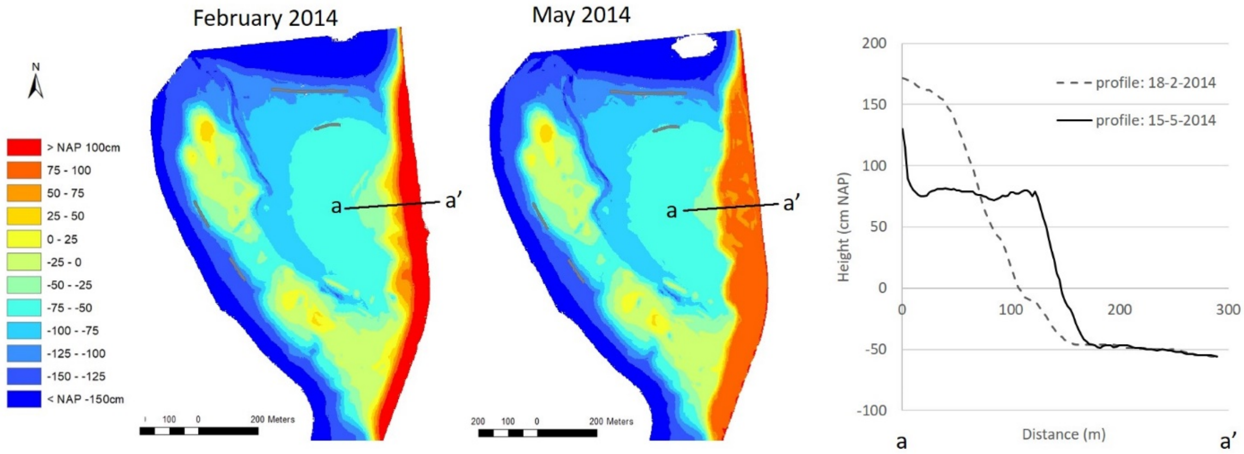

Figure 2-1. Height maps showing the situation before (February 2014) and after (May 2014) the lowering of the dyke foot nourishment to prevent aeolian transport. On the right a profile line at a-a', which shows the maximum lowering of 1m after the reconstruction.

3 RESEARCH METHODOLOGY

3.1 HYDRODYNAMICS AND SEDIMENT TRANSPORT

3.1.1 *MINI SAND NOURISHMENTS*

To understand the relation between wind and sediment transport direction the ‘mini sand nourishment’ method was applied at varying wind conditions. In this method circular piles of sand with a constant volume of about 10 dm^3 and approximate 30 cm in heigtht, are placed on the tidal flat and nourishments at 40 location to get a good special coverage. After two days the changes of piles was measured in eight wind directions. Between March 2014 and May 2015 the method was applied seven times. During the measurements wind speed was 4-7 m/s and the direction varied between 27 and 194 degrees. Wind data was used from the Marollegat measurement station (Figure 1-1). In this method the eolian transport is regarded as negletible.

3.1.2 *FLOW VELOCITIES*

Depth-dependent flow velocities were measured at 9 locations in the vicinity of the Oesterdam in fall 2011, i.e. before nourishment construction. After construction (T_1), flow velocities were measured at 10 other locations in spring 2014. Figure 3-1 shows the before and after measurement locations. These data were used for a better understanding of the hydrodynamics on the Oesterdam tidal flat before and after the nourishment, and to calibrate the Delft3D numerical model.

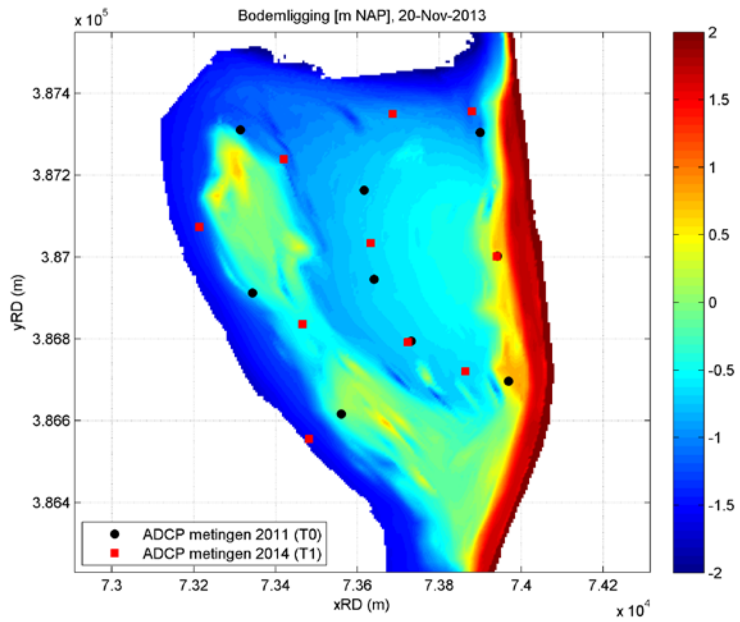

Figure 3-1 Measurement locations before and after (T_1) construction of the nourishment.

3.1.3 *DELFT3D MODEL*

To simulate flow, waves, sand transport and morphological development a depth-averaged (2DH) Delft3D model was set-up. This Delft3D model covers the Oosterschelde including the ebb delta. Through nesting steps, the spatial resolution increases to 30x30 m (flow) and 10x10 m (waves) at the Oesterdam tidal flat. The model shows reasonable agreement with measured water levels (~0.05-0.1 m difference) and wave heights (~0.05-0.2 m difference) in deep water, and flow velocities in 2014 and 2015/2016 after nourishment construction (~0.05-0.1 m/s difference). Although the model showed good agreement with measured wave heights at Marollegat, the wave heights at the Oesterdam tidal flat were largely overestimated (Pezij, 2015). This is mainly attributed to uncertainty in the function to transfer measured pressures to wave heights. Therefore, Kala (2016) chose to directly compare near-bed pressures, and the model is seen to replicate measured pressures reasonably well. Measured and predicted bed level changes between 20 November 2013 and 18 February 2014 were compared. The Oesterdam model does not capture the generation of the channel next to the main sand nourishment (~5-10 m width) which is due to the too low spatial resolution. Both model and data show the erosion of the main sand nourishment, and little bed level change in the tidal flat area behind.

3.1.4 *WAVE LOAD*

One of the objectives of the nourishment is to increase the designed life span of the Oesterdam in the face of increasing wave loads due to structural erosion of the intertidal flats and sea level rise. Rijkswaterstaat estimated that the design life will be extended by 25-30 years due to compensation of the expected erosion rates. However, the effect of the nourishment on the wave load has not been investigated. In order to explore the effect of the nourishment during different environmental conditions, a hydrodynamic/wave model (Delft3D) is required to simulate design storm conditions at the site. However, there must be confidence in the results in order to apply the insights in practice. Specifically, the wave characteristics near the dam must be well represented. In order to build confidence in the model results, the model must be calibrated and validated at the site using measured data.

The approach to answer the research questions is as follows. Data analyses and Delft3D numerical modelling are used to understand and represent the physical processes at the site. Processed water level, wave and current data are used to calibrate and validate the numerical model in normal-day conditions. Projections of erosion are used with a calibrated numerical model to calculate projections of wave loads during design conditions.

3.2 MORPHOLOGY

3.2.1 *MORPHOLOGICAL CHANGES OF NOURISHMENTS*

The morphological changes are measured with a RTK-DGPS (accuracy ± 2.5 cm vertically and 1 cm horizontally). In total 4 measurements are taken before the construction of the nourishment (T_{-3} till T_0) and 9 measurements after the construction T_1 to T_9. On average the time interval between two measurements was around 90 – 150 days. Measurement points were taken at 10 meter intervals on parallel cross-sections with 25 meter spacing. Based on the field measurements a 5x5 meter raster grid was produced with the Digipol interpolation method (a Rijkswaterstaat model for height interpolations) . The interpolated raster grids were used as a base for further calculations and visualisations. For example erosion and sedimentation maps, cross-sections and volume calculations. Secondly during the period 2013-2016 six times the area (or parts of the area) were measured with a multi beam equipment. This data is used to calculated the development of a channel delta in the northern part.

3.2.2 *MORPHOLOGICAL CHANGES AROUND CONSTRUCTED OYSTER REEFS*

Around the constructed oyster reefs RTK-DGPS measurements were taken at a higher resolution. This study focused on the lee areas, just behind the reef. Due to its size and relatively low position on the intertidal flat Reef A was difficult to sample and therefore it was excluded from this analysis. Reef B area is 3400 m^2, reef C 3800 m^2 and reef D 4000 m^2. These areas were compared with equal sized reference areas on both sides of the structures.

The bed level height of the areas were surveyed using a differential RTK-DGPS with an absolute accuracy of 1 cm horizontally and 2.5 cm vertically which allows to quantify the bed level changes over time intervals of maximal of 6 months. The points were not equidistant on the horizontal plane, and the number differs per measurement campaign, which was conducted at least two times per year between 2013 and 2016. The frequency of the measurements was increased to a monthly base in 2015 and 2016; for detailed information on the dates see (Salvador de Paiva et al., 2017).

To quantify the morphological changes, in relation to the presence of the oyster reefs, volume variations and hypsometric curve analysis were performed for each area behind the reefs and the reference areas. The volumes, per measurement, were calculated using the bathymetry map of the area shortly before the nourishment as a reference. Hypsometric curves were constructed by plotting the proportion of the total area height (h/H = relative height) versus the total area (a/A = relative area) (Keller and Pinter, 2002).

3.3 ECOLOGY

3.3.1 *BENTHIC MACROFAUNA*

After the construction of the nourishment, the Oesterdam was sampled in October 2014 (T_1), October 2015 (T_2) and October 2016 (T_3) (Appendix 1). In total 114 sampling locations were monitored at T_1 – T_3 to evaluate the recolonization of the benthic macrofauna on the nourishment in comparison to the benthic community composition on the undisturbed, non-nourished central area.

For each sample station the following abiotic environmental variables were collected: elevation, sediment characteristics (grain size, mud content, chlorophyll-*a*) following standard methodology (Ysebaert et al. 2017). Macrofauna was sorted and identified to the lowest possible taxonomic level in the lab. Biomass was estimated based on the wet weight of the individuals. Ash free dry weight (AFDW) was subsequently determined using existing conversion factors. *Arenicola* castings, subdivided into small and big, were also counted within 0.25 m^2 quadrants (n=10) at each sampling station. In addition four transects on the main sand nourishment were sampled to gain insight in the small-scale spatial changes on the nourishment (Appendix 1).

To show the differences in development after nourishment, the Oesterdam area was divided in three subareas:

- Main sand nourishment (n=43 sampling stations)
- Dyke foot nourishment (n=21 sampling stations)
- Central tidal flat, i.e. the undisturbed central part (n=36 sampling stations)

In this report, the differences between the three subareas in the different years (2014 – 2016) in terms of environmental and biological variables are presented. Since biomass, density and species richness were correlated, but with some degree of variation, the three variables were standardized and combined into a relative integrative univariate measure of ecological richness for each sample (Ysebaert et al., 2009). A multivariate analysis was performed to assess the community structure of the benthic macrofauna using a non-metric multidimensional scaling (NMDS).

Besides the detailed benthic sampling at the above mentioned sampling stations, an area-wide mapping of different benthic parameters was done two months prior to the construction and four months, one year, two years and 3 years after the construction. An area-wide grid was applied (50x50 m), and on the crossings a visual inspection was made of different, in the field identifiable, benthic macrofauna species present. For species like the lugworm (*Arenicola marina*), the sand mason worm (*Lanince conchilega*) and the periwinkle (*Littorina* spp.) the surface area was inspected, for deeper living species like *Hediste* spp., etc. the sediment was digged out and their presence noted. A quadrant of 50x50 cm was used to count *Arenicola* castings and to search for cockles (*Cerastoderma edule*) by hand raking. In addition, the presence of silt and the depth of the oxidation layer was recorded. These data were collected by Rijkswaterstaat (CIV, Mobiel Meten, Team Zee en Delta).

3.3.2 *BIRDS*

Bird surveys took place in the winter months in the period November 2014 till January 2017. Bird counts were performed during low tide, till November 2015 on two consecutive days, afterwards on one day each month. The Oesterdam flat was divided in eight different counting areas, including a reference area more to the south of the nourishment (Figure 3-2). Birds were counted at pre-determined reference points from a car, to keep disturbance at a minimum. Bird species were noted and individuals were counted inside each area. Bird counts were repeated up to seven times during one survey, within a timeframe of two hours before low tide until three hours after low tide. Per species distinction was made between foraging and non-foraging birds.

For the analyses, the same three subareas were used (see above) by combining the eight counting areas, with in addition the reference area that was counted more to the south of the nourishment. Average numbers of birds counted around low tide, using the three counts centred around the low tide period, are presented.

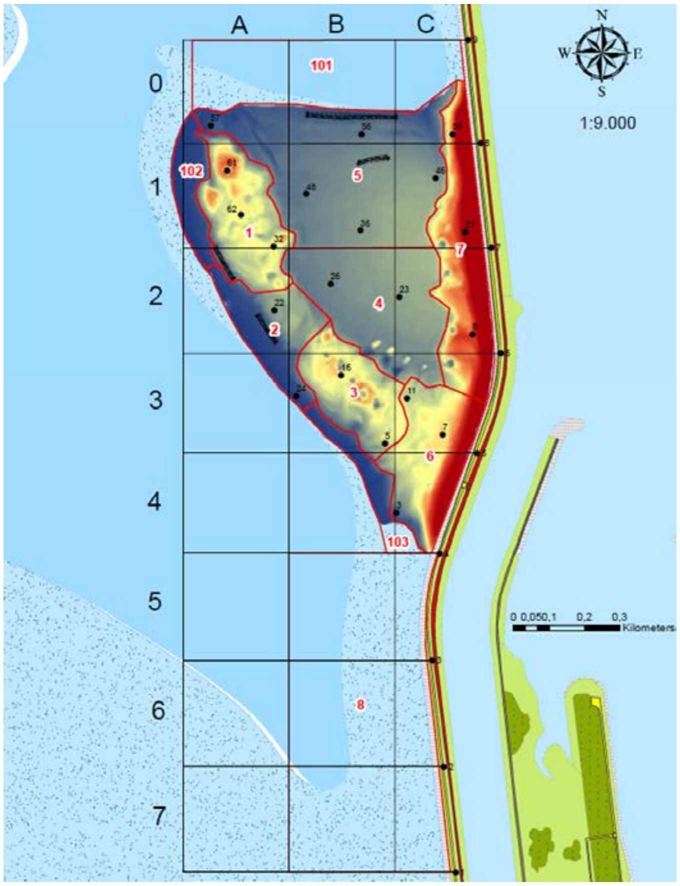

Figure 3-2 Bird counts. The Oesterdam tidal flat was devided in seven different counting areas (1 till 7) and a reference area (8) more to the south.

3.3.3 *BIODIVERSITY ON CONSTRUCTED OYSTER REEFS*

The four constructed oyster reefs were monitored for biodiversity. Each month from July 2015 to June 2016 the reefs were monitored using 50 cm quadrats. On each reef a total of 18 quadrats were used. The species names were recorded and an abundance code was assigned per faunal species (including oyster spat) and a percentage coverage estimate was given per macro-algal species. Whether the species was native or exotic was also recorded. In this way the community of organisms occupying the reef could be identified and monitored over 15 months.

3.4 BIO-PHYSICAL INTERACTION

A way to examine the importance of biophysical interactions and understand the role of benthic organisms on sediment properties, erosion and stability, is to compare the properties of sediment with and without benthos through field observations and in-depth mechanistic laboratory experiments using flumes with different densities of specific bethic model species. Hence, two types of experiments were designed: i) field defaunation experiments and ii) annular flume experiments.

3.4.1 *FIELD DEFAUNATION EXPERIMENTS (2013, 2015, 2016) & ADDITIONAL PRIMING TESTS (2015):*

To study the effects of the presence of benthic animals in real conditions (i.e. field conditions), three large "defaunation" (i.e., benthic animal removal) experiments have been implemented at different locations in the Oosterschelde and Westerschelde. Field sites were choosen to represent a range of elevations (inundation time), sediment characteristics and exposure to hydrodynamics. The first defaunation experiment (2013; before the start of this project) was initiated at 8 sites distributed throughout the Westerschelde and Oosterschelde. The second defaunation experiment (2015) was implemented at the Oesterdam, by selecting 4 sites along a silt content gradient. The final defaunation experiment (2016) was done at 2 sites, one in the Oosterschelde and one in the Westerschelde along an elevation gradient (i.e. 3 elevations per site). The objectives of the various experiments were to assess how benthos may affect the erodibility of a nourishment in relation to:

- *elevation* (i.e. inundation period) (exp. 2013 and 2016)
- *silt content* and sediment composition (exp. 2015)
- *exposure* to hydrodynamics (exp. 2013, and 2016)

As part of the 2015 defanuation experiment, a study was carried out to asses if priming methods for benthos recovery (i.e., methods to add benthos to an area where benthos died due to nourishment), might offer possibilities for accelerating the recovery of benthic communities on nourishments and may lower the risk of the establishment of invasive species (exp. 2015).

All defaunation experiments were initiated by covering the sediment (min 1 month) with heavy quality plastic sails buried on the sides (30-40 cm deep). After 1 month when all macrobenthic animals were dead, the sails were cut open After opening, environmental variables as well as hydrodynamics and benthic recovery were monitored monthly for a period up to 6 months for each defaunation experiments.

ADDITIONAL PRIMING STUDY

Priming was initiated in the 2015 defaunation experiment at the Oesterdam by adding known quantities of cockles (27mm) (*Cerastoderma edule*) or lugworms (*Arenicola marina*) into the defaunated sediment. By adding these species, naturally abundant in this environment and known to be ecosystem engineers, we hypothesised that the presence of such ecosystem engineers would facilitate the recovery of the benthic community. Two densities for each benthic species were added to test the potential limiting effect of this technique (is too high primed density inhibiting the recovery?), creating the following treatments per plots:

- control (n=4)
- defaunated (n=4)
- primed with lugworms in high densities (n=2)
- primed with lugworms in low densities (n=2)
- primed with cockles in high densities (n=2)
- primed with cockles in low densities (n=2)

Table 2. Primed densities at each plot for the 2015 experiment at the Oesterdam

	HD lugworm		LD lugworm		HD cockles		LD cockles	
Plot ID	Rep 1	Rep 2	Rep 1	Rep 2	Rep 1	Rep 2	Rep 1	Rep 2
D (sand)	20	20	5	5	40	40	10	10

E (fine sand)	20	16	5	4	40	28	10	7
F (fine sand)	16	20	4	5	36	40	9	10
G (silt)	16	16	4	4	32	40	8	10

BENTHOS SAMPLING AND ANALYSIS

In order to assess the effect of the different treatments (i.e. defaunation and priming) on the benthic community, benthos samples (10 cm diameter 30 cm deep cores) were taken in the different plots. From this samples, all species were separated, counted and identified to calculate the following indices:

- Abundance = number of individuals per m^2
- Biomass = Species dry weight per m^2
- Evenness = S (= total number of species)
- Richness = $P_i = \frac{n_i}{\sum_{i=1}^{S} n_i}$ (= proportion of S made up of the i species)
- Diversity = $H = -\sum_{i=1}^{S} P_i \ln P_i$ (= Shannon-Wiener diversity index)
- Ecological richness = $\frac{\frac{(B-\bar{B})}{sd(B)}+\frac{(D-\bar{D})}{sd(D)}+\frac{(S-\bar{S})}{sd(S)}}{3}$, where B is log-transformed biomass, D is log-transformed density and S is log-transformed species richness of benthic macrofauna.

3.4.2 *FLUME EXPERIMENTS*

Flume experiments allow the testing of specific mechanistic questions by being able to fully control all environmental conditions. A series of flume experiments was designed to test for the effect of:

a. Cockle body size on the erosion thresholds of sediment with different silt content
b. Cockle density on the erosion of cohesive and non-cohesive sediment
c. Two different benthic organisms on the long-term sediment properties (mudification vs. sandification)

The annular flumes (surface area of 0.157 m^2, see Appendix 2) used for the determination of erosion thresholds and erosion rates were developed following the design described by Widdows et al. (1998). They are used to generate currents and bottom stresses similar to those experienced in field conditions. Erosion rates and thresholds are measured with an Optical backscatter (OBS), measuring turbidity levels in the water column in NTU (Natural Turbidity Unit; i.e., an arbitrary unit indicating the light reflection by the sediment as is derived by an OBS, which needs to be calibrated for the local sediment). Water samples are taken during the experimental runs to calibrate the turbidity levels obtained from the OBS and convert the NTU values into SSC (Suspended Sediment Concentration in g/L). It is noted that in these flume experiments, the concentrations of the sediment get much higher than in the field, because the erosion tests are done in annular flumes, which are filled with a very limited recirculating water volume. Working with such limited volume enables much more sensitive measurements.

Flume preparation: Prior to each experimental run, a 7 cm gravel bed is placed at the bottom of each flume, with a 10 cm sieved sediment layer above it, separated by a plankton net. The gravel bed under the sediment layer is used to drain the water contained in the sediment layer when filling the flume and to consolidate the sediment. The wet sieved sediment is placed into the flumes. The sediment layer is left for consolidation for 4 days by opening the drainage hole under the gravel bed. After sediment consolidation, 31 litre of sea water is pumped into the flumes, while keeping a ‘bubble wrap’ layer on top of the sediment to prevent sediment disturbances. After this step, another 3 days are necessary to enable further sediment consolidation.

Benthic organism addition: The flume experiments were performed to assess the effect of benthic organisms on sediment erosion threshold and suspended sediment concentrations. Only a limited amount of species can be used to efficiently assess the mechanisms of benthic organisms on sediment dynamics. For the purpose of this study, the common cockle, *Cerastoderma edule*, was used as a model species in the flumes, as it is a dominant ecosystem engineer present in the Schelde estuary. An additional species, the invasive clam *Ruditapes phillipinarum* was also used for the flume study looking at the effect of benthic organisms on sediment properties. The animals are collected from the field prior to the experimental runs and left for acclimation in tanks filled with aerated seawater. After acclimation only the active and healthy animals are selected and placed in the annular flumes, previously filled with consolidated sediment (see section above). The animals were given 48 h to settle in the consolidated sediment.

4 HYDRODYNAMICS AND SEDIMENT TRANSPORT

4.1 HYDRODYNAMIC CONDITONS

ADCP flow measurements were used to better understand the flow pattern on the Oesterdam flat, the effect of the nourishment and oyster reefs in particular. It is not easy to determine these effects, as the T_0 and T_1 measurements were carried out at different locations and periods (Figure 4-1), and thus under different meteorological and tidal conditions.

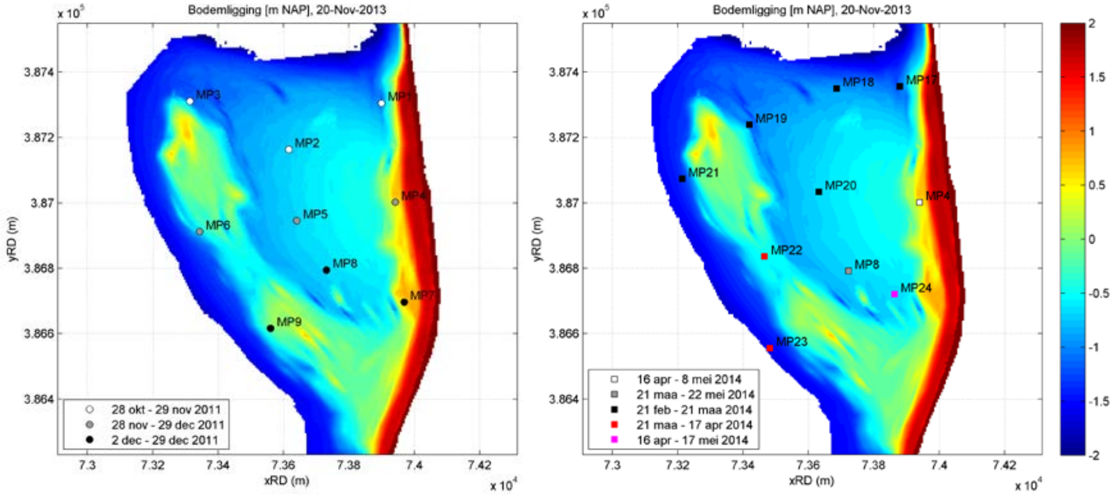

Figure 4-1. Overview T_0 (left) and T_1 (right) velocity measurements

This first analysis focuses on the flow velocities that occurred under 4 types of conditions:

1. Before nourishment construction (T_0), wind force 2 Bft (< 4 m/s): 22 November 2011
2. Before nourishment construction (T_0), wind force 5 Bft (5-10 m/s): 4 November 2011
3. After nourishment construction (T_1), wind force 2 Bft (< 4 m/s): 5 March 2014
4. After nourishment construction (T_1), wind force 6 Bft (10-15 m/s): 18 March 2014

In this study it was not always possible to compare similar tidal conditions for these 4 conditions, because of astronomical and meteorological influences. Tidal velocities at MP1, MP2 and MP3 for T_0 and at MP17-MP20 for T_1 are presented in Figure 4-2, the values are always depth-averaged velocities, see Figure 4-2.

