Ecological landscaping of seabed

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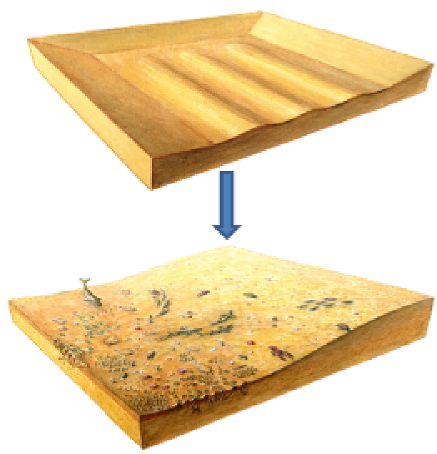


The expected worldwide increase in the demand for marine sand due to economic growth and urbanisation as well as the long-term threats of climate change call for innovative approaches for sand extraction activities. Marine sand extraction traditionally focuses on minimizing environmental impact and quick recovery of seabed sediment composition and benthic assemblages. With large-scale extraction, this conservative approach can lead to constraining mitigation measures. Moreover, the potential of ecological development, cost reduction and a more efficient use of scarce space are not considered.

This Building Solution provides guidance for design, organisation and realisation of ecosystem-based landscaped sand extraction sites, based on research in the Maasvlakte 2 sand extraction site in the North Sea. Ecosystem-based design rules for future sand extraction sites are developed aimed at optimising the balance between impacted surface area, sand yield, costs and ecological effects.

>> Read more

Ecological landscaping of sand extraction sites involves the realisation of seabed level gradients and other morphological features in newly dredged sites. The overall aim is to make the sand extraction site attractive for a variety of macrozoobenthic species that in turn attract demersal fish, mammals and birds. This is done by creating different bedforms and/or combinations of sediment characteristics which provides ideal settlement and habitat circumstances for a larger variety of species. Due to this landscaping, the re-colonization of the mined pit is presumably faster and results in a higher biodiversity than in a traditionally dredged sand extraction site.

In the Netherlands, the demand for marine sand is still increasing. In 2015, a total volume of 26 million m^3 of sand was extracted from the Dutch Continental Shelf for coastal nourishment. Due to the expected sea level rise, the demand for sand to maintain the Dutch coast with nourishments may increase from 12 to 40 - 85 million m^3. To safeguard the supply of sand, new sand extraction strategies are needed and therefore ecosystem-based design rules, which optimise the balance between impacted surface area, sand yield, costs and ecological effects are developed.

5 Basic steps towards Building with Nature

Related Tools

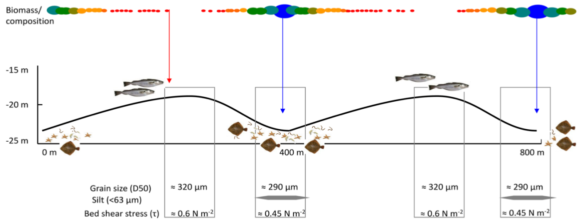
- Biogeomorphological Coastal Modelling System - Delft3D
- Coastline intervention tool - Holland Coast - ITHC
- Ecosystem-Based Design Rules for Sand Extraction Sites
- Including natural value in decision-making - Nature Index
- Interactive Dredge Planning Tool - Singapore
- Interactive group modelling - MapTable
- Morphological predictor for mixed beds
- Probabilistic analysis of ecological effects - Cause-effect chain modeling
- Quick model set-up using open databases - DelftDashboard
- Roughness module for sediment dynamic modelling

Related Projects

- Adaptive monitoring of sand extraction areas - Maasvlakte 2 extension, NL
- Ecological landscaping of sand extraction sites, NL
- Knowledge - Cause - effect chain modelling of sand mining using mussels

Ecological research on tidal sand ridges and sand waves showed that there are differences in the macrozoobenthic species composition present on the troughs, slopes and crests. Ecosystem-based sand extraction can create bedforms of a similar scale as the naturally occurring sand ridges in the area. This approach may result in a higher biodiversity and biomass in the sand extraction site after dredging. An ecological design of an extraction area may help to increase the potential post-dredging value of the area and opportunities can be taken to improve and add to the overall sustainability of the sand extraction project.

