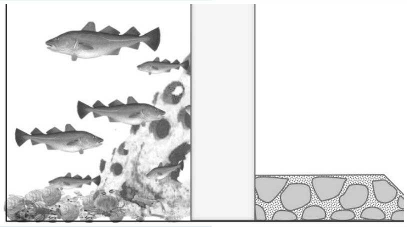
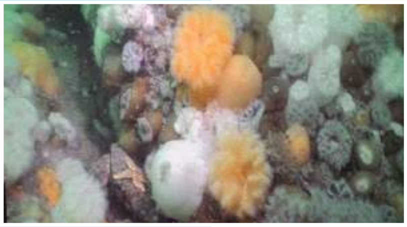
Eco-friendly design of scour protection: potential enhancement of ecological functioning in offshore wind farms

Towards an implementation guide and experimental set-up





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Preface

The Dutch national government has outlined several future scenarios and formulated policies regarding ‘Building with North Sea Nature’ and make use of artificial hard substrate in this context. The concept is implemented in the developments of offshore wind farms (OWFs) now that the plot decisions for planned wind farms include an obligation for the permit holder to design the wind farms with added values for nature: "*The licensee is committed to design the wind farm itself and to realize that park actively contributes to the strengthening of a healthy sea and strengthening of conservation and sustainable use of species and habitats that occur naturally in the Netherlands."*
The aim of this study is to implement ‘Building with North Sea Nature’ and provide a guide towards the eco-friendly design of scour protection structures around monopiles in planned wind farms to enhance native biodiversity.

The guidance committee consists of Edo Knegtering (Ministry of Economic Affairs), Waldo Broeksma (Rijkswaterstaat) and Maarten de Jong (Rijkswaterstaat).

Mark Collier, Tom van der Have (Bureau Waardenburg) Erwin Winter (Wageningen Marine Research) and Tinka Murk (Wageningen University - Marine Animal Ecology Group) contributed to this report. Luca van Duren (Deltares) was in charge of the internal review process.

The authors thank everyone who has contributed to this report.

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Summary

The aim of this study is to explore the possibilities to implement ‘Building with North Sea Nature’ in offshore infrastructures in the North Sea by providing guidelines for the eco-friendly design of scour protection structures around monopiles in planned wind farms to enhance ecological functioning.

The guidelines include specifications on:

- The type of hard substrate material or products available and how these can potentially enhance ecological functioning (and have added value compared to regular types used);
- How different types of hard substrates and configurations can be (experimentally) designed to vary spatially, in such a systematic manner that the effect on ecological enhancement can be determined empirically;
- How the effects of these scour protection structures can be monitored and evaluated;
- Whether site-specific conditions apply to wind planned farm locations in the Dutch North Sea.

Eco-friendly design in this study entails optimising the scour protection of offshore wind farms to enhance its ecological functioning. Enhancement of ecological functioning has been defined as: increasing habitat suitability for species (or communities) occurring naturally in the Dutch North Sea, in particular, for policy-relevant (from a conservation perspective) and endangered species, such as those listed in the EU Habitats Directive, OSPAR or national red lists (see Annex 2 in Bos *et al.* in prep.).

Where previous work has explored the more general possibility for enhancement of ecological functioning in offshore wind farms (van Duren *et al.* 2016; Smaal *et al.* in prep.), this study provides explicit steps towards realising an eco-friendly design of scour protection and a practical field experiment to allow for scientific evaluation.

From an analysis of physical conditions in the North Sea that influence both biodiversity and scouring mechanisms at wind farm locations, it is concluded that scour protection will be required in most, or all, future offshore wind farms on the Dutch Continental Shelf. It is also concluded that scour protection design could be altered to benefit the ecology, but that new designs will require additional testing for anti-scouring effects.

Based on a selection of policy-relevant species for the North Sea, two umbrella species were selected: Atlantic cod (*Gadus morhua*) and European flat oyster (*Ostrea edulis*). Focussing design variables and principles on these two umbrella species is expected to result in optimising the habitat for a wide range of native hard substrate biodiversity.

Based on existing data from current wind farm scour protection, other artificial hard substrates and natural hard substrates from the North Sea, it is hypothesized that an optimised design of scour protection will yield increased populations of umbrella species or increased native biodiversity in general, including policy-relevant species.

Based on available knowledge on ecological principles and expert judgement of North Sea hard substrate ecologists, four design variables for optimised scour protection are defined:

1. Adding larger structures than conventional scour protection to create large holes and crevices, to provide adequate shelter / holes for large mobile species.
2. Adding more small-scale structures than conventional scour protection to create more small-scale holes and crevices but also attachment substrate and settlement substrate.
3. Providing or mimicking natural (biogenic) chemical substrate properties to facilitate species. An example is to provide chalk-rich substrate such as concrete with added chalk, or even natural substrate such as shell material.
4. Active introduction of specimens of target species to enhance establishment of new populations. This is to facilitate recruitment at locations where reproduction by naturally occurring adults is absent or to scarce.

These design variables are made practically applicable by providing example materials and specifications for implementation in the field and, a cost overview is provided for example materials.

Combining the above information, this study provides design guidelines for wind farms with optimised scour protection to enhance ecological functioning. In addition it defines a minimum and a standardized approach for deployment and monitoring of a subset of locations to allow for scientific evaluation. The monitoring techniques that are required to do so, are described and a cost estimate for the monitoring is provided.

In conclusion, this study provides eco-friendly design principles for scour protection and a first experimental design to implement ‘Building with North Sea Nature’: ecological enhancement by optimising scour protection in offshore wind farms. This is considered as a first step in a process that should result in ‘learning by doing’.

1 Introduction

1.1 Background

The Dutch national government has outlined several future scenarios and formulated policy to initiate the combination of infrastructural projects in the North Sea with nature conservation, restoration or stimulation (Building with North Sea Nature). Amongst others, it is intended to make use of artificial hard substrate in this context (Ministry of Economic Affairs in 2014, Ministry of Infrastructure and the Environment and Ministry of Economic Affairs in 2014, 2015a and b).
The concept of ‘Building with North Sea Nature’ includes multi-user spatial collaboration in the North Sea where economic use is combined with enhancing ecological functioning. More specifically, the concept is implemented in the developments of offshore wind farms (OWFs) now that the plot decisions for planned wind farms include an obligation for the permit holder to design the wind farms with added values for nature: "*The licensee is committed to design the wind farm itself and to realize that park actively contributes to the strengthening of a healthy sea and strengthening of conservation and sustainable use of species and habitats that occur naturally in the Netherlands."* (e.g. Ministry of Economic Affairs in 2016). Specifically, for the North Sea, the latter could also be interpreted as strengthening the conservation and sustainable use of species and habitats that naturally occur in the Dutch North Sea.

1.1.1 Previous studies on hard substrate communities in the Dutch North Sea

Communities of hard substrate related species on existing scour protection of the first offshore wind farms are diverse (example OWEZ wind farm in Bouma & Lengkeek 2012). However, at the same time communities with higher biodiversity are observed on other types of artificial hard substrate elsewhere within the North Sea (Lengkeek *et al.* 2013b).

Although the construction of artificial reefs for the sole purpose of stimulating biodiversity or other natural values in the North Sea is subject to discussion (Wolff 1993), the concept of ‘Building with North Sea Nature’ is less controversial (Van Duren *et al.* 2016). Building with North Sea Nature in this context means that when a hard substrate is to be placed in a North Sea location for other purposes, e.g. for scour protection, the design can be modified in such a way that in addition to its primary protective function, it can enhance ecological functioning.

An exploratory study by Van Duren *et al.* (2016) “Rich Reefs” (Rijke riffen) includes opportunities for extensive (experimental) pilots and/or further research into the use of artificial hard substrates in the North Sea. This study describes the European flat oyster as a previously very abundant reef building species that has been lost from the North Sea. This species has therefore been identified as important for follow-up projects to try and restore this to the North Sea.

Smaal *et al.* in prep. have considered physical characteristics on a North Sea scale that are particularly important for the settlement and development of the flat oyster specifically in existing Dutch wind farms and planned Wind Farm Zones. This comprehensive study yields new insight into species specific habitat requirements, and identifies suitable wind farms. However, the project aim did not include project design guidelines or experimental designs.

To explore the possibilities to implement 'Building with North Sea Nature' in scour protection of planned wind farms in the North Sea (this study), information from the above studies was used.

1.1.2 Research in to enhancement of ecological functioning with scour protection

The question is whether wind farms that are to be constructed in the near future can be designed in such a way that the **scour protection** around monopiles:

a) Has properties that enhance ecological functioning, and
b) Can be designed and constructed to vary spatially in such a systematic manner that the relative effects of such variation on the enhancement of ecological functioning can be determined empirically.

Enhancement of ecological functioning specifically entails increasing habitat suitability for species (or communities) occurring naturally in the Dutch North Sea (Bos *et al.* in prep.), for example, endangered species that are listed in the EU Habitats Directive, OSPAR or national red lists (see Annex 2 in Bos *et al,* in prep.). In addition, the enhancement of non-indigenous species is assessed as undesirable.
Scour protection materials are classified as **hard substrate**. Before the 1900s, a substantial part of the North Sea seabed was covered by hard substrates and related native communities. The scour protection of wind farms, although not a natural structure, offers a possibility to regain habitat that is similar in function as previously lost hard substrate. It also may facilitate the return or enhancement of species and biogenic structures that have been lost or reduced to critical levels.
Systematic variation may include substrate type, configuration(s) (for example, a mix of large and small) or constructions along physical gradients in an offshore wind farm. The variation can be realised for example, between or within different wind farm plots.

1.2 Objective

The aim of this study is to explore the possibilities to implement 'Building with North Sea Nature' in offshore infrastructures in the North Sea, thereby providing guidelines for designing scour protection structures around monopiles in wind farms that will enhance ecological functioning.

The guidelines include specifications on:

- The type of hard substrate material or products available and how these can potentially enhance ecological functioning (and have added value compared to regular types used);
- How different types of hard substrates and configurations can be (experimentally) designed to vary spatially, in such a systematic manner that the effect on ecological enhancement can be determined empirically;
- How the effects of these scour protection structures can be monitored and evaluated;
- Whether site-specific conditions apply to planned wind farm locations in the Dutch North Sea.

Main research questions

In order to implement ‘Building with North Sea Nature’ in offshore infrastructures in the North Sea and, specifically the development of scour protection in planned wind farms in the Dutch North Sea, the main research questions are:

What are possible options and experimental designs for hard substrate in scour protection structures around monopiles that:

1. Enhance ecological values;
2. Allow for empirical determination of the relative additional effects of the hard substrate types and/or configurations.

1.2.1 Research questions

To answer the main research questions, eight sub-questions have been formulated:

(A) What are possible “independent variables” when systematically varying hard substrate-related factors (e.g. type, hard substrate configuration(s), (alternation between large and small fractions) or gradients in relation to site-specific physical factors)? Variation may apply to variation between plots or within plots.

(B) Which cost-effective types of hard substrate materials – readily, commercially available or custom made – can be selected, based on their potential to enhance ecological functioning while at the same time meeting the technical requirements for scour protection in a wind farm? What are associated costs?

(C) What species (and communities) naturally occurring in the Dutch North Sea could benefit from applying hard substrate types or configurations (see B)? Special attention will be given to benthos and fish and preferably endangered species or species with negative trends, for example species listed on the Annexes of the EU Habitats Directive, OSPAR or red lists (see Bos *et al.* in prep.).

(D) What is the potential risk of additional establishment or spread of non-indigenous species due to the hard substrate types, or configurations (see B)?

(E) What experimental design allows for spatially varying hard substrate types or configurations in such a systematic manner that the relative effects of this variation (independent variables, see A) on the enhancement of ecological functioning can be empirically determined?

(F) What is a possible, and cost-effective, monitoring program (frequencies, monitoring method, method of sampling and identification, measured variables, duration of monitoring programme to determine the ecology enhancement effects (C) or risk of (invasive) non-indigenous species establishment (D)?

(G) What analysis techniques can potentially be used to process measured variables (e.g. statistical testing)?

(H) What are the possible opportunities, limitations or constraints in responding to the above sub-questions when consideration is given to the specific wind farm locations and the existing habitat conditions?

