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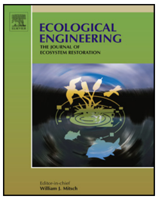

Ecosystem-based design rules for marine sand extraction sites

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ABSTRACT

The demand for marine sand in the Netherlands as well as globally is increasing. Over the last decades, only shallow sand extraction of 2 m below the seabed was allowed on the Dutch Continental Shelf (DCS). To guarantee sufficient supply and to decrease the surface area of direct impact, the Dutch authorities started to promote sand extraction depths over 2 m for sand volumes over 10 million m^3. The ecological effects of deep sand extraction, however, are still largely unknown. Therefore, we investigated short-term effects (0–2.5 y) of deep sand extraction (20–24 m) and compared these with other case studies such as, regular shallow sand extraction on the DCS (2 m) and an 8 m deepened shipping lane. For intercomparison between case studies we used tide-averaged bed shear stress as a generic proxy for environmental and related ecological effects. Bed shear stress can be estimated with a two-dimensional quadratic friction law and showed a decrease from 0.50 to 0.04 $N\,m^{-2}$ in a borrow pit in 20 m deep water and extraction depths up to 24 m. Macrozoobenthos in a borrow pit with a tide-averaged bed shear stress of around 0.41 $N\,m^{-2}$ is expected to return back to pre-extraction conditions within 4–6 year. When tide-averaged bed shear stress decreases below 0.17 $N\,m^{-2}$ enhanced macrozoobenthic species richness and biomass can occur. Below a tide-averaged bed shear stress of 0.08 $N\,m^{-2}$, increasing abundance and biomass of brittle stars, white furrow shell (*Abra alba*) and plaice (*platessa platessa*) can be expected. Below 0.04 $N\,m^{-2}$, an overdominance and high biomass of brittle stars can be expected whereas demersal fish biomass and species composition may return to reference conditions. Next to changes in faunal composition, a high sedimentation rate can be expected.

Ecological data and bed shear stress values were transformed into ecosystem-based design (EBD) rules. At higher flow velocities and larger water depths, larger extraction depths can be applied to achieve desired tide-averaged bed shear stresses for related ecological effects. The EBD rules can be used in the early-design phases of future borrow pits in order to simultaneously maximise sand yields and decrease the surface area of direct impact. The EBD rules and ecological landscaping can also help in implementing the European Union's Marine Strategy Framework Directive (MSFD) guidelines and moving to or maintaining Good Environmental Status (GES).

1. Introduction

Coastal zones are marked by many human activities such as fishing, shipping, wind farming, dredging, disposal of dredged sediment, beach nourishment, sand extraction, and the extraction and transport of oil and gas. These activities have different impacts on the marine environment and most of them are likely to intensify in the future (Jongbloed et al., 2014). Marine sand extraction in the Netherlands as well as globally is also intensifying (Stolk and Dijkshoorn, 2009; ICES, 2014a). In the Netherlands, 24 million m^3 of marine sand is used annually with 12.5 million m^3 for coastal nourishments and 9 million m^3 for construction (ICES, 2014a). An increase up to 85 million m^3 is anticipated to counteract effects of sea level rise (Deltacommissie, 2008). Considerable

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volumes are extracted in surrounding countries, in the UK 16.8 million m^3, in France 12 million m^3 and in Denmark 10.5 million m^3 per year. In Belgium, each year almost 4 million m^3 sand is extracted and 2.5 million m^3 is imported from the Netherlands (ICES, 2014a).

Over the last decades, sand extraction depths were limited to 2 m under the seabed on the Dutch continental shelf (DCS). The potential of sand extraction with depths over 2 m was first explored in 1999 during the PUTMOR study, in a deep borrow pit in front of the Port of Rotterdam (PoR) with sand extraction depths between 5 and 12 m (Boers, 2005). The PUTMOR study concluded that there were no indications that deep sand extraction would lead to unacceptable effects and that recovery of benthic assemblages would be possible (Boers, 2005). Deep sand extraction was therefore considered to be a promising alternative for sand extraction projects over 10 million m^3 sand. For the construction of Maasvlakte 2 (MV2), a 20 km^2 seaward expansion of the PoR, the Dutch authorities permitted sand extraction deeper than the regular 2 m, primarily to decrease the surface area of direct impact. Between 2009 and 2013, approximately 220 million m^3 sand was extracted from the MV2 borrow pit with an average extraction depth of 20 m under the seabed. To guarantee sufficient supply of marine sand in the intensively used coastal zone, the Dutch authorities now allow deep sand extraction for sand extraction volumes over 10 million m^3 (IDON, 2014).

Although deep sand extraction clearly limits the surface area of direct impact, effects of deep borrow pits on marine life on the DCS are still largely unknown. Our objective is to compare effects of extraction depth on macrozoobenthos and demersal fish and to recommend on optimised extraction depths for future borrow pits. We compared ecological effects for three case studies: regular shallow sand extraction (2 m), a deepened shipping lane (8 m) and deep sand extraction (20–24 m) in a large borrow pit.

Macrozoobenthos in the southern North Sea correlates with sediment parameters (Heip et al., 1992; Künitzer et al., 1992; Holtmann et al., 1996; Degraer et al., 1999; Van Hoey et al., 2004, 2007; Degraer et al., 2008; Verfaillie et al., 2009). Next to sediment parameters, salinity (Callaway et al., 2002; Reiss et al., 2010, 2011) and bed shear stress (Herman et al., 2001; Ysebaert et al., 2003; de Jong et al., 2015a) also influence macrozoobenthos.

Bed shear stress the amount of force per unit of seabed surface area exerted by flowing water and plays a role in sediment transport processes, the formation of bedforms, and sedimentation or erosion of the seabed. Bed shear stress is also influencing grain size, mud and organic matter content of the sediment. In the North Sea coastal zone, grain size is positively correlated with bed shear stress (spearman rank correlation: around +0.4) (de Jong et al., 2015a). On the crests of sand waves, shear stress values are generally higher ($\sim$0.6 N m^{-2}) and the sediment is coarser ($\sim$300 μm), whereas in troughs, shear stress is lower (0.44 N m^{-2}) and grain size is finer ($\sim$280 μm) (de Jong et al., 2015a). Due to sand extraction, larger differences in bed shear stress can be expected and correlations between sediment parameters and bed shear stress may become stronger. In the UK, suggested limits for acceptable changes in grain size after marine aggregate extraction were based on the natural range (Cooper, 2012). Sediment characteristics after deep sand extraction continue to change due to sedimentation of fine sediment until the borrow pit is filled (Thatje et al., 1999; Desprez, 2000; de Jong et al., 2015b).

For intercomparison between case studies, we used tide-averaged bed shear stress as a generic proxy for environmental and related ecological effects. Ecological data and bed shear stress values were combined and transformed into ecosystem-based design (EBD) rules. These rules can be used in the design of future borrow pits to maximise sand yields and simultaneously decrease the surface area of direct impact for different ecological scenarios.

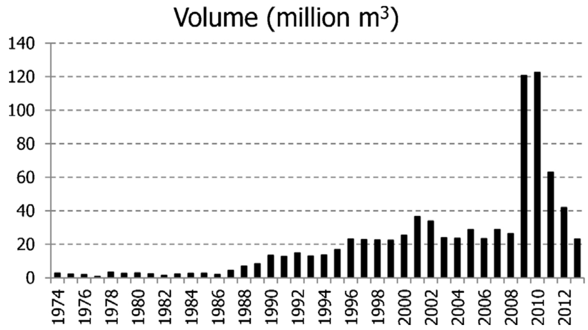

Fig. 1. Total volume of extracted marine sand in million m^3 per year on the DCS. The peak in 2009–2012 is due to the large-scale and deep sand extraction for MV2. *Source:* Rijkswaterstaat (ICES, 2014a).

We aim to answer the following questions:

(i) What are the ecological effects of the different sand extraction depths on the Dutch Continental Shelf (DCS)?
(ii) What are the optimised extraction depths to achieve desired bed shear stresses and related ecological effects for different pre-extraction water depths and flow velocities?
(iii) What role can ecosystem based design rules based on bed shear stress play in the design of future borrow pits outside the DCS?