Knowledge - Cause - effect chain modelling of sand mining using Sandwich terns



Hypothetical benthic fauna distribution at sand waves.

BwN dimension

To safeguard the supply of sand with sand extraction strategies based on ecosystem-based design rules which optimise the balance between impacted surface area, sand yield, costs and ecological effects. Ecosystem-based landscaping will be used to boost habitat heterogeneity and biodiversity.

Usage skills

To properly design a sand extraction scheme knowledge is required of both the hydrological and morphological behaviour of the area under consideration as well of the ecological response of marine organism to the changes in the seabed landscape. For this purpose, data of the local system and from comparable regions need to be collected and statistically analysed.

When specific bedforms are desired, knowledge of construction options and possible complications are required during the preparation phase of the project, combined with monitoring and adaptive management options.

Advantages

- It has been found that ecosystem-based landscaping will help to promote higher biodiversity compared to the traditional dredging approach.
- Enhancing biodiversity and overall sustainability of the sand extraction project may facilitate social and political acceptance and thus accelerating licensing procedures and project realization.

Disadvantages

- The practical feasibility of the design sand extraction sites will be a prerequisite for success.
- The ecologically most favourable set-up and orientation of ecosystem-based sand bars may imply risks to the sand extraction project and productivity.
- Ecosystem-based landscaping might introduce additional costs to the sand extraction project, although it has been shown that with proper design and execution this will be kept to a minimum.
- Application of ecosystem-based landscaping in sand extraction sites implies the transformation of existing habitat into a new habitat which is not embedded in current legislation.

How to Use

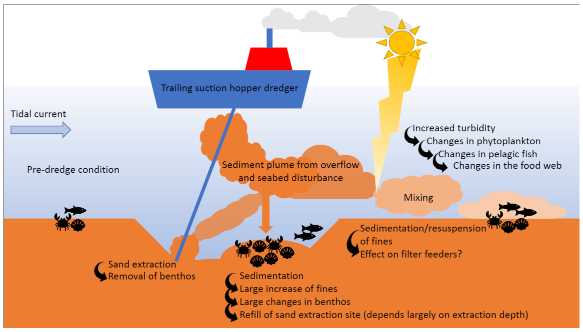
This section describes and gives guidance to the steps to be taken to design landscaping of the seabed on basis of ecosystem approach. The steps are described following the BwN design steps:

1. **Understand the system**

- **>>** Effects of sand extraction

Shallow sand extraction

In general, sand extraction has direct impacts. Benthic organisms are damaged or removed and bathymetry and sediment composition may change considerably. Indirect effects vary from increased suspended matter and turbidity and detrimental effects on filter-feeders, predatory fish and the food web.



Ecological effects of sand extraction, varying from direct effects (alteration of habitat and removal of benthos), to nearby indirect effects (increase of suspended matter, possible effects on filter feeders, sedimentation and resuspension, increased turbidity and detrimental effects on phytoplankton, predatory organism relying on eyesight and the food web).

Until a few years ago, the focus of ecological research was mainly on the on the direct effects of sand extraction. For shallow sand extraction depths, up to -2 m below the original seabed on the Dutch Continental, in general recovery of macrozoobenthos back to pre-disturbance conditions occurs in 2-4 year. For surrounding areas similar recovery times are reported.

Differences in recovery time exists, for shallow coarse sediments with weak tidal bed shear stress a recovery time of 11 year was found (Wan Hussin et al. 2012). Recovery times for dredged estuarine muddy areas are found to be around 6-8 months (Newell et al. 2008). Recovery times of areas with reef building organisms such as the sand mason worm *(Lanice conchilega*), honeycomb worm (*Sabellaria alveolate*) or long-living organism such as the ocean quahog *(Arctica islandica)* would be in the order of decades even after shallow sand extraction.