These figures indicate the following:

- The maximum observed flow velocities were between 0.2 and 0.4 m/s, except for the high ebb velocity (0.56 m/s) in the ebb-channel next to the main sand nourishment;
- Under calm conditions (left panels) the flood current is directed approx. southwards (~180^{o}N) and the ebb current northwards (~0^{o}N);
- The southern wind on 4 November 2011 (T_0, upper right panel) resulted in a reduction of the southward-directed flood velocities and an increase of the northward-directed ebb velocities, compared to the calmer wind condition of 22 November 2011 (upper left panel);
- The ebb velocities on 18 March 2014 (T_1, lower right panel) were more oriented in eastern direction due to the south-westerly wind. Note that the low water level is ~0.5 m higher than during the calm conditions of 5 March 2015 (lower left panel), possibly due to wind set-up;

- The high velocities at MP19, next to the main sand nourishment, on 5 March 2014 (lower left panel) were very likely a direct effect of the nourishment. Especially at the end of the ebb tidal phase, the flow converges here due to which velocities become high and a small channel is created. This did not occur during the stormier T_1 period (18 March 2014, lower right panel). The water levels were much higher then (possibly due to wind set-up), and more water could flow away from the flat through the gap in the main sand nourishment;
- The flood velocities at MP17 during the calm T_1 condition (5 March 2014, lower left panel) were higher than those at MP1 during the calm T_0 conditions (22 November 2011, upper left panel). The locations of MP1 and MP17 were very similar (Figure 4-1). Furthermore, the water seemed to flow on and off the flat in a more northern-southern direction in the T_1 situation. This could be the effect of the nourishment, but it could also be related to differences in the tide and wind conditions.

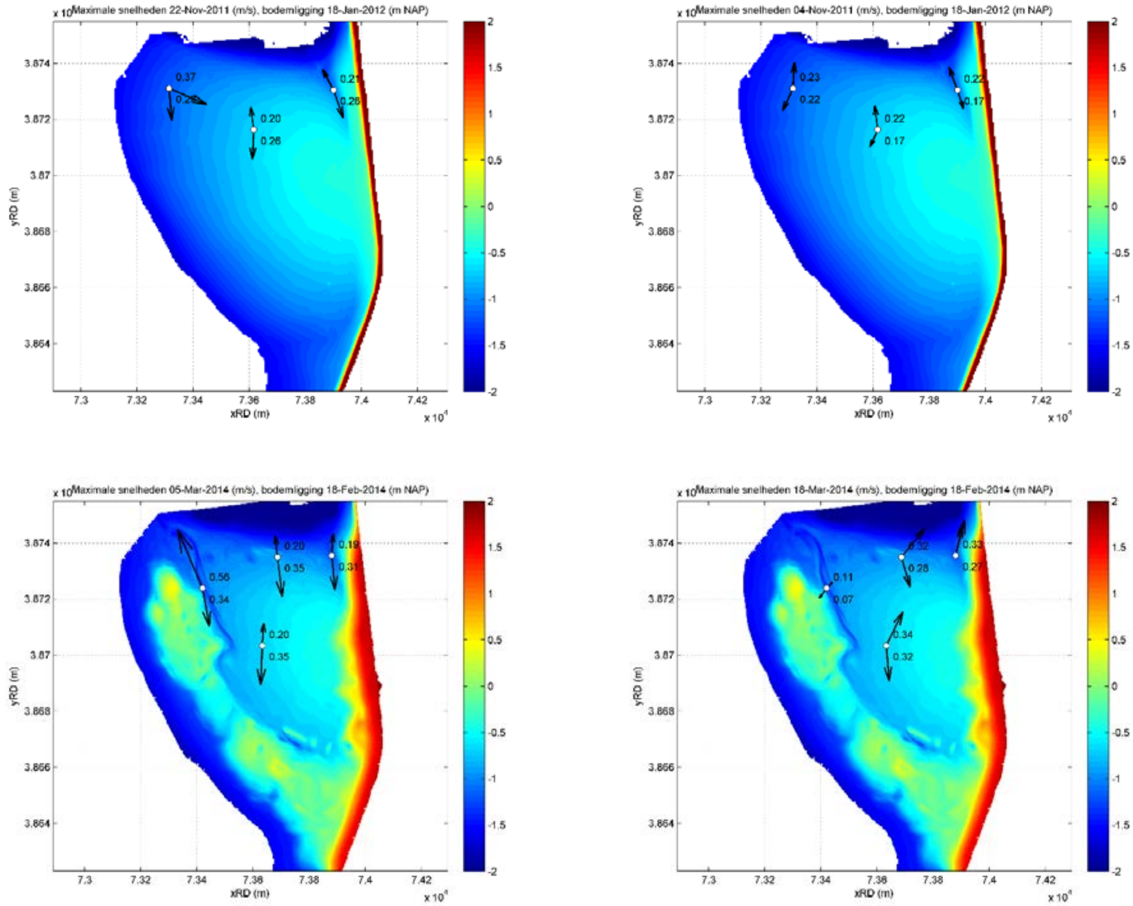

Figure 4-2. Maximum measured ebb and flood velocities on 22 November 2011 (T_0, calm wind), 4 November 2011 (T_0, strong wind), 5 March 2014 (T_1, calm wind) and 18 March 2014 (T_1, strong wind).

4.2 SEDIMENT TRANSPORT

The direction of the sediment transport and the relative magnitude was determined with the 'mini sand nourishment method' (see paragraph 3.1.) Figure 4-3 shows the sediment transport direction and relative magnitude at the study location, over the period 18 March 2014 to 21 March 2014. In this period the wind direction was south-southwest (Figure 4-3) and the average wind speed was 7.2 m/s (based on data collected at the *Marollegat* measurement pole; see for the location Figure 1-1). The picture shows a clear relation between the wind direction and the net sediment transport direction (in red) at the study location. The study of Ikeya (2014) and the field measurements executed by students showed in general a linear relation between the wind direction and the net sediment transport direction at the study location. Furthermore, transport directions at the main sand nourishment were always larger than at the central tidal flat and during days with low wind speeds sediment transport was very limited (Ikeya, 2014).

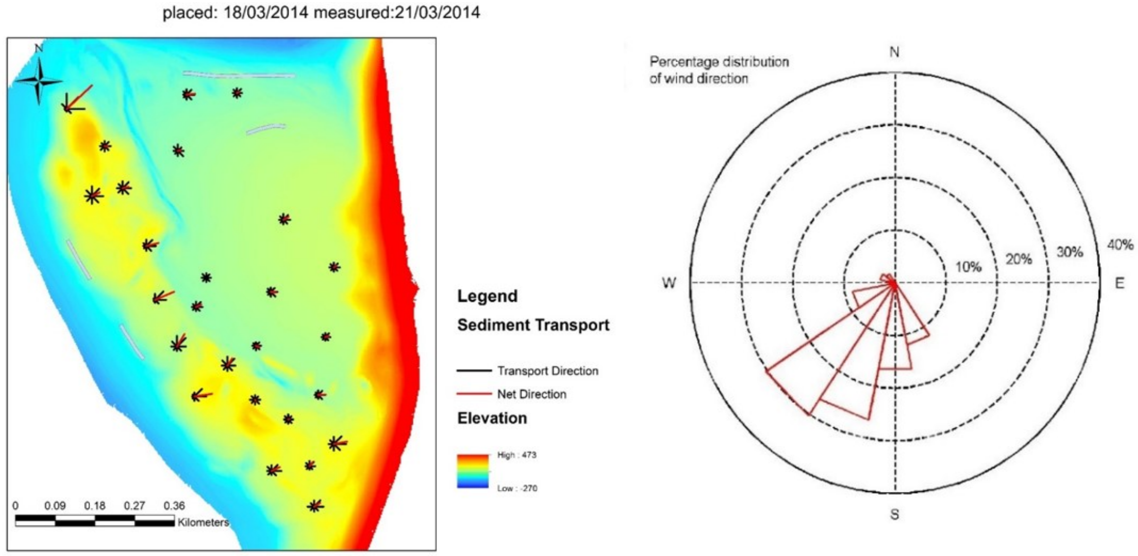

Figure 4-3. Sediment transport direction and magnitude at the Oesterdam (March 2014). Wind chart (right) shows the direction of the wind, based on measurement at the Marollegat measurement pole (Ikeya, 2014)

The measurements of the sediment transport assumed that the morphology of the nourishment was mainly related to wave action. This is supported by the Delft3D modelling result of Pezij (2015). According to the model simulations, the morphological development of the Oesterdam nourishment is controlled by waves and wave-driven current: sediment is stirred up by the waves and transported by currents. This is in agreement with the earlier statement (paragraph 1.3) that the area at the Oesterdam transformed to a wave-dominated situation, caused by the construction of the Delta Works.

4.3 WAVE ATTENUATION

4.3.1 *INTRODUCTION*[2]

One of the objectives of the nourishment is to increase the design life of the Oesterdam in the face of increasing wave loads due to structural erosion of the intertidal flats. Rijkswaterstaat estimated that the design life will be extended by 25-30 years due to compensation of the expected erosion. However, the effect of the nourishment on the wave load has not been investigated.

In order to explore the effect of the nourishment during different environmental conditions, a hydrodynamic/wave model (Delft3D) is required to simulate design storm conditions at the site. However, there must be confidence in the results in order to apply the insights in practice. Specifically, the wave characteristics near the dam must be well represented. In order to build confidence in the model results, the model must be calibrated and validated at the site using measured data.

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[2] This chapter is largely based on the work of Kala (2016) and (to a lesser degree) of Pezij (2015).

4.3.2 *WAVE ATTENUATION NOURISHMENT*

During the T_1 period (2014), the MP20/21 (Figure 4-1) devices were deployed at the same time. The MP08/23 devices were deployed a few weeks later. During the T_2 period (2015/2016), the MP30 and MP44 devices were also deployed at the same time. This allows for an analysis of the effect of the main nourishment. Figure 4-4 shows a schematic cross section of the main sand nourishment with the the measurement point (MP) of wave loggers.

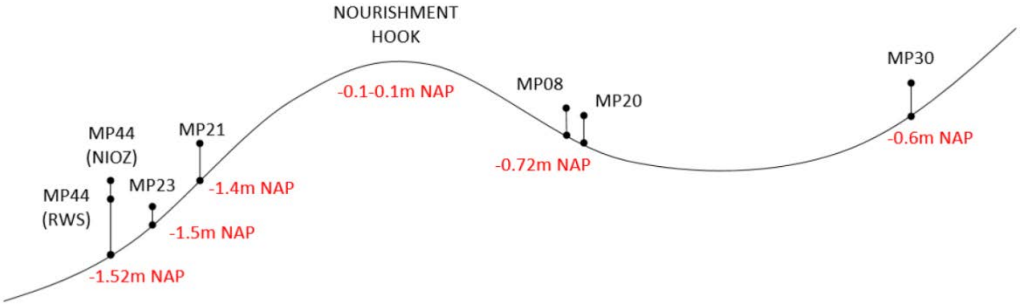


Figure 4-4. Schematised cross-section of the main sand nourishment and dyke foot nourishment (not to scale).

Figure 4-5 shows the wave attenuation/amplification over the hook for a range of water depths (of the offshore instrument), related to tidal water level variations. The figure shows a weak general trend for wave attenuation at shallower water depths and wave growth for deeper depths. The wave growth could be due to shoaling and wind-wave growth over a distance of 300-400 m. It appears that the model simulates wave attenuation to the same order of magnitude when it comes to the difference in wave height over the main sand nourishment at the shallow water depths. However, the model does not show as much wave growth at larger depths as is observed in the data.

The model results for a selected time point were visualised along a transect (Figure 4-6). It is apparent that attenuation occurs over the main sand nourishment at high water and only recovers after a large distance of wave growth. The wave height is nearly recovered by the time the waves reach the dam foot, at which point the waves are further damped by breaking and bottom friction. At low water, the approaching waves are dissipated by both bottom friction (just outside of the hook) and by depth-induced breaking (on the inside of the hook). At mean water, the dissipation over the hook is due to friction, and some wind growth is responsible for partially recovering the wave height by the time it reaches the dyke foot.

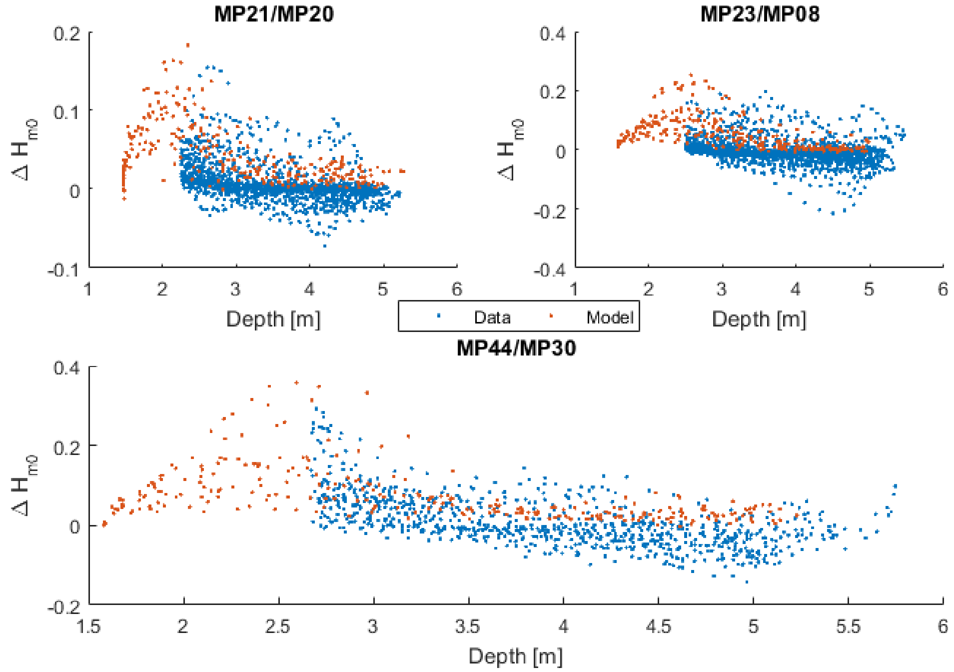


Figure 4-5. Wave attenuation/growth over the nourishment hook; positive values indicate attenuation, negative values indicate growth.

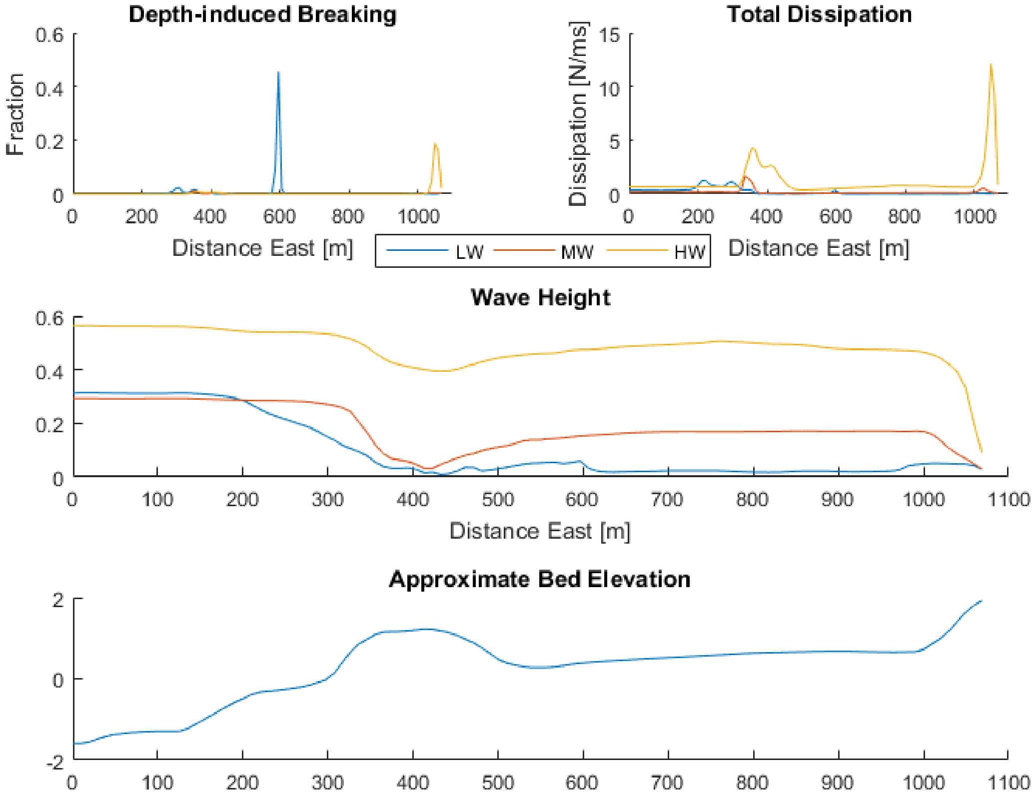


Figure 4-6. Modelled wave attenuation along northern transect during high water, mean water and low water in April 2014.

4.3.3 *PROJECTIONS OF DESIGN WAVE LOADS*

The lower (slow) and upper (fast) linear erosion trends (see Table 3.1 from Kala, 2016) were used to determine bathymetries for the period from 2020 to 2080 starting from i) the 2013 bathymetry without nourishment, ii) the 2013 bathymetry with nourishment, and iii) the 2013 bathymetry with a flat/uniform nourishment with roughly the same volume as the actual nourishment. Subsequently, the wave parameters at the toe of the dam under normative (1/4000) year wind/wave conditions (Arcadis, 2009; Royal Haskoning & Svasek Hydraulics, 2011) were computed with the Delft3D model. Figure 4-7 shows that the main nourishment has a limited influence on the wave height during design conditions with a 4 m water level. While the hook does dissipate the waves (mostly via bottom friction), wind-wave growth in the sheltered area over a distance of 300 m recovers the wave height to match the no-nourishment scenario. The difference between the wave heights at the Oesterdam between the nourishment and no-nourishment scenarios is entirely due to the nourishment at the foot of the dam.

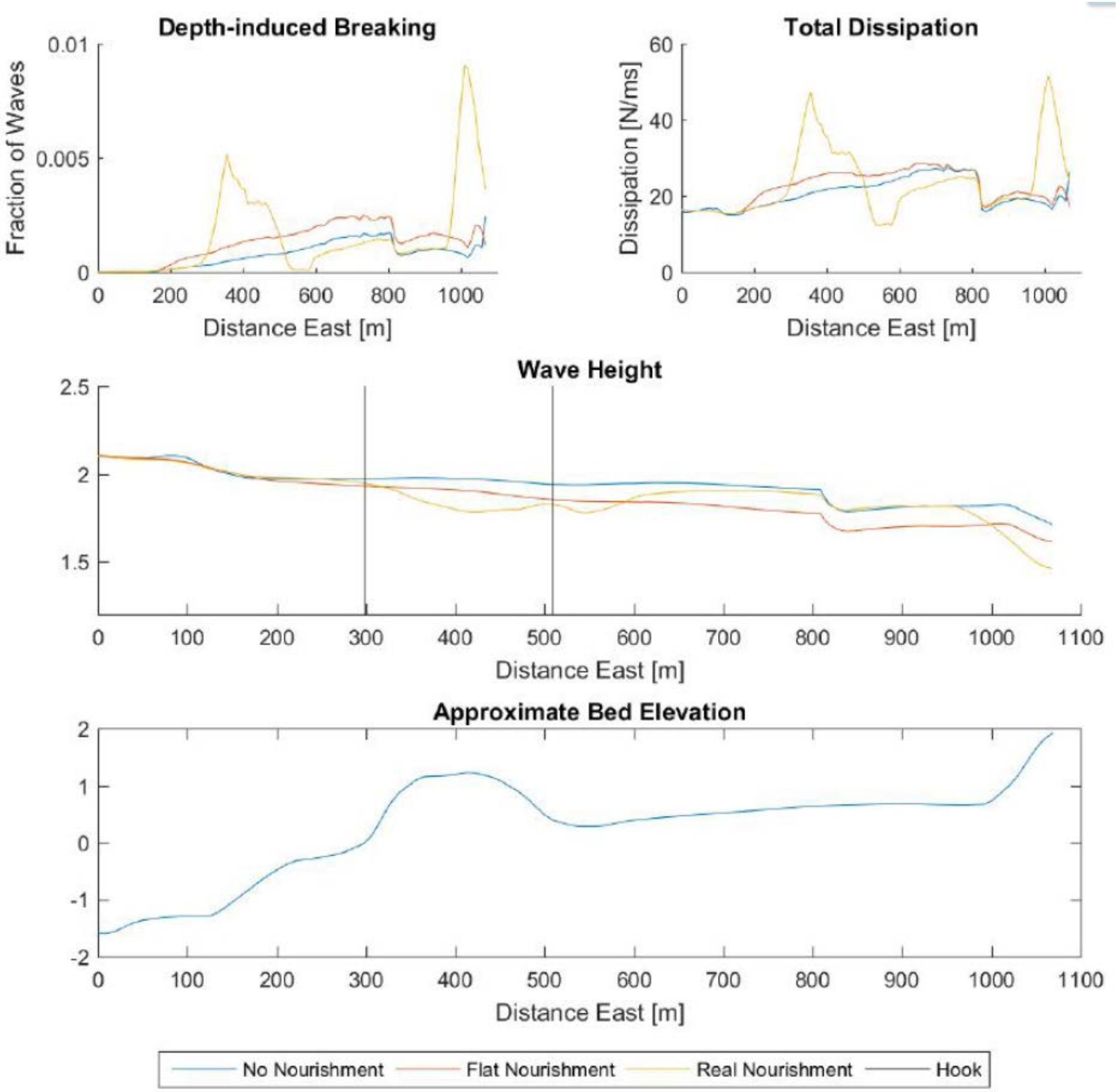


Figure 4-7. Wave dissipation and growth over the Oesterdam flat during design conditions at the 4 m water level. 2020 fast erosion time point.

The projected wave loads for the failure mechanisms of block failure, asphalt revetment failure and overtopping were computed, relative to the 2013 no-nourishment situation. Figure 4-8 shows the results for dam Section 81S, which is behind the main sand nourishment. The rapid change in the overtopping loads relative to the asphalt and block loads is because it is non-linearly related to the wave height, which increases slowly (up to 16% by 2080 for the no-nourishment case). The real nourishment reduces the projected design wave load increase by 50%. The hypothetical uniform nourishment also shows smaller wave loads than the no-nourishment scenario, but has a weaker effect on the wave damping than the real nourishment due to the missing dam foot nourishment (Figure 4-7).