2. Description of different cases of sand extraction depths on the Dutch continental shelf

We describe the following case studies on the Dutch Continental Shelf (DCS): regular shallow sand extraction, the 8 m deepened "Euromaasgeul" shipping lane and the deep and large-scale Maasvlakte 2 (MV2) borrow pit.

2.1. *Shallow sand extraction*

Before 1987 less than 5 million m^3 of marine sand was extracted annually from the Dutch Continental Shelf (DCS) and increased to nearly 20 million m^3 in 1995 (Fig. 1). From 1996 onwards, over 24 million m^3 of marine sand was extracted yearly for coastal nourishments and construction purposes (Stolk and Dijkshoorn, 2009; ICES, 2014a). Generally, only shallow sand extraction of 2 m below the seabed is allowed and only in the area between the continuous 20 m isobath and the 12 nautical mile boundary (Fig. 2) (IDON, 2005, 2014). Between 2006 and 2014 the surface area impacted by sand extraction increased from 7.5 to 45 km^2 (ICES, 2014a).

2.2. *Shipping lane*

North of the MV2 borrow pit (Fig. 2, no.1), a 57 km long and 23 m deep shipping lane "the Euromaasgeul" is situated which was realised in the 1970s to guarantee access to the Port of Rotterdam (PoR). Fine dredged material from the entrance of the shipping lane is dumped at the deepened disposal site "Verdiepte Loswal" (Fig. 2, no. 3) and the coarse fraction at disposal site North "Loswal Noord" near the entrance of the PoR. In the specific sampling area within the shipping lane, 8 m sand was extracted.

2.3. *Maasvlakte 2 (MV2) borrow pit*

For the harbour extension Maasvlakte 2 (MV2), approximately 220 million m^3 of sand was extracted between 2009 and 2013 (Fig. 1) from the MV2 borrow pit with an average extraction depth of 20 m under the seabed (Fig. 2, no. 1). This reduced the surface area of the borrow pit from 110 km^2 at 2 m extraction depth to only

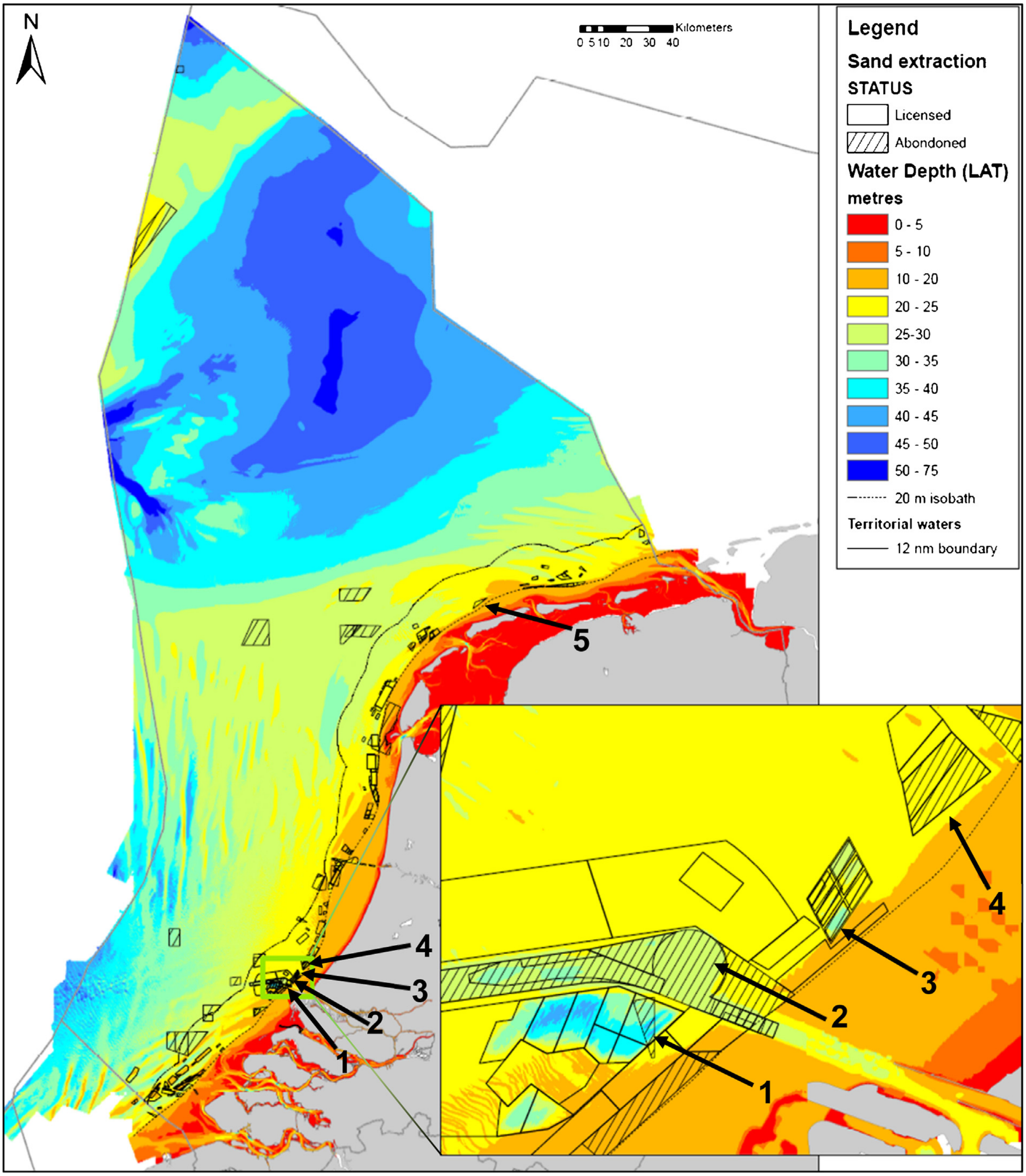

Fig. 2. Solitary licenced (black boxes) and abandoned (black hatched boxes) borrow pits with shallow extraction (2 m) except, **1**–**4**. The 20 m deepened Maasvlakte 2 borrow pit is denoted with (**1**), the 8 m deepened shipping lane (**2**), the 5–12 m deep temporary borrow pit (PUTMOR) which is nowadays used as disposal sites for dredged fine sediment (**3**), a 6 m deep borrow pit for the "Sand Engine" (**4**) and the shallow sand extraction site North of the barrier island Terschelling (**5**). The inset shows **1**–**4** in higher detail. *Source:* Rijkswaterstaat.

11 km^2 at 20 m extraction depth (de Jong et al., 2014, 2015b). The MV2 borrow pit is situated in front of the Port of Rotterdam outside the continuous 20 m isobath and is 2 km long and 6 km wide (Fig. 2, no. 1). An exclusion area, consisting of non-erodible clay covered by a 1 to 4 m thick layer of sand with sand waves, separates a larger northern and smaller southern borrow pit (Klein and van den Boomgaard, 2013; Stolk, 2014). Sediment in the surrounding area consists of fine to medium sand with small fractions of mud and very fine sand, and low sediment organic matter content (SOM).

2.4. *Ecological landscaping*

In the Maasvlakte 2 sand borrow pit, ecosystem-based landscaping techniques were used. Two sandbars mimicking natural sand waves, were left behind after sand extraction, to increase habitat heterogeneity and to influence post-dredging macrozoobenthic and demersal fish assemblages (van Raalte et al., 2007; van Dalfsen and Aarninkhof, 2009; Borsje et al., 2011; de Jong et al., 2014).