In general, demersal fish are closely linked to macrozoobenthos which can be severely influenced by sand extraction. In France, it was found that aggregate extraction can also lead to new seabed habitats which may favour certain macrozoobenthic and demersal fish species (Desprez et al. 2000). Fishing fleets near aggregate extraction sites were not deterred and fishing effort of potters and English dredgers were positively related to extraction intensity Marchal et al. 2014). Sand extraction sites may even attract marine mammals (Todd et al. 2014).

Deep sand extraction

It appeared that in the Netherlands there is little experience with the effects of deep sand extraction sites on existing values and user-functions, due to Dutch legislation prior to 2000. In 2000, possibilities of extraction depths larger than 2 m below the seabed were explored (Boers 2005). It became clear that in water depths of less than 40 m, the chance of reduced seawater oxygen content is rather small and that re-establishment of organisms on the seabed is possible.

Baseline data from the Port of Rotterdam which was collected in 2006 and 2008 in a 2500 km^2 large research area showed that the benthic system can be changed considerably by sand extraction and sediment disposal and that these changes persists in time (De Jong et al. 2015).

More information on the effects of sand extraction can be found in Tool – Ecosystem-based Design Rules for Sand Extraction Sites and Case - Ecosystem-based design of sand extraction sites – Pilot MV2 Sand Extraction site.

2 . **Identify realistic alternatives**

- **>>** Assumptions in the approach of landscaping

Based on literature, it is recognised that differences in the (chemical - physical) habitat is reflected in differences in community composition. Colonisation of areas will be an ongoing process, but follows the physical starting point. After a certain period, some organisms may be capable to influence their environment (eco-engineers) causing a reverse situation in which some physical parameters will follow the community development.

Important chemical-physical parameters are: salinity and dissolved oxygen content of seawater, sediment organic matter and silt content, sediment grainsize distribution, the existence of 'hard' substrate and seabed morphology. Most of these parameters are interrelated, being the result of transport mechanisms or existing energy at a certain location. A good indicating parameter for energy is bed shear stress. Relevant ecological parameters are species composition, species richness, diversity and biomass and could be determined for the infauna, the epifauna and demersal fish. Species composition has relevance to life history, age structure and feeding traits. Bed shear stress is linked with in- and epifaunal and demersal fish species composition (De Jong et al. 2014, De Jong et al 2015a, De Jong et al. 2015b). Bed shear stress is directly related to the extraction depth of sand extraction and can therefore be used in the design of extraction sites.

- **>>** Guidelines and boundary conditions

A top-down approach to determine the feasibility and design of a landscaped ecological sand extraction site is made along 3 steps. First, the feasibility of a landscaped ecological sand extraction site is determined using rules-of-thumb. Then a preliminary design of the landscaped ecological sand extraction site is determined using simple tools and parameterizations. The basic design can then be optimized in a detailed assessment using process-based models (3D hydrodynamical models) and species response curves and habitat rules.

Step 1: determine the feasibility of landscaping an ecosystem-based sand extraction site.

- determine the location of the extraction site, the total extractable volume, and existing legislation and potential objections to ecological sand extraction.
- determine the characteristics of the extraction site (sediment characteristics, hydrodynamics, sediment transport, morphology, ecology etc.)
- make designs for a regular sand pit and a design for a deep pit with an extraction depth of about 8 to 30 m and a design for the deep pit with ecosystem-based sand bars.
- determine the life span of the designs, cost for implementing, safety issues and potential for ecosystem-based sand extraction.