1.3 Outline

Chapter 2 begins with a brief description of the methods and processes.
Part I entails guidelines for eco-friendly design of scour protection in planned wind farms, including design principles and recommendations for an experimental design (Chapter 3) and monitoring (Chapter 4) and a synthesis with recommendations (Chapter 5)
In Part II, background information and justification is provided. This part introduces ecological principles and habitat requirements of species (Chapter 6), physical conditions in wind farms and technical background on scour protection (Chapter 7) and provides information on potential output of eco-friendly scour protection, including “added value” for native species compared to regular scour protection types and risks of enhancing alien species (Chapter 8). A synthesis is provided in Chapter 9. Part II provides detailed information used as input for Part I.

2 Materials and methods

2.1 Knowledge base and definitions

Information in this report is based on information made available through:

- Monitoring of North Sea wind farms (OWEZ, PAWF)
- Rijke Riffen project (van Duren *et al.* 2016)
- WOZEP report (Jak & Glorius in prep.)
- Habitateisen platte oester report (Smaal *et al.* in prep.)
- North Sea species list, including the policy status of individual species (Bos *et al.* in prep.)

This information has been integrated in a “knowledge base” and complemented with:

1. (inter-)national scientific literature
2. Reports (“grey literature”) of offshore wind farm designs.
3. North Sea data (§2.2)
4. Personal observations during North Sea dives carried out by several of the authors.

Definitions of terms

The following terms and abbreviations are used throughout this report:
Target species: specific target species of action or measure
Focal species: species of interest and / or study
Umbrella species: species selected to represent the need of a group of other species
Policy-relevant species: species listed in Annex II of Bos *et al.* in prep.
OWEZ: Offshore Wind farm Egmond aan Zee
PAWF: Prinses Amalia Wind Farm
WEG: Wind Energie Gebied
WFZ: Wind Farm Zone
WOZEP: Wind op Zee Ecologisch Programma
DCS: Dutch Continental Shelf

2.2 Ecology on currently used scour protection

To evaluate the potential benthic biodiversity on the scour protection in Dutch wind farms, datasets available from the OWEZ (Bouma and Lengkeek 2008; Bouma and Lengkeek 2012), PAWF (Vanagt *et al.* 2013; Vanagt and Faasse 2014), Horns Rev 1 wind farm (Leonhard & Pedersen, 2005) monitoring as well as species inventories of the Cleaver Bank by van Moorsel (2003) and Grontmij | AquaSense (unpublished data 2015) and an inventory of 10 shipwrecks (Lengkeek *et al.* 2013b) were used. All these datasets contain epifouling community data obtained from samples on rocks at the seabed or from steel and wooden structures at ship wrecks. The Cleaver bank surveys were included to evaluate the benthic diversity on wind farm scour protection in comparison with a natural reef. The shipwreck dataset was included to evaluate the long-term colonisation potential as well as to include data from a larger area of the Dutch North Sea.

The datasets were combined and all taxonomic records were updated using the World Register of Marine Species (WoRMS Editorial Board 2016) as reference of taxonomic nomenclature.

2.3 Experimental basics

This study provides basic and practical ingredients for ‘Building with North Sea Nature’ that could be used in planned offshore wind projects. To date, however, this has not been brought into practice in the Dutch North Sea, empirical knowledge on what works and what doesn’t work is absent, so the aim in planned wind projects is to start learning by doing. To facilitate the learning process, this study also provides an experimental design to allow for evaluation of effectiveness of proposed methods for enhancement of ecological functioning.

Chapter 6 and 7 provide details on experimental design, monitoring and analysis. This was elaborated in the workshop and complemented with expert knowledge. The ingredients include:

- Materials to be tested
- Experimental design (locations, treatments, replica’s)
- Variables to be measured
- Monitoring techniques
- Analysis
- Costs

2.4 Workshop

During an expert meeting (16 January 2017 at Deltares, Delft, NL), the guidance committee and 10 experts discussed the following topics:

- Scope of the study, regulation 2.15 and other legislation
- Technical requirements of scour protection in wind farms
- How to select focal species and subsequently define goals, target species and their habitat requirements
- Categorising available materials

2.5 Scope of the study, regulation 2.15 and other legislation

The study includes scour protection around monopiles and passive enhancement of ecological functions only.

Regulation 2.15 that is included in the plot decisions is stated as "*The permit holder must make demonstrable efforts to design and build the wind farm in such a way that it actively enhances the sea's ecosystem, helping to foster conservation efforts and goals relating to sustainable use of species and habitats that occur naturally in the Netherlands. Extra installations are not allowed and facilities must be directly related to the to be installed wind turbines. In this respect the company is required to create an action plan, to be delivered to the Ministry of Economic Affairs no later than 8 weeks before the commencement of construction. Construction work must adhere to this action plan"*. A random mixture of artificial structures is not desirable under current legislation and no installations may remain after the operating phase. A permit (Water Act permit) may be obliged for installations outside the scour protection zone potentially involving extra time / money costs for the operator, which may not be desirable. The Dutch government oversees planning, managing and licensing the sea floor between the turbines.

2.6 Technical design principles

Technical requirements are elaborated in §7.3, a few basic design principles:

- There is a difference in required scour protection layer thickness and armour rock size based on storm-induced wave loads on the scour protection in the North Sea basin and the dimensions and shapes of the wind turbine support structures;
- The horizontal extent of the scour protection typically scales with the monopile diameter;
- For the Dutch North Sea, the basic approach is a filter layer and an armour layer, made of natural crushed rock material (mostly Norwegian granite), so this should be observed as a baseline when valuing "added values";
- Bed protection is needed on (the ever-increasing number) cable crossings as well, but the current study will focus on scour protection around monopiles;
- Any innovative scour protection, or large "add-on" structures, should be tested in the lab for failures and be approved by a certifying body, before they can be applied in the field, as they can either become unstable themselves or cause neighbouring scour protection materials to become unstable under hydraulic design conditions. Mixing in <5% of other material in a standard scour lay-out is a potentially feasible option that can be tested in the field on the short term.
- Costs are lowest for materials that can be mixed in.

2.7 Focal species selection

A pre-selected short list (§3.1) was discussed. Experts highlighted three main topics:

1. There is a lack of information on habitat requirements of individual (focal) species and therefore the grouping of species or selection of umbrella species is required.
2. The focus should be on policy-relevant focal species that are native and under pressure. However, the enhancement of a particular focal species may contribute to the overall native biodiversity. Conservation of native biodiversity is an important overarching management goal on a national scale. The government supports the conservation and sustainable exploitation of biodiversity at both national and international level (e.g. via Natural Capital Implementation Agenda and international biodiversity agreements such as the Convention on Biological Diversity (CBD) and the European Birds Directive and Habitats Directive.) Therefore, ‘overall native biodiversity’ and ‘number of policy-relevant species’ are defined as additional (to focal species groups) desired output parameters. Selecting focal species will provide knowledge to take targeted remedial measures. The pilot may test materials that are predicted to contribute significantly to the species.
3. Umbrella species (focal species that are good representatives for certain habitat requirements) can be selected for their keystone function (e.g. creating habitat for other species on the short list) or habitat requirements that overlap with those of many other species on the short list. Furthermore, a need for easy monitoring of the focal species was considered an important criterion for selection.

These principles have been elaborated in Chapter 3.

2.8 Categorising materials

In the workshop, it was determined that different materials have collective properties and can serve the same ecological function. Whilst using natural materials (rocks and boulders) is often suggested to be preferable over man-made structures, within specific categories there are no data yet available to suggest one specific material is better than any other. Therefore, rather than providing a design with specific materials it is preferable to provide a design based on ecological principles, that can be realised by using different types of materials. To facilitate this, different materials are categorised into groups allowing for the integration of ecological principles in a design of scour protection materials.

PART I Design guidelines, experimental design and monitoring

3 Design principles and experimental design

We provide recommendations to implement ‘eco-friendly’ design variables for scour protection in a planned wind farm. **The largest positive effect possible will be obtained when the design variables are implemented to all turbine locations in the wind farm that are suitable.**

Objective of a first experimental design
The objective of this first experimental design for an ‘eco-friendly scour protection’ is two-fold:

1. To provide design principles for a more optimised scour protection in a new wind farm based on the best available knowledge to date and expert judgement of North Sea-ecology experts;
2. To allow for adequate monitoring and evaluation of the effect of this first experimental design, to increase the available knowledge for future wind farm developments.

Based on the workshop (§2.4 and species selection (Chapter 8) two umbrella species were selected: Atlantic cod and European flat oyster. An optimised design for these species is expected to result in optimised design for biodiversity of native species and number of policy-relevant species (e.g. maximize the number of occurring native species). Additionally, the enhancement of alien species should be avoided.

Based on existing data from current wind farm scour protection, other artificial hard substrates and natural hard substrates from the North Sea, a prediction is made that an optimised design of scour protection may yield increased populations of umbrella species and increased native biodiversity in general.

3.1 Design principles

Based on the relevant ecological principles (§ 6.3) and selection of focal umbrella species (chapter 6 and § 2.4), four types of design principles are proposed for ‘eco-friendly design of scour protection’ that could readily be incorporate into the design of planned wind farms:

1. Adding larger structures than conventional scour protection to create large holes and crevices, to provide adequate shelter / holes for large mobile species. I.e. to create more habitat complexity on a large scale. Size of holes or crevices should be 1-2 metres diameter or more. This treatment may improve the habitat of large mobile species such as the umbrella species Atlantic cod. Many other species may benefit from this treatment (§5.4).
2. Adding more small-scale structures than conventional scour protection to create more small-scale holes and crevices but also attachment substrate and settlement substrate; i.e. to create more habitat complexity on a small scale.

Size of holes and crevices should be a few centimetres-decimetres. This treatment may improve the habitat of egg-, larvae- or juvenile stages of many species, such as umbrella species Atlantic cod, or other species such as queen scallop or species of squid. It is also expected to improve habitat quality for small species (including adult stage), such as the rock gunnel and the shore clingfish.

3. <u>Providing or mimicking natural (biogenic) chemical substrate properties</u> to facilitate species. An example is to provide chalk-rich substrate such as concrete with added chalk, or even natural substrate such as shell material. This treatment may facilitate the settlement of specific target species that seek known- or unknown chemical cues that are normally associated with their natural settlement substrate. Larvae of the European flat oyster, for instance, are known to settle better on chalk-rich substrates such as empty shells of oysters or mussels. Because many chemical cues may still be unknown, it is preferred to provide natural substrates over mimics where possible.
4. <u>Active introduction of specimens of target species</u> to enhance establishment of new populations. This is to facilitate recruitment at locations where reproduction by naturally occurring adults is absent or to scarce. An example is to actively introduce a small population of adult European flat oysters of different sizes to provide a larvae source on a location where that is absent in the current situation. Dispersal of flat oyster larvae is limited due to a relatively short pelagic phase (Smaal *et al.* 2015; in prep.). This treatment may facilitate the establishment of populations in areas beyond the reach of natural recruitment in the current situation.

N.B.1 Durability

It is important to consider the durability of provided habitat characteristics. For example, relevant for principle 2, when small-scale habitat complexity is provided close to the sandy bottom, it may trap sand that can fill up the holes and cervices. When this happens the provided habitat characteristics are lost. A more adequate design will be to provide small-scale complexity on locations where it can be expected to trap less sand (i.e. on dynamic locations, or location further away from the sandy bottom). A way to attain this goal is to place larger elements (such as boulders) on a (specifically for this purpose extended) filter layer. This will prevent sinking of the large boulders into the seabed. If the right orientation with respect to the monopile is chosen, then also the risk of sedimentation due to upstream sediment supply can be minimized. Also, large boulders installed closer to the monopile would experience less sedimentation in the pores between the boulders, because of higher flow and turbulence levels in this area. Durability of attempted habitat characteristics should be assessed for every design.

N.B. 2 Stability

In §3.3 it is motivated that the stability of the habitat is important for slower growing species. For example, slow growing species such as sponges or oysters may be damaged when they grow on a rock that is rolled over in a storm. This factor is not separately taken into the experimental design, because this effect is already known. It should be considered that stable substrates should be preferred over less stable substrates. This would advocate longer extents of scour protection with increased stability because the stability of substrates will increase with increasing distance from the monopile.

N.B. 3 Placement options within scour protection zone of a single monopile.
As described in chapter 4, current speed and bed shear stress are affected by the placement of a monopile and the scour protection layers. Close to the piles currents are generally stronger. Therefore, in designing the eco-friendly scour protection it is important to focus mostly on the outer edges of the scour protection bed. This does not only enhance potential for ecology due to less extreme conditions, it also aids in avoiding the lines attached to the pile and will therefore be a more interesting design choice for wind farm operators. However, an optimal balance needs to be found with habitat durability without the substrate getting covered by sand and tolerable conditions with respect to bed shear stress. This would advocate increasing the diameter of the monopile.