One sandbar parallel to the tidal current was completed in spring 2010. This parallel sandbar has a length of 700 m, a width at the crest

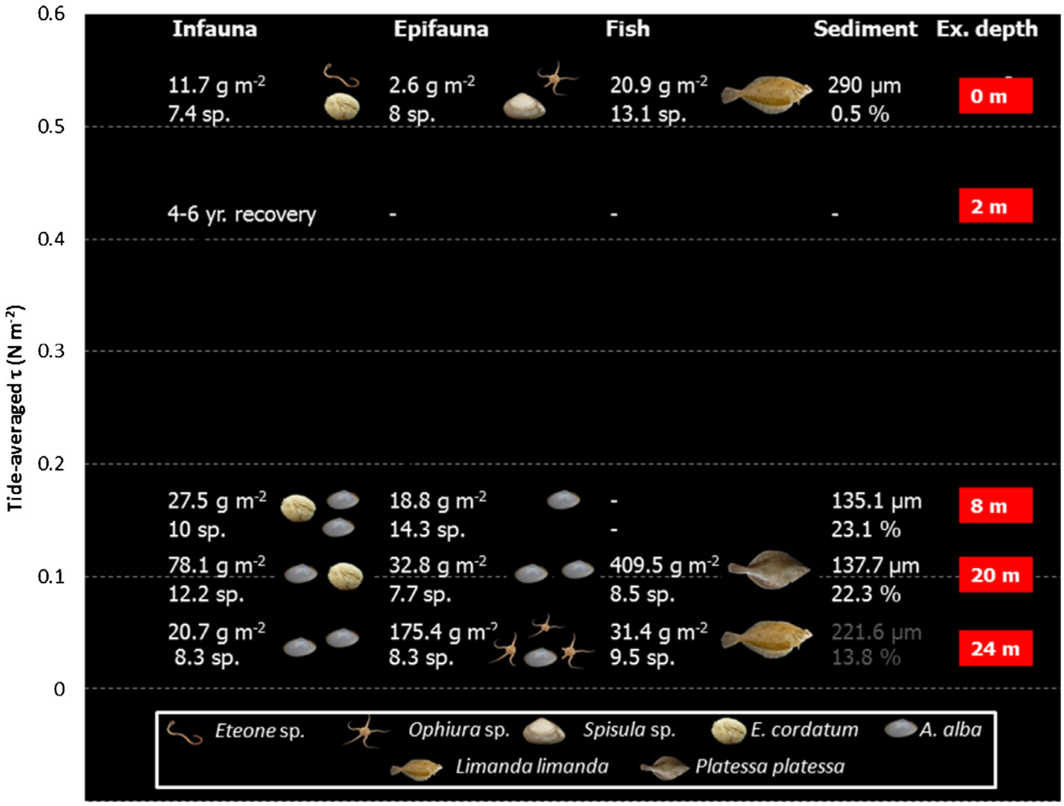

Fig. 3. Summary of in- and epifaunal and demersal fish assemblages depths of the case studies in the Dutch coastal area with 20 m pre-extraction water depth and a flow velocity of 0.65 m s^{-1} (top 2 most abundant species based on biomass) and median grain size and mud content of the case studies in the Dutch coastal area with 20 m pre-extraction water depth and a flow velocity of 0.65 m s^{-1}. Infaunal biomass values are measured as ash-free dry weight (AFDW), epifauna and demersal fish as fresh weight. Grain size and mud content in the deepest area of MV2 borrow pit are underestimated due to failure of boxcore sampling.

of 70 m, and slopes of 140 m. The crest of the sandbar is located at a water depth of 30 m and the troughs are more than 40 m deep. In 2011, the second sandbar with an orientation oblique to the tidal current was completed. The length and width are similar to the parallel sandbar but, due to time constraints, the difference in depth between crest and trough is less pronounced. The crest is situated at a water depth of 28 m and the northern trough is 36 m deep. A narrow and 32 m deep trench separates the crest from the slope of the borrow pit (de Jong et al., 2014, 2015b).

3. Effects of different extraction depths and ecological landscaping on the benthic ecosystem

Here, we summarise the effects of different extraction depths of the case studies on the benthic ecosystem and sediment characteristics.

3.1. Shallow sand extraction (2 m)

The long-term effects of shallow sand extraction on macrozoobenthos were studied at a site North of the Dutch barrier island Terschelling. A volume of 2.1 million m^3 of marine sand was extracted from a 1.4 km^2 large area with pre-extraction water depths of 20–23 m, extraction depths of 1.5 m and a depth-averaged flow velocity of 0.5 m s^{-1} (van Dalfsen et al., 2000; Tonnon et al., 2013). Recovery time of macrozoobenthos to pre-extraction conditions (species assemblage, species richness and biomass) at Terschelling was estimated to be 4–6 years (van Dalfsen et al., 2000; van Dalfsen and Essink, 2001). No changes in sediment characteristics after sand extraction were observed, only SOM appeared to be lower after dredging (van Dalfsen et al., 2000). Similar recovery times were found for other shallow borrow pits in France near Dieppe (Desprez, 2000; Desprez et al., 2010; Desprez et al., 2014) with water depths of 10–15 m and a depth-averaged flow velocity of 1.5 m s^{-1} (Le Bot et al., 2010) and extraction depths up to 2 m (Desprez et al., 2014). In the UK, recovery times at site Area 222, a borrow site 20 miles off Felixstowe at the southeast coast of England were 7 years at low dredging intensity (Boyd et al., 2005) and 15 years at high dredging intensity (Waye-Barker et al., 2015). The water depth in Area 222 site varied from 35 m at the high intensity dredging area, 27 m in the low dredging intensity area and 32 m in the reference area and extraction depths were in the same order as for the Terschelling case (Cooper et al., 2013). The depth-averaged flow velocity in Area 222 is around 1.11 m s^{-1} (Boyd et al., 2003).

3.2. Extraction in the shipping lane (8 m)

During the baseline study of the PoR in 2006 and 2008, in- and epifaunal samples were collected in the “Euromaasgeul” shipping lane (Fig. 2, no. 3). In 2012, additional samples were taken: 4 in- and 3 epifaunal. Full details on sampling procedures are given in de Jong et al. (2014, 2015b,a). Maintenance dredging works were not carried out in the last years in the specific sampling area (Rijkswaterstaat, pers. comm.). In 2006, 2008 and 2012, a significant distinct, very productive and species-rich assemblage dominated by white furrow shell (*Abra alba*) was observed in the shipping lane. Average biomass of in- and epifauna was respectively 27.5 g AFDW m^{-2} and 18.8 g WW m^{-2} and significantly higher than reference values, respectively 11.7 AFDW m^{-2} and 2.6 g WW m^{-2} (de Jong et al., 2015b) (Fig. 3). The median grain size of the sediment in the shipping lane in 2006, 2008 and 2012 is gradually becoming finer (229, 194 and 135.1 µm) and richer in mud (8, 3, 25%) and organic matter content (1, 1, 4%) (de Jong et al., 2015b).

Table 1
Summary of changes related to different extraction depths of the case studies in the Dutch coastal area with 20 m pre-extraction water depth and a flow velocity of 0.65 m s^{-1}.

Extraction depth	Infauna	Epifauna	Demersal fish	Sediment
2	no	nd	nd	Mud: 0.5% < SOM
8	[*], 2×	[*], 6×	nd	Grain size: factor 2 decrease and mud 231%
20	[*], 7×	[*], 12×	[*], 20×	Grain size: factor 2 decrease and mud 223%
24	[*], 2×	[*], 67×	no, 1.5×	Smaller grain size and mud 138%
Sandbars	[*]	[*]	[*]	[*]

[*] Significant changes compared to reference (no sand extraction), nd: no data and, no: no change. Grain size and mud content in the deepest area of MV2 borrow pit are underestimated due to failure of boxcore sampling.

3.3. Short-term effects of deep and large-scale MV2 borrow pit (20–24 m)

In the MV2 borrow pit, macrozoobenthic species composition and biomass was significantly correlated with time after cessation of sand extraction and with sediment and hydrodynamic characteristics (de Jong et al., 2015b). Two years after cessation of sand extraction, infaunal biomass (organisms living in the seabed) increased sevenfold and epifaunal biomass (organisms on the seabed) increased twelvefold in the 40 m deep areas (20 m extraction) of the MV2 borrow pit (Table 1). Species composition changed significantly and white furrow shell (*A. alba*) became abundant in terms of density and biomass. Demersal fish biomass increased 20-fold (Table 1) and species composition was significantly different (dominance of plaice, *Platessa platessa*) compared to reference areas (de Jong et al., 2014). Next to ecological differences, sediment characteristics also changed significantly. Sediment grain size decreased and the fraction very fine sand, mud and OM increased. In the deepest parts of the borrow pit (44 m, 24 m extraction depth), infaunal biomass was only twofold higher compared to reference values (Table 1). Epifaunal biomass, however, increased more than 67-fold and species composition changed from *A. alba* to brittle stars whereas demersal fish biomass dropped almost to reference levels (de Jong et al., 2015b). Next to the large faunal differences, a sedimentation rate of up to 75 cm y^{-1} was observed. The ecological and environmental effects of the Dutch case studies are summarised in Fig. 3 and Table 1.