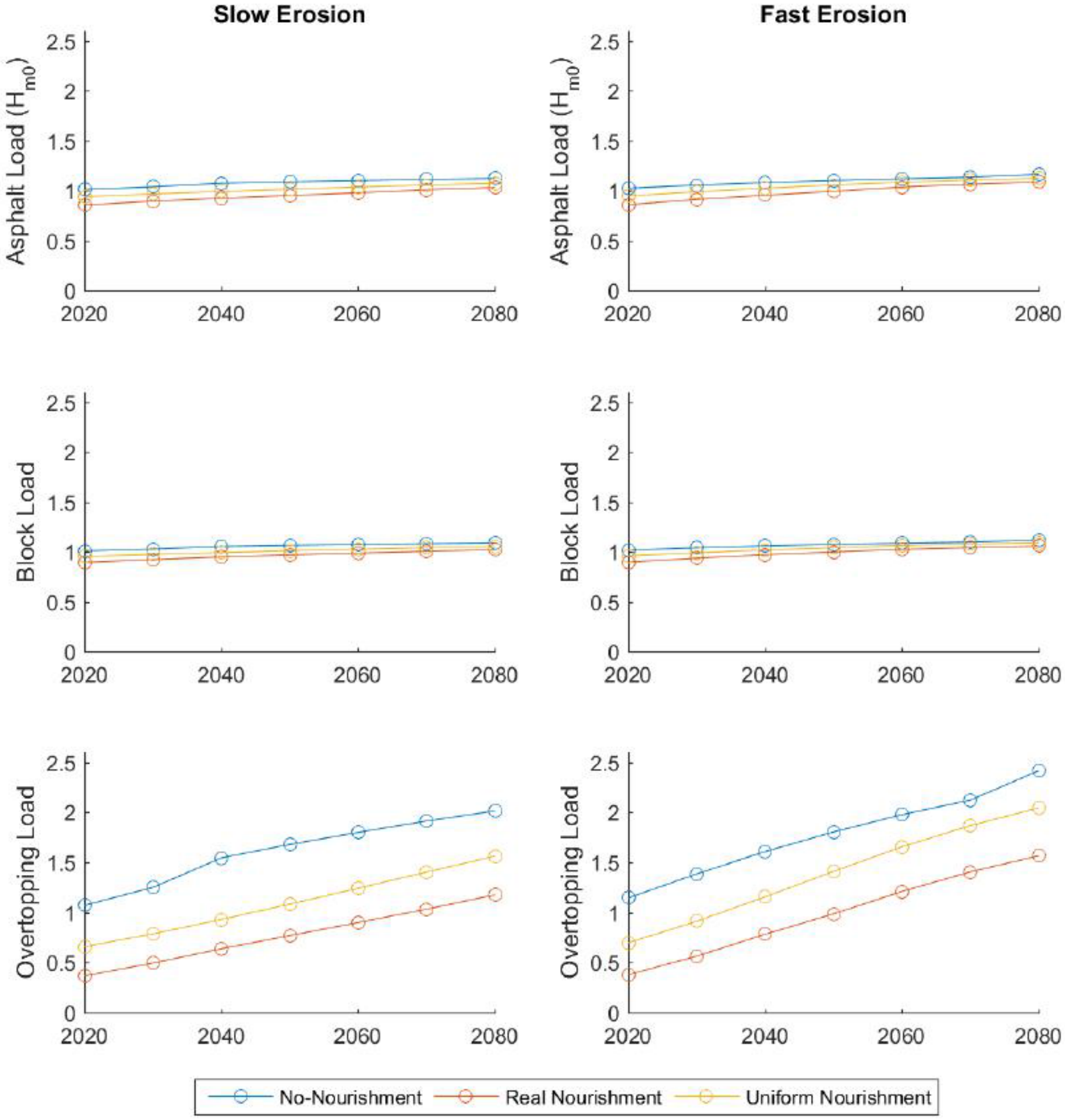


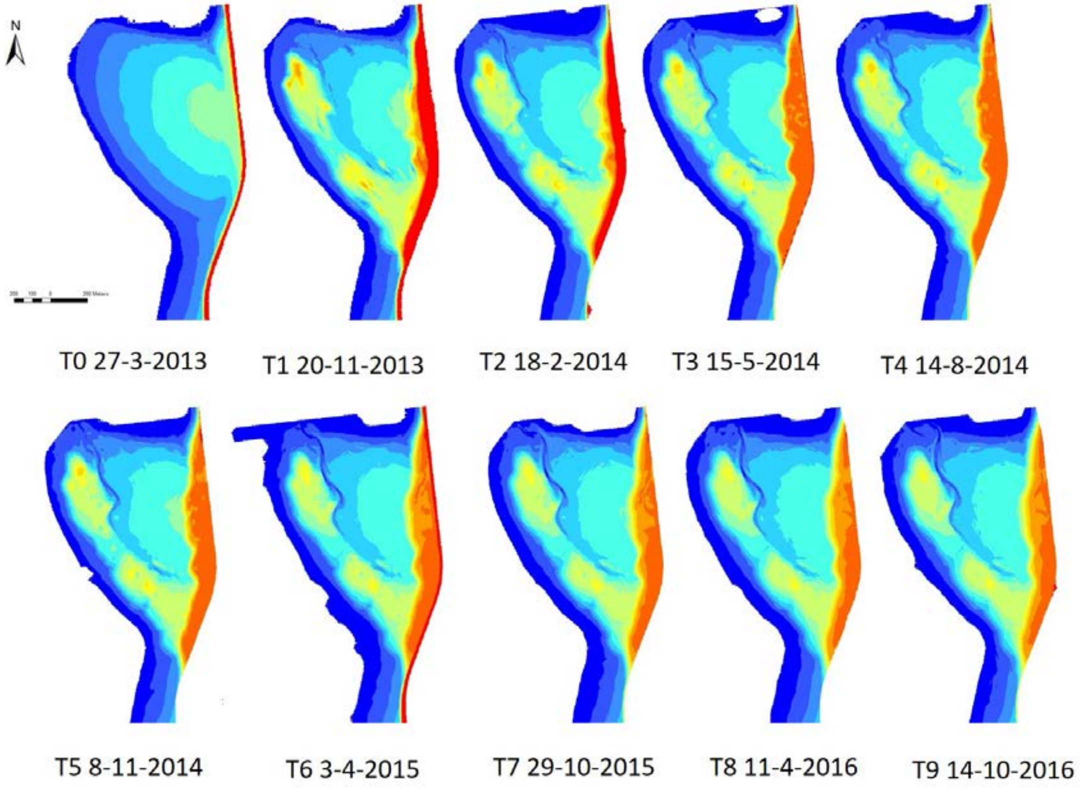
Figure 4-8. **Projected (normalized) design wave loads for the asphalt revetments, block revetments, and for overtopping using a design water level of 4 m. Section 81s of the Oesterdam.**

5 MORPHOLOGY

5.1 MORPHOLOGICAL CHANGES OF NOURISHMENTS AND TIDAL FLAT

Based on measurements of the contractor Van Oord it is expected that the primary consolidation process (this is the process were water content of the sand body decreases) was only active in the first four months. After this period morphological changes were the result of erosion and sedimentation, caused by hydrodynamic forces. Morphological changes are visible in Figure 5-1 (T_0 to T_9). In the initial phase, the first four months after the nourishment was constructed, relative large changes are visible. In the northern part, the top of the main nourishment was lowered with 25 cm.

In the pictures the earlier discussed man-made change of the dyke foot nourishment is visible when comparing the maps of T_2 and T_3. The figure shows relative little changes at the central tidal flat.



T0 27-3-2013 T1 20-11-2013 T2 18-2-2014 T3 15-5-2014 T4 14-8-2014

T5 8-11-2014 T6 3-4-2015 T7 29-10-2015 T8 11-4-2016 T9 14-10-2016

Figure 5-1. Height maps of the study area over the period: March 2013 till October 2016.

Figure 5-2 shows the erosion and sedimentation pattern over the period from May 2014 (T_3) till October 2016 (T_9). The higher parts of the main sand nourishment show a more erosion. Also the edge of the dyke foot nourishment is eroding relatively fast, and on the lower part sedimentation is visible. In other words the waves on the dyke are creating a more gentle slope of the dyke foot nourishment, than initially constructed at March 2014 (see also Figure 2-1). The undisturbed tidal flat at the western side of the main sand nourishment and the central tidal flat show little changes.

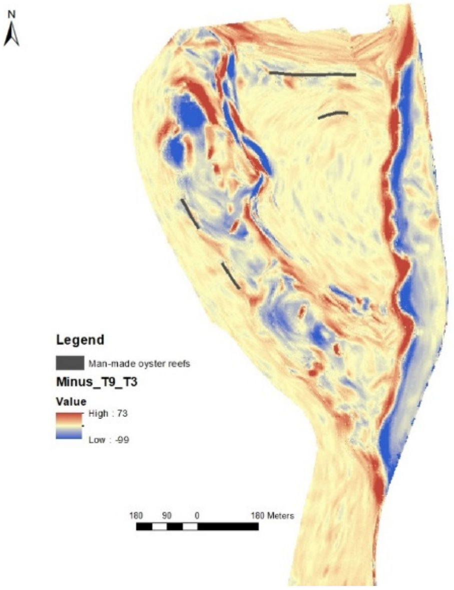


Figure 5-2. Erosion (blue) and sedimentation (red) map over the period May (T_3) 2014 till October 2016 (T_9).

Looking at the cross-sections 1, 2, 3 and 4 (Figure 5-3) a slow landward movement of the main nourishment is visible, especially in the cross-sections 2 and 3, indicating that most of the wave energy is dissipation on the western side of the nourishment, resulting in erosion. On the lee side of the main nourishment, sedimentation is visiable indicating a movement of sediment form the stoss stide to the lee side of the main nourishment.

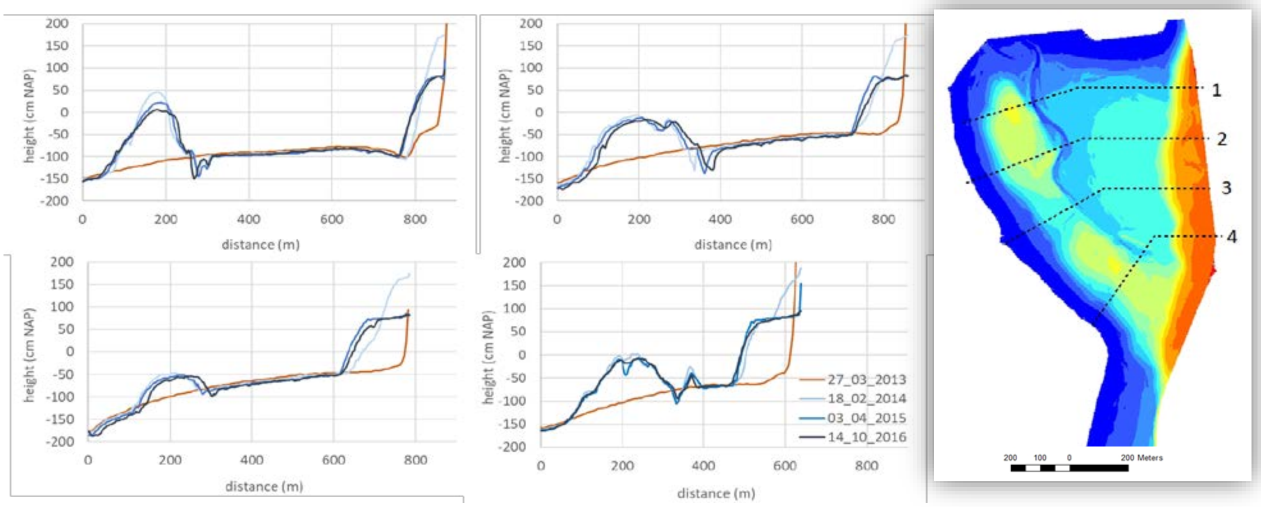


Figure 5-3. Cross-section 1, 2, 3 and 4.

5.2 DRAINAGE CHANNEL

Shortly after the realization of the sand nourishment (November 2013), a drainage channel developed along the east side of the main sand nourishment. This channel was already visible in the height maps three months after the construction of the nourishment (Figure 5-1). Although meander bends are shifting in northern direction caused by ebb dominated flow velocities (Figure 4-2), the general location of the channel is from the start more or less stable. This fixed location becomes clear when looking at the cross-sections (Figure 5-3). The water is collected at the lowest point of the central tidal flat, draining the water from the tidal flat during the ebb phase. The presence of the main sand nourishment is directing the flow in northern direction.

It is important to know whether the discharge of the channel is in equilibrium with the size of the cross-section, since the water flow can erode the main sand nourishment, and this sand will not be available anymore to nourish the central tidal flat (one of the objectives of the nourishment). An increasing channel size (size of the cross-section) can result in an increasing erosion risk for the main sand nourishment. Calculations of the cross-sectional area (Martens, 2015) and volume calculations of the channel area (Figure 5-6) showed that the channel dimensions are in equilibrium with the discharge after two years (for more details about the meander shifting see the study of Martens, 2015). Also when the channel size is in equilibrium with the discharge, netto sediment transport in northern direction (ebb phase) is possible, because the flow can pick up new sediment which settled on the lee side of the main sand nourishment. But the delta, created by the newley created tidal channel (Figure 5-6) is in size also in equilibirium with the total eroded volume of the channel. This is an indication that not mutch extra sediment is is picked-up by the channel, resulting in erosion of the main nourishement.

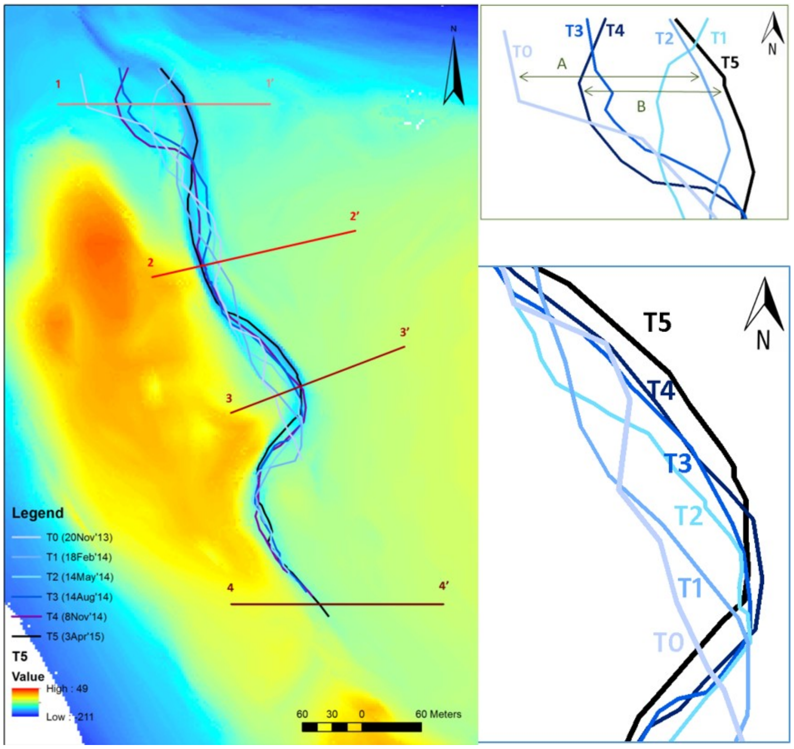
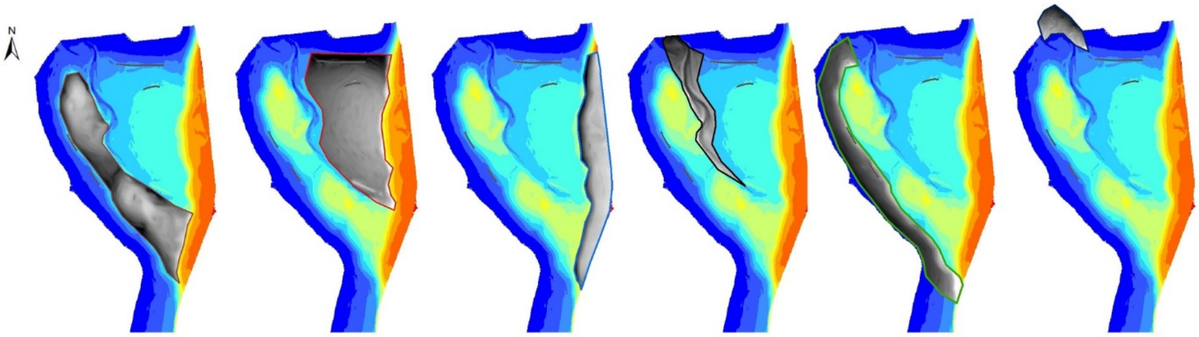


Figure 5-4. Meander bend migration of the drainage channel (Martens, 2015)

5.3 SAND BALANCE AND EROSION TREND

To understand the erosion trend and sediment balance at the study area several morphological elements are used for calculating the average height (m NAP) and volume change (m^3). Figure 5-5 shows six morphological elements: main sand nourishment, central tidal flat, dyke foot nourishment, drainage channel, lower foreshore and the delta of the drainage channel. For each element the volume change is calculated in m^3, see Figure 5-6. These volume changes are relative to the T_1 situation, the first measurement after the construction. Downward sloping lines are indicating an erosion trend, upward lines a sedimentation trend. Points above the zero line show net sedimentation, and points below the zero line net erosion.



Main nourishment 20.5 ha

Tidal flat 26.2 ha

Dyke foot nourishment 13.6 ha

Drainage channel 7.5 ha

Lower foreshore 17.5 ha

Delta channel 3.1 ha

Figure 5-5. Location and size of area’s used for volume and height calculations

The dyke foot nourishment showed the largest loss of volume, up to ≈23,000 m^3 over the measurement period of three years, which is 7% of the total nourishment volume (350,000 m^3; Table 3). This is related to the relative high dyke foot nourishment (60 to 70 cm NAP;), so more wave energy dissipation takes place compared to the main sand nourishment (height: -30 to -34 cm NAP); see also chapter 5 about wave attenuation. But also the main sand nourishment showed a volume loss of around 13,000 m^3 over the measurement period (Figure 5-6), which is 3.6% of the nourishment volume (Table 3).

The volume changes in the area of the drainage channel showed an initial erosion (5000 m^3), and after 2015 the erosion trend was changing in a stable situation without significant erosion and sedimentation. This suggests that the depth and width of the drainage channel was from that time on in equilibrium with the discharge. The delta of the drainage channel followed the opposite trend, showing sedimentation and shifting to an equilibrium state.

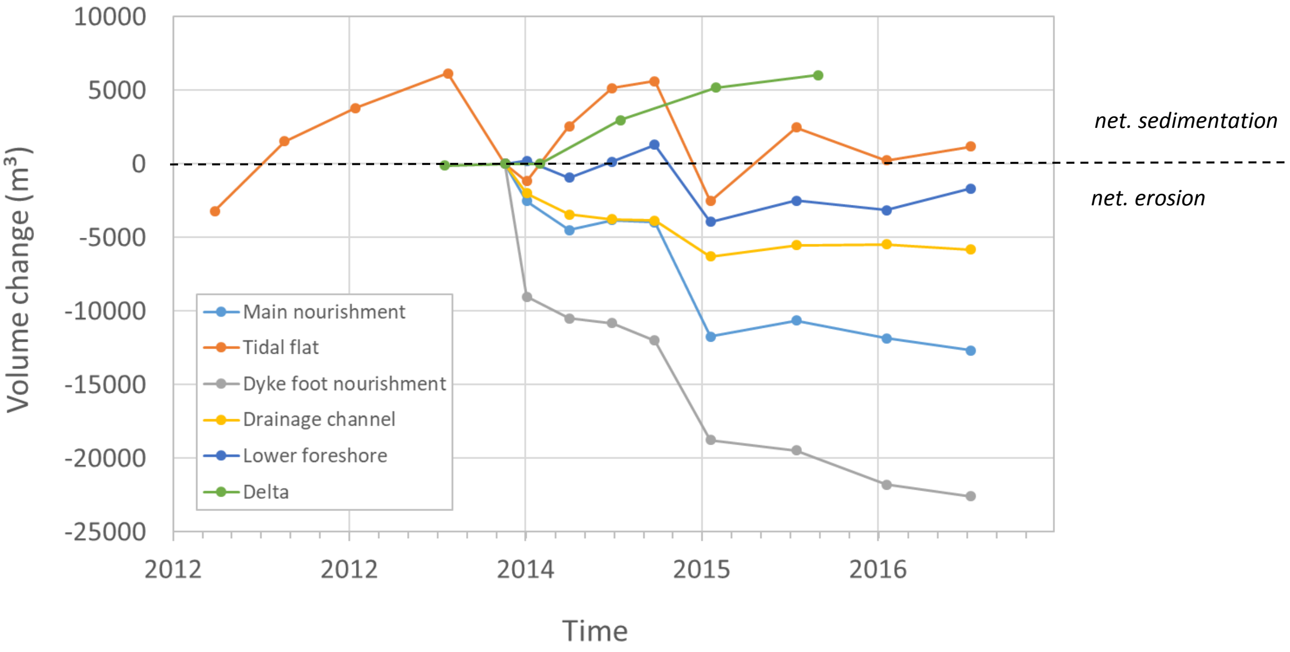


Figure 5-6. Volume changes in respect to the T_1 situation (November 2013). The delta area (green line) is based on less frequently applied multi beam measurements. The other areas are covered with the RKT-DGPS measurements

The central tidal flat showed periods of sedimentation and periods dominated by erosion, but in general the net changes are around zero. In the study of De Graaf (2012) erosion levels in the nearby tidal flats were analysed and showed values of 0.5 to 2 cm/year (period 1990-2010), which was based on Vaklodingen data and RTK-DGPS measurements. This negative trend is not visible at the central tidal flat after the Oesterdam sand nourishment. However, it cannot be concluded that this is caused by the presence of the main sand nourishment, that protects and acts as a sand source for the central tidal flat, because also in the pre-nourishment measurements (T_{-3}, T_{-2}, T_{-1} and T_0) sedimentation trends were observed. Only longer measurement periods could tell more about the effect of the main nourishment on the central tidal flat.

Looking at all the morphological elements altogether a clear erosion trend was visible. In total 10% of the nourished sand was removed and transported outside the study area, in the period between November 2013 and October 2016.

Table 3. Volume changes in % of the total nourished volume (350,000 m³)

date mid interv.	interval (days)	Main nourishm. Δ V (%)	Tidal flat Δ V (%)	Dyke foot nourish. Δ V (%)	Drainage channel Δ V (%)	Lower foreshore Δ V (%)
27-3-2012	139		1.3%			
19-8-2012	150		0.6%			
13-1-2013	145		0.7%			
24-7-2013	238		-1.8%			
20-11-2013		0	0	0	0	0
4-1-2014	90	-0.7%	-0.3%	-2.6%	-0.57%	0.1%
2-4-2014	86	-1.3%	0.2%	-3.0%	-0.99%	-0.3%
29-6-2014	91	-1.1%	0.7%	-3.1%	-1.07%	0.0%
26-9-2014	86	-1.1%	0.1%	-3.4%	-1.10%	0.4%
20-1-2015	146	-3.3%	-2.3%	-5.4%	-1.80%	-1.1%
16-7-2015	209	-3.0%	1.4%	-5.6%	-1.58%	-0.7%
19-1-2016	165	-3.4%	-0.6%	-6.2%	-1.56%	-0.9%
13-7-2016	186	-3.6%	0.3%	-6.5%	-1.66%	-0.5%

date mid interv.	interval (days)	Delta channel Δ V (%)
jul-13	275	-0.03%
nov-13	0	0.00%
jan-14	121	0.00%
jul-14	214	0.85%
jan-15	181	1.48%
aug-15	245	1.73%
		-10.2%

Table 4. Average height levels in m NAP at the different morphological units

name	date	Main nourishm. av. height (m NAP)	Tidal flat av. height (m NAP)	Dyke foot nourish. av. height (m NAP)	Drainage channel av. height (m NAP)	Lower foreshore av. height (m NAP)
T-3	18-1-2012		-0.74			
T-2	5-6-2012		-0.72			
T-1	2-11-2012		-0.71			
T0	27-3-2013	-1.07	-0.70	-0.51	-1.00	-1.40
T1	20-11-2013	-0.28	-0.73	0.78	-1.01	-1.34
T2	18-2-2014	-0.29	-0.73	0.71	-1.04	-1.34
T3	15-5-2014	-0.30	-0.73	0.70	-1.06	-1.34
T4	14-8-2014	-0.30	-0.72	0.70	-1.06	-1.34
T5	8-11-2014	-0.30	-0.72	0.69	-1.06	-1.33
T6	3-4-2015	-0.33	-0.75	0.64	-1.09	-1.36
T7	29-10-2015	-0.33	-0.73	0.64	-1.08	-1.35
T8	11-4-2016	-0.33	-0.74	0.62	-1.08	-1.35
T9	14-10-2016	-0.34	-0.73	0.61	-1.09	-1.35

name	date	Delta channel av. height (m NAP)
T-1	1-3-2013	-2.14
T0	1-12-2013	-2.14
T1	1-4-2014	-2.04
T2	1-11-2014	-1.97
T3	1-5-2015	-1.94
T4	1-1-2016	-1.89

Erosion rates for the main sand nourishment and dyke foot nourishment are calculated and presented in Figure 5-7. The main sand nourishment is eroding ≈2 cm/year (average height) and the dyke foot nourishment show erosion levels over ≈5 cm/year. Assuming that the wave climate in the period 2013-2016 is representative for the future and the erosion rate is not a function of the nourishment height, a prediction is made for the life time of the two nourishments (Figure 5-7). The picture shows that the main sand nourishment have a lifespan until 2030-2035, and the dyke foot nourishment until 2040-2045. These numbers are just an indication because, it is unclear what is the impact of future storms (more erosion). If these storms impact is limited, most likely the lifespan of the nourishments is longer.