Step 2: determine a basic design for landscaping an ecosystem-based sand extraction site

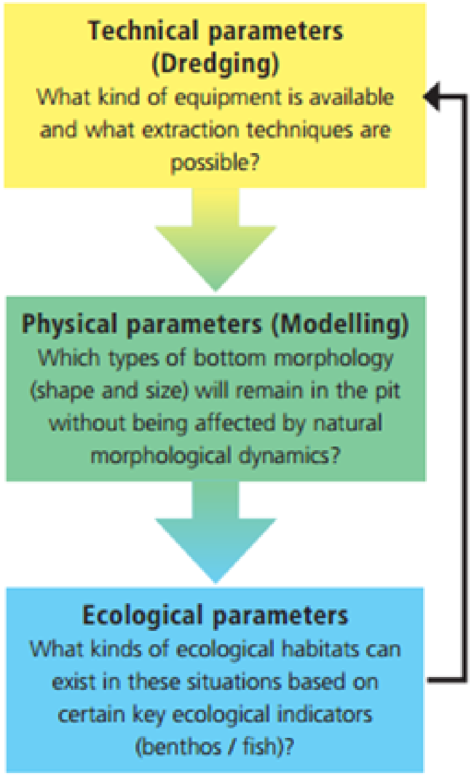
- choose design scenario (to increase biodiversity or biomass etc.).
- determine criteria for evaluation, what result is required to make the project a success?
- determine the most descriptive and influencing abiotic parameter(s) for ecological development. Changing this parameter(s) will determine the chance of successfully creating habitat conditions for the preferred post-dredge situation.
- create and compare histograms of time-averaged bed shear stresses for the traditionally and ecosystem-based landscaped sand extraction site designs using formulae for bed shear stresses under uniform flow. Assuming time-averaged bed shear stresses to be the most descriptive and deterministic abiotic parameter(s) for ecological development.

Step 3: optimize the design for an ecosystem-based landscaped ecological sand extraction site

- set-up and run a process-based hydrodynamic, water quality, sediment transport and morphological models of the regular sand extraction site design and the ecosystem-based sand extraction site, extract year-averaged bed shear stresses, dissolved oxygen levels, organic matter and mud content and seabed morphology.
- determine future ecological response using classification schemes, habitat rules, species response curves or other statistical approaches.
- iteratively optimize the ecosystem-based design based on the design scenario scores.

- **>>** Determine the feasibility of an ecosystem-based sand extraction site

The basis for an extraction design is the amount of marine sand needed and the quality. Other practical considerations are also important, for instance legislation, economical aspects (sailing distance) and the method of extraction. This leads to a reconnaissance of potential areas that can provide these conditions. The selected extraction site can be characterized by location (orientation, depth), hydrodynamics (waves, currents), sediment (transport, -type, -distribution, percentage organic matter, stratigraphy), morphology (sand waves or sand ridges) and ecology (assemblage). Given the characteristics of the area, a preliminary design of the ecosystem-based sand extraction can be determined, considering a number of technical, physical, and ecological parameters. The life span of the design, the costs for implementing, safety issues and potential of ecosystem-based sand extraction should be determined .



Flow chart showing the process used to accumulate requirements for designing the bed forms at existing extraction sites.

Technical parameters

Trailer Suction Hopper Dredgers (TSHD's) are the most efficient tool for sand extraction and they vary in size and capacity. To avoid unnecessary high cost and loss of time, several technical parameters have to be taken into account when designing an ecosystem-based extraction site.

Technical parameter	Description	Reference
Dredging depth	The maximum dredging depth of the TSHDs should be considered to avoid excessive cost and loss of time. Only a few TSHDs can create deep troughs.	Rijks, 2011
Manoeuvrability	The manoeuvrability of the ships to create specific shapes should be considered to avoid excessive cost and loss of time. The sharper the shapes, the more time it will take to create.	Rijks, 2011

Capacity	The capacity of the ships and the specific sailing lengths to fill the hopper should be taken into account to avoid excessive cost and loss of time. The smaller the shapes, the less likely TSHDs will reach an optimal dredging volume during one track and thereby increasing dredging effort and cost.	Rijks, 2011
Hydraulic conditions	For economic and technical reasons shapes should preferably not lie perpendicular to the main current directions as ships and dredging operations are limited under these circumstances, increasing time and costs.	Rijks, 2011