3.4. Short term effects of ecological landscaping in the MV2 borrow pit

The landscaped sandbars significantly influenced species composition of macrozoobenthos and demersal fish and changed sediment characteristics (de Jong et al., 2014, 2015b).

4. Ecosystem-based design (EBD) rules for future borrow pits

For intercomparison between the case studies, we used the tide-averaged bed shear stress as a generic proxy for environmental and related ecological effects. Depth-averaged (2DH) bed shear stress $\left(\vec{\tau}_{b\ \ 2DH}\right)$ can be estimated with a quadratic friction law (Eq. (1)) (Soulsby, 1997).

$$\vec{\tau}_{b\ \ 2DH} = \frac{\rho_{\text{seawater}} * g * \left|\vec{U}\right|^2}{C^2} \tag{1}$$

For the Chézy roughness (C), we used a value of 65 m$^{1/2}$ s^{-1} for the reference area and shallow sand extraction areas, 80 m$^{1/2}$ s^{-1} for the shipping lane of the PoR and MV2 borrow pit due to the high mud content and 110 m$^{1/2}$ s^{-1} (Van Rijn, 1993; Winterwerp et al., 2004) for the deepest parts of the MV2 borrow pits due to the observed thick soft muddy bed (de Jong et al., 2015b). The density of seawater (ρ) was set to 1023 kg m^{-3} and the gravitational acceleration (g) was set to 9.81 m s^{-2}. The magnitude of the depth-averaged flow velocity $\left(\left|\vec{U}\right|\right)$ in the area of the MV2 borrow pit is 0.65 m s^{-1} (Borsje et al., 2009). From the law of conservation of mass, there is a negative linear relation between the increase in water depth and decrease in depth-averaged velocity. Doubling of the water depth results in a halving of the depth-averaged velocity, in the case of 20 m deep sand extraction in 20 m deep water with a depth-averaged flow velocity of 0.65 m s^{-1}, the depth-averaged velocity is reduced to 0.325 m s^{-1}. When we assume a symmetrical diurnal tide, the tide-averaged bed shear stress equals:

$$\vec{\tau}_{b\ \ \text{tide-averaged}} = \frac{\tau_{b\ \ 2DH}}{2} \tag{2}$$

Applying Eqs. (1) and (2) for given parameter values lead to a relationship of tide-averaged bed shear stress $\left(\vec{\tau}_{b\ \ \text{tide-averaged}}\right)$ and sand extraction depth as shown in Fig. 4. The tide-averaged bed shear stress shows a strong decrease at small sand extraction depths and smaller decreases at larger extraction depths. The tide-averaged bed shear stress is 0.5 N m^{-2} in 20 m deep reference areas, 0.41 N m^{-2} at 2 m extraction depth, 0.17 N m^{-2} at 8 m extraction depth, 0.08 N m^{-2} at 20 m and 0.04 N m^{-2} at 24 m extraction depth. The stepwise changes in Fig. 4 are induced by the changes in Chézy roughness parameter values.

For differing tide-averaged bed shear stress values we derived different ecological effects from the DCS case studies. This implies that extraction depth can be chosen such that desirable ecological effects can be achieved. We can now define ecosystem-based design (EBD) graphs for extraction depth based on pre-extraction water depth and pre-extraction flow velocity. These EBD graphs can be used for the design of future borrow pits to optimise extraction depths in relation to ecological effects on the seabed. Extraction depths needed to reach the time-averaged bed shear stress values of the case studies (Fig. 4) at different combinations of different pre-extraction water depths and flow velocities can be determined with Eqs. (1) and (2) resulting in ecosystem-based design (EBD) graphs (Fig. 5). With increasing pre-extraction depth-averaged flow velocities and water depths, larger extraction depths can be applied to

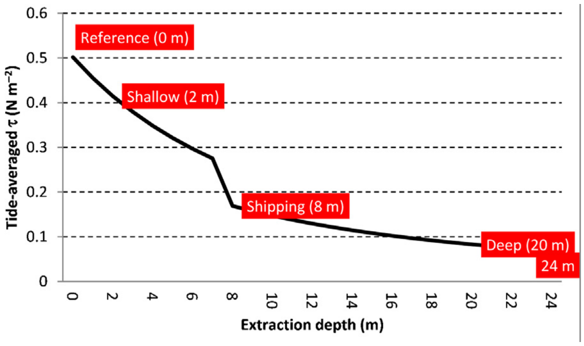

Fig. 4. Tide-averaged bed shear stress $\vec{\tau}_{b\ \ \text{tide-averaged}}$ as a function of sand extraction depth at 20 m pre-extraction water depth and using a Chézy roughness value of 65 m$^{1/2}$ s^{-1} for sand extraction depth interval 0–8 m, 80 m$^{1/2}$ s^{-1} for 8–20 m and 110 m$^{1/2}$ s^{-1} for the deepest extraction depth. The reference situation and case studies (shallow sand extraction, shipping lane and deep sand extraction: 20 and 24 m) are indicated with the red text labels.