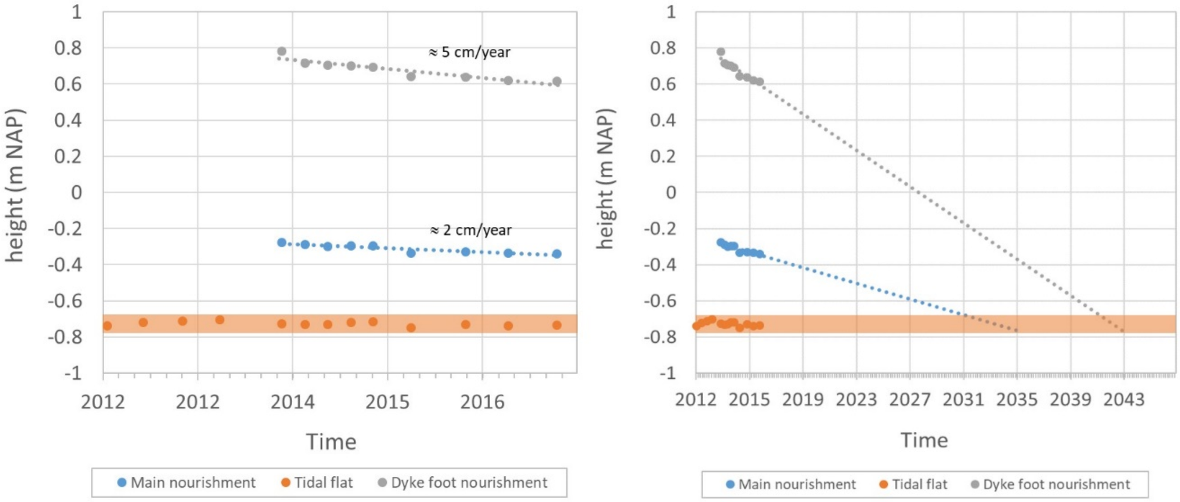


Figure 5-7. Erosion trend at the main sand nourishment, dyke foot nourishment and tidal flat (left), possible future erosion trend (right).

5.4 INFLUENCE OF MAIN SAND NOURISHMENT ON CENTRAL TIDAL FLAT

One of the objectives of the main sand nourishment is to protect the central tidal flat and create a more sheltered area. It is obvious that the presence of a large sand body create some protection for benthic species especially in the vicinity of the nourishment. What the result is during more severe weather conditions is less clear and this will be discussed in chapter 4.3. In Figure 6-4 it can be seen that the ecological richness increased behind the protection of the sand nourishment, most likely caused by lower hydrodynamic loads and morphological changes.

Since the erosion and sedimentation levels at the central tidal flat showed some variation around zero, also in the pre-nourishment period, it is not clear if the main sand nourishment acts as a sand source for the central tidal flat. But looking at grain-size distribution over the area (Figure 5-8) the sediments on the tidal flat is getting coarser. This increase in median grain-size at the tidal flat is a strong indication that the main sand nourishment but also the dyke foot nourishment, which have much coarser sand (D_{50} = 285 µm), is able to transport sand in direction of the central tidal flat (D_{50} = 185 µm). Most likely this process will happen during flood, when the nourishment is submerged and waves are breaking over the main nourishment, and on the dyke foot nourishment. In this tidal phase, the drainage channel is not very active, so no flow will move the particles in northern direction.

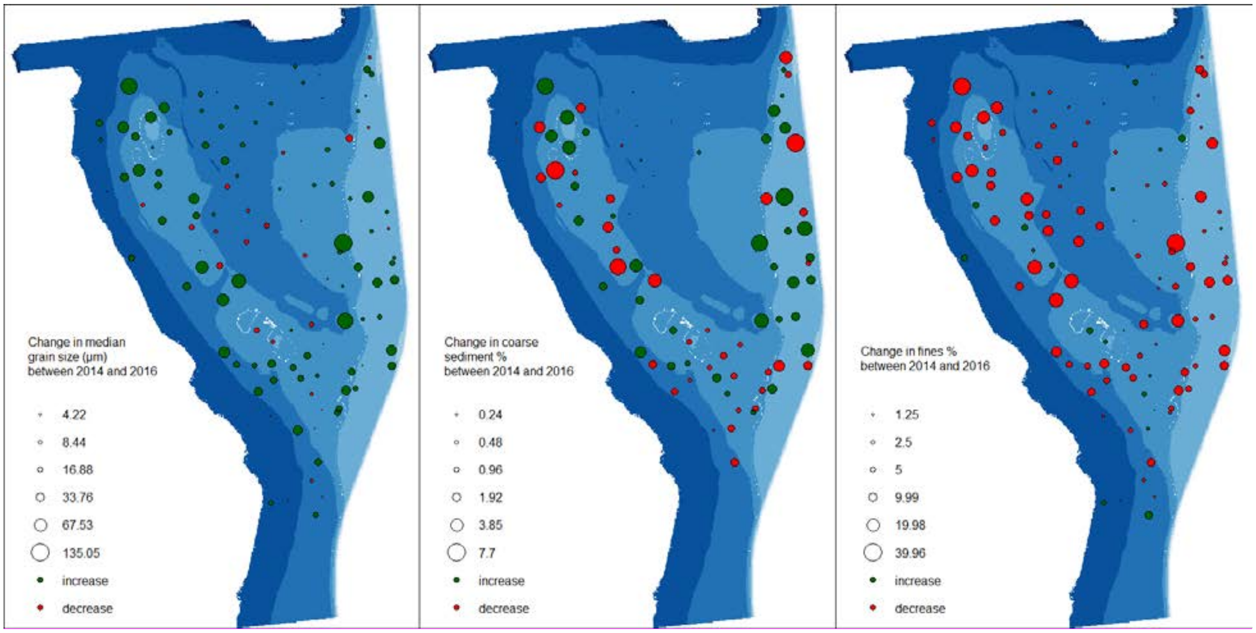


Figure 5-8. Grainsize changes between 2014 and 2016, for the median grainsize (left), coarse sand (middle) and fine sand (right). The radius is proportional to % increase (in green) or decrease (in red).

A second indication that the main sand nourishment is a sand source for the central tidal flat is shown in Figure 5-9. The main sand nourishment and the central tidal flat show a same sand colour, with is different from the colour at the adjacent tidal flats.

Figure 5-9. Orthogonal image of the Oesterdam sand nourishment at May 2014, image is created with a large number of photos taken by a drone.

5.5 DELFT3D MODELLING TO BETTER UNDERSTAND CONTROLLING PROCESSES

The Delft3D model was used to identify the mechanisms that control the morphodynamic impact on the Oesterdam tidal flat nourishment (see Pezij, 2015 for details).

Figure 5-10 shows the impact of the nourishment on the computed wave heights on 13 February 2014. This corresponds to south-western wind and wave directions, and the beginning of ebb tide. For this wave direction, the main sand nourishment reduces the wave heights. Wave energy is able to penetrate through the lower part of the nourishment. Still the wave heights in the entire sheltered area behind the main sand nourishment are reduced.

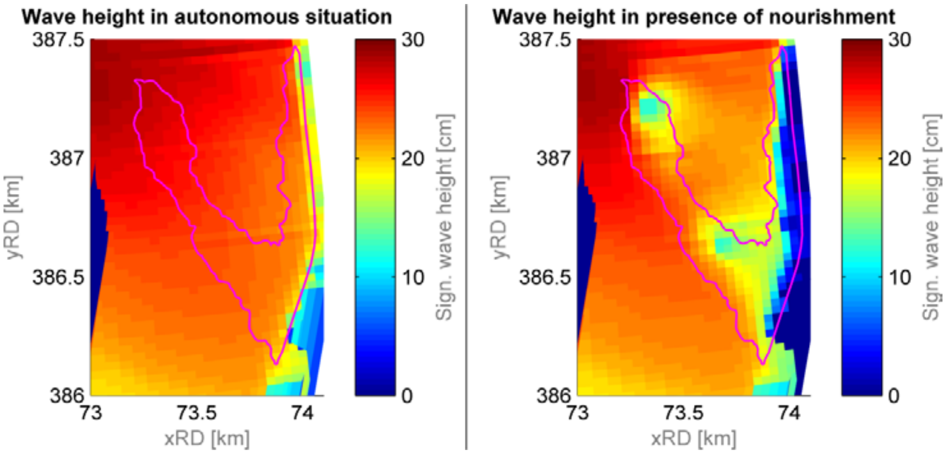


Figure 5-10. Computed significant wave heights on 13 February 2014 (begin of ebb tide). The purple line indicates the initial nourishment contour. On the left the situation without nourishment, on the right with nourishment.

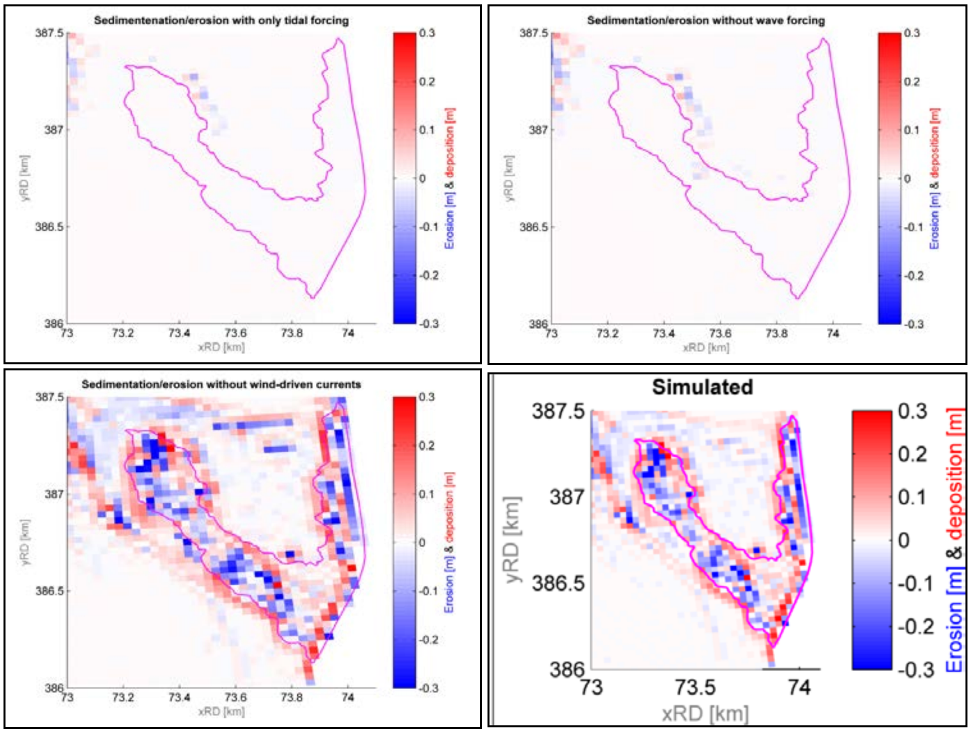


Figure 5-11. Predicted sedimentation and erosion for a 3-month period after nourishment construction. Top left: only tide, top right: tide + wind, bottom left: tide + wave, bottom right: tide + wave + wind. The purple line indicates the initial nourishment contour.

In order to identify the relative importance of tide, wind and waves, 3 additional morphological simulations were carried out: i) with tidal forcing only, ii) with tide + wind, and iii) with tide + waves. The last simulation does include the effect of wind on wave generation, but doesn't include the wind-driven set-up and currents. Figure 5-11 shows the computed sedimentation and erosion patterns 3 months after the nourishment. This figure shows that the morphological changes are small if wave forcing is absent (top plots Figure 5-11). Only some morphological activity can be seen just east of the main sand nourishment, which is related to flow contraction. Apparently, the bed shear stresses and vertical mixing without wave action are too small to induce significant sediment transport rates. The effect of wind-driven currents and set-up on the sedimentation and erosion patterns is very small, also according to the simulations with waves (bottom plots Figure 5-11). The morphological development of the Oesterdam nourishment is thus mainly controlled by the combined wave and tide action: sediment is stirred up by the waves and transported by the tide- and possibly also the wave-driven currents.

5.6 MORPHOLOGICAL IMPACT OF ARTIFICAL OYSTER REEFS

Morphological impact of the constructed oyster reefs was mainly studied on the level of sediment stabilisation. The results obtained during the monitoring period shows that the erosion-sedimentation around the reefs is strongly linked to the wind and waves direction, see (Salvador de Paiva et al., 2017). For instance, in the study area the predominant wind is coming from south and south-west, and in this situation reef B, located on the northern side, works as a barrier for sand transport, from currents and winds. The sand accumulation next to the reef when compared to the reference areas is particularly clear on Figure 5-12, representing an increase of 9.71 m^3/year while the reference areas show a decrease of 27.38 m^3/year, on the left side, and 25.56 m^3/year, on the right side.

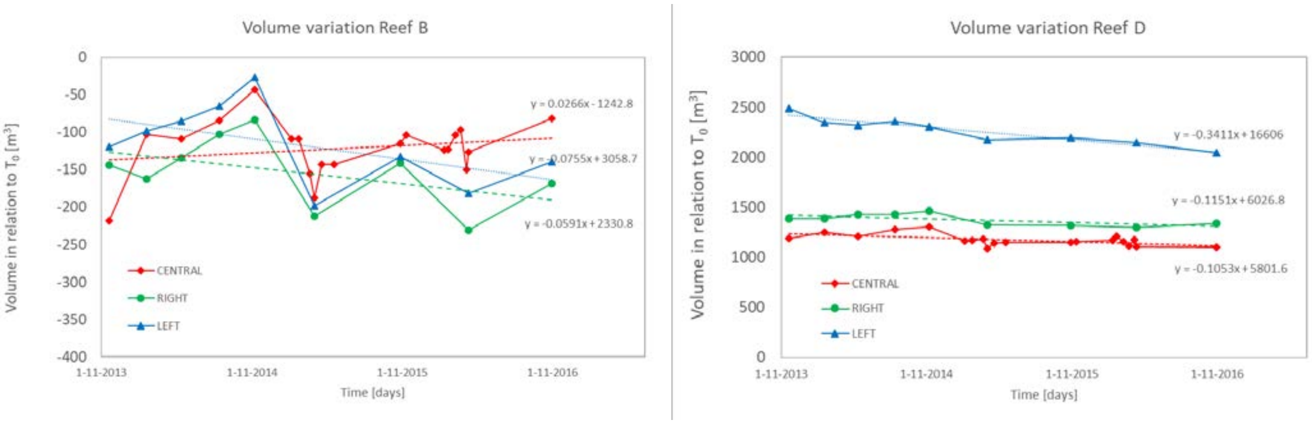


Figure 5-12. Total volume variation (CENTRAL) on reef B and D in m^3. The rate of change expressed in the charts is in m^3/day. The reference areas (LEFT and RIGHT) are similar in dimensions and characteristics but located on the left and right of each reef at a certain distance to make sure that they are outside the influence area of the reefs.

In the case of Reef D which is directly exposed to wind and waves it seems to be functioning as typical detached submerged break water, reducing wave energy at the lee side of the structure. This is particularly clear when observing the sediment distribution pattern, Figure 5-13, which a typical tombolo shape formation on the lee area of the reef. The volume change variation is also lower behind the reef when comparing to the reference areas, Figure 5-12.

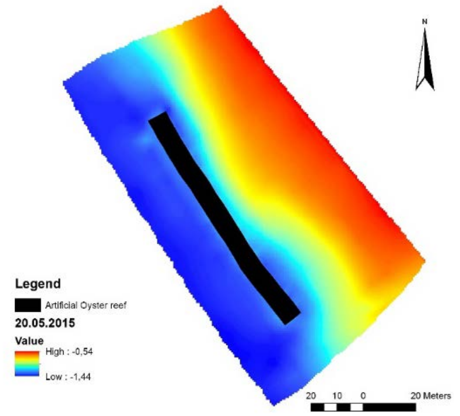


Figure 5-13. Reef D showing a tombolo formation on the lee side of the reef.

When looking at the volume changes (erosion and sedimentation) behind the reefs compared with the reference areas of the same size on both sides of the reefs, no major differences are visible. Figure 5-15 shows the difference between sediment changes behind the reefs, and at the reference areas. Values above zero indicate that the areas behind the reefs are accumulating more sediment than the reference areas, values below zero indicate more erosion. The figure shows that the impact of reefs has a small positive effect in the range of 0 to 50 m^3 for reef B, the reefs C and D are fluctuating around zero. In general the extra accumulation or erosion behind the reefs are negligible compared to the total volume changes of the main sand nourishment (Figure 5-6), which is 13,000 m^3 over the measurement period (2013-2016).

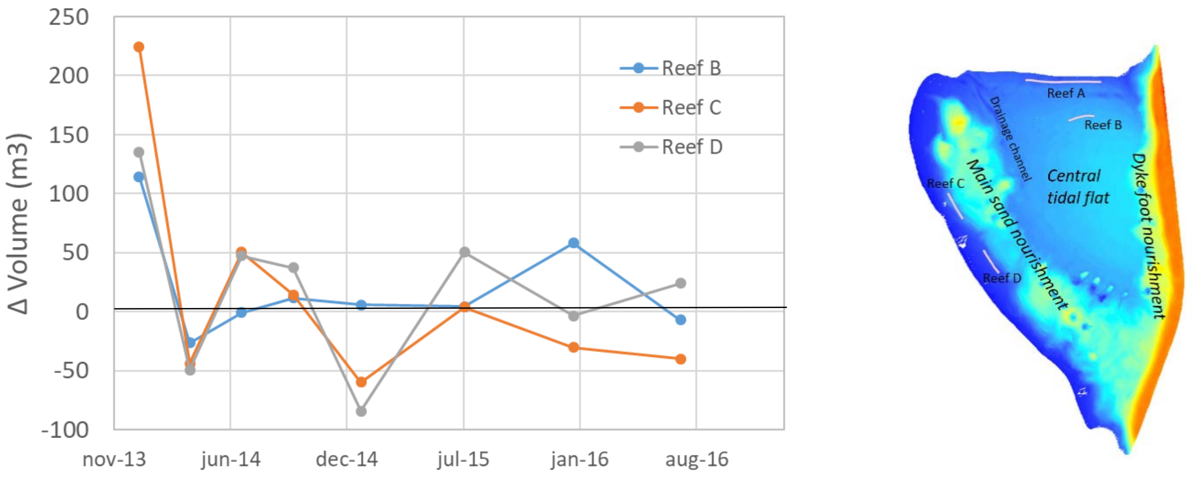


Figure 5-14. Difference between sediment loss or sediment accretion between the area behind the reef and the reference area. If area behind the reefs (A, B or C) are behaving equal as the reference areas than ΔV = 0. When ΔV = positive than the area behind the reef are collection more sand than the reference areas.

To conclude the use of constructed oyster reefs is a suitable as ecosystem based solutions to locally stabilize the sediment. The results show that these structures have a local capability to stabilize sediment and that when more than one of these structures are applied their effect may be even higher. On the scale of the main sand nourishment these reefs have very limited effect.

6 ECOLOGICAL DEVELOPMENT ON SOFT SEDIMENT

6.1 CHARACTERISATION OF THE OESTERDAM TIDAL FLAT AFTER NOURISHMENT (T_1, T_2, T_3)

Environmental conditions such as grain size, emersion time and hydrodynamics, determine to a large extent the distribution of benthic macrofauna on a tidal flat. Nourishments change these conditions and to interpret the ecological developments insight in the change in environmental conditions is needed. The nourishment resulted in a significant change in elevation and slope of large parts of the Oesterdam intertidal flat. The average elevation of the central tidal flat (based on the sampling locations) was -0,80 m NAP without significant temporal changes over the years (Figure 6-1). The sampling locations on the nourished areas had significantly higher elevations, with the main sand nourishment having an average elevation of -0.28 m NAP (2014) up to -0.31 m NAP (2016), and the dyke foot nourishment +0.57 m NAP (2014) up to +0.50 m NAP (2016). The nourished sampling stations, therefore, became lower in elevation, especially the highest locations, although no significant differences were observed within each area. Erosion of the top parts of the nourishment is in line with the general morphological development of the nourishment. This was also confirmed by the detailed transect measurements, showing clear erosion on the higher parts and deposition at the edges (Figure 6-2).

As a consequence of the nourishment, also emersion time differed significantly among areas, with the sampling stations on the central tidal flat having an average emersion time of 29%, on the main sand nourishment 43% and on the dyke foot nourishment 64%.

The median grain size of the sampling stations on the nourishment was significantly higher compared to the central tidal flat in all three years, but was not significantly different between the two nourished areas (Figure 6-1). The central tidal flat showed an average median grain size of 180 µm, which increased to 185 µm in 2015 and 192 µm in 2016. Also on the nourishment a coarsening was observed over the years, with on the main sand nourishment average values of 275 µm in 2014, 285 µm in 2015 and 296 µm in 2016 and on the dyke foot nourishment average values of 292 µm in 2014, 287 µm in 2015 and 307 µm in 2016. Similar trends were observed for the different sediment fractions. Summarizing, sediments on the nourished areas were significantly coarser compared to the central tidal flat, and over time sediments on average became slightly coarser and an overall decrease in the fraction fine sediment was observed, especially on the main sand nourishment. To visualise spatially these changes, Figure 6-2 shows the changes between 2014 and 2016 for elevation and median grain size. Also the transect measurements showed the increase in median grain size over time (Figure 6-2).

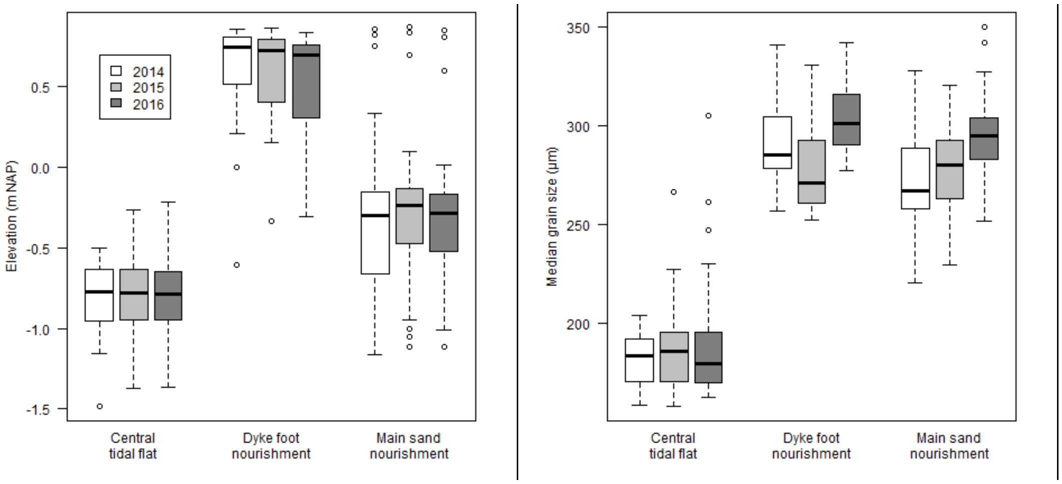


Figure 6-1. Box-plots of elevation (m NAP) and median grain size (µm) showing differences among areas (central tidal flat, dyke foot nourishment, main sand nourishment) and years (2014, 2015, 2016).