N.B. 4 Gravel in conventional scour
Gravel beds are included in conventional scour protection and the filter layer extends beyond the armour layer in all Dutch wind farm designs.

N.B. 5 Testing new designs
Scour protection design can be altered to the benefit of ecology, but new designs will require additional testing for anti-scouring effects (Chapter 7).

3.2 Potential materials

Table 3.1 presents an inventory of materials that can potentially be used in wind farms to increase habitat suitability of scour protection. Some material may be considered as an alternative to conventional scour protection. Other materials cannot function as scour protection and should be considered as an add-on to scour protection. This is not by any means an exhaustive inventory.

Based on the workshop (§2.4.4) a subdivision of materials is provided (Table 3.1; Figure 3.1). Larger structures (Category 2) are potentially suited to enhance umbrella species Atlantic cod, whilst Category 4 materials potentially enhance European flat oyster (Figure 3.2). For ‘overall native biodiversity’ or ‘number of policy-relevant species’ Categories 2-4 are potentially suitable.

Table 3.1 Materials used and potentially suited for scour protection. Sources: 1.Lindquist & Cessna 2.http://www.nappex.fr/en/ecological-solutions/biohut/ 3. http://www.xbloc.com/ 4 Peters & Werth 2012 5. TU Delft 6. EDF.com 7. N.B. the order of the materials in this table is random and does not indicate any form of prioritising or preference.

	Materials
Category 1: Conventional scour protection material	
1	Boulders
2	Gravel
Category 2: Large structures providing holes	
3	Concrete with holes
4	Reef hives / Reef balls
5	Xbloks
6	Prefab collar
7	SeaCult Reef system
8	Biodegradable concrete reefs
9	3d printed concrete reefs
10	SubCon Artificial reefs
11	Econcrete
12	Drainage pipes
Category 3: Smaller-scale structures providing fine habitat complexity	
13	Oyster Catcher
14	Biohut
15	Fibre mesh enclosed stone bundles
Category 4: Materials that provide or mimic natural (biogenic chemical substrates	
16	Shell material loose
17	Shell material in bags
18	Oyster cages with live oysters
19	Biorock
20	BESE-elements
Category 5: Materials without added value and / or contain harmful substances (plastics)	
21	Scour mats
22	Geotextile containers
23	Rubber mat
24	Synthetic sea fronds/ seaweed matrasses


1


2


3


4


5


6


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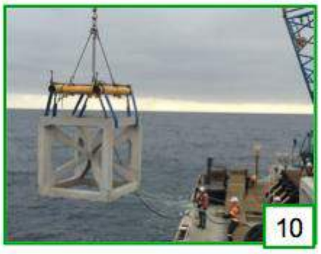
8/9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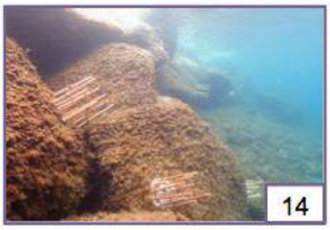
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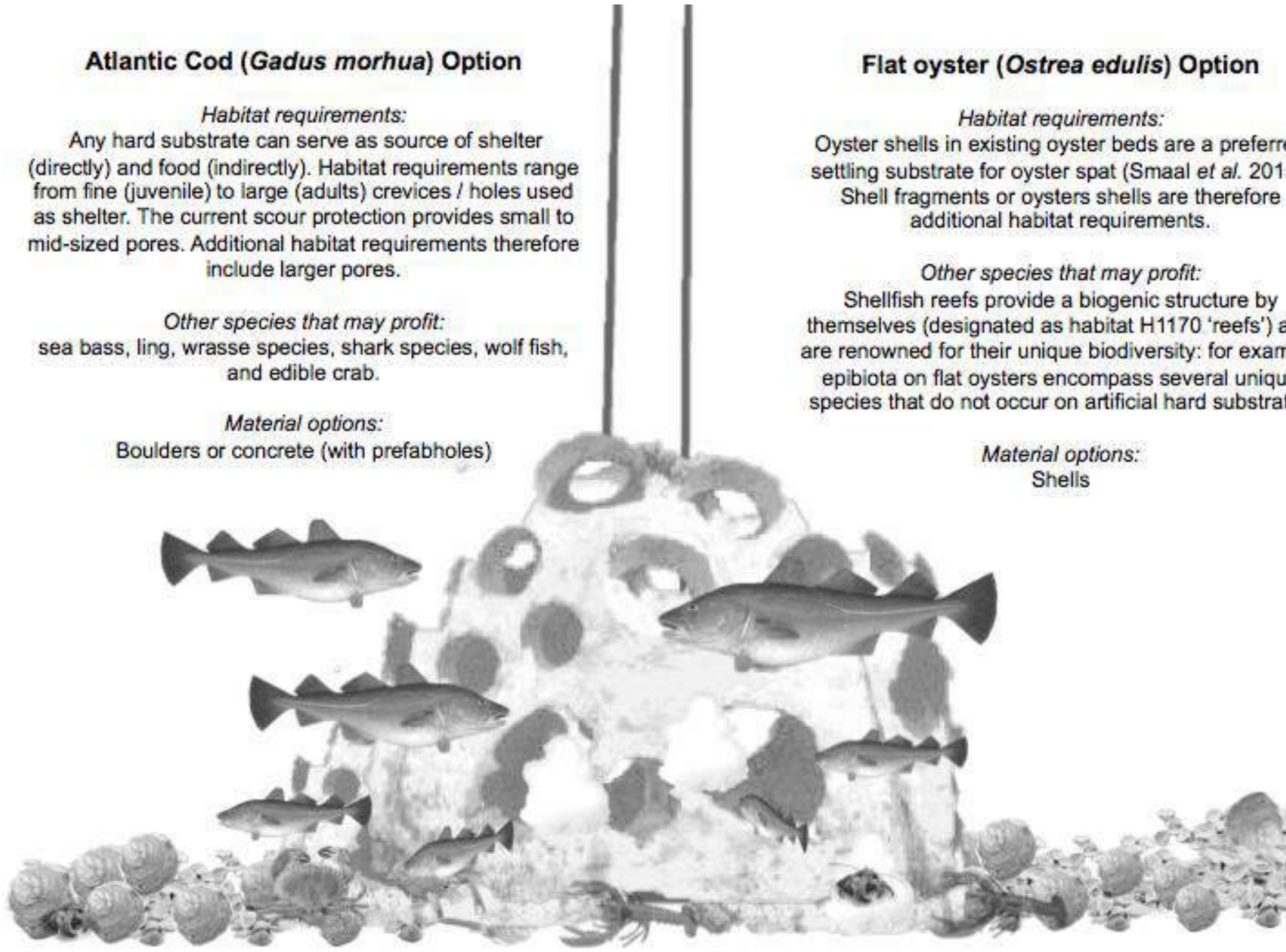
Figure 3.1. List of potential materials (picture number corresponds to numbers in Table 6.1).



Atlantic Cod (*Gadus morhua*) Option

Habitat requirements:
Any hard substrate can serve as source of shelter (directly) and food (indirectly). Habitat requirements range from fine (juvenile) to large (adults) crevices / holes used as shelter. The current scour protection provides small to mid-sized pores. Additional habitat requirements therefore include larger pores.

Other species that may profit:
sea bass, ling, wrasse species, shark species, wolf fish, and edible crab.

Material options:
Boulders or concrete (with prefabholes)

Flat oyster (*Ostrea edulis*) Option

Habitat requirements:
Oyster shells in existing oyster beds are a preferr
settling substrate for oyster spat (Smaal *et al.* 201
Shell fragments or oysters shells are therefore
additional habitat requirements.

Other species that may profit:
Shellfish reefs provide a biogenic structure by
themselves (designated as habitat H1170 'reefs') a
are renowned for their unique biodiversity: for exam
epibiota on flat oysters encompass several uniqu
species that do not occur on artificial hard substrat

Material options:
Shells

Figure 3.2 Materials and umbrella species, illustration of habitat requirements (Source: Bureau Waardenburg).

3.3 Location criteria

From an analysis of physical conditions in the North Sea that influence both biodiversity and scouring mechanisms at wind farm locations (chapter 7) it is concluded that scour protection will be required in most, or all, future offshore wind farms on the Dutch Continental Shelf.

WFZ Borssele has the highest sand waves of all locations, which needs to be taken into account especially when considering scour protection. For ecology, the importance of these sand waves is unclear (Van Duren *et al.* 2016). The sand waves at WFZ Borssele migrate up to a few metres per year, but based on detailed knowledge of the Borssele morphodynamics (Deltares 2016; in prep.) locations can be selected that are most stable and will experience limited seabed level changes.

Smaal *et al.* (in prep.) studied the suitability of existing and planned wind farms for the settlement, growth and sustainability of European flat oyster populations in the Dutch part of the North Sea. The suitability was assessed by combining information on bottom shear stress, sediment composition, suspended inorganic sediment, recruitment opportunity and historical situation. They concluded that the wind farm locations Zee-energie and Buitengaats (in the Wind Farm Zone “Ten noorden van de Waddeneilanden”), Wind Farm Luchterduinen and the Wind Farm Zone Borssele are suitable for the development of flat oyster beds. It is recommended to carry out further pilot studies for empirical testing of the assumptions and to reduce the uncertainties.

3.4 Recommended experimental design for monitoring and evaluation

The largest positive effect possible will be obtained when the design variables are implemented to all turbine locations in the wind farm that are suitable. Monitoring of a larger than necessary number of turbine locations, however, may be undesirable from a cost perspective. For a good scientific result, possibly not all turbine locations need to be monitored in detail. Adequate scientific analysis of results will be possible so long as a certain minimum and standardized effort is maintained. A design for a minimal and standardized approach is:

- One treatment should be placed at one wind turbine; treatments should not be mixed at this stage (Figure 3.4). This may however be interesting in experiments at a later stage.
- The configuration of treatments should be adjusted to the final wind farm design. Treatments should be located in areas that are suggested to be suitable for ecological developments and not too dynamic (§3.3 and Chapter 7) and to the specific physical requirements of certain species should be integrated in the experimental design.

- Treatments should have a certain minimal size, to be able to attract target species (Figure 3.3).
    - Treatment 1, adding larger structures, should entail a minimum area of 10 metres diameter, approximately 1-3 metres* high.
    - Treatment 2, adding more small-scale structures, should entail a minimum area of 10 metres diameter. A thin layer (few dm) on top of other scour protection should be sufficient.
    - Treatment 3, providing or mimicking natural (biogenic) chemical substrate properties, should entail a minimum area of 10 metres diameter. A thin layer (few dm) on top of other scour protection should be sufficient.
    - Treatment 4, active introduction of specimens of target species, should entail a cage or several cages with at least 1000 flat oysters and sufficient quantity of fresh shell material. It is important to include all relevant age classes ranging from 1-3 year old, which function exclusively as males, to 4-8 years old potentially functioning as females. The larval output should be at least 50 individuals per m^3 directly above the settling substrate in the experimental site (Smaal *et al.* in prep.).
    - Treatment 5, control treatment, one of the objectives of this first experimental design is to test for the effect of optimised scour protection. To facilitate this, results of optimised design treatments should be directly compared to a 'control' situation, which consists of conventional scour protection.
- A minimum number of replicas has been chosen, to allow for adequate statistical analysis but achieve cost-effectiveness as much as possible: recommended number of replicas N=4.
- 5 separate treatments x 4 replicas give 20 experimental units equal to 20 wind turbine locations (of which 4 are control and therefore not manipulated) (Figure 3.4).
- This approach with only separate treatments will not result in a full factorial design in which treatments are also combined / crossed. A full factorial design, or a fractional factorial design (in which some treatments are crossed) may be recommended at a later stage when the results of this experiment can be used for designing later phases. For now, the most cost-effective and feasible approach is to start with separate treatments only and learn what the individual treatments do.