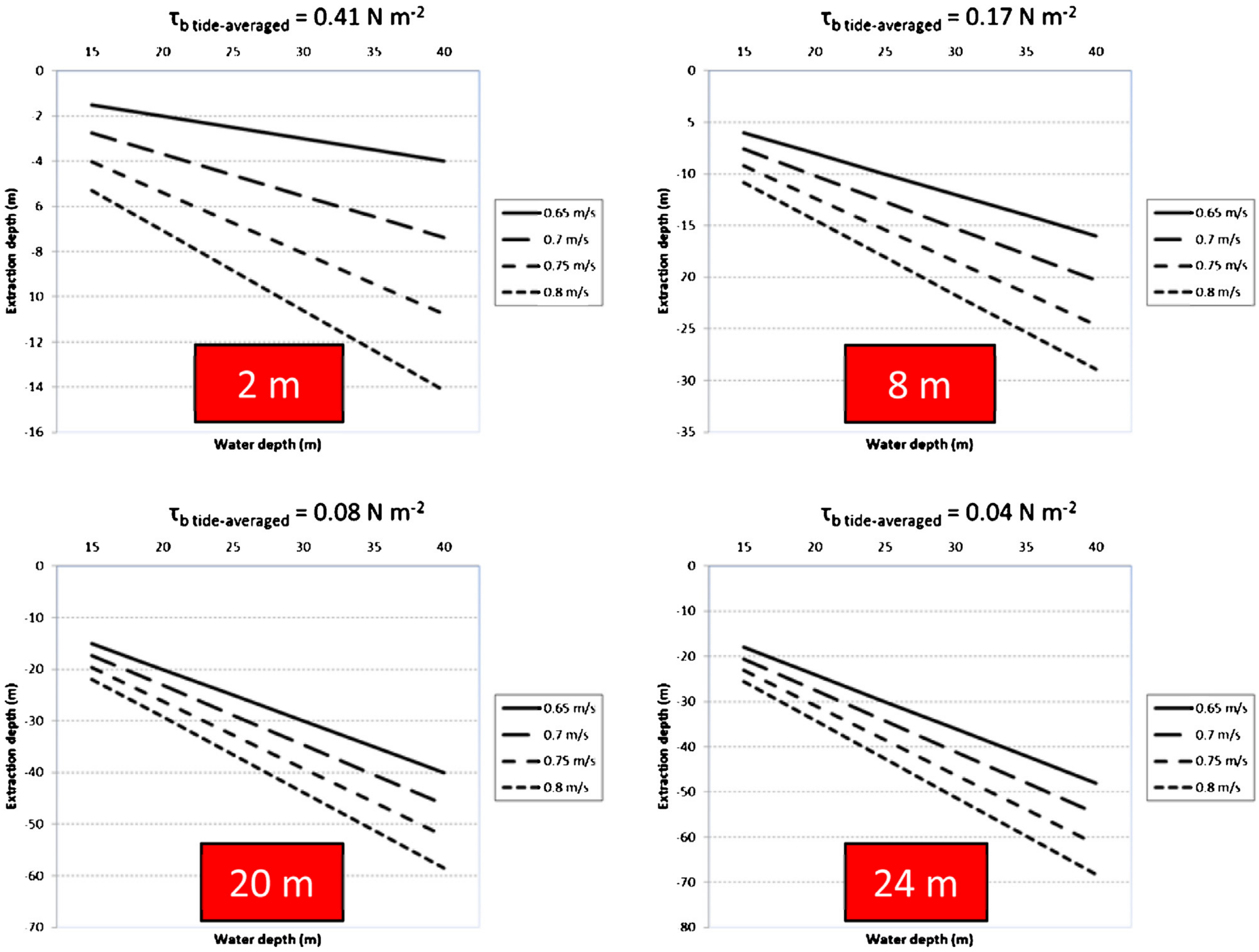

Fig. 5. EBD graph to reach $\vec{\tau}_{b \text{ tide-averaged}}$ values of the DCS case studies (0.41, 0.17, 0.08 and 0.04 N m^{-2}) at the seabed of a borrow pit as a function of extraction depth, at a range of pre-extraction water depths (15–40 m) and varying pre-extraction depth-averaged flow velocity magnitudes (0.65–0.8 m s^{-1}). We used Chézy roughness values 65, 65, 80 and 110 m$^{1/2}$ s^{-1}.

Table 2
Influence of higher flow velocities (0.7, 0.75 and 0.8 m s^{-1}) on extraction depths needed to achieve desired bed shear stresses of the DCS case studies for 20 m pre-extraction water depths.

DCS case studies		Extraction depth required to reach $\vec{\tau}_{b \text{ tide-averaged}}$ of the case studies (m)		
Extraction depth (m)	$\vec{\tau}_{b \text{ tide-averaged}}$ (N m^{-2})	0.7 m s^{-1}	0.75 m s^{-1}	0.8 m s^{-1}
Reference	0.5	–	–	–
2	0.41	3.7	5.4	7.1
8	0.17	10.2	12.3	14.5
20	0.08	23.1	26.2	29.2
24	0.04	27.4	30.8	34.2

Table 3
Influence of higher pre-extraction water depths (25, 30 and 35 m) on extraction depths needed to achieve desired bed shear stresses of the DCS case studies for cases with a flow velocity of 0.65 m s^{-1}.

DCS case studies		Extraction depth required to reach $\vec{\tau}_{b \text{ tide-averaged}}$ of the case studies (m)		
Extraction depth (m)	$\vec{\tau}_{b \text{ tide-averaged}}$ (N m^{-2})	25	30	35
Reference	0.5	–	–	–
2	0.41	2.5	3	3.5
8	0.17	10	12	14
20	0.08	25	30	35
24	0.04	30	36	42

reach the tide-averaged bed shear stress values calculated for the DCS case studies (Tables 2 and 3).

5. Discussion

5.1. Ecosystem based design rules (EBD rules)

In the UK, limits for acceptable changes in sediment grain size after marine aggregate extraction based on the natural range were proposed, with the aim of ensuring the return of the pre-dredge faunal assemblage after dredging (Cooper, 2012). Sediment characteristics after deep sand extraction continue to change due to sedimentation of fine sediment until the borrow pit is filled (Thatje et al., 1999; Desprez, 2000; de Jong et al., 2015b). It is for this reason that grain size is not considered to be a suitable candidate for setting limits for acceptable change in large-scale and deep borrow pits where there is no prospect of a return of pre-dredge conditions. We therefore developed ecosystem-based design (EBD) rules based on bed shear stress, which can be used to determine extraction depths to reach desirable bed shear stresses and related ecological effects for a range of flow velocities and pre-extraction water depths. In general, with increasing flow velocity and water depth, larger extraction depths can be used.

The EBD rules and ecological landscaping techniques can also help in implementing the European Union's Marine Strategy Framework Directive (MSFD) guidelines and safeguarding or achieving Good Environmental Status (GES) of marine waters. The MSFD consists of 10 GES descriptors: "Biodiversity", "Non-indigenous species", "Commercial fish and shellfish", "Food webs", "Eutrophication", "Sea-floor integrity", "Hydrographical conditions", "Contaminants", "Contaminants in seafood", "Marine litter" and "Energy and underwater noise". When MFSD requires for example that the seabed has to remain in the original physical condition to enable the return of pre-extraction faunal assemblages, shallow sand extraction with 2 m extraction depth is the best option for 20 m deep pre-extraction areas $\left(\vec{\tau}_{b\ \text{tide-averaged}} : 0.41\ \text{N m}^{-2}\right)$. No significant changes in macrozoobenthos were observed 4–6 year after the cessation of shallow sand extraction (van Dalfsen et al., 2000; van Dalfsen and Essink, 2001). If there are no stringent limitations, 8 m deep sand extraction $\left(\vec{\tau}_{b\ \text{tide-averaged}} = 0.17\ \text{N m}^{-2}\right)$ may be the limit for areas with a pre-extraction water depth of 20 m as only sediment characteristics and macrozoobenthic species composition significantly changed, and biomass increased more than twofold. At a tide-averaged bed shear stress of $0.08\ \text{N m}^{-2}$, macrozoobenthic species composition is even more disturbed and biomass increased more than 7-fold. Demersal fish composition changed significantly and biomass increased 20-fold. Below a tide-averaged bed shear stress of $0.04\ \text{N m}^{-2}$, infaunal biomass was only twofold higher compared to reference levels. Epifaunal biomass, however, increased more than 67-fold due to a dominance of brittlestar and fish biomass and composition returned to reference conditions. Next to large faunal differences, a high sedimentation rate up to $75\ \text{cm y}^{-1}$ was observed.

The most relevant MSFD descriptors for deep sand extraction are: descriptor 1 "Biodiversity" (Patrício et al., 2014) with the addition of ecological functioning (Bremner, 2008; Törnroos et al., 2015), descriptor 3 "Commercial fish and shellfish", descriptor 6 "Seabed integrity" (Rice et al., 2012; ICES, 2014b) and descriptor 7 "Hydrography" (OSPAR, 2012). The MSFD can be used as an assessment framework for deep sand extraction. The implementation of MSFD into legislation is in progress and therefore maybe not all final criteria of the descriptors are mentioned. The MSFD may have implications for deep sand extraction. The ecological effects of the different extraction depths and ecological landscaping in view of the criteria of the descriptors are summarised in Table 4.

5.2. Limitations of ecological data and recommendations

We compared the ecological effects of different sand extraction depths. The ecological effects due to shallow sand extraction were investigated in the 1990s (van Dalfsen et al., 2000; van Dalfsen and Essink, 2001). The impact of the 8 m deepened shipping lane was first investigated in 2006, 2008 and 2012. We recommend additional research for shallow extraction depths (2 m) on the DCS because only one case-study near Terschelling is described in the literature. For the 8 m deepened shipping lane, only a small number of samples were collected and data on maintenance dredging are available but it remains difficult to assess other influences such as anchoring of ships or the influence of movements of ships on sedimentation patterns.

No data were available from case studies with intermediate extraction depths (2–5 m) but the borrow pit which was used for the "Sand Engine", a 20 million m^3 sand nourishment north of Rotterdam with extraction depths of 6 m (de Vriend et al., 2015), would be very relevant to study. Other interesting cases are the borrow pits used for the beach nourishments "Zwakke schakels" of the province of Noord-Holland with a total volume of 40 million m^3 and extraction depths between 2 and 8 m.