Physical parameters

Physical parameter	**Description**	**Reference**
Location	The location determines the characteristics of the extraction site including hydrodynamics, metocean and geotechnical conditions, sediment transport, morphology and ecology.	Rijks, 2011
Shape	The shape of the extraction site is often determined by other user functions. The shape will determine what kind of ecosystem-based bed form design can be planned in the extraction site.	Rijks, 2011
Sediment	The extraction site needs to contain sufficient sand of the desired grain size. The natural variation in grain sizes and percentage fines can be used in the creation of different landscapes and related ecological habitats. If needed, overflow from dredging equipment can be stimulated to ensure that more fines are left behind in certain areas for the development of specific habitats.	Rijks, 2011
Morphology	The occurrence and dimensions of naturally existing morphological bed forms in the wider extraction area can be copied in the extraction site although they may need another orientation with regards to the tidal current.	Rijks, 2011
Infrastructure	The presence of wrecks, cables and pipelines determine the shape of the extraction site and ecosystem-based bed forms.	Rijks, 2011

Ecological parameters

Ideally, the dredged seabed has variation in substrate composition (grain size, mud and organic matter content)and containing series of bed forms with variation in steepness and orientation with regards to the tidal current. Each combination will be tailor made to create a certain ecological habitat. This means that the relation between seabeds, via hydrodynamics and physics, and ecology must be clear when determining the goals of ecosystem-based landscaping. Knowledge on the relationship between marine organisms and sediment characteristics, water depth, hydrodynamics, sediment transport and morphology is the subject of a PhD study within the Building with Nature programme. Preliminary results indicate that the sediment characteristics and time-averaged bed shears stresses are important parameters determining ecological response and therefore of use in the design of ecosystem-based seabeds (De Jong et al. 2015).

3. **Valuate the qualities of alternatives and pre-select an integral solution**

- **>>** Determine a basic design for a landscaped ecological mining pit

The results presented in a report (Tonnon, 2013) and study (De Jong et al. 2015b) support the hypothesis that ecosystem-based landscaping increases biodiversity in the sand extraction site. Moreover, based on the bed shear stress, a distinction could be made between two clusters (the *Albra* alba assemblage and the *Echinoidea spp. - phoronidea* assamblage). The *Albra* assemblage was roughly found in areas having a bed shear stress smaller than 0.4 N m^{-2} and the *Echinoidea spp. - phoronidea* assemblage was roughly found at bed shear stresses larger than 0.4 N m^{-2}.

Ecological data and bed shear stress values were transformed into ecosystem-based design rules for the Dutch Continental Shelf. 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 (De Jong et al., 2016). The Ecosystem Based Design (EBD) rules can be used in the early-design phases of future sand extraction sites 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).

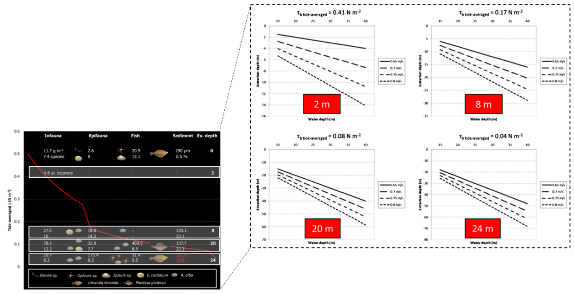
The ecological effects of the different extraction depths and ecological landscaping in view of the criteria o f the MSFD descriptors for the Dutch coastal area with 20 m pre-extraction water depth and a flow velocity of 0.65 m s-1. Green: positive effects, yellow: minor effects, red: negative aspects and brown intermediate effects (positive and negative)