**Conventional scour protection includes boulders with a maximum size of 70 cm, it is feasible to use these on the short term. Larger structures (1-3 metres), with larger pores will potentially be more suited for enhancement of ecological functioning. However, these materials or application of a thicker armour layer should be tested in laboratory settings first.*

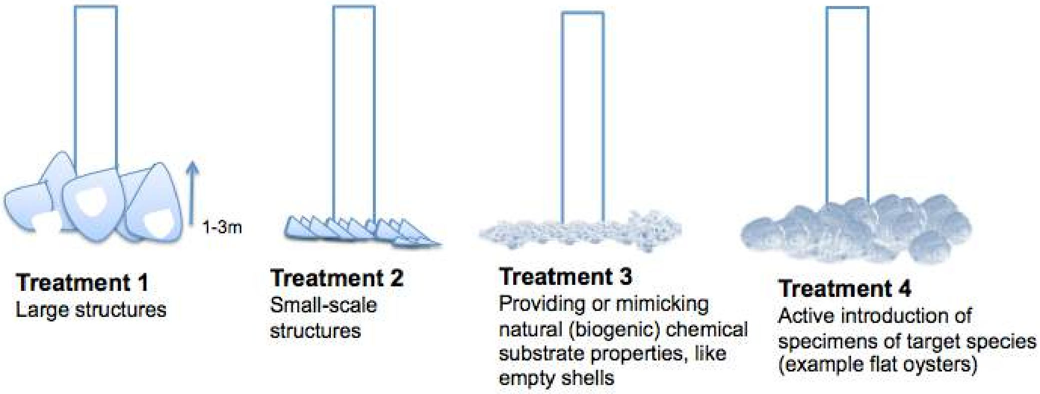


Figure 3.3. Recommended experimental design: Side view of potential treatments.

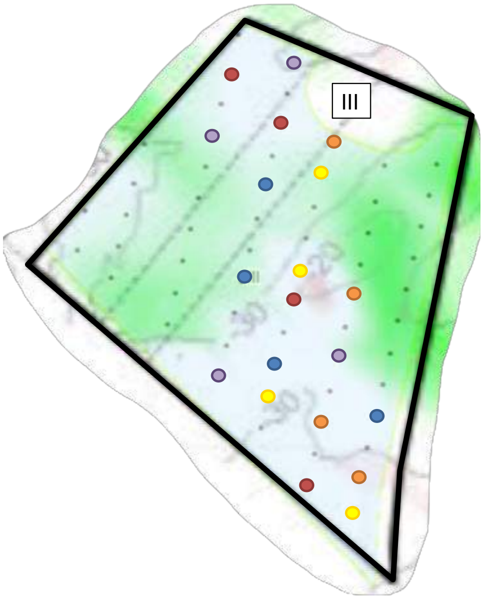


Figure 3.4. Illustration of recommended Experimental Design: Hypothetical randomisation of treatments in hypothetical placement of monopiles in Borssele zone (III). Each colour represents a different treatment, including the “control” treatment. Experimental and / or monitoring locations should be selected in areas with low migration speed of sand waves (Figure 7.4).

3.5 Some cost estimates of example materials

Costs indications of some potential example materials for different treatments are listed in Table 3.3.

Table 3.3 Cost indications of some (potential) example materials for the different treatments. Information based on experience from previous deployment and interviews with suppliers. This list of examples provides an indication of possible costs. It is not in any form a recommendation of these specific materials over others. Mentioning, or not mentioning materials here does not indicate a preference.

Treatment	**Example material**	**Size indication**	**Price 1 pc (euro)**	**Amount per monopile**	**Amount 4 replicas**	**Costs per monopile exc. placement (euro)**	**Total costs exc. placement (euro)**
1. Adding large structures	Reef balls / hyves	2m ⦸	1,000	50	200	50,000	200,000
	Xblock	2,3m ⦸ ($4m^3$)	800	50	200	40,000	160,000
	Large boulders	?	?	?	?		
2. Adding small structures	Smallest possible fraction conventional scour gravel	-	-	-	-	-	No cost additional to conventional scour
	BESE-elements mixed through conventional scour	-	4	500	2,000	2,000	8,000
3. Chemical properties	Empty mussel or oyster shells	1 m^3 units	20-100	50	200	1,000-5,000	4,000-20,000
4. Active reintroduction	Iron cages with oysters (1000 live + empty shell)	2 m^3	4,000	5	20	20,000	80,000
5. Control	-	-	-	-	-	-	No additional costs

4 Monitoring and analysis

4.1 Monitoring techniques

Potential monitoring techniques are listed in Table 4.1

Table 4.1. Summary of potential survey and monitoring methods for scour protection structures in offshore wind farms (partially based on Saunders et al. 2011; Jak & Glorius in prep.). Numbers in superscript correspond with the following references 1. Pearce et al. 2014; 2. Bos et al. 2014; 3. Coolen et al. 2015; 4. Lengkeek et al. 2010; 5. Vander Stap et al. 2016; 6. Coates et al. 2016; 7. Bergman et al. 2015; 8. Leonhard & Pedersen 2006; 9. Zintzen et al. 2006; 10. Coolen et al. 2017; 11. Bouma & Lengkeek 2012; 12. Vanagt & Faasse 2014; 13. Vandendriessche et al. 2013; 14. Vandendriessche et al. 2015; 15. Bergman et al. 2012; 16. Unpublished North Sea data Lengkeek & Coolen; 17. Griffin et al. 2016.

Method	Metric	Equipment required	Survey design	Suggested monitoring interval	Analyses of change	Applied in North Sea?	Comments
Acoustic survey	Substrate distribution Habitat/ community distribution	Acoustic ground discrimination systems (AGDS), side scan sonar Multibeam	Overlapping parallel tracks	One pre-installation then every 2-5 years.	Visual comparison of seabed maps, GIS spatial analysis	YES	May not be necessary if more frequent monitoring methods indicate no direct substrate or bathymetric modifications
Drop-down video/ photography	Distribution of habitat/ community/ biotope	Drop-down imaging system	Grid arrangement, Random sampling, stratified random sampling, transect sampling	One pre-installation then annually	Chi-square or Wilcoxon signed rank test comparison of biotope composition of site Simple visual comparison of biotope frequency data	YES	Fastest flowing or most turbulent and vertical rock habitats may be under-recorded
	Presence of specified species	Drop-down imaging system	Random sampling, stratified random sampling, transect sampling	One pre-installation then annually	Comparison of proportional occurrence		
	Maintained presence of priority species at specific locations	Drop-down imaging system	Directed visual sampling	One pre-installation then annually	Simple confirmation of presence		Note that the failure to detect a species in the sampling programme does not mean that the species is absent.
ROV video/ photography	As for drop-down video	Remotely Operated Vehicle (ROV)	As for drop-down video	As for drop-down video	As for drop-down video	YES	As for drop-down video

Method	Metric	Equipment required	Survey design	Suggested monitoring interval	Analyses of change	Applied in North Sea?	Comments
Grab or core sampling	Species abundance per unit area Species richness Diversity indices	Van Veen grab Day grab Hamon grab box corer	Grid arrangement, Random sampling, stratified random sampling, transect sampling	Annually, but at least two at pre-installation to establish natural variability	ANOVA, GLM(M), GAM(M)	YES	Note that the Hamon grab is the least reliable for quantitative recovery, but is most reliable for recovery of recover coarse sediments.
	Community composition	Van Veen grab Day grab Hamon grab box corer	Grid arrangement, Random sampling, stratified random sampling, transect sampling	Annually, but at least two at pre-installation to establish natural variability	Ordination (MDS, PCA) ANOSIM		
Diver core sampling	Species abundance per unit area Species richness Diversity indices	SCUBA, diver-deployed cores (HAPS, GHAP)	Random sampling, stratified random sampling, transect sampling	Annually, but at least two at pre-installation to establish natural variability	ANOVA, GLM(M), GAM(M)	YES	
	Community composition	SCUBA, diver-deployed cores (HAPS, GHAP)	Grid arrangement, Random sampling, stratified random sampling, transect sampling	Annually, but at least two at pre-installation to establish natural variability	Ordination (MDS, PCA) ANOSIM		
Diver video/ photo-graphy	Broad community character and substrate condition	SCUBA, underwater video or stills camera	Location directed	One pre-installation, then every 3-6 months (or syn-chronise with other diving tasks)	Simple visual comparison	YES	Should target locations where physical damage is expected
Diver transects (visual survey)	Semi-quantitative species abundance (MNCR Phase 2 surveys) Biotope presence and distribution	SCUBA (under-water video or stills camera optional)	Transects, stratified random sampling, directed ‘spot dives’	One pre-installation, then a minimum of two per year	Direct comparison of community attributes (semi-quantitative abundance, biotope presence	YES	Can be combined with video or photographic documentation. Sample times should be selected to correspond to periods of maximum species presence i.e. avoid times when some species may be inactive, dormant or undergoing die-back

Method	Metric	Equipment required	Survey design	Suggested monitoring interval	Analyses of change	Applied in North Sea?	Comments
Diver quadrats	Species abundance (individual abundance or % cover)	SCUBA, quadrat,	Replicated samples from plots arranged along transects	At least one pre-installation, then a minimum of two per year	Ordination (MDS) ANOSIM, SIMPER	NO	Size of quadrat dependant largest species present (see section 15.4 Saunders *et al.* 2011)
	Species richness/ diversity	SCUBA, quadrat	Replicated samples from plots arranged along transects	At least one pre-installation, then a minimum of two per year	ANOVA, GLM(M), GAM(M)		
	Abundance of selected conspicuous species	SCUBA, quadrat	Replicated samples from plots arranged along transects	At least one pre-installation, then a minimum of two per year	ANOVA, GLM(M), GAM(M)		
Airlift sampling	Species abundance per unit area Species richness Diversity indices	SCUBA or Surface Supplied Equipment (SSE) diving, diver operated airlift sampler	Grid arrangement, Random sampling, stratified random sampling, transect sampling	Annually after installations		YES	High volumes of air required for airlift, preferably carried out using SSE
	Community composition	SCUBA or SSE, diver operated airlift sampler	Grid arrangement, Random sampling, stratified random sampling, transect sampling	Annually after installations			
Net scrape sampling	As for Airlift sampling	SCUBA, scraper and collection net	As for Airlift sampling	As for Airlift sampling	As for Airlift sampling	YES	
Shrimp trawl	Species abundance and weight per unit area Species richness Diversity indices	Shrimp trawl net	Grid arrangement, Random sampling, stratified random sampling, transect sampling	One pre-installation then annually	ANOVA, GLM(M), GAM(M)	YES	Large area covered with single haul
	Community composition	Shrimp trawl net	Grid arrangement, Random sampling, stratified random sampling, transect sampling	One pre-installation then annually	Ordination (MDS, PCA) ANOSIM		

Method	Metric	Equipment required	Survey design	Suggested monitoring interval	Analyses of change	Applied in North Sea?	Comments
Triple-D dredge	Species abundance and weight per unit area Species richness Diversity indices		Grid arrangement, Random sampling, stratified random sampling, transect sampling	One pre-installation then annually	ANOVA, GLM(M), GAM(M)	YES	Large area covered with single haul
	Community composition		Grid arrangement, Random sampling, stratified random sampling, transect sampling	One pre-installation then annually	Ordination (MDS, PCA) ANOSIM		
Baited Remote Under water Video (BRUV)	Presence/ absence large mobile species	BRUV system	Random sampling, stratified random sampling, transect sampling	One pre-installation then annually	Comparison of proportional occurrence	YES	Proof of concept is available from Irish Sea study

4.2 Recommended monitoring & analysis

4.2.1 Atlantic cod abundance.

To assess whether Atlantic cod abundance increases on scour protections with changed structures, monitoring using remote non-destructive techniques is advised. Baited Remote Underwater Video (BRUV) setups can be used to quantify the amount of Atlantic cod utilising the structures. BRUVs are composed of (multiple) under water video camera(s) attached to a frame that is either placed on the seabed by divers or lowered to the seabed from ships. Directly in front of the camera, bait is placed on a bait pile to attract predators. Bait can be composed of herring, pilchards, mackerel, lugworm, and mixed fish scraps or pre-mixed bait pellets (Roberts *et al.* 2016). By deploying BRUVs using a standard method at all the replicates, relative differences between replicates can be detected. BRUVs have been applied successfully in monitoring fish and motile benthic species presence in wind farms in the Irish Sea (Griffin *et al.* 2016).

Atlantic cod are known to utilise wind farm structures during daytime in summer and only during night in winter (Winter *et al.* 2010). Therefore, monitoring effort should be concentrated in summer to increase the encounter rate of Atlantic cod and consequently the statistical power of subsequent statistical analyses. BRUV should be deployed at several experimental sites at the same time to decrease differences in abiotic variables such as light, current speeds, visibility, etc. BRUVs are preferably deployed simultaneously at every experimental option for 60 minutes. The next hour BRUVs can then be deployed at the next replicate in the experiment. During the next survey, care should be taken to randomise the BRUV deployment order within each experimental option.