Macrozoobenthos correlated with time after cessation which is an indication that an equilibrium was not yet reached. The full range of ecological effects on the seabed of MV2 borrow pit can only be defined after several years. The most severe effects occurred in the deepest parts of the borrow pit which coincided with significant changes in epifaunal and demersal fish assemblage and it is likely that it will not only be restricted to the deepest areas in the future. Ongoing monitoring is therefore recommended to define medium or long-term effects on macrozoobenthos and demersal fish. Furthermore, the inclusion of sedimentation rate and oxygen content measurements is recommended because two years after cessation of sand extraction, a high sedimentation rate and significant differences in epifaunal and demersal fish in the deepest parts of the MV2 borrow pit were encountered (de Jong et al., 2015b). When the EBD rules are applied in regions outside the Dutch continental shelf, ecological data is needed as the ecological response may be different. It is however likely that white furrow shell (*A. alba*) will increase as a result of deep sand extraction due to the pan-European distribution.

5.3. Limitations of two-dimensional bed shear stress estimates

Here we applied a 2D approach to estimate the magnitude of bed shear stress estimates. For a more accurate assessment, 3D hydrodynamical modelling approaches are required to cope with the impact of complex bathymetries such as the MV2 borrow pit with polygonal edges (Fig. 2, no. 1). Furthermore, complex hydrographic conditions are present with periods of strong density stratification due to the region of fresh water input (ROFI) from the river Rhine (de Boer et al., 2009), density-driven cross-shore flows (van der Hout et al., 2015), up- and down welling, wind-driven flow and wind and wave-induced mixing. The supply of sediment can also vary between regions and tide-averaged bed shear stresses from Eqs. (1) and (2) assume symmetrical tides but in reality tides are often asymmetrical. Modelling oxygen concentration and sedimentation rates of cohesive and non-cohesive sediment in future borrow pits is also recommended (de Jong et al., 2015b).

In Belgium, effects of sand extraction depths of 5 m were investigated on sandbanks orientated parallel to the tidal current (Bonne, 2010; De Backer et al., 2014). Complex three-dimensional modelling approaches are required to determine bed shear stresses

Table 4
The ecological effects of the different extraction depths and ecological landscaping in view of the criteria of the MSFD descriptors for the Dutch coastal area with 20 m pre-extraction water depth and a flow velocity of 0.65 m s^{-1}.

	Extraction depth (m)				
	2	8	20	24	Ecological landscaping
Biodiversity	🟨 Temporary changes, back to reference conditions in 4–6 y.	🟩 Higher diversity, shift to *A. alba*, more deposit feeding	🟥 Lower diversity, shift to *A. alba*, more deposit feeding	🟥 Low biodiversity, shift to Ophiuroids, only deposit feeding	🟫 Increase in heterogeneity, and biodiversity, differences in assemblage
Commercial fish and shell fish	Only temporary changes (?), direct negative for long-living shellfish	🟩 Increase in biomass (?), shift to *P. platessa* (?), direct negative impact for long-living shellfish	🟩 20-fold increase in biomass, shift to *P. platessa*, negative conditions for long-living shellfish (?)	🟨 Biomass back to reference level, *L. limanda*, negative conditions for long-living shellfish (?)	🟫 In troughs, increase in biomass, increase in overall biodiversity, negative for long-living shellfish but maybe positive on the long-term (?)
Sea-floor integrity	🟨 Minor changes in bathymetry and sediment characteristics	🟥 Smaller grain size, higher mud, very fines and OM	🟥 Smaller grain size, higher mud, very fines and OM, high sedimentation rate	🟥 Smaller grain, higher mud, very fines and OM, high sedimentation rate	🟫 Impact depends on configuration, increase in habitat heterogeneity
Hydrographical conditions	🟨 Decrease in shear stress from 0.50 to 0.41 N m^{-2}	🟨 0.17 N m^{-2}	🟥 0.08 N m^{-2}, higher sedimentation	🟥 0.04 N m^{-2}, higher chances of hypoxia due to stratification and sedimentation	🟫 Impact depends on configuration and circumstances, increase in habitat heterogeneity (stratification, salinity, oxygen, sedimentation rate)

No colour: no changes or only temporary, green: positive impact, yellow: minor negative impact, brown: positive or negative impact, red: negative impact. The question marks indicate possible changes as no data on demersal fish for shallow sand extraction and the shipping lane was collected.

around sandbanks and sandbanks with sand extraction (Briere et al., 2010). Regions with erosion and sedimentation were observed resulting in a variety of ecological responses (Bonne, 2010; De Backer et al., 2014). Due to the orientation of the sandbanks and sand extraction on the crests which are parallel to the tidal current, channelling of the flow can occur resulting in higher flow velocities and bed shear stresses (Roos et al., 2008; Werf van der and Giardino, 2009). The Belgian sand extraction cases are therefore excluded in our present study because flow channelling cannot be predicted with the two-dimensional quadratic friction law. For the described French case study, the EBD graphs are of limited use due to the complex hydrodynamic circumstances. Water depths are smaller (15 m) and large tidal amplitudes are present which makes the area prone to the influence of waves resulting in higher bed shear stress values which cannot be predicted with the used 2D approach. The orientation of the borrow pit and furrows are parallel to the tidal current so that flow contraction again may occur and instead of sediment deposition as in the MV2 borrow pit, erosion may occur. The case study in the UK (area 222) is in deeper water and therefore EBD rules can be applicable.

In the MV2 borrow pit, high sedimentation rates and altered macrozoobenthic and demersal fish assemblages were observed (de Jong et al., 2015b). Due to continuing sand extraction on the Dutch Continental Shelf (DCS), a mega-scale trench may emerge. With the orientation of the trench parallel to the tidal current, flow contraction may occur (Roos et al., 2008) resulting in increased flow velocities and bed shear stresses. Instead of sedimentation, erosion of the seabed may even occur. The implications for macrozoobenthos and demersal fish are unknown and deserve attention.

5.4. Use of the EBD design rules

This paper is meant to connect ecologists, coastal morphologists and engineers, coastal zone managers and dredging companies in order to maximise sand yields and, simultaneously decrease the surface area of direct impact for different ecological scenarios. Future policy, for example resulting from the EU Marine Strategy Framework Directive (MSFD) presumably requires dredging companies or principals of dredging works to leave the seabed in certain physical conditions to promote or maintain specific ecological conditions. The EBD rules and ecological landscaping techniques can help in implementing MSFD guidelines and safeguarding or achieving Good Environmental Status (GES) of marine waters.

6. Conclusions

For intercomparison between sand extraction case studies, we used the tide-averaged bed shear stress as a generic proxy for changed environmental conditions and related ecological effects. Bed shear stress can be estimated with a two-dimensional equation using extraction depth and depth-averaged flow velocity magnitude. We developed Ecosystem-based design (EBD) rules for future borrow pits based on ecological data and bed shear stress.

In a borrow pit with a pre-extraction water depth of 20 m and sand extraction depths over 20 m, tide-averaged bed shear stress showed a decrease from 0.50 to 0.04 $N\,m^{-2}$. Recovery time of macrozoobenthos to pre-extraction conditions (species assemblage, species richness and biomass) after shallow sand extraction (2 m) near Terschelling site was estimated to be 4–6 year (van Dalfsen et al., 2000). Borrow pits with a decrease in tide-averaged bed shear of less than 0.33 $N\,m^{-2}$ (8 m, 0.17 $N\,m^{-2}$) may lead to enhanced species richness, biomass and significant increase of white furrow shell (*A. alba*). At tide-averaged bed shear stresses of 0.08 $N\,m^{-2}$ (20 m extraction depth), macrozoobenthic biomass increased 7-fold and demersal fish biomass 20-fold. At bed shear stress values of 0.04 $N\,m^{-2}$, increasing abundance of epifaunal brittle stars may be expected and detrimental effects such as high sedimentation rates and reduced dissolved oxygen levels may emerge.

In general, at higher depth-averaged flow velocities and pre-extraction water depths, larger sand extraction depths can be applied to reach a desired tide-averaged bed shear stress. The EBD rules can be used for early-design phases of future borrow pits in the southern North Sea in order to maximise sand yields and, simultaneously decrease the surface area of direct impact. The EBD rules can help in implementing MSFD guidelines and safeguarding or achieving Good Environmental Status (GES) of marine waters. For comparable regions in the southern North Sea, EBD rules can also be formulated but ecological data from areas with low shear stress values such as abandoned borrow pits or dredged shipping lanes are required. Ecological landscaping techniques can also be applied in comparable areas. We recommend using three-dimensional model approaches for later design phases or other regions with complex hydrodynamical circumstances to determine more accurate and high resolution bed shear stress data.