	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 shellfish	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 (?)
Seabed 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
Hydrographic circumstances	Decrease in shear stress from 0.50 to 0.41 N m^{-2}	Decrease in shear stress from 0.50 to 0.17 N m^{-2}	Decrease in shear stress from 0.50 to 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)

More detailed information of the EBD-rules can be found in Ecosystem-Based Design Rules for Sand Extraction Sites

- **>>** Ecosystem-based design rules for the minimum excavation depth ecological mining sites

Based on the simple calculation rules for the computation of depth-averaged velocities and time-averaged bed shear stresses recommendations can be obtained for a minimum excavation depth of ecological sand extraction sites along the Dutch coast. Given a pre-extraction water depth and depth-averaged peak flow velocity, the minimum excavation depth resulting in time-averaged bed shear stresses of about 0.4 N m^{-2} in the bottom of the sand extraction site can be determined from figure 5. This figure gives minimal excavation depths (resulting in time-averaged bed shear stresses in the bottom of the pit of about 0.4 N m^{-2}) as a function of water depth for depth-averaged peak flow velocities of 0.55, 0.65 and 0.75 m s^{-1}. Given the extraction volume, the length and width of the ecological mining pit can be chosen subsequently.



Left panel: Data on infauna (biomass in g m^{-2}, number of species and dominant species), epifauna (biomass in g m^{-2}, number of species and dominant species), fish (biomass in g m^{-2}, number of species and dominant species), sediment (grain size in µm, volume percentage of fines) and extraction depth (0, 2, 8, 20, 24 m below the seabed). The red line is the estimated bed shear stress of the case studies 1: 20 m deep regions without sand extraction, 2: shallow sand extraction (2 m) near barrier island Terschelling, 3: intermediate deep sand extraction (8 m) in the turning basin of the Euromaasgeul shipping lane, 4: deep sand extraction (20 and 24 m).

Right panel: Calculated extraction depths needed to reach bed shear stress values of each case study (2 m: 0.41, 8 m: 0.17, 20 m: 0.08 and 24 m: 0.04 N m^{-2}), for areas with different depth averaged flow velocity (solid lines: 0.65, large-dash lines: 0.7, intermediate- dash lines: 0.75 and small dash lines: 0.8 m s^{-1}) and initial water depth at the x-axes (15, 25, 30, 35, 40 m).

With the design graph, the minimum excavation depth of can easily be determined. The total area of the mining pit can then be computed by dividing the required sand extraction volume by the excavation depth. From the total area of the sand extraction site, the length and width of the extraction site can be selected based on available space and restrictions.

- Step 1: Determine the water depth and depth averaged peak-flow velocity in the extraction area. Along the Dutch coast, the depth-average peak flow velocities (M2 velocity amplitudes) are between 0.55 and 0.75 m s^{-1} (Fig. 12 of Ecosystem-Based Design Rules for Sand Extraction Sites)
- Step 2: Determine the minimum excavation depth using the design graph.
- Step 3: Compute the surface area of the mining pit by dividing the required extraction volume by the determined sand extraction depth. From the total surface area of the sand extraction site, the length and width of the site can be selected based on available space and restrictions.

4. **Elaborate selected alternatives**.

- **>>** Optimize the design for an ecosystem-based landscaped sand extraction site

Using a combination of (field) data, process-based (model) data and ecological analyses, a prediction of macrozoobenthic and demersal fish assemblage distribution for a traditional sand extraction site design and an ecosystem-based landscaped sand extraction site can be made. The design of the ecosystem-based landscaped sand extraction site can iteratively be optimized.

- **>>** Determine construction costs for seabed landscaping of sand extraction pit

To assess the (additional) cost for ecosystem-based landscaping the contractors need to be consulted. They can provide information on:

- critical depth thresholds for sand extraction and costs per type of TSHD, as limitations to the maximum extraction depth;
- design boundary conditions for ecosystem-based sand extraction sites based on technical feasibility;
- unit cost for sand extraction or cost function per m^3 and sailing distance; the cost for the sand extraction works itself;
- additional cost for ecosystem-based sand extraction projects, like creating deep troughs or leaving shallow crests.