Analysis
No data are available to estimate the statistical power needed to detect differences between the experimental options. However, based on experience with previous studies we expect that it will be possible to detect these differences by measuring each of 4 replicates 4 times or each of 3 replicates 5 times. Each experimental option then gives 15 (3x5) or 16 (4x4) data points. It is expected that differences in these data may then be detected using Generalised Linear Mixed Modelling (GLMM) techniques or equivalent statistical tests. An example of survey design is given in Table 4.2.

Table 4.2. Example of an experimental setup of two options with 4 replicates and 4 surveys and a random order of BRUV deployments during each survey.

Experiment	Survey1	Survey2	Survey3	Survey4
1.1	1	3	2	4
1.2	2	1	4	3
1.3	3	4	1	2
1.4	4	2	3	1
2.1	1	4	3	2
2.2	2	3	2	3
2.3	3	2	4	4
2.4	4	1	1	2

4.2.2 Oyster settlement

To monitor oyster recruitment by estimating settlement rate and survival after introduction of live oysters, the cages with oysters and settlement material can be lifted from the water using a ship’s crane. Once taken on board samples can be taken from the settlement material to determine settlement rate of oysters and other biota by laboratory analysis. The status of adult oysters in the cages (alive/dead) can be assessed directly on board in the cages. This method is similar to that applied in oyster restoration pilots in the Dutch Voordelta area (Sas *et al.* 2016).

To monitor settlement of oyster spat on other substrates in the wind farm, especially in earlier stages with small oyster specimens, benthic surveys by divers may be needed. Possible methods to inventory settlement of small specimens are scrape samples taken from the substrates and deposited in macrofauna nets, such as applied in the OWEZ and PAWF wind farms (Bouma and Lengkeek 2013; Vanagt and Faasse 2014) or diver operated airlift samplers such as applied during epifouling sampling at offshore oil and gas platforms (Coolen *et al.* 2017).

If it is possible to collect small stones or gravel from the scour protection using ROVs, it may also be feasible to estimate settlement rate of oyster spat.

4.2.3 Biodiversity (overall native biodiversity, policy-relevant species)

Several methods are available to monitor the diversity of benthic fouling species colonising scour protection. Larger species can be detected using ROV surveys, possibly including surveys that are carried out already as part of a technical monitoring scheme. ROV images can then be analysed during a desk study where cover and abundance of large species can be quantified. Analysis of ROV images has been carried out recently with images from offshore platforms in the Dutch North Sea (van der Stap *et al.* 2016). Analysis of these images can be carried out bi-annually, starting a year after installation of the scour protection.

To monitor the colonisation success of smaller benthic species, benthic samples should be taken from larger scour protection boulders or by collecting smaller stones or gravel by hand. Samples from the boulders can be taken by scraping the fouling and collecting the specimens in macrofauna nets such as applied in the OWEZ and PAWF wind farms (Bouma and Lengkeek 2013; Vanagt and Faasse 2014) or diver operated airlift samplers such as applied during epifouling sampling at offshore oil and gas platforms (Coolen *et al.* 2017). At each experimental replicate, 3 samples should be taken during each survey. Surveys should be repeated every 5 years. Identification of benthic species in the samples can be done in the lab by visual identification using stereo microscope or using DNA meta-barcoding techniques. The latter is less costly than the first but does not result in quantitative data. Species abundance and biomass can only be measured using visual identification techniques.

Statistical analysis of the changes in the various experimental options can be performed on species community data using multivariate analysis techniques (e.a. PERMANOVA, multi-dimensional scaling or equivalent methods) or on biodiversity indices (e.g. species richness, Shannon-Wiener index, etc.), used in Generalised Linear Mixed Models, GLMM, or General Additive Models, GAM.

4.3 Cost estimates

The costs of a potential monitoring programme are listed in Table 4.3.

Table 4.3 Cost indication of potential proposed monitoring programme

Objective	**Activity**	**Effort per assessment (days)**	**Repetitions**	**Costs (total)**
Atlantic cod				
	Field work	10	3	30,000
	Video analysis	10	3	30,000
	Data analysis and reporting	15	3	45,000
	Material			40,000
	Total excluding ship costs			**€ 145,000**
European flat	*Oyster*			
	Field work	6	6	36,000
	Lab analysis	5	6	30,000
	Data analysis and reporting	15	6	90,000
	Material			10,000
	Total excluding ship costs			**€ 166,000**
Biodiversity	*Overall native / policy relevant species*			
	Field work (dive team)	20	3	60,000
	ROV video analysis	10	3	30,000
	Lab analysis epifouling	120	3	360,000
	Data analysis and reporting	15	3	45,000
	Material			10,000
	Total excluding ship costs			**€ 505,000**

4.4 Opportunities for cost reduction in monitoring

4.4.1 Synergy: combining vessel logistics

A substantial part of the costs involved with monitoring results from logistics: Certified vessels and crews will have to be deployed to be able to carry out any work in the offshore wind farm.

A possible reduction of costs can be realised by using so-called ‘ships of opportunity’: cost-reduction by combining logistics with on-going activities such as technical inspections and maintenance works. At least part of the monitoring activities can be performed by using a variety of ships, making it likely that it can be combined with other activities in the wind farm.

4.4.2 Monitoring techniques

Quantifying abundance of Atlantic cod

The recommended monitoring technique for Atlantic cod is the use of Baited Remote Underwater Video (BRUV) setups. A clever BRUV design can be made in such a manner, that no diving is needed to deploy the cameras. It can be a system that is prepared on deck of the ship and hoisted in and out by a small crane or A-frame. A multitude of support or maintenance vessels and their crews that enter the offshore wind farm should be suitable for this task. The biologists that carry out the monitoring should join the vessel to ensure adequate deployment.

Options to combine the monitoring techniques even further, such as by attempting to quantify Atlantic cod abundance by using ROV-images from maintenance inspections, is considered not applicable. The presence of a moving ROV is considered too disturbing and too short in time, to allow for accurate quantification.

Monitoring oyster-settlement

Two parts of monitoring oyster settlement have been prosed: 1) Deploying cage setups with live specimens and settlement substrate and 2) Monitoring oyster spat on surrounding substrates.

The same synergy can be pursued as explained above for Atlantic cod. The preferred monitoring option for the surrounding substrates is by making use of the diving operation deployed for biodiversity monitoring. A reasonable alternative, if available against less cost than the preferred option, is by attempting to sample substrates by using an ROV. This can be considered as a suitable technique to proof presence of oyster settlement. The technique is not accurate enough however to conclude that no settlement has occurred when no settlement is observed.

Quantifying biodiversity

To evaluate the effect of optimising scour protection design on biodiversity, it should be quantified that more biodiversity is observed on optimised designs compared to conventional designs. Thus biodiversity on conventional designs of scour protection layers should be quantified as well. Only accurate sampling of biodiversity has the potential to detect the differences between scour protection designs.

We propose two techniques to monitor the development of biodiversity: 1) Bi-annual ROV-surveys and 2) sampling by divers once every 5 years.

Similar to the oyster monitoring, ROV-surveys can be combined with maintenance inspection work. The sampling by divers is essential to achieve the level of accuracy needed for this evaluation. This activity probably cannot be combined with maintenance work, as many present day offshore wind farms operate without divers for maintenance. Options for cost reduction by combining logistics with on-going activities such as maintenance are limited.

Frequency

For scientific purposes, more frequent monitoring will yield stronger results. From a cost perspective however, a minimum monitoring frequency is desirable. As the development of hard substrate communities can take a considerable amount of time, not all components need to be monitored frequently:

- For overall native biodiversity, policy-relevant species and Atlantic cod abundance, minimum of 3 surveys (years 5, 10 and 15) is recommended. As stated before, additional more frequent ROV analysis may offer a cost-effective way to improve knowledge on the on-going development.
- Active introduction of European flat oyster should be monitored more frequently, especially in the beginning, to allow for ‘learning by doing’. A total of 6 surveys is recommended: (years 1, 2, 3, 5, 10 and 15).

4.4.3 Synergy with other offshore wind ecological monitoring programmes (WOZEP)

To evaluate the effect of optimised scour protection designs a very accurate and standardized monitoring is needed to gain scientific evidence of the effect. This hampers the direct use of data obtained at other locations as an alternative for data from the same wind farm site.

Options for cost reduction by using data from other wind farm monitoring programmes such as WOZEP are therefore considered as limited. It is however valuable to include results from other programmes in evaluation of effects.

5 Part I: Synthesis and recommendations

Where previous work has explored the more general possibility for enhancement of ecological functioning in offshore wind farms (van Duren *et al.* 2016; Smaal *et al.* in prep.), this study provides explicit steps towards realising an eco-friendly design of scour protection and a practical field experiment to allow for scientific evaluation.

From an analysis of physical conditions in the North Sea that influence both biodiversity and scouring mechanisms at wind farm locations, it is concluded that scour protection will be required in most, or all, future offshore wind farms on the Dutch Continental Shelf. It is also concluded that scour protection design could be altered to benefit the ecology, but that new designs will require additional testing for anti-scouring effects.

Based on a selection of policy-relevant species for the North Sea, two umbrella species were selected: Atlantic cod and European flat oyster. Focussing design variables and principles on these two umbrella species is expected to result in optimising the habitat for a wide range of native hard substrate species and biodiversity.

Based on existing data from current wind farm scour protection, other artificial hard substrates and natural hard substrates from the North Sea, it is hypothesized that an optimised design of scour protection will yield increased populations of umbrella species or increased native biodiversity in general.

Based on available knowledge on ecological principles and expert judgement of North Sea hard substrate ecologists, four design variables for optimised scour protection are defined. Furthermore, they are made practically applicable by providing example materials and specifications for implementation in the field. Ultimately, a cost overview is provided for example materials.

Combining the above information, this study provides a design guideline for a wind farm with optimised scour protection to enhance ecological functioning. In addition it defines a minimum and a standardized approach for deployment and monitoring of a subset of locations to allow for scientific evaluation. The monitoring techniques that are required to do so, are described and a cost estimate for the monitoring is provided.

In conclusion, this study provides design principles and a first experimental design to implement ecological enhancement by optimising scour protection in offshore wind farms. This is considered as a first step in a process that should result in ‘learning by doing’. To facilitate this process, we propose the following recommendations:

- This design should be considered as a first step for the first planned wind farm. Subsequent wind farms should use a similar experimental approach in which the lessons learned from the evaluation should be incorporated in future wind farm designs and design principles.

- Adequate monitoring and (scientific) analysis is essential to evaluate the results and define options for improvement where possible.

- Zone and location specific information and resulting physical conditions should always be considered when making future eco-friendly designs, and should be considered at a North Sea scale. Not all species will find their required habitats at all zones or locations. North-south distribution (related to temperature), nutrient-levels and turbidity, depth, current patterns (and resulting water retention time within a wind farm location), sand waves and food abundance are examples of location specific factors that can influence potential habitat quality for species.

- This first experiment proposes not to cross design principles within treatments. The combined effects of design variables will therefore not become clear from this first experiment. It is recommended that in subsequent experiments the combined effects will be investigated.

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PART II Justification and Background

6 Ecological principles

In the present-day situation, the North Sea seabed largely consists of soft sediments such as sand and silt. Most abundant species communities are therefore characterised by soft sediment fauna. Before the 1900s however, a substantial part of the North Sea seabed was covered by hard substrates. Those substrates where formed by moorlog (ancient tree and plant remnants, e.g. peat, gravel and rock, and an area estimated to be over 25,000 km^2 covered by a biogenic reef of European flat oysters (Figure 6.1; Olsen 1883, 1885, de Vooys *et al.* 2004, Smaal *et al.* 2015). Species communities dominated by hard substrate fauna must have been highly abundant in the North Sea, but knowledge of benthic fauna from that time is scarce.