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References

Boers, M., 2005. Effects of a Deep Sand Extraction pit, Final Report of the PUTMOR Measurements at the Lowered Dump Site. RIKZ.

Bonne, W., 2010. Macrobenthos characteristics and distribution, following intensive sand extraction from a subtidal sandbank. J. Coastal Res. 51, 141–150.

Borsje, B.W., de Vries, M.B., Bouma, T.J., Besio, G., Hulscher, S., Herman, P.M.J., 2009. Modeling bio-geomorphological influences for offshore sandwaves. Cont. Shelf Res. 29, 1289–1301.

Borsje, B.W., van Wesenbeeck, B.K., Dekker, F., Paalvast, P., Bouma, T.J., van Katwijk, M.M., de Vries, M.B., 2011. How ecological engineering can serve in coastal protection. Ecol. Eng. 37, 113–122.

Boyd, S.E., Limpenny, D.S., Rees, H.L., Cooper, K.M., 2005. The effects of marine sand and gravel extraction on the macrobenthos at a commercial dredging site (results 6 years post-dredging). ICES J. Mar. Sci. 62, 145–162.

Boyd, S.E., Limpenny, D.S., Rees, H.L., Cooper, K.M., Campbell, S., 2003. Preliminary observations of the effects of dredging intensity on the re-colonisation of dredged sediments off the southeast coast of England (Area 222). Estuarine Coastal Shelf Sci. 57, 209–223.

Bremner, J., 2008. Species' traits and ecological functioning in marine conservation and management. J. Exp. Mar. Biol. Ecol. 366, 37–47.

Briere, C., Roos, P.C., Garel, E., Hulscher, S.J.M.H., 2010. Modelling the morphodynamics of the Kwinte Bank. Subject to sand extraction. J. Coast. Res. 51, 117–126.

Callaway, R., Alsvag, J., de Boois, I., Cotter, J., Ford, A., Hinz, H., Jennings, S., Kroncke, I., Lancaster, J., Piet, G., Prince, P., Ehrich, S., 2002. Diversity and community structure of epibenthic invertebrates and fish in the North Sea. ICES J. Mar. Sci. 59, 1199–1214.

Cooper, K., Burdon, D., Atkins, J.P., Weiss, L., Somerfield, P., Elliott, M., Turner, K., Ware, S., Vivian, C., 2013. Can the benefits of physical seabed restoration justify the costs? An assessment of a disused aggregate extraction site off the Thames Estuary, UK. Mar. Pollut. Bull. 75, 33–45.

Cooper, K.M., 2012. Setting limits for acceptable change in sediment particle size composition following marine aggregate dredging. Mar. Pollut. Bull. 64, 1667–1677.

De Backer, A., Van Hoey, G., Coates, D., Vanaverbeke, J., Hostens, K., 2014. Similar diversity-disturbance responses to different physical impacts: three cases of small-scale biodiversity increase in the Belgian part of the North Sea. Mar. Pollut. Bull. 84, 251–262.

de Boer, G.J., Pietrzak, J.D., Winterwerp, J.C., 2009. SST observations of upwelling induced by tidal straining in the Rhine ROFI. Cont. Shelf Res. 29, 263–277.

de Jong, M.F., Baptist, M.J., Lindeboom, H.J., Hoekstra, P., 2015a. Relationships between macrozoobenthos and habitat characteristics in an intensively used area of the Dutch coastal zone. ICES J. Mar. Sci. 72, 2409–2422.

de Jong, M.F., Baptist, M.J., Lindeboom, H.J., Hoekstra, P., 2015b. Short-term impact of deep sand extraction and ecosystem-based landscaping on macrozoobenthos and sediment characteristics. Mar. Pollut. Bull. 97, 294–308.

de Jong, M.F., Baptist, M.J., van Hal, R., de Boois, I.J., Lindeboom, H.J., Hoekstra, P., 2014. Impact on demersal fish of a large-scale and deep sand extraction site with ecosystem-based landscaped sandbars. Estuarine Coastal Shelf Sci. 146, 83–94.

de Vriend, H.J., van Koningsveld, M., Aarninkhof, S.G.J., de Vries, M.B., Baptist, M.J., 2015. Sustainable hydraulic engineering through building with nature. J. Hydro-Environ. Res. 9, 159–171.

Degraer, S., Verfaillie, E., Willems, W., Adriaens, E., Vincx, M., Van Lancker, V., 2008. Habitat suitability modelling as a mapping tool for macrobenthic communities: an example from the Belgian part of the North Sea. Cont. Shelf Res. 28, 369–379.

Degraer, S., Vincx, M., Meire, P., Offringa, H., 1999. The macrozoobenthos of an important wintering area of the common scoter (*Melanitta nigra*). J. Mar. Biol. Assoc. U.K. 79, 243–251.

Deltacommissie, 2008. Samen werken met water. In: A Living Land Builds for its Future. Hollandia Printing, Den haag, pp. 1–140.

Desprez, M., 2000. Physical and biological impact of marine aggregate extraction along the French coast of the Eastern English Channel: short- and long-term post-dredging restoration. ICES J. Mar. Sci. 57, 1428–1438.

Desprez, M., Le Bot, S., Duclos, P., De Roton, G., Villanueva, M., Ernande, B., Lafite, R., 2014. In: PURH (Ed.), Monitoring the Impacts of Marine Aggregate Extraction. Knowledge Synthesis 2012 (GIS SIEGMA). Rouen and Le Havre, la France. , pp. 1–43.

Desprez, M., Pearce, B., Le Bot, S., 2010. The biological impact of overflowing sands around a marine aggregate extraction site: Dieppe (eastern English Channel). ICES J. Mar. Sci. 67, 270–277.

Heip, C., Basford, D., Craeymeersch, J.A., Dewarumez, J.M., Dorjes, J., de Wilde, P., Duineveld, G., Eleftheriou, A., Herman, P.M.J., Niermann, U., Kingston, P., Kunitzer, A., Rachor, E., Rumohr, H., Soetaert, K., Soltwedel, T., 1992. Trends in biomass, density and diversity of North Sea macrofauna. ICES J. Mar. Sci. 49, 13–22.

Herman, P.M.J., Middelburg, J.J., Heip, C.H.R., 2001. Benthic community structure and sediment processes on an intertidal flat: results from the ECOFLAT project. Cont. Shelf Res. 21, 2055–2071.

Holtmann, S.E., Groenewold, A., Schrader, K.H.M., Asjes, J., Craeymeersch, J.A., Duineveld, G.C.A., Van Bostelen, A.J., Van der Meer, J., 1996. Atlas of the Zoobenthos of the Dutch Continental Shelf. Ministry of Transport, Public Works and Water Management, North Sea Directorate, Rijswijk.

ICES, 2014a. First Interim Report of the Working Group on the Effects of Extraction of Marine Sediments on the Marine Ecosystem (WGEXT). Rijswijk, The Netherlands., pp. 1–67.

ICES, 2014b. Report of the Workshop to Review the 2010 Commission Decision on Criteria and Methodological Standards on Good Environmental Status (GES) of Marine Waters; Descriptor 6. ICES Headquarters, Denmark, pp. 1–37.

IDON, 2005. Integrated Management Plan for the North Sea 2015 (IMPNS 2015). Rijswijk, The Netherlands., pp. 1–166.

IDON, 2014. Integraal Beheerplan Noordzee 2015 [IBN]. Herziening, Rijswijk.

Jongbloed, R.H., van der Wal, J.T., Lindeboom, H.J., 2014. Identifying space for offshore wind energy in the North Sea Consequences of scenario calculations for interactions with other marine uses. Energy Policy 68, 320–333.

Klein, M.D., van den Boomgaard, M., 2013. Evaluatie van zandwinputten MV2. Svasek Hydraulics, Rotterdam.