Practical Applications

Examples are:

- Gravel-seeding techniques to restore the seabed to pre-dredge conditions after gravel extraction in the English part of the North Sea (Cooper et al., 2011). Changes in bed shear stress values after sand extraction also the main drivers of ecological changes although not yet fully recognised. Optimisations in bed shear stress values, by fine-tuning extraction depths and orientations of the sand extraction sites with respect to the tidal current are possible (e.g. to prevent against sedimentation which may be harmful to hatching herring larvae on the gravelly seabed).
- Seine estuary cooperation between dredging and fishing industries (Desprez, 2000; Marchal et al., 2014). Optimisations in bed shear stress values, by fine-tuning extraction depths and orientations of the sand extraction sites with respect to the tidal current are possible.
- Maximum allowable changes in seabed level and bed shear stress values after sand extraction to maintain original macrozoobenthic characteristics (poster and oral sessions of Koen Degrendele and Dries van den Eynde at the ICES Annual Science Conference 2016) http://www.ices.dk/news-and-events/asc/ASC2016/Pages/Theme-session-K.aspx
- Maintenance dredging in river and estuarine systems (Yuill et al., 2016).
- Rijke riffen (van Duren et al., 2016), Building with North Sea Nature: eco-friendly scour protection (Lengkeek et al., 2017) and construction of artificial reefs in Japan (Thierry, 1988).
- Rejuvenation dredging of tidal creeks in a mangrove systems (Bonaire and Curaçao). Habitat requirements for mangroves and Ecological rehabilitation Lac Bay Mangroves, Bonaire

Specifically, more information on the lessons-learned from the Maasvlakte 2 practical example are given below, discussing a range of factor around the project planning, execution and evaluation

>> read more

Lessons Learned

During the project, new insights were gained concerning technical and ecological aspects of the design and the organisation of a large-scale and deep sand extraction project with ecosystem-based sand bars.

The project also generated a broad discussion amongst the various stakeholders on how changing physical conditions can trigger ecological development of new habitats.

The most important lesson learned is that seabed landscaping in sand extraction sites only makes sense if:

- the sand extraction volume and sand extraction site is large enough for landscaping to have added value;
- landscaping is indeed expected to yield added ecological value; and
- landscaping can be carried out during the extraction process without additional equipment mobilisation and with minimal hindrance to the production process. Overall, it became clear that it is still too early to prescribe or promote landscaping to other sand extraction projects, even if they meet the above described conditions. The seabed and assemblages are not yet in a stable state so the added ecological value remains to be proven.

Few of the other learned on project realisation are:

1. Take a joint approach involving all stakeholders, from initiator, consultant (technical) experts and contractor to permitting authority.
2. Make sure the decision to include ecosystem-based landscaping is taken early in the (design) process.
3. Use expert knowledge and numerical models to predict the behaviour of the bedforms in the sand extraction site to make sure that they are relatively stable and allow sufficient time for ecological development.
4. Make sure that there is enough space around the bedforms for the dredging equipment to manoeuvre.
5. The extraction depth influences the potential of the landscaped area. If the extraction is too deep, the effect of morphological landscaping may be dominated by the hydrodynamic effects of the deep pit (e.g. high sedimentation rate).
6. Discuss and investigate the potential of landscaping in a certain extraction area within the prevailing permit limitations before the design is made (input for design);
7. Ensure frequent updates of the bathymetry of the created bedforms, in order to be able to monitor their development and steer expectations among stakeholders. Morphological monitoring will enable evaluation of the design, predict the longevity and assess the effectiveness of reaching the original goals (e.g., increasing biodiversity or biomass).
8. Apply adaptive processes to the ecological monitoring strategy: tune next monitoring to developments found at previous efforts, while still maintaining consistency in data collection for good comparison objectives.

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