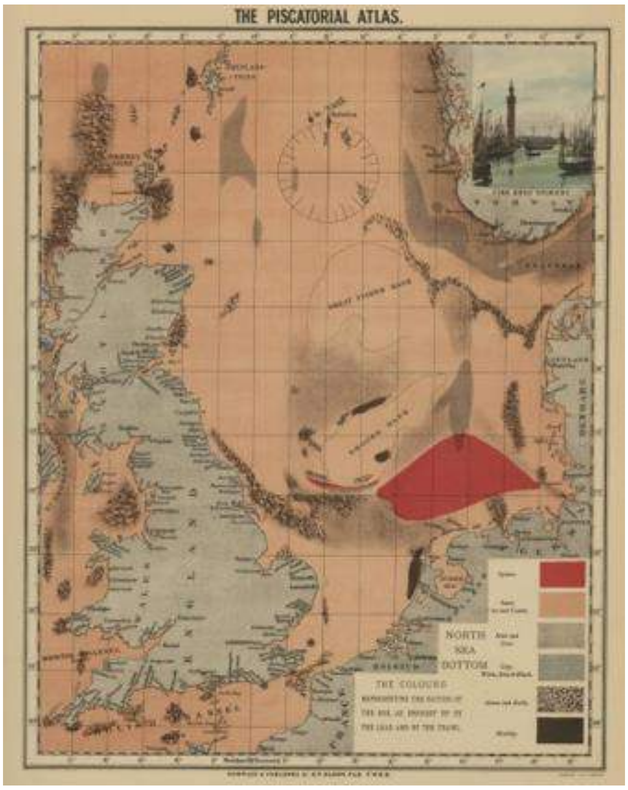

Figure 6.1 Map of Olsen 1885 indicating the occurrence of natural hard substrates in the North Sea in the nineteenth century.

In the past century, large areas of hard substrate (mineral and biogenic) have been removed from the North Sea by bottom disturbing activities leading to the current fairly uniform habitat of sandy substrate (Coolen 2017). The loss of the previously present areas of hard substrate has led to a loss of habitat and a loss of biodiversity on an ecosystem scale, as well as a reduction of keystone species that were iconic for the North Sea. The scour protection of wind farms, although not a natural structure, offers a possibility to regain habitat that is similar in function to previously lost hard substrate. It also may facilitate the return or enhancement of species and biogenic structures that have been lost or reduced to critical levels.

Eco-friendly design in this study entails optimising the scour protection of offshore wind farms to enhance its ecological functioning. Enhancement of ecological functioning has been defined as: increasing habitat suitability for species (or communities) occurring naturally in the Dutch North Sea, in particular, for endangered species such as listed in the EU Habitats Directive, OSPAR or national red lists (see Annex 2 in Bos *et al.* in prep.). In addition, the enhancement of alien species is regarded as undesirable.

Three possible results of successful increased habitat suitability are:

- Increased population size of specific target species;
- Increased population size and species numbers of a specific group of (native) species (e.g. policy-relevant species);
- Increased overall (native) biodiversity.

As adding scour protection to the Dutch North Sea seabed generally means adding hard substrate to a soft bottom habitat, the potential for increasing population size or biodiversity thus specifically applies to hard or mixed substrate species.

6.1 Focal species

In order to assess the potential of species occurring at a prioritised wind farm location, first a selection of focal species for settlement on hard artificial substrate in the North Sea wind farms was made.

The comprehensive list of species to focus on was created by combining the following policy-relevant species lists (Appendix A):

1. The Red lists for the Netherlands (fish: Kranenbarg and Spikmans 2013, Gmelig Meyling and Van Moorsel 2013, mammals: Zoogdiervereniging 2007; overall: Ministry of Economic Affairs 2015);
2. Natura 2000 H1170 “Reefs of the open sea” typical species for the Netherlands (Ministry of Economic Affairs 2014);
3. OSPAR list of endangered and protected species and habitats (OSPAR Commission 2008) from which only a sub-list of species present in the Netherlands (Bos *et al.* in prep.) was taken;
4. Indicator species for hard substrates in the Dutch MSFD monitoring program (Ministerie van I&M and EZ 2014);
5. Species from the Dutch shark action plan (Walker *et al.* 2015, Ministry of Economic Affairs 2016).

From this extensive list, a selection was made by removing species that had the following criteria:

1. Species that are exclusive to soft substrates;

2. Species that occur exclusively at the intertidal zone, as this study focuses on deeper waters around the turbine foundations, which are unsuitable for intertidal species;
3. Species that occur exclusively at coastal locations, as the proposed wind farms assessed in this study are all to be installed offshore (at least 10-12 nautical miles offshore).

This first selection led to a shortlist of 30 species (Table 6.1).

Table 6.1 Short list of focal species including common Dutch and English names.

Scientific name	**Dutch common name**	**English common name**
Aequipecten opercularis	Wijde mantel	Queen scallop
Alcyonium digitatum	Dodemansduim	Dead man's fingers
Aporrhais pespelecani	Pelikaansvoet	Pelican's foot
Arcopagia crassa	Stevige platschelp	Blunt tellin
Buccinum undatum	Wulk	Whelk
Chone duneri	Borstelwormsoort	Polychaete species
Dasyatis pastinaca	Pijlstaartrog	Common stingray
Dosinia exoleta	Gewone artemisschelp	Rayed artemis
Gadus morhua	Kabeljauw	Atlantic cod
Galathea intermedia	Oprolkreeft	Squat lobster
Haliclona (Haliclona) oculata	Geweispons	Mermaid's glove
Leucoraja naevus	Grootoogrog	Cuckoo ray
Liparis liparis liparis	Slakdolf	Sea snail
Lithothamnion sonderi	Kalkroodwiersoort	Coralline algae species
Micrenophrys lilljeborgii	Noorse zeedonderpad	Norway bullhead
Microstomus kitt	Tongschar	Lemon sole
Monia patelliformis	Manteldekschelp	Ribbed saddle-oyster
Mustelus asterias	Gevlekte gladde haai	Starry smooth-hound
Mustelus mustelus	Gladde haai	Smooth-hound
Ostrea edulis	Platte oester	European flat oyster
Phrynorhombus norvegicus	Dwergbot	Norwegian topknot
Raja brachyura	Blonde rog	Blonde ray
Raja clavata	Stekelrog	Thornback skate / ray
Raniceps raninus	Vorskwab	Tadpole-fish
Sabellaria spinulosa	Zandkokerworm	Ross worm
Scyliorhinus canicula	Hondshaai	Dogfish
Scyliorhinus stellaris	Kathaai	Nursehound
Simnia patula	Stiefelslak	Cowrie species
Trisopterus minutus	Dwergbolk	Poor cod
Urticina felina	Zeedahlia	Dahlia anemone

6.2 Habitat requirements of focal species

Table 6.2 Selected focal species to benefit from hard artificial substrate in the North Sea wind farms and the way they utilise hard substrates and known depth ranges (in metres).

Scientific name	**English common name**	**Primary substrate function**	**Depth (m)**
Aequipecten opercularis	Queen scallop	nursery	0-100
Alcyonium digitatum	Dead man's fingers	attachment surface	0-100
Aporrhais pespelecani	Pelican's foot	attachment surface/foraging	0-180
Arcopagia crassa	Blunt tellin	infauna gravel	0-100
Buccinum undatum	Whelk	attachment surface/foraging/reproduction	0-1200
Chone duneri	Polychaete species	infauna gravel	0-1500
Dasyatis pastinaca	Common stingray	foraging	5 - 200
Dosinia exoleta	Rayed artemis	infauna gravel	0-100
Gadus morhua	Atlantic cod	nursery	1-1105
Galathea intermedia	Squat lobster	hiding space/foraging	0-25
Haliclona (Haliclona) oculata	Mermaid's glove	attachment surface	0-100
Leucoraja naevus	Cuckoo ray	foraging	20 - 500
Liparis liparis liparis	Sea snail	hiding space/reproduction	1-182
Lithothamnion sonderi	Coralline algae species	attachment surface	2-39
Micrenophrys lilljeborgii	Norway bullhead	reproduction/foraging	31-110
Microstomus kitt	Lemon sole	shelter	1-1105
Monia patelliformis	Ribbed saddle-oyster	attachment surface	2-123
Mustelus asterias	Starry smooth-hound	foraging	0 - 350
Mustelus mustelus	Smooth-hound	foraging	5 - 624
Ostrea edulis	European flat oyster	attachment surface	0-40
Phrynorhombus norvegicus	Norwegian topknot	shelter	10-237
Raja brachyura	Blonde ray	foraging	10 - 380
Raja clavata	Thornback skate / ray	foraging	1-620
Raniceps raninus	Tadpole-fish	Hiding space/foraging	16-528
Sabellaria spinulosa	Ross worm	attachment surface	0-100
Scyliorhinus canicula	Dogfish	foraging	10 - 780
Scyliorhinus stellaris	Nursehound	foraging	1 - 400
Simnia patula	Cowrie species	attachment surface/foraging	15-75
Trisopterus minutus	Poor cod	foraging	1-1105
Urticina felina	Dahlia anemone	attachment surface	2-100

6.2.1 Hard substrate requirements

A next step towards determining an optimal design or artificial hard substrate for the selected focal species is to group them based on the favoured type of hard (naturally occurring) substrate. This grouping was based on expert judgement and experience of occurrence in the field. This selection step yielded two groups of species that may benefit from creating either small-scale hard structures (in the present natural situation gravel beds) or by creating large-scale hard structures (in the present natural situation rocky reefs) (Table 6.3).

Table 6.3 Selected focal species with their potential to increase during different life stages by adding large structures or gravel beds to wind farms. Life stage effects were based on literature or estimated based on unpublished field observations by the authors. Stages are indicated with E: Egg deposition, J: Juvenile, A: Adult. Note that gravel beds may be utilised by most species at some stage of their life, but that they may need large structures during adult life stages.

Scientific name	**English common name**	**Large structures**	**Gravel beds**
Aequipecten opercularis	Queen scallop		J
Alcyonium digitatum	Dead man's fingers	JA	JA
Aporrhais pespelecani	Pelican's foot		E
Arcopagia crassa	Blunt tellin		A
Buccinum undatum	Whelk	EJA	EJA
Chone duneri	Polychaete species		A
Dasyatis pastinaca	Common stingray		A
Dosinia exoleta	Rayed artemis		A
Gadus morhua	Atlantic cod	A	J
Galathea intermedia	Squat lobster		JA
Haliclona (Haliclona) oculata	Mermaid's glove	JA	JA
Leucoraja naevus	Cuckoo ray		A
Liparis liparis liparis	Sea snail	A	A
Lithothamnion sonderi	Coralline algae species	A	A
Micrenophrys lilljeborgii	Norway bullhead		EJA
Microstomus kitt	Lemon sole	A	A
Monia patelliformis	Ribbed saddle-oyster	A	A
Mustelus asterias	Starry smooth-hound		A
Mustelus mustelus	Smooth-hound		A
Ostrea edulis	European flat oyster	JA	JA
Phrynorhombus norvegicus	Norwegian topknot	JA	JA
Raja brachyura	Blonde ray		A
Raja clavata	Thornback skate / ray	A	EJA
Raniceps raninus	Tadpole-fish	JA	
Sabellaria spinulosa	Ross worm	JA	JA
Scyliorhinus canicula	Dogfish	E	EJA
Scyliorhinus stellaris	Nursehound	EJA	
Simnia patula	Cowrie species	EJA	EJA
Trisopterus minutus	Poor cod	JA	JA
Urticina felina	Dahlia anemone	JA	JA

From this classification, it is clear that both types of changes to the scour protection (adding larger or smaller structures) have a high potential to increase species of conservation interest. Most species may benefit from the extra addition of small-scale structures such as gravel beds to the scour protection, meaning an increase in the surface area of gravel that is already placed in current scour protection designs. Some species utilise gravel beds throughout their life, often as attachment substrate in the case of epifouling species (e.g. the coral dead man's fingers, ross worm and dahlia anemone). These species potentially benefit from all hard substrates that are added to scour protection. Other species however, do need larger structures as well at some stage in their life. Atlantic cod for example, may use gravel beds to forage and hide between small crevices therein during its first year of development, but needs hiding space in large pores between rocks (or other structures) in their adult life stage. Some species are not dependent on the substrates as such, but inhabit species that are dependent on the substrates. For example, the cowrie species lives on dead man's fingers, a cold-water coral and is therefore indirectly dependent on hard substrates.

Chemical substrate requirements

Species may also benefit from certain chemical properties of hard substrates. This may specifically apply to biodiversity, which is characteristic for biogenic reefs, as hard substrate formed by biogenic reefs can hold substantially different chemical properties than naturally occurring rock. A problem is that biogenic reefs, such as oyster reefs, have become extremely rare in the North Sea and knowledge on this topic is scarce.

For the European flat oyster, and all other shellfish, it is known that larvae use chemical cues to actively seek out optimal settling substrate (Vasquez *et al.* 2014).