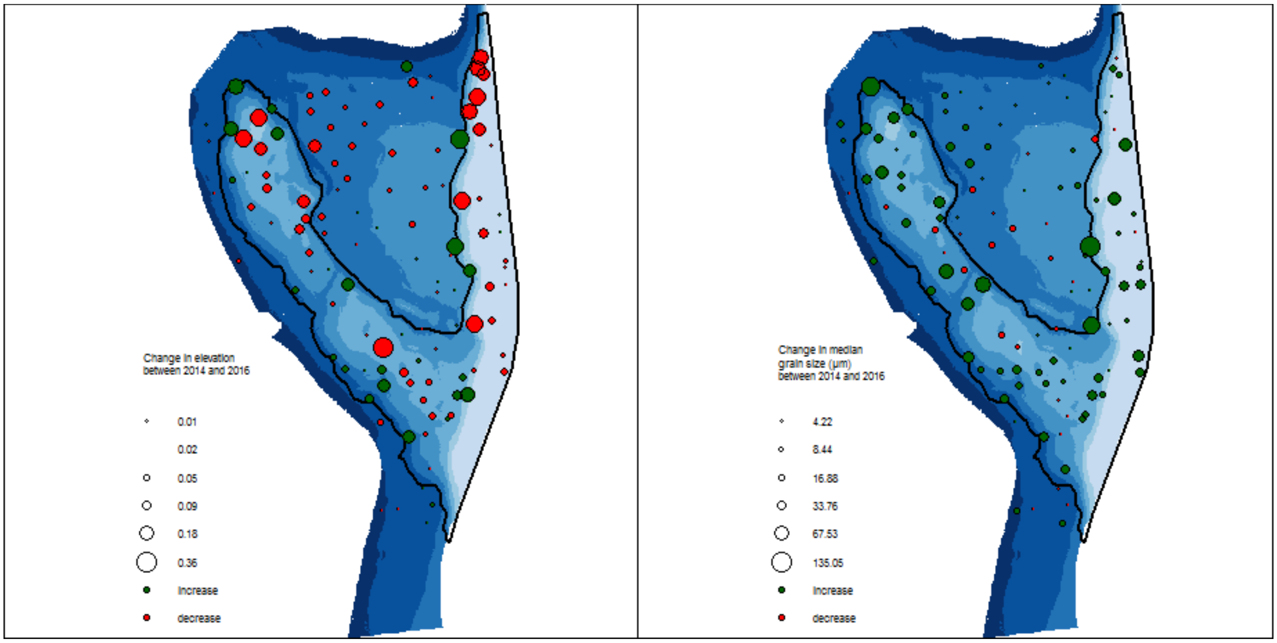


Figure 6-2. Changes in elevation and median grain size between 2014 and 2016. Green dots represent an increase in elevation of median grain size, red dots a decrease.

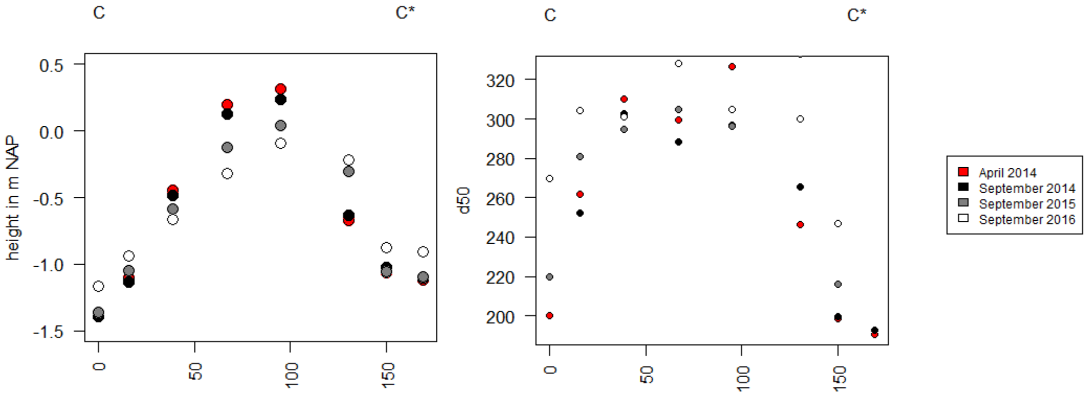


Figure 6-3. Change in elevation (left) and median grain size (right) along transect C–C on the main sand nourishment. See Appendix 1 for the position of the transects.*

6.1.1 *BENTHIC MACROFAUNA CHANGES*

GENERAL CHANGES

The total number of taxa observed in 2014, 2015 and 2016 (n=100 sampling stations each year) was 53, 54 and 53 taxa respectively. The average number of taxa per station varied between the different areas, with in 2014 significantly lower values on the dyke foot nourishment compared to the two other areas ($p<0.001$), which didn't show a significant difference ($p>0.05$) between each other (Table 5). In 2015 the central tidal flat had a significantly higher number of taxa compared to the nourished areas ($p<0.01$). In 2016 there was a significant higher number of taxa on the central tidal flat compared to the dyke foot nourishment ($p<0.001$) and a higher nuber of taxa on the main sand nourishment compared to the dyke foot nourishment ($p<0.05$). Over all years average number of taxa per station on the central tidal flat was similar compared to the situation prior to the nourishment.

Total density of the benthic macrofauna showed large variation among sampling stations and differed largely between areas and years (Table 5). In 2014 total density was significantly larger on the main sand nourishment compared to the central tidal flat ($p<0.05$). In 2015 and 2016 no significant differences in total density were observed among areas. Total density in general was much higher compared to the situation prior to the nourishment, also on the central tidal flat. This was mainly caused by the very high densities of the mud snail *Peringia ulvae*, which was very abundant in the years 2014-2016, especially in 2016. *Peringia ulvae* represented 72% of the total density on the central tidal flat in 2014, and on the nourished areas 93-94%. In 2015 it represented 92% of the total density in all three areas, and in 2016 even 93-98%. Other species are much less abundant. On the central tidal flat the benthic community was in all three years, in addition to *Peringia ulvae*, numerically dominated by the amphipod *Urothoe poseidonis*, the polychaetes *Scoloplos armiger* and *Streblospio shrubsolii*, and the bivalve *Cerastoderma edule*, but the relative contribution changed between the species. On the dyke foot nourishment also species like *Scoloplos armiger* and *Cerastoderma edule* dominate, but here also other species are observed such as the bivalves *Ruditapes philipinnarum* and *Limecola balthica*, and the amphipod *Bathyporeia* spp. On the main sand nourishment species like the polychaetes *Aphelochaeta marioni*, *Scoloplos armiger* and *Pygospio elegans*, and bivalves like *Ruditapes philippinarum*, *Limecola balthica* and *Cerastoderma edule* numerically dominated.

Table 5. Species richness (average number of taxa per sampling station), average density (ind/m^2) and average biomass (g AFDW/m^2) in 2014, 2015 and 2016 on the central tidal flat, main sand nourishment and dyke foot nourishment respectively.

Variable	*Species richness*	*Density*	*Biomass*
2014			
Central tidal flat	10.2 ± 0.57	8869 ± 3146	21.9 ± 7.4
Main sand nourishment	9.9 ± 0.61	34155 ± 7964	14.2 ± 3.5
Dyke foot nourishment	6.0 ± 0.64	12033 ± 2770	5.8 ± 2.8
2015			
Central tidal flat	12.1 ± 0.66	28032 ± 16638	15.6 ± 2.5
Main sand nourishment	8.6 ± 0.51	21352 ± 5367	16.8 ± 1.8
Dyke foot nourishment	8.3 ± 0.87	12697 ± 4340	8.6 ± 4.2
2016			
Central tidal flat	10.1 ± 0.65	36754 ± 13256	20.9 ± 6.7
Main sand nourishment	8.7 ± 0.54	48428 ± 12017	18.4 ± 4.2
Dyke foot nourishment	6.3 ± 0.57	37756 ± 9902	23.9 ± 8.9

Total biomass was in 2014 significantly higher on the central tidal flat compared to the nourished areas (Table 6). In 2015 biomass reached similar values on the central tidal flat and the main sand nourishment. In 2016 all three areas showed similar values. *Cerastoderma edule* contributed on average most to the biomass, representing between 23 and 69% of the total biomass (Table 6). Its importance became more important in 2016. The very high densities of *Peringia ulvae* resulted also in relatively high biomass values. *Arenicola marina* had relatively high biomass values in 2014, but its importance dropped over time. The opposite was observed for *Limecola balthica*, that relatively became more important over time, especially on the main sand nourishment.

Table 6. Biomass of the four most dominant species on the Oesterdam (in g AFDW/m²). Between brackets the contribution of the species to the total biomass is mentioned.

Variable	*C. edule*	*P. ulvae*	*A. marina*	*L. balthica*
2014				
Central tidal flat	12 (55%)	0.8 (4%)	4.1 (19%)	0.08 (0.4%)
Main sand nourishment	8.5 (60%)	2.2 (15%)	1.6 (11%)	0.06 (1%)
Dyke foot nourishment	1.3 (23%)	1 (18%)	3 (51%)	0.08 (0.4%)
2015				
Central tidal flat	15.6 (48%)	2.9 (19%)	1.8 (11%)	0.03 (0.2%)
Main sand nourishment	16.8 (38%)	5.8 (35%)	1.2 (7%)	0.4 (2%)
Dyke foot nourishment	8.6 (33%)	1.6 (19%)	1.9 (22%)	0.06 (1%)
2016				
Central tidal flat	13.1 (62%)	1.5 (7%)	0.9 (4%)	0.5 (2%)
Main sand nourishment	8.2 (44%)	4.2 (23%)	0.8 (4%)	2.5 (14%)
Dyke foot nourishment	16.4 (69%)	4.1 (17%)	0.4 (2%)	0.6 (2%)

Ecological richness, a combined measure for species richness, density and biomass (Ysebaert et al. 2017), is an additional univariate ecological indicator to express relative differences in macrofauna richness within the Oesterdam. The average ecological richness centres around 0 in a given data set. Our data set ranges from -2.88 (low ecological richness) to 1.90 (high ecological richness). Ecological richness showed clear spatial clusters in each year (Figure 6-4). Highest ecological richness is observed in the southeast part of the Oesterdam, both on the central tidal flat as on the nourished areas. Also behind the lowered area of the main sand nourishment a high ecological richness is observed. A relative low ecological richness is observed on the main sand nourishment at the tip, on the dyke foot nourishment in the north and at some sites on the central tidal flat.

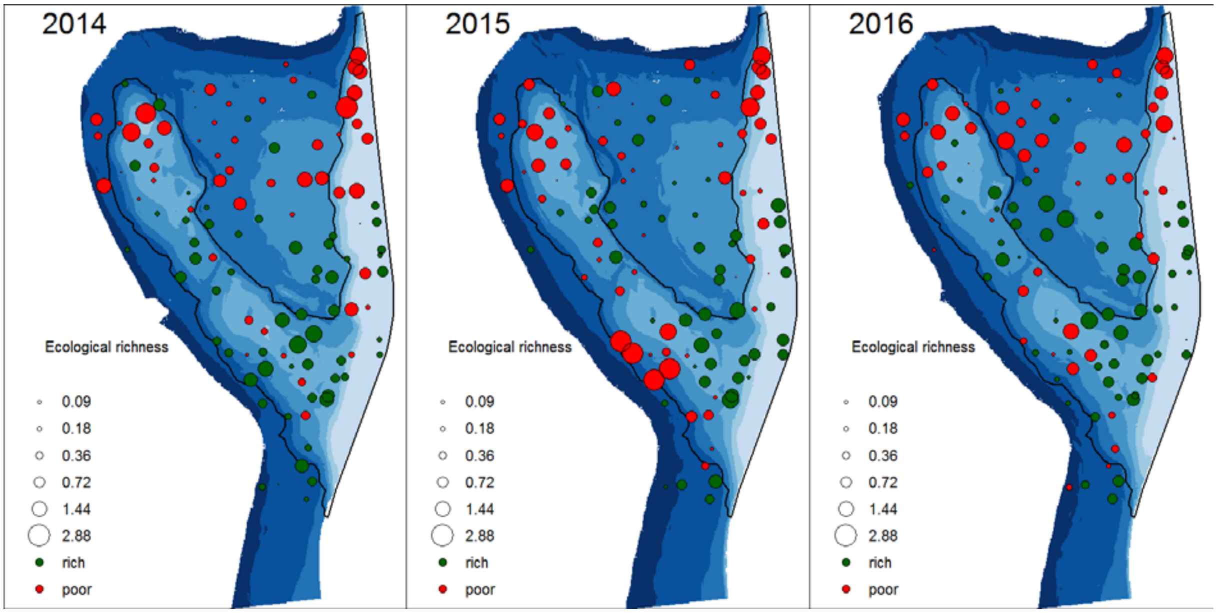


Figure 6-4. Distribution map of ecological richness on the Oesterdam in 2014, 2015 and 2016: green dots: positive values denoting relatively ecologically rich locations, red dots: negative values, denoting ecologically poor sampling stations. The radius is proportional to the ecological richness.

COMMUNITY CHANGES

The multivariate analysis on all stations showed significant differences in benthic community composition among areas and years (Figure 6-5). The benthic community of the central tidal flat seems to become more variable in 2016 compared to 2014 and 2015, as seen from the larger spreading of the sampling stations in 2016 in the n-MDS plot. Lowest dissimilarity in benthic community composition was observed for the main sand nourishment, whereas the dyke foot nourishment showed larger variability, especially in 2015.

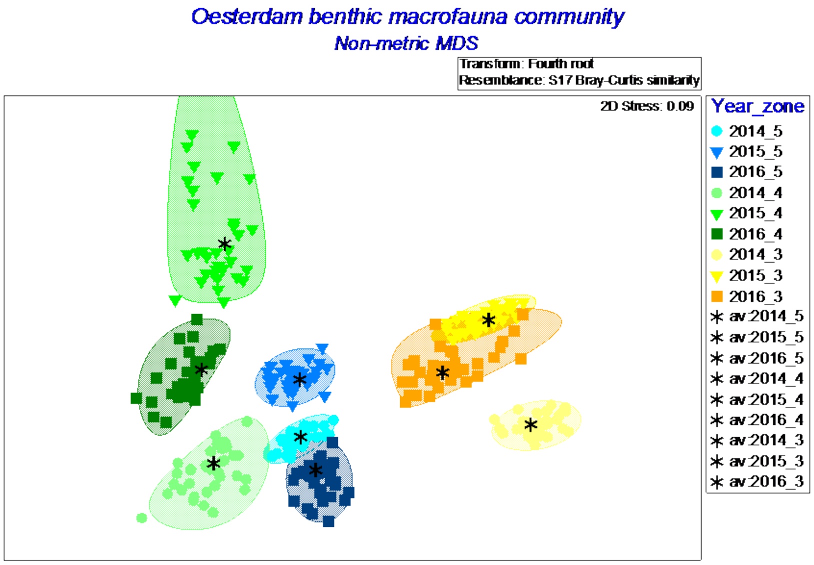


*Figure 6-5. nMDS-plot of the changes in benthic community composition from 2014 till 2016 for the central tidal flat (zone 3), the dyke foot nourishment (zone 4), and the main sand nourishment (zone 5) based on density data. Each point represents a sampling station and the distance between the points is a measure of the (dis)similarity in benthic community composition. The coloured areas denote the 95% confidence interval for each particular area in each year: yellow colours: central tidal flat, green colours: dyke foot nourishment, and blue colours: main sand nourishment. The * represents the averages for each particular area in each year.*

SPATIO-TEMPORAL CHANGES IN INDIVIDUAL SPECIES

As an example of trends in species occurrence data are presented for three characteristic bivalve species: the cockle *Cerastoderma edule*, the manila clam *Ruditapes philippinarum* and the Baltic tellin *Limecola balthica*. After the nourishment, these three species colonized the nourished areas and spatfall was observed in each year (Figure 6-6). For *C. edule* also settlement on the central tidal flat was observed, whereas the two other bivalve species remained more restricted to the nourished areas. In 2015 and especially 2016 *C. edule* numbers were very high on the central tidal flat near the main sand nourishment, with somewhat lower densities on the nourishment itself. Locally high densities of > 2000 ind/m^2 can be observed, the result of a large spatfall. *C. edule* is by far the most important species in terms of biomass. Other species are discussed in more detail in Ysebaert et al. (2017).

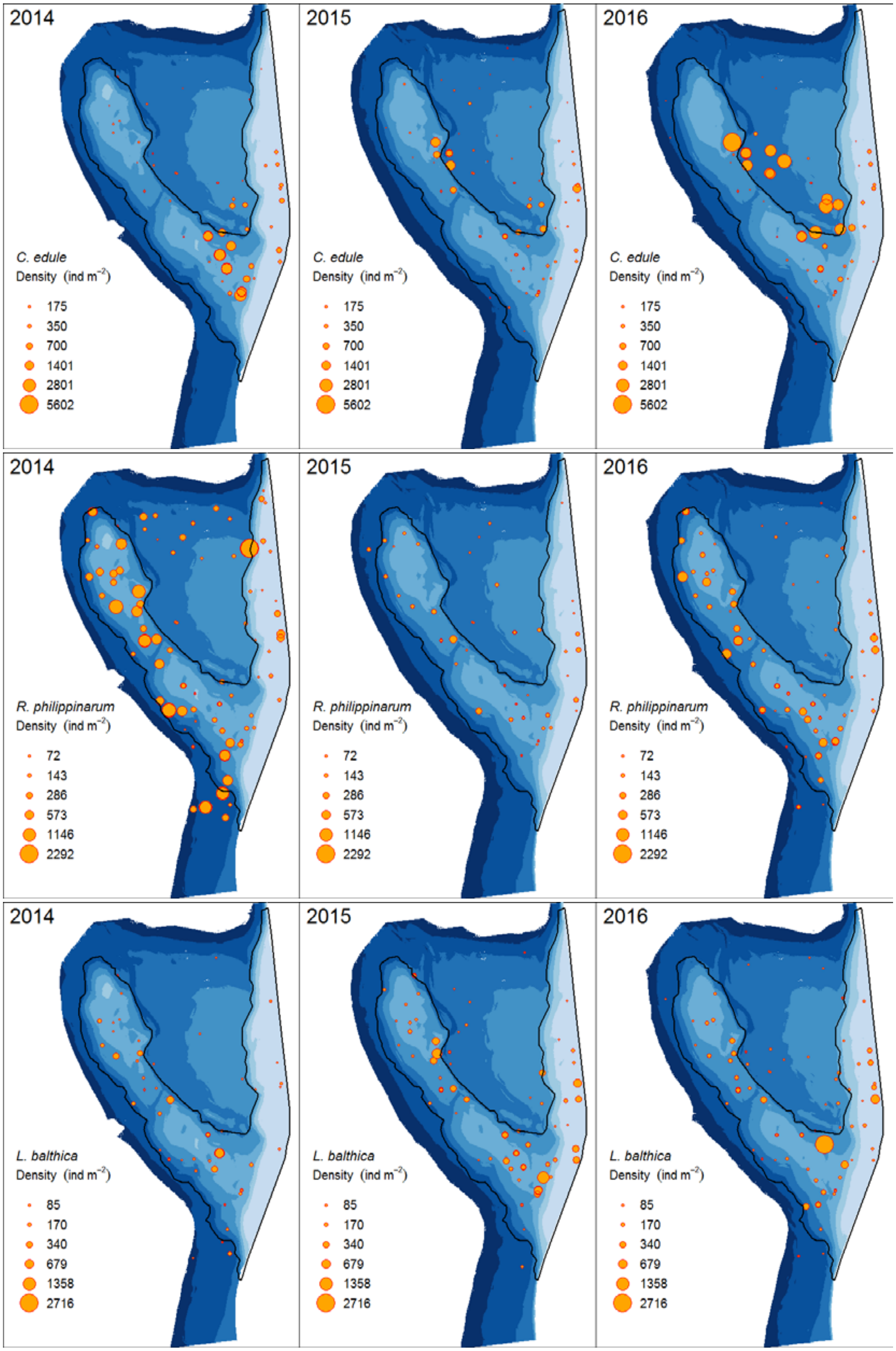


Figure 6-6. Distribution map of Cerastoderma edule, Ruditapes philippinarum and Limecola balthica density (ind/m^2) on the Oesterdam in 2014, 2015, and 2016. The original contour of the nourishment is indicated by the black line.

AREA-WIDE MAPPING OF BENTHIC SPECIES

The area-wide inventory of some benthic species showed in general good correspondence with the benthic macrofauna sampled in more detail at the 100 stations. Two species are discussed here, the lugworm *Arenicola marina* and the mudsnail *Peringia ulvae*. The lugworm *Arenicola marina* is the most common species observed in the qualitative monitoring. The lugworm was observed at almost every sampling point in August 2013, prior to the nourishment (Figure 6-7). In April 2014, some juvenile and medium-sized lugworms were observed on the main sand nourishment, whereas no lugworms were observed on the dyke foot nourishment, due to the re-profiling of this nourishment section in March 2014. In September 2014 and 2015 juveniles are abundant on the nourishment, especially on the dyke foot nourishment. In September 2016 the lugworm seems to become less abundant, both on the nourished areas as on the central tidal flat.

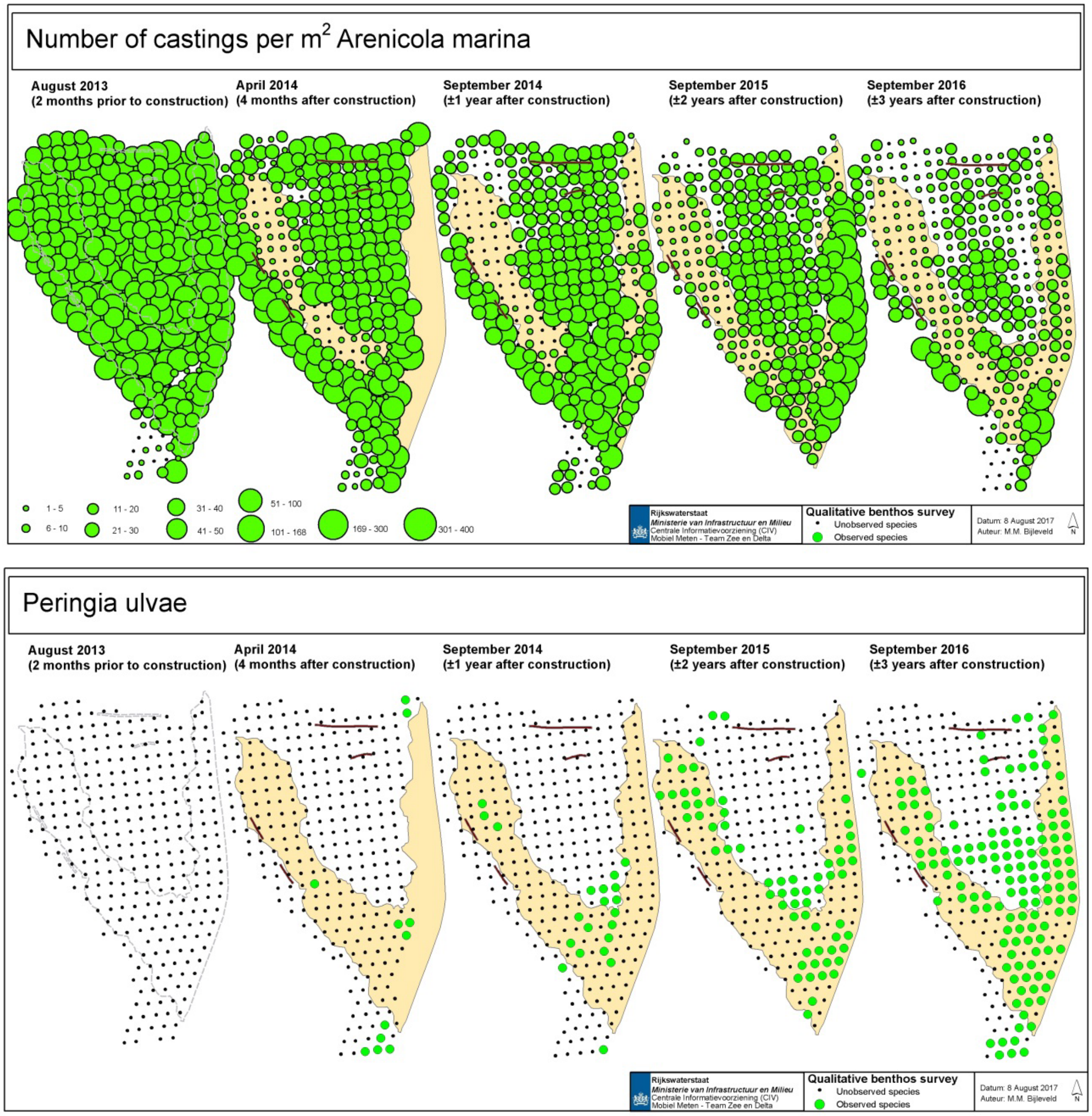


Figure 6-7. Distribution of the lugworm Arenicola marina (top) and the mudsnail Peringia ulvae (bottom) on the Oesterdam. For Arenicola marina the number of castings per m^2 are presented, for Peringia ulvae presence-absence.