Künitzer, A., Basford, D., Craeymeersch, J.A., Dewarumez, J.M., Dörjes, J., Duineveld, G.C.A., Eleftheriou, A., Heip, C., Herman, P., Kingston, P., Niermann, U., Rachor, E., Rumohr, H., de Wilde, P.A.J., 1992. The benthic infauna of the North Sea: species distribution and assemblages. ICES J. Mar. Sci. 49, 127–143.

Le Bot, S., Lafite, R., Fournier, M., Baltzer, A., Desprez, M., 2010. Morphological and sedimentary impacts and recovery on a mixed sandy to pebbly seabed exposed to marine aggregate extraction (Eastern English Channel France). Estuarine Coastal Shelf Sci. 89, 221–233.

OSPAR, 2012. MSFD Advice Document on Good Environmental Status—Descriptor 7: Hydrographical Conditions. London, United Kingdom.

Patrício, J., Teixeira, H., Borja, A., Elliott, M., Berg, T., Papadopoulou, N., Smith, C., Luisetti, T., Uusitalo, L., Wilson, C., Mazik K, N.N., Cochrane, S., Andersen, J.H., Boyes, S., Burdon, D., Carugati, L., Danovaro R, N.H., 2014. DEVOTES Recommendations for the Implementation of the Marine Strategy Framework Directive. Deliverable 1.5. DEVOTES project. JRC92131., pp. 1–71.

Reiss, H., Cunze, S., König, K., Neumann, H., Kröncke, I., 2011. Species distribution modelling of marine benthos: a North Sea case study. Mar. Ecol. Prog. Ser. 442, 71–88.

Reiss, H., Degraer, S., Duineveld, G.C.A., Kroncke, I., Aldridge, J., Craeymeersch, J.A., Eggleton, J.D., Hillewaert, H., Lavaleye, M.S.S., Moll, A., Pohlmann, T., Rachor, E., Robertson, M., Vanden Berghe, E., van Hoey, G., Rees, H.L., 2010. Spatial patterns of infauna, epifauna, and demersal fish communities in the North Sea. ICES J. Mar. Sci. 67, 278–293.

Rice, J., Arvanitidis, C., Borja, A., Frid, C., Hiddink, J.G., Krause, J., Lorance, P., Ragnarsson, S.Á., Sköld, M., Trabucco, B., Enserink, L., Norkko, A., 2012. Indicators for sea-floor integrity under the European marine strategy framework directive. Ecol. Indic. 12, 174–184.

Roos, P.C., Hulscher, S., de Vriend, H.J., 2008. Modelling the morphodynamic impact of offshore sandpit geometries. Coastal Eng. 55, 704–715.

Soulsby, R.L., 1997. Dynamics of Marine Sands: a Manual for Practical Applications. Thomas Telford, London.

Stolk, A., 2014. Evaluatie MEP Aanleg Maasvlakte 2 2013. Rijkswaterstaat, Water, Verkeer en Leefomgeving, Rijswijk.

Stolk, A., Dijkshoorn, C., 2009. Sand extraction Maasvlakte 2 Project: License, Environmental Impact Assessment and Monitoring, EMSAGG (European Marine Sand and Gravel Group) Conference—a Wave of Opportunities for the Marine Aggregates Industry Rome , Italy.

Thatje, S., Gerdes, D., Rachor, E., 1999. A seafloor crater in the German Bight and its effects on the benthos. Helgoland Mar. Res. 53, 36–44.

Tonnon, P.K., Borsje, B., De Jong, M., 2013. BwN HK2.4 Eco-Morphological Design of Landscaped Mining Pits, final ed. Deltares, Delft.

Törnroos, A., Bonsdorff, E., Bremner, J., Blomqvist, M., Josefson, A.B., Garcia, C., Warzocha, J., 2015. Marine benthic ecological functioning over decreasing taxonomic richness. J. Sea Res. 98, 49–56.

van Dalfsen, J.A., Aarninkhof, S.G.J., 2009. Building with Nature: Mega nourishments and ecological landscaping of extraction areas., European Marine Sand and Gravel Group—a Wave of Opportunities for the Marine Aggregates Industry EMSAGG Conference , 7–8 May, Frentani Conference Centre, Rome, Italy.

van Dalfsen, J.A., Essink, K., 2001. Benthic community response to sand dredging and shoreface nourishment in Dutch coastal waters. Senckenb. Biol. 31, 329–332.

van Dalfsen, J.A., Essink, K., Madsen, H.T., Birklund, J., Romero, J., Manzanera, M., 2000. Differential response of macrozoobenthos to marine sand extraction in the North Sea and the Western Mediterranean. ICES J. Mar. Sci. 57, 1439–1445.

van der Hout, C.M., Gerkema, T., Nauw, J.J., Ridderinkhof, H., 2015. Observations of a narrow zone of high suspended particulate matter (SPM) concentrations along the Dutch coast. Cont. Shelf Res. 95, 27–38.

Van Hoey, G., Degraer, S., Vincx, M., 2004. Macrobenthic community structure of soft-bottom sediments at the Belgian Continental Shelf. Estuarine Coastal Shelf Sci. 59, 599–613.

Van Hoey, G., Vincx, M., Degraer, S., 2007. Temporal variability in the *Abra alba* community determined by global and local events. J. Sea Res. 58, 144–155.

van Raalte, G., Dirks, W.M.T., Dalfsen, J., van Erftemeijer, P., Aarninkhof, S., Otter, H., 2007. Building with nature: Creating sustainable solutions for marine and inland water constructions. In: New Research Initiative Towards a Centre of Excellence, Proceedings of the Eighteenth World Dredging Congress (WODCON XVIII), Lake Buena Vista, Florida USA, pp. 637–648.

Van Rijn, L.C., 1993. Principles of Sediment Transport in Rivers Estuaries and Coastal Seas. Aqua Publications, The Netherlands.

Verfaillie, E., Du Four, I., Van Meirvenne, M., Van Lancker, V., 2009. Geostatistical modeling of sedimentological parameters using multi-scale terrain variables: application along the Belgian Part of the North Sea. Int. J. Geogr. Inf. Sci. 23, 135–150.

Waye-Barker, G.A., McIlwaine, P., Lozach, S., Cooper, K.M., 2015. The effects of marine sand and gravel extraction on the sediment composition and macrofaunal community of a commercial dredging site (15 years post-dredging). Mar. Pollut. Bull. 99, 207–215.

Werf van der, J., Giardino, A., 2009. Effect van zeer grootschalige zandwinning langs de Nederlandse kust op de waterbeweging zandtransporten en morfologie. Deltares, Delft, the Netherlands, pp. 1–74.

Winterwerp, J.C., van Kesteren, W.G.M., Johan, C.W., Walther, G.M.v.K., 2004. 6-Sediment-Fluid Interaction, Developments in Sedimentology. Elsevier, Amsterdam, pp. 161–210.

Ysebaert, T., Herman, P.M.J., Meire, P., Craeymeersch, J., Verbeek, H., Heip, C.H.R., 2003. Large-scale spatial patterns in estuaries: estuarine macrobenthic communities in the Schelde estuary, NW Europe. Estuarine Coastal Shelf Sci. 57, 335–355.

Glossary

Bed shear stress: the amount of force per unit of seabed surface area exerted by flowing water ($\mathrm{N\,m^{-2}}$)

Grain size: median grain size of sediment particles (μm)

Mud: sediment particles smaller than 63 μm (vol%)

OM: organic matter (mass%)

Infauna: animals living in the sediment sampled with a box-corer

Epifauna: animals living on the sediment sampled with a bottom dredge

Macrozoobenthos: in-and epifauna

Demersal fish: fish living on or near the seabed

C: Chézy roughness, parameter describing the hydraulic roughness of the seabed ($\mathrm{m^{1/2}\,s^{-1}}$)

ρ: the density of seawater ($\mathrm{kg\,m^{-3}}$)

g: gravitational acceleration ($\mathrm{m\,s^{-2}}$)

U: the magnitude of the depth-averaged flow velocity ($\mathrm{m\,s^{-1}}$)