6.3 Main ecological principles for habitat optimisation

Based on the previous paragraph, we seek to optimise habitat characteristics for species that naturally benefit from gravel-like structures, large rocky reef-like structures or both. In some cases, we also seek to mimic certain chemical properties of substrates. When doing so, certain ecological principles should be considered:

1. Species-specific habitat requirements
2. Habitat complexity
3. Habitat variability
4. Habitat stability
5. Habitat durability
6. Source populations

1: Species-specific habitat requirements.

Some species may benefit from very specific requirements. The first habitat requirement, of course, is the presence of hard substrate itself. This requirement applies to all focal species in the study, but also, more species-specific properties may be required. Chemical properties, for instance may be highly specific for a species or species group. It is known for oyster larvae, for instance, that recruitment can be promoted by using specific compounds present on the shell of living oysters (Vasquez *et al.* 2014). Tuning in on specific habitat requirements may lead to increased population size of specific target species.

2: Habitat complexity

Holes and crevices in between hard substrates may function as shelter for multiple species. This is an important property of hard substrate habitats for mobile species. A large Atlantic cod may typically shelter in a hole of more than a metre-deep, whilst a clingfish or a juvenile Atlantic cod may typically seek a hole of only a few centimetres. Generally, the more variable the sizes of holes and crevices, the more different species or size classes are attracted to the habitat. Thus, maximizing habitat complexity may lead to both increased population size as well as biodiversity.

3: Habitat variability

In part, this ecological principle overlaps with the previous, but not entirely. This principle emphasises that species will benefit from a variety of habitats (material), rather than a single habitat material differing in complexity. Several species are known to prefer gravel-based habitats, although these are not typically habitats with high levels of complexity. Therefore, a mix of complex structures with more uniform gravel-based habitat may lead to a higher native biodiversity than a complex habitat without gravel.

4: Habitat stability

Especially slower growing organisms, such as sponges, oysters and corals, can only develop over time when the hard substrate habitat is stable. When substrates such as rocks are small or light enough to be moved around by wave action or currents, generally a much poorer epifaunal community develops (Waardenburg 1990; van Moorsel en Waardenburg 1999). Stable hard substrates are therefore essential for the development of a diverse community.

5: Habitat durability

A potential problem with hard substrates in a sandy environment is that they trap sand to such an extent that they lose their hard substrate properties. Important holes and crevices may fill up and no longer serve as shelter. Hard surfaces may be covered by sand and no longer serve as attachment substrate. It is essential to design the hard substrate habitat in such a way that the relevant properties are maintained over time, also when sand from the surrounding habitat is trapped.

6: Source populations

When an optimal habitat is provided in the marine environment, it is generally expected that the required native organisms will settle and colonise naturally. For most species, this expectation is correct, because most marine organisms have fairly large dispersal potential through larval stages that float in the water column for elongated periods of time before they settle. This expectation is wrong for some species that have shorter dispersal potential or are particularly rare. In both cases larvae, may not reach the optimised habitat within acceptable time. In this case, there is a lack of a *source population* of adults that provide recruitment on the new substrate. This is almost certainly the case for the European flat oyster on many locations in the North Sea. This species has become extremely rare and has limited dispersal potential. To have this species colonise a new artificial substrate, it will be necessary to actively (re-)introduce an adult source population.

In conclusion, with regard to materials that should enhance ecological functioning in comparison with standard deployed scour protection:
Increased habitat complexity, variability and stability will yield potential for increased biodiversity and populations sizes. In addition, optimising species-specific habitat requirements will yield potential to increase population size of specific species or species groups. Ultimately, for some species it can be necessary to actively (re-) introduce a source population of adults.

6.4 Umbrella species and focal species selection

For the design of optimised scour protection in a first field experiment and the selection monitoring techniques, we chose to focus on a limited selection of 'umbrella species'. This makes this study, but also the field experiment at hand, conceivable and understandable for a wide audience.

The idea of umbrella species is straightforward: propagation of some species (or in other cases used for conservation of some species) is thought to provide a protective umbrella to numerous co-occurring species.
It is often more understandable to design an optimised habitat for one or several species, rather than a long list. It is often faster and less expensive to sample a few species than it is to survey the entire assemblage (Fleishman *et al.* 2000). Hence, umbrella species can make a design more conceivable for a non-specialist and can reduce the investments in sampling that are necessary when prioritising materials or monitoring techniques.
Importantly: Enhancing habitat for well-selected umbrella species is expected to imply habitat enhancement for many other species at the same time.

Selection of umbrella species is prospective and based on objective criteria:

1. Co-occurrence of species: umbrella species should be earmarked based on co-occurrence with other species: protecting species with large area requirements will conserve habitat for species that are more insular or sedentary.
2. Degree of ubiquity: an ideal umbrella species candidate should be neither ubiquitous nor extremely rare but instead should strike a balance between these two extremes.
3. Sensitivity to human disturbance: selecting umbrella species recognizes that species respond differently to various disturbances.

For selecting species that profit from *optimised* scour protection in the North Sea a fourth criterion was defined.

4. Additional habitat requirement: representative of a habitat requirement that is lacking in currently used scour protection.

Based on the list of focal species a selection was made for two umbrella species and overarching species groups ‘overall native biodiversity’ and ‘number of policy-relevant species’ (§2.4). Firstly, since many species on the short list profit from a change in scour protection from uniform rocks of small to intermediate size to a scour protection created from a larger diversity of sizes, a species that profits from different sizes of rocks (or other materials) during different stages in its development, was selected: Atlantic cod. Atlantic cod (*Gadus morhua*) is listed as “near threatened” on the Dutch Red List of fish species. This fish is known to utilise offshore wind farm foundations as a habitat (Winter *et al.* 2010) during adult stages and has been observed to use ship wrecks during its younger life stages (Lengkeek *et al.* 2013a). Furthermore, Atlantic cod abundance has been shown to increase locally after the introduction of large sized boulders in a rocky reef in Denmark (Stenberg *et al.* 2015).

Additional habitat requirements: The introduction of small hiding spaces between small rocks may therefore increase juvenile Atlantic cod and larger holes and crevices between large boulders, may improve habitat for large adult cod.

Secondly, a keystone habitat altering species was selected. If this species is successful in colonising the scour protections, it may increase the habitat available to other species on the short list as well. Here, the European flat oyster was selected. This bivalve is a bio-engineer (Smaal *et al.* 2015) and it has potential to be reintroduced in some existing and planned wind farms in Dutch waters (Smaal *et al.* in prep.). Furthermore, the oyster is known to facilitate a large number of associated benthic species, in some cases resulting in higher species richness than found on non-living hard substrates (Smyth and Roberts 2010).

Additional habitat requirements: Apart from physical characteristics (Smaal *et al.* 2015; Smaal *et al*. in prep.) European flat oyster spat needs a source of calcium for shell calcification after settlement, which can be provided via the water or substrate. Oyster shells in existing oyster beds are a preferred settling substrate for oyster spat (references in Smaal *et al.* 2015, in prep.). Shell fragments or oysters shells are therefore additional habitat requirements.

Atlantic cod

1. Co-occurrence of species (i.e. species that benefit from same improved habitat characteristics): large mobile (hard-substrate associated) species will generally benefit from large holes and crevices, similar to large Atlantic cod. Examples are sea bass, ling, wrasse species, shark species, wolf fish and edible crab.
2. Degree of ubiquity: listed as OSPAR species, National red list species with status “near threatened” and typical species with a North Sea wide distribution and known for its affiliation with artificial hard substrates.
3. Sensitivity to human disturbance: representative of species sensitive to pelagic fishing.
4. Additional habitat requirement: any hard substrate can serve as source of shelter (directly) and food (indirectly). Habitat requirements range from fine (juvenile) to large (adults) pores/ holes used as shelter. The current scour protection provides small to mid-sized pores. Additional habitat requirements therefore include larger pores.

Flat oyster

1. Co-occurrence of species: keystone species: shellfish reefs provide a biogenic structure by themselves (designated as habitat H1170 ‘reefs’) and are renowned for their unique biodiversity: for example, epibiota on flat oysters encompass several unique species that do not occur on artificial hard substrates (Smyth & Roberts 2010).
2. Degree of ubiquity: OSPAR species, species of policy plans with actions regarding the reintroduction of flat oysters and element of habitat H1170 (an attribute of structure and function of habitat type H1110)
3. Sensitivity to human disturbance: representative of species sensitive to demersal fishing.
4. Additional habitat requirement: oyster shells in existing oyster beds are a preferred settling substrate for oyster spat (Smaal *et al.* 2015). Shell fragments or oysters shells are therefore additional habitat requirements.

Last, ‘overall native biodiversity’ and ‘number of policy-relevant species’ are defined as focal species (groups) on which design of scour protection, the design of the first experiment and monitoring should focus. Successfully increasing overall native biodiversity on scour protection is a strong indicator for successful optimised design.

7 North Sea conditions and scour protection

7.1 Physical conditions at wind farm sites

The physical system of the Dutch Continental Shelf (DCS) has been described in relation to the development of artificial hard substrate for ecological enhancement in Van Duren *et al.* (2016). The DCS has a soft sediment seabed and generally lacks rocky substrate or reefs except for artificial substrates. Consequently, sediment characteristics and dynamics play an important role in shaping the physical conditions characterising the North Sea together with hydrodynamics. By mirroring the physical conditions to habitat requirements for a (number of) species, an estimate of the potential for species occurrence at these wind farm locations can be made. Furthermore, the development of artificial hard substrate can be optimised for species that are likely to occur at the wind farm locations with their preferred physical conditions.

In this report the focus of physical conditions will be specifically on a number of wind farm locations in the DCS, due to their potential to include ecological enhancement in hard substrates during construction. These locations include the following so-called Wind Farm Zones (WFZ or WEG "Windenergiegebieden") assigned for wind energy: "Borssele", "IJmuiden Ver", "Hollandse Kust" and "Ten noorden van de Waddeneilanden" (Figure 7.1). For the overview of some physical conditions at these zones we show the range of conditions in the North Sea as a whole.

Physical characteristics were chosen based on their ability to affect habitat suitability and potential for enhancement of ecological functioning. Van Duren *et al.* (2016) and Smaal *et al.* in prep. have discussed a number of physical characteristics that are important when considering specific wind farm locations in the DCS and potential for ecological enhancement. These conditions are mostly related to sediment dynamics and include parameters such as current speed, bed shear stress, particulate suspended matter, suspended sediment in the lower layer, depth and sand waves. Smaal *et al.* in prep. have considered physical characteristics which are particularly important for the settlement and development of the flat oyster in existing and planned Dutch wind farms specifically. They considered the following factors as being important for flat oyster settlement: (i) large scale dynamics (sand waves) and small-scale dynamics (bed shear stress) of the sediment, (ii) sediment composition, (iii) suspended matter in the water column and (iv) the possibility for successful recruitment (dependent on the adult population and water movement).

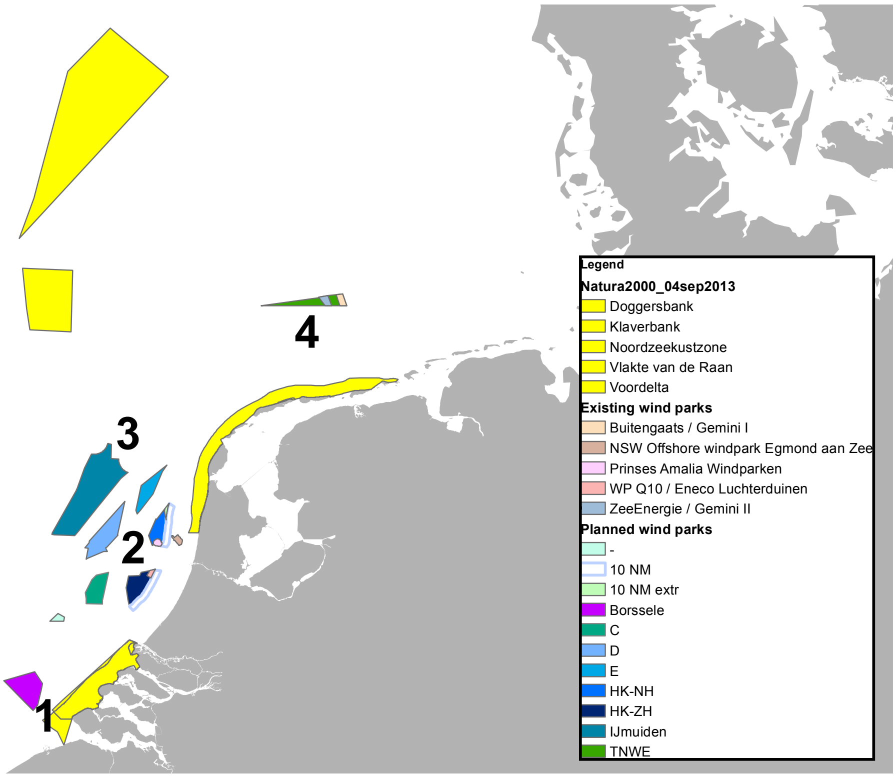

Figure 7.1 Overview of planned and existing wind farms in the Dutch North Sea Focal locations of this study include the planned wind farms in the Wind Farm Zones 1) "Borssele", 2) Hollandse Kust", 3) "IJmuiden Ver", 4) "Ten noorden van de Waddeneilanden". Natura 2000 areas in the Dutch North Sea are shown in yellow.