The mudsnail *Peringia ulvae* was not observed during the qualitative monitoring in August 2013, and at only a few stations in April 2014 (Figure 6-7). In the situation prior to the nourishment, based on the detailed benthic samples, *Peringia ulvae* was observed more frequently, but most likely the small size of *Peringia ulvae*, together with low densities at that time, might explain the low occurrence based on the qualitative method. From September 2014 till September 2016, *Peringia ulvae* is increasingly observed, especially on the nourished areas, but also on the central tidal flat in 2016. As densities were high in this period, *Peringia ulvae* was most likely more easily detected during the qualitative monitoring.

6.1.2 *BIRD CHANGES*

With an increase in emersion time, foraging time increased at the Oesterdam area. However, bird counts in the winter period at low tide revealed that only two wader species used the Oesterdam area on a regular basis as foraging area, the oystercatcher *Haematopus ostralegus* and the curlew *Numenius arquata*. Oystercatchers foraged on average most on the central tidal flat and on the main sand nourishment, less in the reference area and least on the dyke foot nourishment. Already in the winter of 2014, Oystercatchers made use of the nourishment as foraging area, but there is no clear trend over time. Curlews foraged on average most in the reference area, although the central tidal flat and main sand nourishment were also used as foraging area. Like for the Oystercatcher, Curlews foraged least on the dyke foot nourishment.

Other waders like Dunlin (*Calidris alpina*), Redshank (*Tringa totanus*) and Grey Plover (*Pluvialis squatarola*) were mostly restricted to the reference area more to the south of the Oesterdam and were only rarely seen on the central tidal flat or the nourished areas. Other wader species are rare in het whole area.

Two ducks/geese species were abundant in the Oesterdam area, the Shellduck (*Tadorna tadorna*) and the Brent Goose (*Branta bernicla*). Shellducks were most abundant on the central tidal flat, but they also frequently used the main sand nourishment as foraging area. Shellducks used less the reference area and the dyke foot nourishment as foraging area. Brent geese used all areas to forage on, but highest densities were observed on the central tidal flat and in the reference area. The reference area was also used as a resting area.

Gulls were frequently seen on the Oesterdam, with the Black-headed gull (*Chroicocephalus ridibundus*) and the European herring gull (*Larus argentatus*) as most dominant gull species. Black-headed gulls foraged mainly in the reference area and on the central tidal flat, while they used the dyke foot nourishment mainly as resting area. The main sand nourishment was also used as a foraging area, but in less high densities. European herring gulls used the Oesterdam area mainly as resting area, especially the nourished areas. Foraging birds were mainly seen on the main sand nourishment and in the reference area, and to a lesser extent on the central tidal flat.

6.1.3 *MUSSEL SEED AND SEA GRASS*

In 2017 mussel seed (*Mytilus edulis*) was observed in the vicinity of the main tidal flat nourishment, on the central tidal flat of the Oesterdam, covering an area of approximately 8500 m^2. Also several patches of sea grass *Zosterna noltii* were observed in 2017, both on the nourishment and on the central tidal flat. In total 74 patches of sea grass were observed with an average size of 0.89 m^2 and an average coverage of 23% (pers. obs. D de Jong and M van Katwijk).

6.1.4 *PUBLIC USE*

While the Oesterdam sand flat is open to the public, the mudflat south of the nourishment is closed to the public (i.e. the reference area used for the bird counts). The use of the Oesterdam sand flat by the public was diverse and included walking, dog-walking (with or without leash), bait digging for worms/clams, swimming, kite and wind surfing, horse riding, etc. (pers. Observ.) (Figure 6-8). During the bird counts disturbances were observed in all areas, including the reference area. On the central tidal flat bait digging was the main activity. The more sandy nourished areas tend to be used by people to walk and take out their dog. The Oesterdam has become a hotspot for kite surfing (Figure 6-8).

Figure 6-8. Recreational use on the Oesterdam. Left: people taking out their dog. Right: kite surfing on the Oesterdam (Photos: Tom Ysebaert).

7 ECOLOGICAL DEVELOPMENT ON CONSTRUCTED OYSTER REEFS

The Ecological development on hard substrate (the constructed oyster reefs), focused on the number and type of epifaunal species and algae. Typical hard substrate species, common in the Oosterschelde such as the periwinkle (*Littorinidae*), mussels (*Mytilus edulis*), and various crabs (*Carcinus maenas*, *Hemigrapsus takanoi* and *Porcellana platychelles*) were found on all reefs throughout the year. The proportion of exotic species was comparable between reefs. Similarly, the number and type of algal species were also similar between reefs. The local environments on each reef differ so negligibly that they all fall within the range of suitable habitat for the species present.

Furthermore, the relative abundance of each faunal species was also comparable between reefs. In general the majority of the fauna observed on the reefs were mussels and periwinkles. However, it is notable that while on Reefs A, B and D both species showed similar relative abundance, Reef C was dominated by periwinkles. Whether this dominance of periwinkles on Reef C can be attributed to any of the specific properties of the reef is unclear, but this dominance of periwinkles was consistent throughout the sampling period, which suggests there was an environmental influence. As Reef D shared more or less the same orientation and inundation time as Reef C, but did not show such an obvious periwinkle dominance, these factors are unlikely to result in the observed differences. The most obvious difference between Reefs C and all other reefs was the intactness of the reef itself. It is possible that the loose packing of the oyster shells within Reef C was more favorable to periwinkles due to a lack of competitors who were less tolerant of the scouring experienced on the reef when the shells moved with the wave action. Alternatively, the difference in dominance of periwinkles on Reef C may be due to the lower success of mussels on the Reef. Mussels require a stable substrate on which to attach. As Reef C did not provide as stable a substrate compared with the other reefs, it may have resulted in lower success of mussels and therefore proportionally more periwinkles.

No obvious dominance was observed in the algae species in general, but there was some differences between years in both coverage and species present. Reef C had considerably total lower algae coverage compared with the other reefs. On Reefs A, B and D the total amount of algae coverage had also increased in September 2016 compared toSeptember in the previous year(s), while on Reef C the coverage had decreased. Furthermore on Reefs A, B and D, *Polysiphonia lanosa* made up the majority of the algae coverage in 2016, while *Fucus vesiculosus* made up the majority of the algae coverage, on reef C. Again, the likely explanation of these results is the lower intactness of Reef C compared with the other, more intact reefs. The movement and scouring effect of the shells in the loosely packed reef is likely detrimental to the establishment and survival of algae species.

The number of settled oyster spat was also comparable between reefs during the monthly monitoring. On all four reefs there was a peak in observed oyster spat in the spring. When observing the settlement disks the number of oyster spats per m2 varied a lot. Initially reef A and D were performing very good when compared with the other two reefs. The spat values on these reefs were constant over the monitoring period as the numbers didn't change that much. On contrary in 2016 the number of new oyster spat settled in reef B and D is much higher than on reef A and D, see Figure 7-1.

The results suggest that the oyster reefs are successfully receiving settling spat and developing into living reefs. Once the metal mesh has been removed or eroded, it is likely that the oyster reefs will maintain their integrity for some time. Whether these reefs will remain long-term as permanent features of the Oesterdam is yet to be seen.

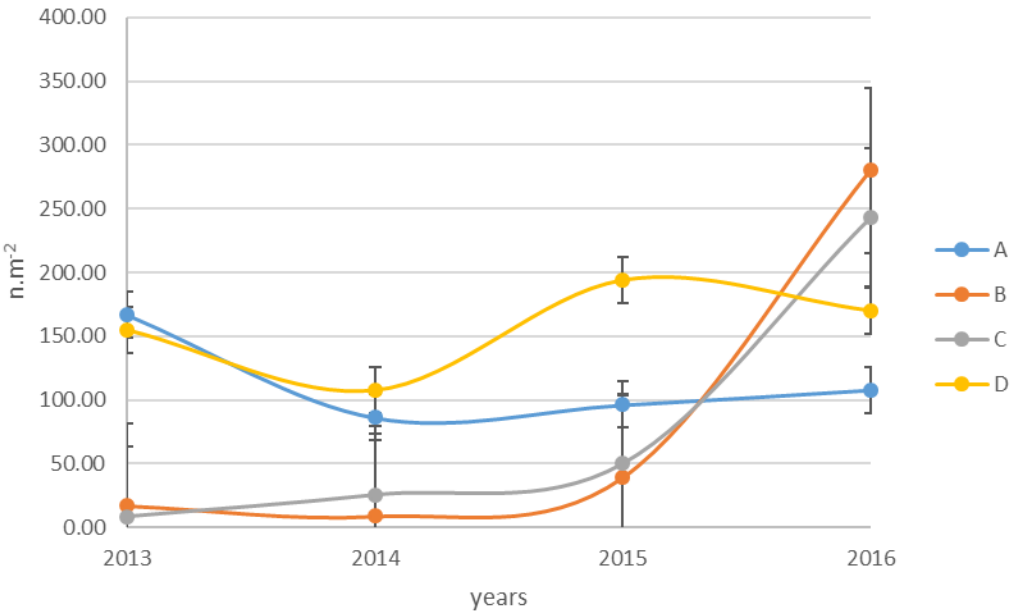


Figure 7-1 Numbers (n) of Oyster spat per m² over the monitoring period (2013-2016).

8 INFLUENCE OF BIOPHYSICAL INTERACTION ON SEDIMENT DYNAMICS

8.1 DEFAUNATION & PRIMING FIELD EXPERIMENTS

8.1.1 *DEFAUNATION AND PRIMING EFFECTS ON ENVIRONMENTAL VARIABLES:*

In general, defaunation did not lead to significant changes in sediment properties such as sediment D_{50} (median grain size) and the silt content. Chl-a content in the sediment was higher in defaunated plots at sites located at a higher elevation, particularly in May and June (T_5 and T_6) for the 2013 defaunation experiment (Figure 8-1). This is most likely due to lowered benthic grazing in the defaunated plots. This result was confirmed by a general increase in Chl-a content following defaunation in the 2015 plots and at the high elevation plots in the 2016 experiment. It is noted that in 2015 all plots were located at a relative high elevation, comparable to the high elevation plots in 2016.

Defaunation significantly decreased the depth of the oxidation layer as compared to controls, as seen in the more muddy sites E and G of the 2015 defaunation experiment (Figure 8-2). This effect was not altered by the priming treatment (Figure 8-2). No other major significant effect were observed at the end of the experiment.

The most surprising finding was that in general, defaunation did not cause reduced erosion or increased sediment accretion. This makes a marked contrast to earlier studies at Paulinapolder (Westerschelde) (Montserrat et al. 2008), where defaunation caused initial elevation in the bed level due to diatom mat development. Only a higher variation was observed in defaunated and primed plots at site D for erosion resistance as measured with a shear vane and the sulphide content at all sites (Figure 8-2). The annular flume experiments were used to gain understanding of this surprising findings.

In general, no significant differences in environmental variables were found between primed and defaunated plots, indicating that the priming had relative little effect. We think that the latter is due to a too small scale of the priming treatments. It would be useful to study how larger-scale priming may affect the system development, before deciding on the use of priming as a potential method to accelerate ecological recovery.

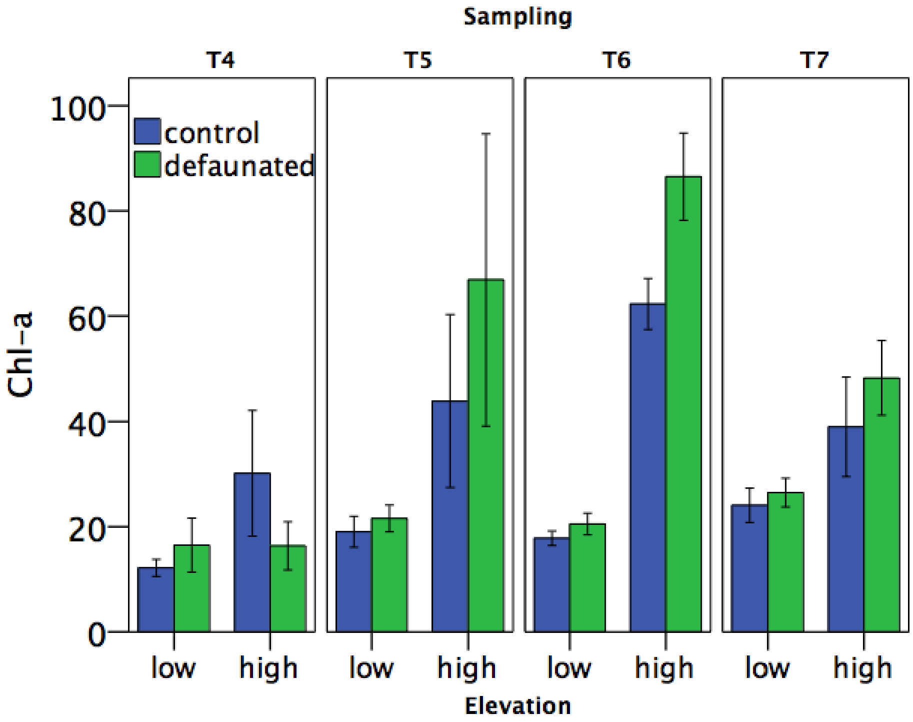


Figure 8-1. Details on sediment chlorophyll-a concentration for the different sampling times (T4 to T7) and comparing sites as a function of their elevation along the tidal gradient (low vs. high). Values from the 2013 defaunation experiment. Bars represent the standard error of the mean.

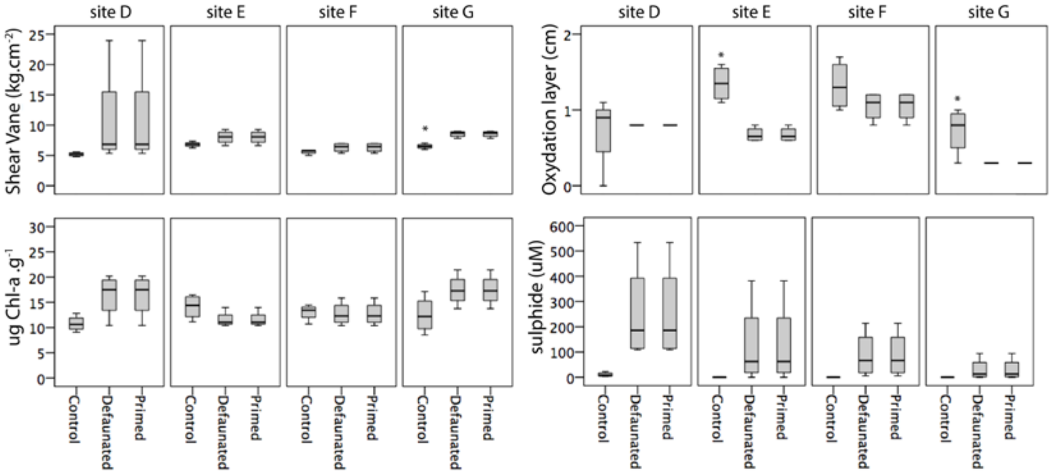


Figure 8-2. Treatment (defaunation and priming) effect on environmental variables for the 2015 defaunation experiment.

8.1.2 DEFAUNATION AND PRIMING EFFECT ON THE BENTHIC COMMUNITY

A general decrease in richness and abundance was observed at all locations following defaunation (based on data from the 2015 defaunation experiment, Figure 8-3). Interestingly, species diversity decreased only at plot D, the sandiest location. Only small differences were observed between primed and defaunated treatments: lower evenness and higher abundance at plot D in primed treatments and a lower diversity at plot E (fine sand) for the primed treatment.

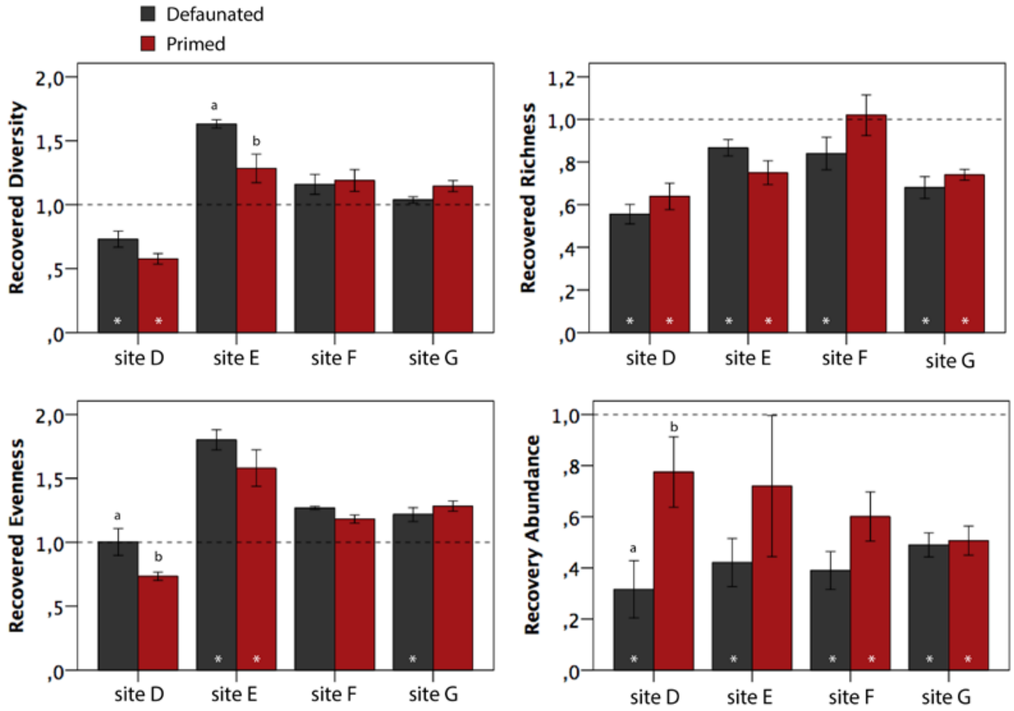


Figure 8-3. Diversity indexes to describe the changes in the benthic community following defaunation and priming at the different selected site at the Oesterdam (2015 defaunation experiment). The indexes are calculated for each bar relative to the control plots. Small letters (a and b) represent statistical differences between treatments per site. Stars (*) represent statistical differences between the treatment and control value (control = 1 = dotted line).

In the 2015 experiment, cockles and lugworms were counted in 50x50 cm frames to evaluate the effect of priming on the primed species dynamics. Adding different densities of cockles and lugworms seemed to affect their recovery as seen with higher counts of the primed individuals, particularly when primed in high densities (Figure 8-4). It appears that the primed cockles were still present by the end of the experiment, whereas lugworm count was higher in control plots (Figure 8-4). No cockles were found in the primed lugworm plots, except for site D, which presented on average higher cockle counts for all treatments (Figure 8-4). It could be that the presence of lugworms prevented establishment of cockles in favour of their own establishment, hence showing a potential positive effect of priming for the primed species.

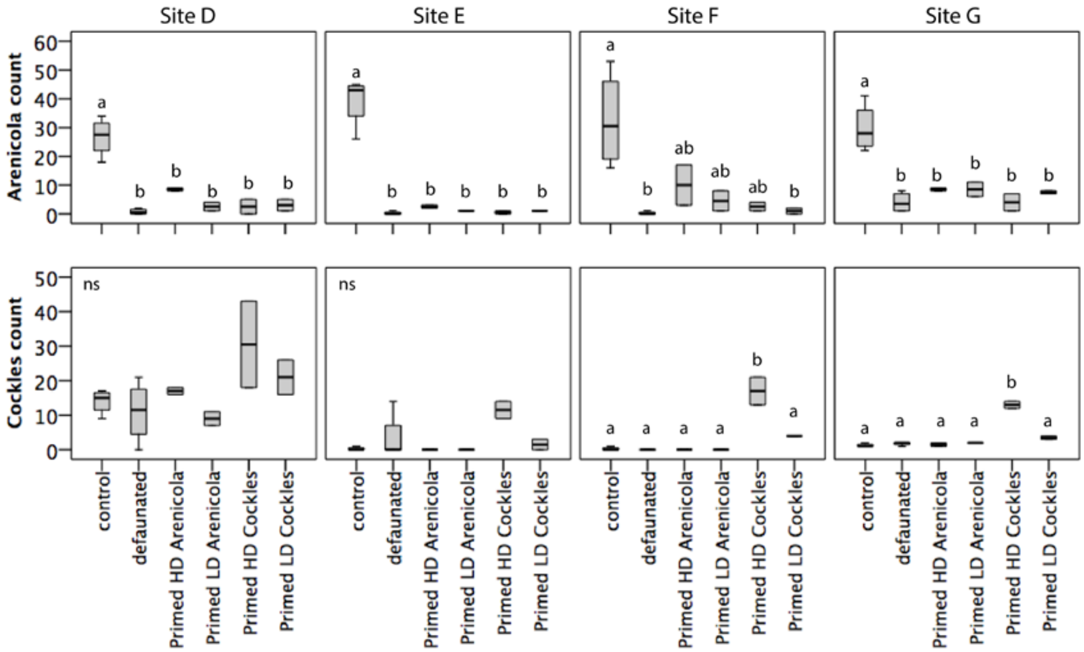


Figure 8-4. Effect of primed densities on cockles and lugworms (arenicola) counts at the end of the 2015 defaunation experiment.

8.1.3 *FLUME EXPERIMENTS*

Several flume experiments were performed but only the results of the last two experiments will be discussed here. The flume experiments showed a marked increase in suspended sediment concentration due to the presence of cockles in cohesive sediment, while the erodibility of non-cohesive sediment (Figure 8-5). The latter may be explained by the observation that the erosion of non-cohesive sediment is already high as result of current stress only (Figure 8-5). The increase in cohesive sediment resuspension due to cockle bioturbation was positively correlated with both current velocity and bioturbators densities. The presence of cockles make the cohesive sediment behave as non-cohesive sediment.

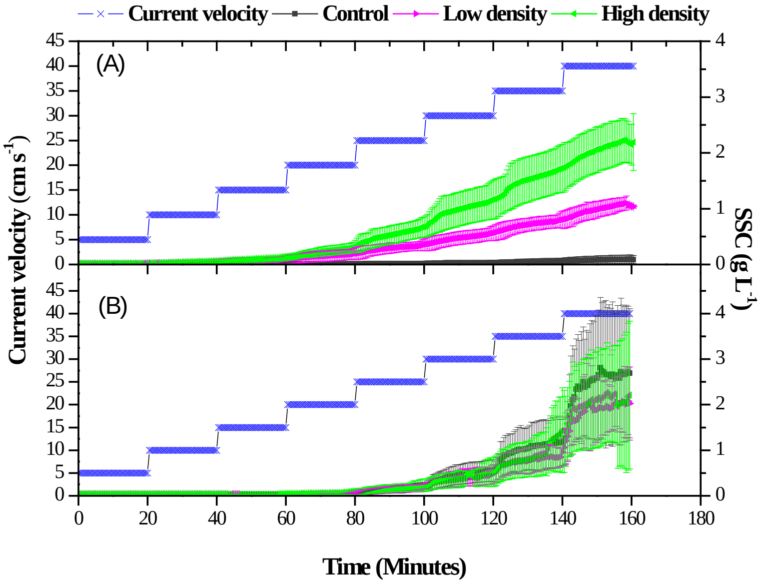


Figure 8-5. Time series of suspended sediment concentration in response to increased current velocity (blue lines, from 5 to 40 cm s-1) in (A): cohesive (40% silt) and (B): non-cohesive (5% silt) sediment for different densities of cockles: control = no cockles added (black line); low density (pink line) and high density cockles (green light). This figure is taken from Li et al. (2017)

For a given current velocities, the influence of benthic organisms to sediment resuspension depends on the environmental condition: i.e. sediment type and suspended sediment concentration in the water column. This is illustrated by how the presence of benthic organisms such as *Cerastoderma edule* (referred to as cockles) or *Ruditapes philipinarum* (referred to as invasive clam) affects over time the suspended sediment concentration (SSC) in the water column. In sandy environment, SSC decreased significantly over time, when cockles and invasive clams were present in the system. This suggest that these animals burry the the fine materials into the sandy sediment, making the system muddier. In contract, in muddy sediments these same cause an increase in SSC (Figure 8-6).

By resuspending fine particles into the water column due to their movement and feeding activity, benthic organisms may increase suspended sediment concentration (Figure 8-6). This may potentially lead to a decrease in sediment silt content and thus over time in a slight sandification of the sediment. This is the case for muddy and cohesive sediment. However, for sandy or no-cohesive sediment, the same benthic organisms can actively contribute to sediment modification by by trapping silt particles into the sediment thereby reducing the sediment median grain size. By doing so, they may cause over time in a muddification of sediment.

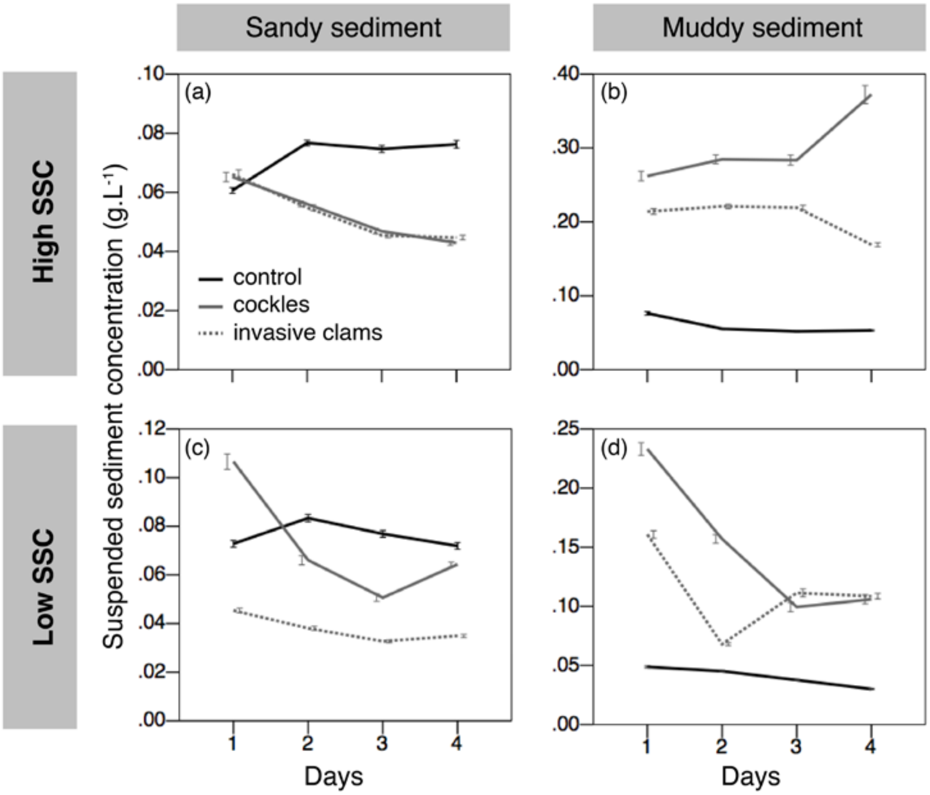


Figure 8-6. Suspended sediment concentration (SSC) in g. L-1 per day for the different organisms (control = no animal, cockles, invasive clams). (a) represents SSC for the sandy sediment in high SSC conditions; (b) represents SSC for the muddy sediment at high SSC; (c) represents SSC for the sandy sediment at low SSC; and (d) represents SSC for the muddy sediment at low SSC. Bars represent the standard error of the mean (figure taken from: Soissons et al., 2017 in prep).

8.1.4 *SUMMARY AND IMPLICATIONS FOR MANAGEMENT:*

Increasing evidence proves that biophysical interactions play a role in the sediment dynamics of tidal flats, especially on relatively short time scales. Organisms influence their environment, and by doing so, they also affect sedimentation and erosion processes on tidal flats. Recent observations showed that the impact organisms have on sediment dynamics are context dependent, depending both on the species (or trait) under consideration, as well as the local environmental conditions, especially the sediment composition. When designing nourishments to conserve or develop tidal flats, taking into account these bio-physical interactions will contribute to a better prediction of the impact and evolution the nourishment will have on the ecological functioning of the tidal flat over time.

1. Recent observations related to the field and flume experiments show that:
   - If nourishments are very sandy, and consists of non-cohesive sediment (as is the case for the Oesterdam):
     - Benthos has negligible effect on erodibility (as shown by annular flume experiments in Li et al. (2017) & defaunation field experiments);
     - Erosion is hence fully determined by physical processes from waves and tidal currents and the sediment grain size properties;
     - Benthos can gradually enhance the silt content of the nourishment by mixing in part of the daily tidal sediment deposition, as shown conceptually, by relative short-term annular flume experiments (Soissons et al. in prep.).

- If nourishments (or natural tidal flats) do consist of cohesive sediments:
    - Benthos can have a major effect on the sediment erodibility (as shown by annular flume experiments: Li et al. 2017; Cozzoli et al submitted; Soissons et al. in prep.);
    - This benthos effect appears to be directly related to the benthos characteristics and traits, being their body size, density and total biomass, as shown by annular flume experiments (Cozolli et al. submitted);
    - This benthos effect only occurs if the hydrodynamic energy (waves of flow) is high enough, as shown by annular flume experiments (Cozolli et al. submitted);
- Priming treatments had relative little effect, which we expect to be due to the too small experimental scale being studied. It is recommended to implement larger-scale experiments in future nourishment projects, before deciding on the use of priming as a potential method to accelerate ecological recovery.

2. The large-scale implications of the aforementioned field and flume experiments are that:
    - Benthos effects on sediment erodibility appears to be a spatial specific phenomena imposed by gradients in biomass and hydrodynamic forcing. First model explorations suggest that.benthos mainly affect the sediment erosion in those areas where both the benthos density is relatively high and the hydrodynamic energy is relatively high. If one of the two is low, the effect of benthos on erosion seems to be low.
    - Benthos may be expected to gradually decrease the silt content of a sandy nourishment by specifically resuspending the fine fraction, while maintaining the course fraction in place (i.e., conceptually shown in annular flume experiments; Soissons et al. in prep).

When integrating all our experiments in a general consideration on sediment nourishments that are aimed to contribute to ecosystem diversity, we like to highlight the following trade-off. For ecological purposes it may often be desirable to use relatively fine sand with relative high silt content (i.e., cohesive sediments), so that more rich benthic communities may be expected to settle. Present study shows that such benthic communities will have significant impact on the erodibility of the cohesive sediment, thereby reducing the life span of the nourishment.

9 IMPROVEMENT OF EDUCATION

This project was provided with a financial contribution of the Ministry of Education within the framework of the Centre of Expertise Delta Technology. One of the main objectives of this projects was to enhance the quality of education by providing a real case study for students and give teachers/researchers an opportunity to develop their research skills.

This project provided an excellent case study for students to work on. In total 28 student projects were realized from a 2nd year level to Master level (see Appendix 3). Furthermore a course module was developed by HZ-staff which provided large groups of students (≈250; see Appendix 4) an opportunity to study an applied coastal adaptation strategy focusing on safety and ecological restoration. This hands on approach, and being involved with a real world project, provided the students with valuable experiences that will prepare them for a future postion in water management.

9.1 SECOND YEAR STUDY PROJECT

Study Projects are carried out by 2nd year students, and have the size of one course (210 hours) for the Aquatic Eco technology students this assignment is linked to the project management course (70 hours). This input of students is especially meant to introduce research for students, for acquiring basic research skills and skills in the field of project management. Supervision of the process is the responsibility of an AET lecturer. See for an overview Appendix 1 with a list of the study projects.

9.2 MINOR SPECIALIZATION WATER RESEARCH

The project offered assignments within the framework of the Minor Water Research. The research staff are the clients for this assignments. This particular minor was not compulsory; 3rd year students are free to choose from a range of case studies including this one. The Water Research minor focusses on acquiring knowledge and, more importantly for the student, on acquiring research competencies. The research minor takes one semester full time, therefore, 840 sbu. A quarter of this time is reserved for a literature research assignment on a different subject, specifically meant to acquire competencies in this field (retrieve-digest-repackage. Subjects for these literature assignments are formulated by research staff, therefore, these literature assignments are usually related to current research topics of the research group. See for an overview Appendix 1 with a list of the minor projects.

Students who did their minor with the research group Building with Nature were also given an opportunity to present posters of their work at the VLIZ Young Scientists conference in Brugge. One of the students, Jesse van der Pool, presented his research in a poster on the biodiversity on the oyster reefs at the Oesterdam at the conference in 2016. He was awarded 3rd prize out of ¬300 posters for his work (Appendix 5).

9.3 INTERNSHIP AND FINAL THESIS

Research groups of the Delta Academy offer assignments for internships and final theses, similar to other research institutes. When students are doing an internship or final thesis at one of the research groups the research staff is responsible for the supervision of the student. This stimulates the student's acquisition of knowledge and experience and provides resources available for the research groups and the educational programmes.

9.4 COURSE ECOLOGICAL ENGINEERING AND COASTAL ENGINEERING

The *Building with Nature* approach is closely related to Ecological Engineering approaches. The courses Ecological Engineering and Coastal Engineering were the most obvious ones for integrating *Building with Nature* themes within the educational programmes of the Delta Academy.

Within the course Ecological Engineering, the research group offered the ‘Benthos module’, within the framework of the Oesterdam project (see picture in Figure 9-1). The module began with three preparatory lessons, including guest lectures and instruction films followed by a day of fieldwork at the Oesterdam where sediment samples were taken at various locations on and around the sand nourishment.

These samples were then analysed by students for the benthic biota and the sediment grain sizes in the lab over two days under the supervision of in-house experts. Students were required to use laboratory equipment such as sediment sieves and scales, as well as species identification keys. The results were then checked by the experts and data was compiled, analysed by the researchers and presented to the students in a feedback lesson. During the lesson the students were also required to present their literature research of one common species found during the practical work in a Powerpoint presentation.

The benthos module combined traditional methods of knowledge acquisition in lessons; practical, hands on experience in the field; laboratory methods that required the students to think critically, take initiative and work precisely; an independent literature research assignment to encourage students to gather existing knowledge; and verification and application of the work done through feedback. In total over four years, 134 Aquatic Eco-technology, and 118 Civil Engineering students took part in the Benthos module (See Appendix 4).

Furthermore, the benthos module was developed into a SPOC (Small Private Online Course) where students can access information and instructions related to the module. The SPOC includes seven weblectures by Tom Ysebaert and assignments. This SPOC is intended to be further developed and applied in module 8 of the new Water Management curriculum (Ecological Engineering).

Figure 9-1. **Students involved in the fieldwork and lab work of the ‘Benthos module’ where they sampled and analysed the sediment at the Oesterdam.**

10 DISCUSSION

10.1 EVALUATON OF DESIGN

The nourishment at the Oesterdam consists of two parts, the dyke foot nourishment and the main sand nourishment (Figure 1-1), to meet two objectives: protection of habitat (less erosion caused by the sand deficit problem) and protection of the dyke by a decrease in wave load. This design seems to be a good choice. The importance of the dyke foot nourishment is studied in paragraph 4.3 and it shows that this nourishment is mainly responsible for wave attenuation. The ability to act as a sand source, concerning the main sand nourishment, is less clear from available data, but there are indications that the main sand nourishment is able to transport sand to the central tidal flat. Most important indicater is the increase in grain size at the tidal flat, caused by a input of courser sand for the nourishments.

The shape of the main sand nourishment, which is connected to the Oesterdam dyke, creates a small protected basin at the central tidal flat. Drainage during the ebb phase is only possible in northern direction. Since the slope of the tidal flat is perpendicular with the main nourishment, this creates flow concentration and channel development. This could be harmful for the main sand nourishment, since channel erosion can influence the main sand nourishment. In this study it's concluded that this negative impact of the drainage channel is limited. For further nourishments it is recommended to check the development of flow concentration, by a simple drainage pathway analysis.

The main sand nourishment has a lower part in the middle (Figure 1-1) to provide a diversification of the inflow to the central tidal flat and also make drainage more easy. Since the main nourishment is dominated by wave-action, these depressions have the tendency to disappear. For future designs it might be better to make a lower opening, so drainage is possible through channel flow. Secondly, more openings will make drainage more easily creating less flow concentration and channel erosion. This design is creating islands, which can result in less human activity and disturbance (see section 8.3).

The used method for height with RKT-DPGS is not accurately enough to see small changes at the central tidal flat, so it is difficult to conclude that the tidal flat is stabilizing by the presence of the nourishments, and locally the erosion trend, caused by the sand deficit problem, is stopped.

10.2 ECOLOGICAL IMPACT

Whereas beach nourishments are common pratice, nourishment of intertidal flats to mitigate erosion is not a common management practice. In recent years, although, dredged material has become regarded as a potential resource and used to create and/or improve intertidal habitats (so-called beneficial use schemes). This triggered several studies on the effect of sediment deposition and hypoxia on intertidal macrobenthic communities. Both manipulative field experiments (e.g. defaunation or smothering experiments) as well as large-scale interventions (e.g. recharge schemes) have indicated that intertidal benthic macrofauna communities show a high resilience to disturbances, with large numbers of early colonizers appearing within weeks or months following the impact (Ysebaert et al. 2017). So recolonization can be rapid and is sourced from a species pool already present in the surrounding, undisturbed communities. Recovery mechanisms differ and are dependent on the scale of disturbance in intertidal habitats. Given the thickness of the nourishment, and the observations shortly after the construction that no benthic life was observed in the nourished areas (pers. observ.), recolonizing individuals either arrived from the undisturbed intertidal flat surrounding the nourished areas or from the water column. As most macrobenthic species have planktonic larval stages, most likely the latter was the main dispersal mechanism at the Oesterdam (Ysebaert et al., 2017).

Any estimate of recovery success, however, depends on the criteria used. This can be more traditional criteria such as species richness, abundance, biomass or community composition, but can also be based on more functional criteria based on biological traits. Furthermore, recovery will vary with *measure-dependent* variables (e.g. thickness of the sediment disposal, sediment properties of the disposal, timing and design of the nourishment) and *location-dependent* variables (e.g. bed level, hydrodynamics, salinity). This implies that measuring recovery success based on a comparison with a suitable reference area is often problematic, as identical conditions are hard to find in intertidal habitats. The nourishment on the Oesterdam resulted in a significant change in elevation (from -0.93m in 2012 to -0.28m at the main sand nourishment and +0.57m on the dyke fout nourishment in 2014) and therefore emersion time (29% on the central tidal flat, 43% on the main sand nourishment and 64% on the dyke nourishment), most likely affecting community composition (Ysebaert et al. 2017). On top of that, sediment grain size increased on the nourished areas (from 174µm to 180 µm on the central tidal flat, 275 µm on the main sand nourishment and 292 µm on the dyke foot nourishment in 2014) due to the use of more coarse sediment, also possible affecting the community composition. Comparing the nourished areas (main sand nourishment and dyke foot nourishment) with the undisturbed intertidal flat (central tidal flat), univariate and multivariate variables showed considerable variation, in all three years considered. Communities changed from year to year, also on the central tidal flat, but after three years, i.e. in 2016, the communities on average still differ significantly between the nourished areas and the undisturbed central tidal flat. But also between the two nourished areas, the main sand nourishment and the dyke foot nourishment, differences between benthic communities were significant.

The spatial distribution of ecological richness and coldspots and hotspots (see Ysebaert et al. 2017) clearly showed that recovery of the benthic macrofauna on the nourished areas appeared heterogeneous. Some areas on the nourishment showed fast recolonization, other areas showed only little recovery. Also within the two subareas, the main sand nourishment and the dyke foot nourishment, variability in recolonization is large, so recolonization of certain benthic macrofaunal species cannot only be attributed to changes in elevation (emersion time) or changes in sediment composition on the nourishment. Apparently favourable conditions were created on the nourishment, especially in the area where the main sand nourishment is connected to the dyke foot nourishment. This area can be considered as more sheltered, as it is in the lee side of the main sand nourishment. Less favourable conditions, based on a lower ecological richness and the presence of coldspots, can be found on the tip of the main sand nourishment and the northern part of the dyke foot nourishment. Here conditions seem to be more dynamic.

Also on the central tidal flat an increased variability in benthic macrofauna appeared. Especially at the lee side of the main sand nourishment an area arose with a high ecological richness and in the northwest an area with lower ecological richness (Ysebaert et al. 2017). The reason for the overall decrease in *Arenicola marina* numbers in 2015 and especially 2016, observed in the detailed monitoring as well as in the area-wide inventory, is unknown. Especially the fact that this was also observed on the central tidal flat was unexpected.

Although behind the scope of the original monitoring, it was an unexpected observation to see a young mussel bed (*Mytilus edulis*) and sea grass patches of *Zostera noltii* appearing in the early summer of 2017. Intertidal mussel beds are hardly found in the Oosterschelde, except for mussels found in oyster reefs (*Magallana gigas*). This young mussel bed was observed on the central tidal flat, at the lee side of the main sand nourishment. The area corresponded with the hot spot area observed in 2016, this is an area with a high ecological richness. In this area also high densities of the cockle *Cerastoderma edule* and the polychaete *Aphelochaeta marioni* were observed. The sea grass *Zostera noltii* has become a relatively rare species in the Oosterschelde, with the most nearby population found in the Roelshoek-Oostdijk area (Krabbendijke), 6-9 km west from the Oesterdam. Most likely the observed population observed at the Oesterdam nourishment was established through seed dispersal by plant parts.

The nourishment was constructed in order to conserve and restore the natural value of the area for Natura2000 bird species. This concerns mainly wader species that use the intertidal flats to forage during low tide. With an increase in emersion time, foraging time increased at the Oesterdam area. Bird counts showed that Oystercatcher and Eurasian Curlew were foraging in the Oesterdam study area. Oystercatchers were foraging most on the central tidal flat and on the main sand nourishment, less in the reference area and least on the dyke foot nourishment. Other waders like Dunlin (*Calidris alpina*), Redshank (*Tringa totanus*) and Grey Plover (*Pluvialis squatarola*) were mostly restricted to the reference area more to the south of the Oesterdam and are only rarely seen on the central tidal flat or the nourished areas. Other wader species were rare in het whole area.

10.3 DISTURBANCE IMPACT

Disturbance on the Oesterdam is frequent, as was observed during the bird counts or other visits to the area. Bait digging, walking (with dogs), but also kite surfing causes a relatively high disturbance pressure on the area, which will certainly affect bird presence. It is known that birds are disturbed at relatively short distances (e.g. walkers disturb oystercatchers at a distance of 125m whereas curlews are disturbed already at 375m distance), depending on the type of disturbance. At this moment, no regulations are considered for this area, but it is clear that the ecological value is negatively impacted by all these recreational activities. Also the seagrasses could be negatively impacted due to trampling of the vegetation. Zoning of activities might help in reducing the disturbance impact on the area.

11 CONCLUSION

The conclusions of this monitoring-, and research project are mainly related to the objective 3: ***Contributing to the development of knowledge related to the effectiveness of local sand nourishment to mitigate the negative effects of sand deficit in the Oosterschelde, and to flexible, climate-adaptable and cost effective coastal management*** (see paragraph 1.4).

The main conclusions of this research are:

1. Erosion trends show that the dyke foot nourishment is eroding faster (5 cm/year) than the main nourishment (2 cm/year). In total around 10% of the nourished volume is lost in the period 2013-2016;
2. The nourishments act as a sediment source for the central tidal flat, indicated by an increase in grain size at the tidal flat, but this process is not resulting in a significant increase in elevation of the tidal flat. The height changes of the tidal flat are fluctuating around zero;
3. The main sand nourishment is creating extra shelter at the central tidal flat which has positive effect on the benthic fauna (species richness and biomass), and the nourishments show in general a fast colonization of benthic species, which is also visible in the usage of birds;
4. Decrease of wave load during normative wave conditions (1/4000 year storm) on the Oesterdam is entirely due to the presence of the dyke foot nourishment; the influence of the main sand nourishment on the decrease of wave height there is very limited;
5. Constructed oyster reefs are creating extra shelter for benthic species at the lee side of the structure and the reefs are creating habitat for hard substrate species, althouth the size of the area is limited. The four reefs have very limited impact on he overall morphological behavior of the study area, and life span of the nourishments. The constructed oyster reeft are becoming strong structures caused by the internal cohesion of the oysters.

Below more detailed conclusion per research subject:

Morphology and hydrodynamics

- The sediment balance calculations show a loss of 10% of the initial volume of 350,000 m^3, over the 3 year measurement period, at the nourished areas. The main sand nourishment lost around 13,000 m^3, and the dyke foot nourishment 23,000 m^3. The central tidal flat net volume changes are close to zero. The drainage channel show initial erosion of 5,000 m^3; after 2015 major volume changes are present within the channel area. The initial volume loss of the channel is in equilibrium with the volume gain of the channel delta;
- The erosion trend of the average bed level height of the main sand nourishment is ≈ 2 cm/year. The erosion trend of the dyke foot nourishment is ≈ 5 cm/year. The central tidal flat doesn't show significant changes in erosion and sedimentation;
- The main sand nourishment and/or dyke foot nourishment is able to act as a sand source for the tidal flat, although this is not visible in volume changes. The increases of the grain size at the central tidal flat originating from the more coarse main sand nourishment, is an most likely indication for this process;
- The drainage channels is not likely to be an obstacle for the transportation of sand from the main sand nourishment to the tidal flat. Volume calculations of the drainage channel and channel delta show the that these morphological units are related and equal in size. This is a strong indication that the channel is not able to have a significant eroding effect on the main sand nourishment;

Wave impact

- The main mechanisms for wave attenuation at the Oesterdam are white capping and bottom friction. Net wave growth is observed during high water.
- The main sand nourishment has a limited influence on the wave height during design conditions with a 4 m water level. The difference between the wave heights at the Oesterdam between the nourishment and no-nourishment scenarios is entirely due to the dyke foot nourishment.
- With the projected erosion at the Oesterdam, only the overtopping discharge during design conditions is expected to significantly increase. The nourishment reduces the projected design wave load increase by approximately 50%.

Ecology

- The Oesterdam nourishment showed a fast recolonization of benthic macrofauna. After one year (2014) already species richness and abundance was similar or higher on the nourished areas, but biomass on average was still lower compared to the undisturbed central tidal flat.
- In the following years (2015, 2016) the recovering community still differed from the ambient, undisturbed, sediments due to enhanced recruitment success of long-living species (i.e. bivalves *Cerastoderma edule* and *Limecola balthica*), presumably resulting from the lowered interference from bioturbation by the lugworm *Arenicola marina* during the first recovery stage in the nourished areas. Also the non-indigenous bivalve *Ruditapes philippinarum* colonized the nourished areas.
- Recolonization on the nourishment appeared patchy, with large spatial variability. Some areas could be identified as ecological hotspots with a high ecological richness; these areas were situated in the more sheltered, lee side of the main sand nourishment and dyke foot nourishment. Here, high densities of cockles *Cerastoderma edule* and mudsnails *Peringia ulvae* were observed. In the same areas also a mussel bed (*Mytilus edulis*) and several sea grass (*Zostera noltii*) patches were observed in 2017.
- Some areas were identified as ecological coldspots with a low ecological richness; these were the more exposed areas on the main sand nourishment and the dyke foot nourishment. Here changes in elevation (erosion) and grain size (increase in median grain size) were obvious.
- The nourishment also had an indirect effect on the benthic community of the undisturbed central tidal flat, as ecologically rich areas were created at the lee side of the main sand nourishment, for instance promoting the settlement of cockle *Cerastoderma edule*.
- Oystercatchers and Eurasian Curlews used the Oesterdam as foraging area, including the nourished areas (especially the main sand nourishment). Other wader species were hardly observed, although they were frequently seen foraging south of the Oesterdam study area. The relatively fast recolonization of the benthic macrofauna (especially the occurrence of several bivalve species and *Peringia ulvae*) and an increased in emersion time should be profitable for waders like Oystercatcher and Knot.
- The lack of other wader species on the Oesterdam study area could be due to disturbance by humans, as the area is frequently used for bait digging, walking and kite surfing. These activities are allowed but are considered as a threat to the area with respect to its function as foraging area for waders.
- Also the observation of sea grass patches (endangered and protected species) and a mussel bed in 2016 needs further consideration and might need some additional measures in relation to the human disturbances in the area.

Constructed oyster reefs

- This study showed that the extent that these structures affect the tidal flat morphology is dependent on local climate and hydrological conditions but also of their exposure to elements such as winds and wave;
- The impact of the oyster reefs on the scale of the sand nourishment and central tidal flat is very limited;

- The differences between reefs in terms of species composition appears to be negligible as the reefs all provide comparable habitats for the same type of species. The fact that Reef C was more loosely packed compared with the other reefs may have resulted in the considerable dominance of periwinkles, the noticeably lower algae coverage, and dominance of the algae cover being *F. vesiculosus* rather than *P. lanosa*;
- The constructed oyster reeft are becoming strong structures caused by the internal cohesion of the oysters.

12 RECOMMENDATIONS

1. The capacity of the main nourishment, and the dyke foot nourishment to supply the central tidal flat should be evaluated with other techniques, for example tracers, or high frequency sedimentation measurements. Longer monitoring can also provide more information with the used techniques (RTK-DGPS), to see a possible change in the erosion trend at the tidal flat;
2. In future nourishments designs an analysis of drainage patterns is important, to see if not too large water volumes are draining through concentrated pathways and creating channel erosion;
3. Further validation of the Delft3D model for larger storms than occurred during the T_1 and T_2 measurements.
4. Semi-annual bathymetric surveys for more robust trend analyses of erosion (before and after the storm seson).
5. Detailed safety assessment of the Oesterdam, with future erosion projections, using the standard tools.
6. It is important to study the drainage paths ways over the tidal flat (with simple GIS tools) as part of the design of a new sand nourishment;
7. Three years of monitoring the recolonization and recovery of the benthic macrofauna is still short, and the long-term evolution (5-10 years) of the benthic macrofauna needs to be assessed to determine the exact functioning of this area as foraging ground for birds. Recreation pressure, and changes in elevation and therefore emersion time, need to be taken into account in this long-term evaluation.
8. Impact of disturbance due to the various recreational activities should be evaluated.
9. The resolution of the Delft3D model was too coarse to capture the channel just east from the main sand nourishment, which probably plays an important role in the drainage and maybe also in the morphological development of the tidal flat. To capture this feature without much additional computational time the newest Delft3D-FM (Flexible Mesh) software should be used (or could be used);
10. Measurements of suspended sediment concentrations on the tidal flat as well as in deeper water in front of it. This would give the opportunity to better understand the sediment transport processes, and further tune the numerical model.

ACKNOWLEDGEMENTS

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Ysebaert T., E. Brummelhuis, D. van den Ende, L. van Ijzerloo, J. van Dalen, B. Walles. 2017. The conservation of eroding intertidal flats through nourishments: Ecological development on the Oesterdam tidal flat (Oosterschelde, the Netherlands). Wageningen Marine Research Report.

Justification

Report C031/18

The scientific quality of this report has been peer reviewed by a colleague scientist and a member of the Management Team of Wageningen Marine Research

Approved: Dr. ir. J.W.M. Wijsman

Researcher

Signature:

Date: April 26th 2018

Approved: Drs. J. Asjes

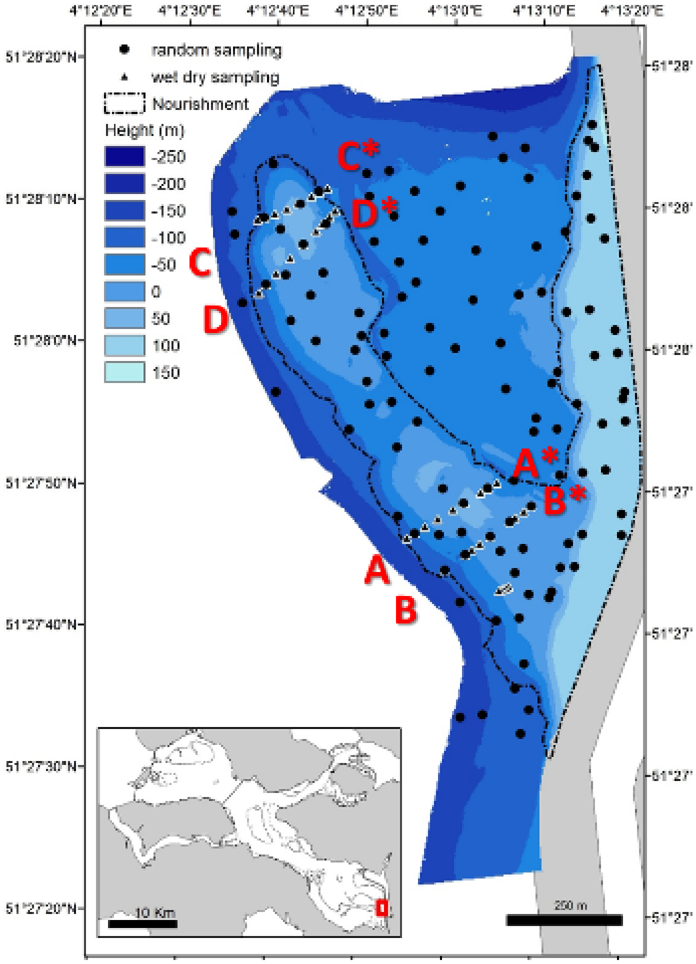
Manager integration

Signature:

Date: April 26th 2018

Appendix 1.

Sampling stations for benthic macrofauna (black dots and the four transects A-A*, B-B*, C-C*, D-D*) at the Oesterdam tidal flat, located in the eastern part of the Oosterschelde (inset map). Dashed line indicates the contours of the nourishment. Underlying elevation map (in cm NAP) of November 2014. These stations were sampled in the autumn of 2014 (T_1), 2015 (T_2) and 2016 (T_3).



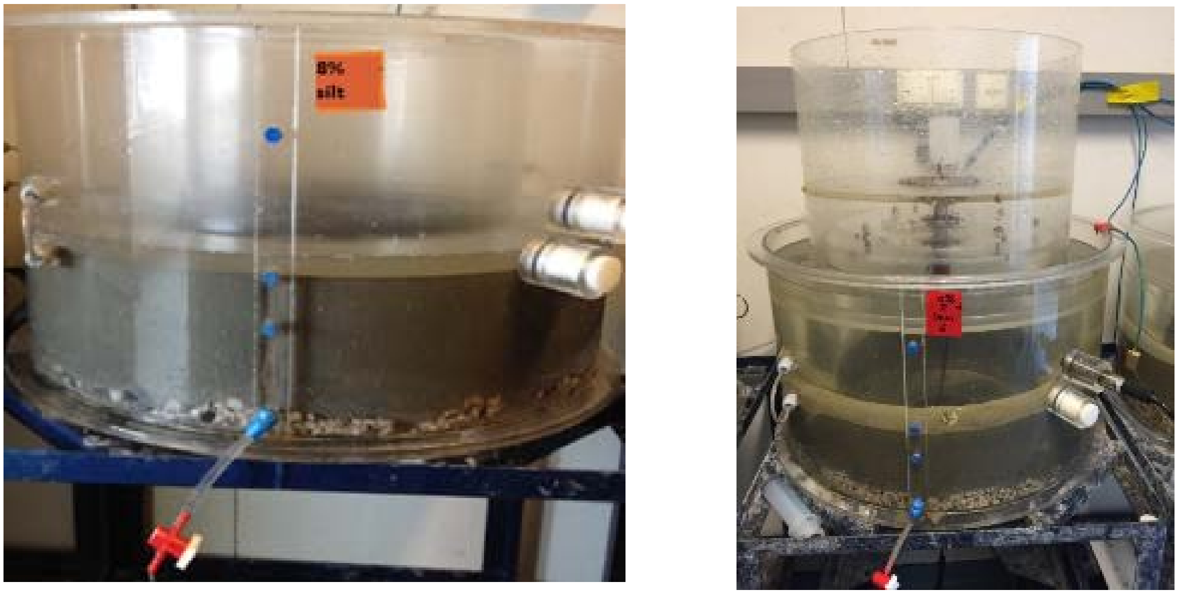
Prior to the nourishment (May 2012, October 2012, April 2013), T_1 (October 0214, T_2 (October 2015) and T_3 (October 2016) sampling for elevation, sediment grain size and benthic macrofauna at the Oesterdam prior. N = number of sampling stations.

Sampling date	Name	Elevation	Sediment grain size	Benthic macrofauna
May 2012	Prior to the nourishment	58	59	21
October 2012	Prior to the nourishment	-	56	20
April 2013	Prior to the nourishment	-	56	20
October 2014	T_1	114	114	114
October 2015	T_2	114	114	114
October 2016	T_3	114*	144	114

*Elevation was measured in May 2017.

Appendix 2.

Sediment compaction in a flume before running experiments. The OBS is placed in the upper plug on the side of the flume. The rotor is placed on top of the flume. Water samples are taken from the small plugs on the left hand side of the flume.



Appendix 3.

Overview of student projects (internships, 2nd year research (=Lectoren), monior research, BSc. Thesis, and MSc. Thesis)

study year semester	title report	names	number of students	host organisation	type of assignment	supervisors
2013-2014 semester 2	Morphodynamics and Sediment transport at the Oesterdam sand nourishment	Victor Kenji Ikeya	1	HZ	INTERNSHIP	Joao Paiva; Matthijs Boersema
2014-2015 semester 1	Morphological dynamics at the Oesterdam nourishment and the influence of artificial Oyster reefs	Frank Herrewijn	1	HZ	INTERNSHIP	Joao Paiva; Matthijs Boersema
2014-2015 semester 1	Kick-start Biodiversity	Alya al-Nabhani, Jesse van der Pool, Ella Bijkerk, Mike Hoeder, Marjolein van Vliet	5	HZ	LECTOREN	Anneke van den Brink, Niek Koelen
2014-2015 semester 1	Water Retention	Inigo Collins, Chris Meerman, Janniek Schrijver, Maurits van der Schraaf	4	HZ	LECTOREN	Anneke van den Brink, Niek Koelen
2014-2015 semester 2	Tidal channel developement at the Oesterdam sand nourishment	Mireille Martens	1	HZ	MINOR	Matthijs Boersema
2014-2015 semester 2	The community compositon of native and exotic spieces on the artifical oyste reefs at the Oesterdam in the Eastern Scheldt 1	Samara Hutting	1	HZ	BSC THESIS	Anneke van de Brink
2014-2015 semester 2	Morphodynamics and sediment transport at the Oesterdam sand nourishment	Robert Bijvank, Tony Mendez-Groot	2	HZ	MINOR	Joao Paiva; Matthijs Boersema
2014-2015 semester 2	Quantifying biotic effects on sediment erodibility: when and how much?	Tatiana Gomes	1	NIOZ	BSC THESIS	Tjeerd Bouma; Anneke van den Brink
2014-2015 semester 2	The community compositon of native and exotic spieces on the artifical oyste reefs at the Oesterdam in the Eastern Scheldt 2	Marina Arias	1	HZ	BSC THESIS	Anneke van den Brink
2014-2015 semester 2	Understanding the morphological development of the Oesterdam nourishment	Michiel Pezij	1	Deltares	MSC THESIS	Jebbe van der Werf
2015-2016 semester 2	The efficiency of oyster reefs on coastal protection in the foreshore areas: Oesterdam Case	Silvia Cilli	1	HZ	MSC THESIS	Joao Paiva; Matthijs Boersema
2015-2016 semester 2	The community compositon of native and exotic spieces on the artifical oyste reefs at the Oesterdam in the Eastern Scheldt 3	Niek Visschedijk Jesse van der Pool	2	HZ	MINOR	Anneke van de Brink
2015-2016 semester 2	Species Diversity within the Artificial Oyster Reefs at Oesterdam	Carly van Daele; Carlene Perkin	2	HZ	INTERNSHIP	Anneke van den Brink
2015-2016 semester 2	Wave attenuations over the Oesterdam tidal flat nourishment	Yahia Kala	1	Deltares	MSC THESIS	Jebbe van der Werf
2015-2016 semester 2	Submerged breakwaters design development based on Artificial oyster reef in Oesterdam	Chatchanok Ketsiri	1	HZ	INTERNSHIP	Joao Salvador de Paiva
2015-2016 semester 2	Qualitative Benthos Surveys: data analysis and development of a survey protocol	Natasha Walch	1	HZ / WMR	INTERNSHIP	Carla Pesch, Edwin Paree, Tom Ysebaert
2016-2017 semester 1	Artificial oyster reefs on the Oesterdam safety buffer project location	Celina de Ruiter, Lars van Diejen	2	HZ	MINOR	Joao Salvador de Paiva

totaal	28

Appendix 4.

Student names from the Aquatic Eco-technology course Ecological Engineering who took part in the 'Benthos Module'

2013/14

Dijk, Laurens van
Gerull, Nadja
Goethem, Thomas van
Gremmen, Thomas
Hahn, Levi
Hankinson, Paul
Hoenjet, Nieke
Hu, Tianyi
Janse, Benno
Jeworrek, Anna
Leuchter, Lennet
Malawauw, Rémon
Mustalahti, Vesa
Pranger, Anton
Schraaf, Maurits van der
Vries, Anne de

2014/15

Al-Nabhani, Alya
Alvarez Luckow, Cristian
Barker, Ross
Coomans, Dirk
Dekker, Dennis
Drenth, Pim
Eijkelhof, Yoeri
Goorden, Irene
Hoeder, Mike
Jansen, Kas
Kablau, Chico
Kemink, Sjoerd
Koeijer, Kevin de
Kort, Sven
Martens, Mireille
Meerman, Chris
Pool, Jesse van der
Rommens, Johnny
Rooij, Ger de
Scholtens, Sam
Schreur, Bo
Sisselaar, Samuel
Solé, Liliane
Tange, Sjaak
Verbeeke, Gabrielle
Visschedijk, Niek
Vliet, Marjolein van
Wokke, Menno
Zijlstra, Iris

2015/16

Allard, Silvan
An, Yingjie
Baars, Joshu van
Bastiaansen, Tom
Bijkerk, Ella
Boer, Xander de
dos Reis, Hélen
Deitelzweig Senior, Patrick
Djojodimedjo, Andrew
Dong, Linyinxue
Feng, Chanyan
Filutás, Filu
Gillissen, Lasse
Goethem, Thomas van
Gu, Yifei
Guijt, Willem
Heijden, Luuk van der
Hogeweg, Micha
Kampen, Luuk van
Keur, Martijn
Kloet, Jonas
Kraa, Axel de
Leeuwen, Mark van
Leijs, Thomas
Maljaars, Thijs
Oosse, Sem
Oosterwal, Sake
Peng, Tian
Poppe, Wilco
Ruijs, Nijs
Schaier, Sylvester
Smits, Nadine
Spaans, Hedzer
Speelman, Elias
Stouten, Marijn
Tanis, Remko
Vega Garre, Beatriz
Wagenaar, Niels
Wang, Jiaqi

2016/17

Abbenis, Serena
Avontuur, Stan
Bakker, Lisa
Benaduce Ortiz, Beatriz
Bergen, Michael van
Boer, Eva den
Bonné, Yves
Bortoluzzi, Pietro
Breunesse, Sara
Chen, Ruby
Duan, Ashley
Dubbeldam, Mathijs
Duren, Lars van
Elliot, Lauren
Favier, Lucas
Gonguet, Gabriel
Hoexum, Maeike
Huitema, Max
Huizer, Mikayla
Jin, Yujin
Jong, Loes de
Kauhl, Luc
Koeijer, Phiel de
Kooiman, Maurice
Krielen, Rein
Lambregts, Kayleigh
Leeuwen, Dorian van
Mast, Ivory
Nolte, Dana
Parasirisakun, Ronnaklit
Peene, Kristof
Phuwarueangrat, Nopphakrit
Pompoes, Richard
Pons, Charlotte
Portier, Joey
Rosien, Jean-Luc
Sande, Joris van der
Schaap, Daniel
Temmerman, Ymke
Teng, Sean
Thewissen, Tim
Tran, Phat quang
Truong, Uyen hai
Vlieger, Owen de
Wahl, Marie
Wens, Justin
Witte, Bart de
Zhang, Chi
Zhang, Seven
Zhao, Randy

Student names from the Civil Engineering course Coastal Engineering who took part in the 'Benthos Module'.

2013/14

Švežika, July
Abrawi, Shafa al
Ahmed Nabil Mohamed, Ahmed
Bijvank, Robert
Gheorghe, Teodor
Janga, Denzel
Meijer, Anthony
Mendez Groot, Tony
Munteanu, Ioana
Zodila, Emil
Boeren, Gorian
Bolijn, Stefan
Dekker, Michael
Francke, Niek
Gillissen, Joren
Heij, Werner
Hollemans, Ruben
Hoogstrate, Miquel
Jonge, Ries de
Kingma, Matthijs
Klooster, Marjanne van der
Kool, Rick
Kooman, Levi
Maas, Hannelore van der
Maas, Jelte
Migalski, Jos
Musters, Kenneth
Peijl, Robert van der
Rietveld, Jacintha
Rijckaerd, Huub
Thilleman, Kevin
Walhout, Korné
Witte, Dennis

2014/15

Bielskus, Andrius
Gorsel, Jan van
Halley, Matthew
Jastrumskis, Gediminas
Johnson, Mattaniah
Meskenaite, Viktorija
Nieuwenhuizen, Christian van
Olosunde, Demi
Srisuttisaard, Phongsatorn
Zhang, Brian
Alleyne, Richard
Cilli, Silvia
Cuthill, Aidan
Flikweert, Dies
Keeney, Jordan
Kreike, Boris
Ngirubiu, Isaac I.
Richards, Hilary
Rook, Sandra
Zimina, Mikelina

2015/16

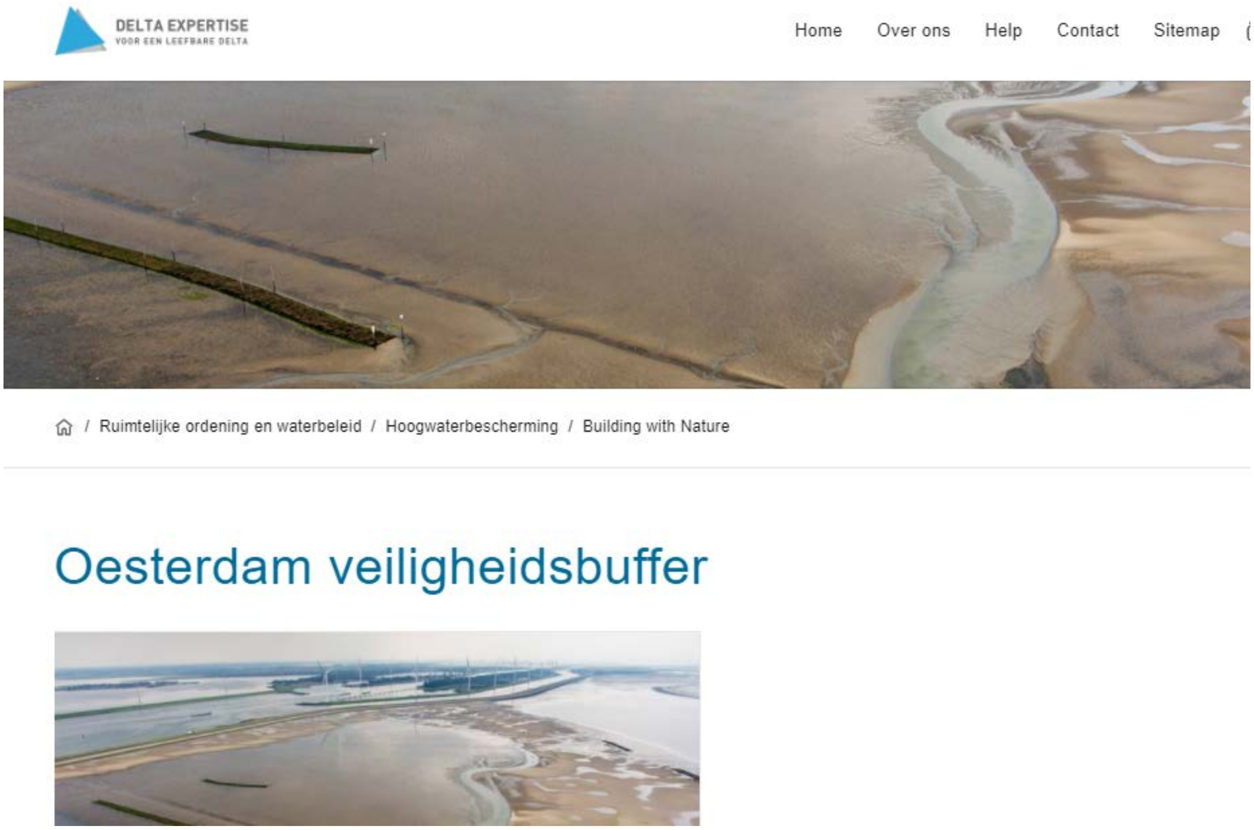
Belzen, Dieko van
Calbo, Ian
Heeren, Dennis van
Janse, Jurgen
Lauret, Niek
Nieuwpoort, Bas
Noteboom, Ramon
Pijl, Michael
Rikkers, Reindert Jan
Splunter, Max van
Steur, Jesper
Boden, Stijn
Bulman, Tom
Dekker, Thomas
Feber, Fabian le
Gillissen, Kees
Jonge, Marijn de
Kock, Joris de
Maljers, Dylan
Nugteren, Jorrit
Rooij, Pieter de
Rossum, Kim van
Smits, Daniël
Steketee, Christa
Tilburg, Sjoerd van
Verhulst, Rens

2016/17

Bödges, Scott
Breda, Lars van
De Neef, Michaël
Dingemanse, Dennis
Eshuis, Olivier
Grinwis, Lars
Houte, Thijs van
Jacobs, Wilmer
Lous, Robin
Murre, David
Neels, Jack
Nijskens, Bastiaan
Poorter, Arne de
Poortvliet, Gerard
Slabbekoorn, Gert
Tiegelaar, Femke
Traas, Ralph
Verhage, Jan
Visser, Patrick
Al-Azri, Ahmed
Amor dos Santos, Geanny
Chidi-Njemanze, Philip
Dremdjieva, Boyana
Dykmans, Georges
Ellis, Sheldon
Habtezghi, Alex
Meylemans, Celine
Nooteboom, Cees
Paul, Byron
Pauls, Rihards
Ramos Arboleda, Mauricio
Ratchakom, Nat
Razali, Tedric
Rijke, Demi de
Rodrigues da Silva, Adão
Roos, Mark
Safonova, Dasha
Tiersen, Michiel
Zee, Siebe van der

Appendix 5. Exposure

All information of the project is made available on the DeltaExpertise-site:
https://www.deltaexpertise.nl/wiki/index.php/Oesterdam_veiligheidsbuffer_VN (Dutch)



Oesterdam veiligheidsbuffer