Bed shear stress represents the force of water flows (currents and waves) on the seabed. The bed shear stress affects grain size and organic matter content in the sediment (De Jong *et al.* 2015) and can influence macrobenthic community structure (Herman *et al.* 2001; Ysebaert *et al.* 2003; de Jong *et al.* 2015). It also determines whether particles will sink to the seafloor or are suspended in the water column (Smaal *et al.* in prep.). Bed shear stress (maximum and average) in the North Sea is shown in Figure 7.2. Average values (Figure 7.2B) show that especially the Borssele zone is located in a more dynamic part, whereas maximum values (figure. 7.2A) are lower in Borssele than in other zones. This indicates that the Borssele zone has on average higher dynamics than for example the zones 'Hollandse Kust' and 'Ten noorden van de Waddeneilanden', but conditions are more constant. This is caused by the fact that the tidal velocities are larger in the southern part of the Dutch North Sea, while storm-induced waves are typically larger in the northern part of the Dutch North Sea. Since tidal motion occurs all year round and storms are rare events, the environment of the Borssele zone is more constantly dynamic, but less variable than of the zone Ten noorden van de Waddeneilanden.

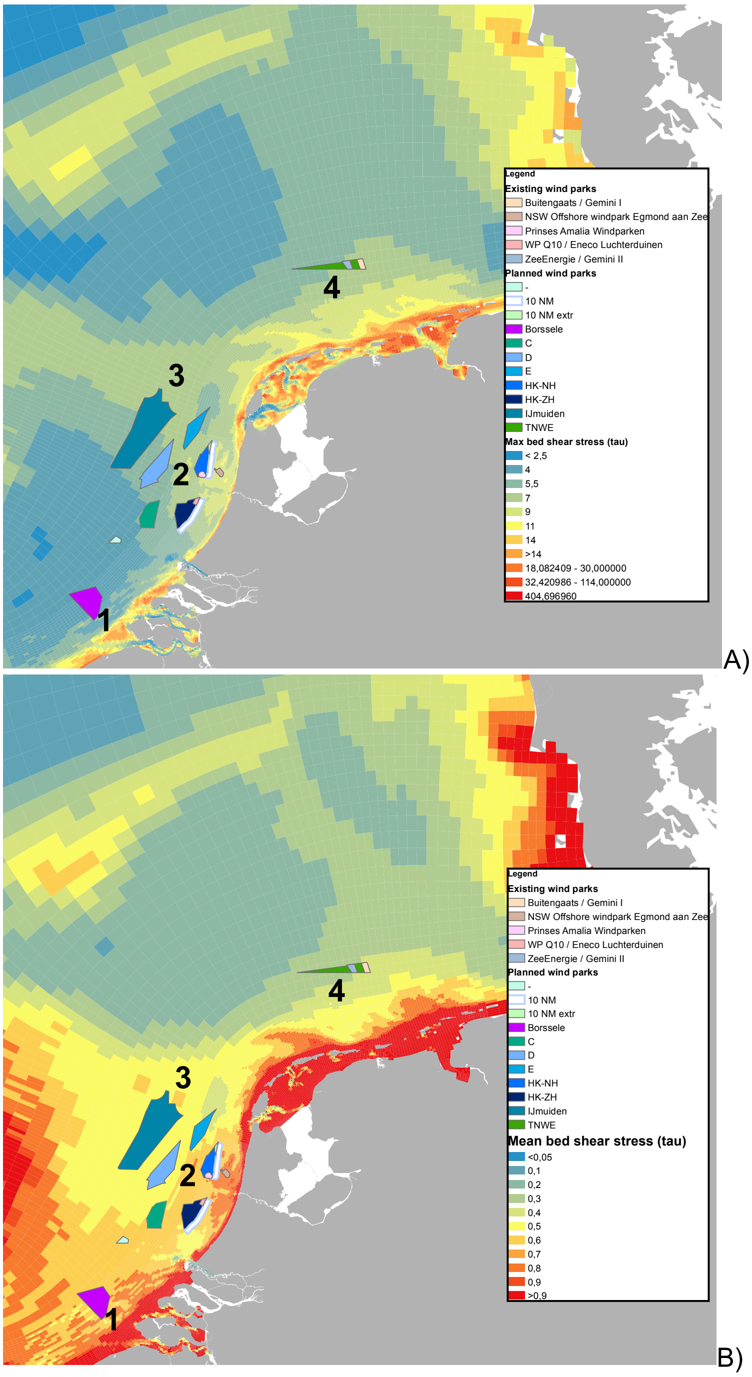

Figure 7.2 Bed-shear stress (tau in N/m^2) in the North Sea (based on model simulations of the “MER-zandwinning” project): A (upper) shows maximum values and B (lower) shows average values (Source: van der Kaaij et al. in prep).

Sediment mobility and the height and frequency of sand waves differ between the different locations. Sand waves are especially occurring in the southern part of the Dutch North Sea, for example where the Borssele zone is located, but also the areas

Hollandse Kust (zuid) and part of Hollandse Kust (noord) and the zone IJmuiden Ver are covered with sand waves (Figure 7.3). However, these sand waves move relatively slowly compared to a biological timescale. Nearshore sand waves migrate relatively fast (6.5-20 m/year), offshore migration speeds range between 3.6 and 10 m/year (Van Dijk & Kleinhans 2005). Around the 'Zeeuwse banken', near wind farm zone Borssele, migration speeds range around 2.5 m/year (Hasselaar *et al.* 2015). The extent to which sand waves affect species is not well understood, however it is thought to affect successful settlement for certain longer living species (Van Duren *et al.* 2016).

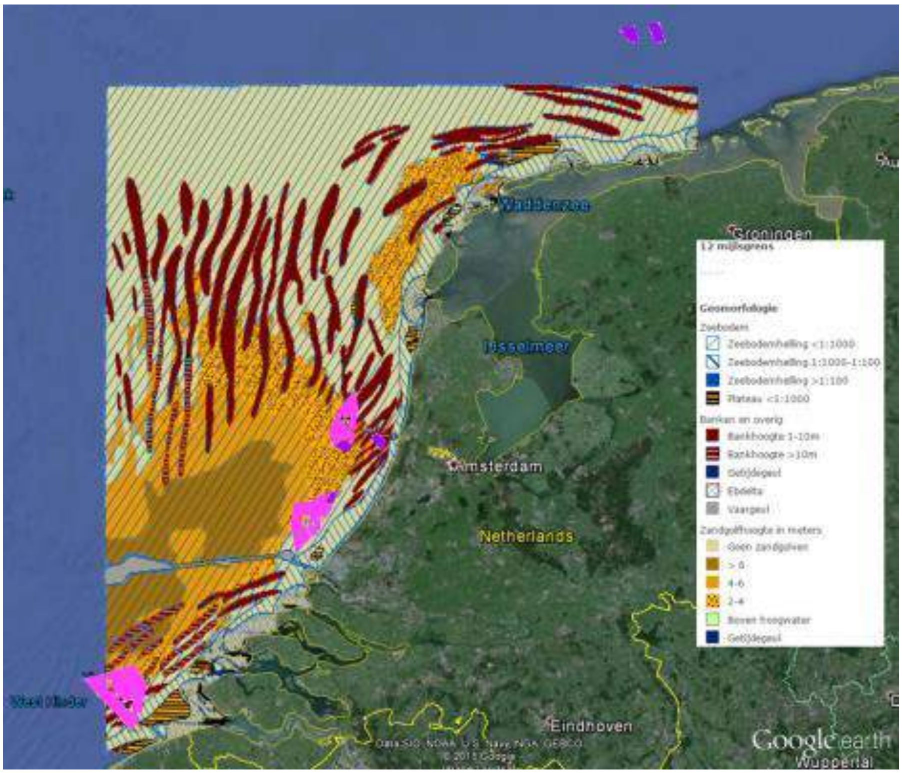

Figure 7.3 Sand waves in the North Sea. (Source: Rijkswaterstaat Noordzeeatlas; Noordzeeloket 2016b).

Smaal *et al.* (in prep.) have considered sand waves with respect to the boundary conditions of the flat oyster for the Borssele zone in particular and showed that certain parts within the Borssele zone are likely too dynamic for the species. Smaal *et al.* (in prep) showed that the white areas in Figure 7.4 were suited for flat oysters due to their lower wave migration speeds. Although larger sand waves occur in the Borssele zone, other locations such as off the coast of Noord Holland (e.g. Wind farm Luchterduinen) have sand waves that move more rapidly, making the location dynamic as well, though in a different frequency and timescale. Thus, conditions and the level of dynamics differ both between locations as well as within wind farms. Borssele zone however, is expected to be most dynamic due to its strong current dominated character. Therefore, other wind farms and zones are expected to provide suitable potential habitat with respect to sediment dynamics for the flat oyster (Smaal *et al.* in prep).

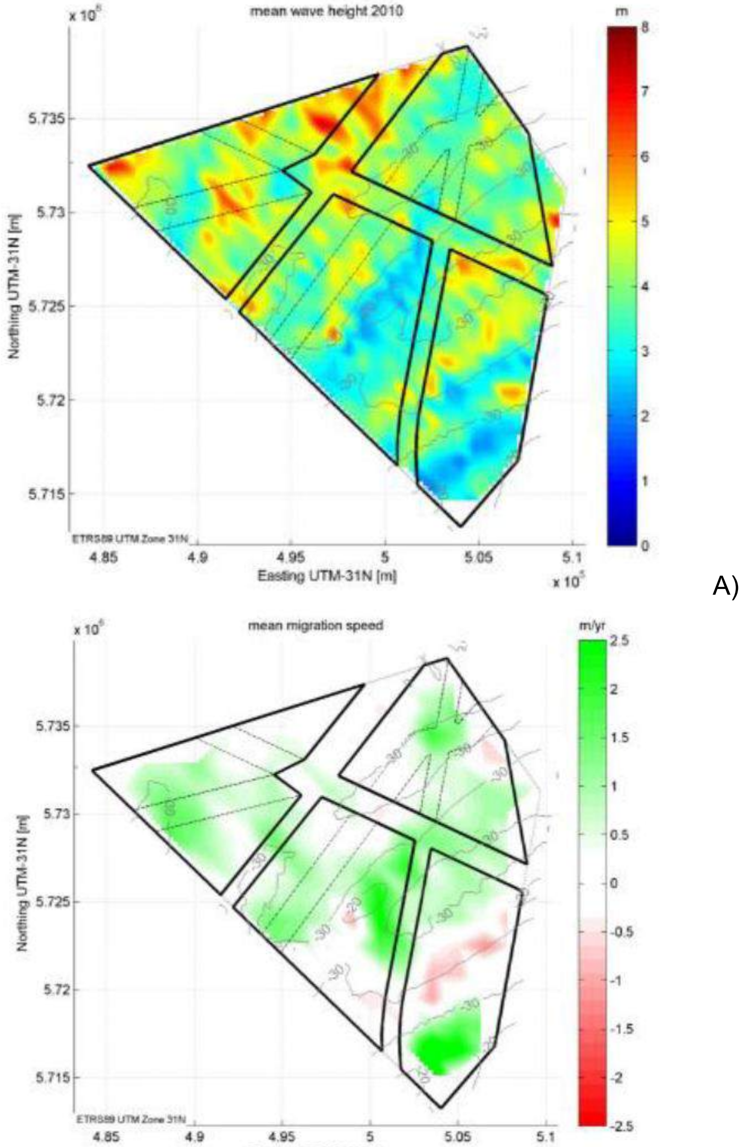

Figure 7.4 Height (A) and migration speed (B) of sand waves within Borssele zone (Source: Smaal et al. in prep.).

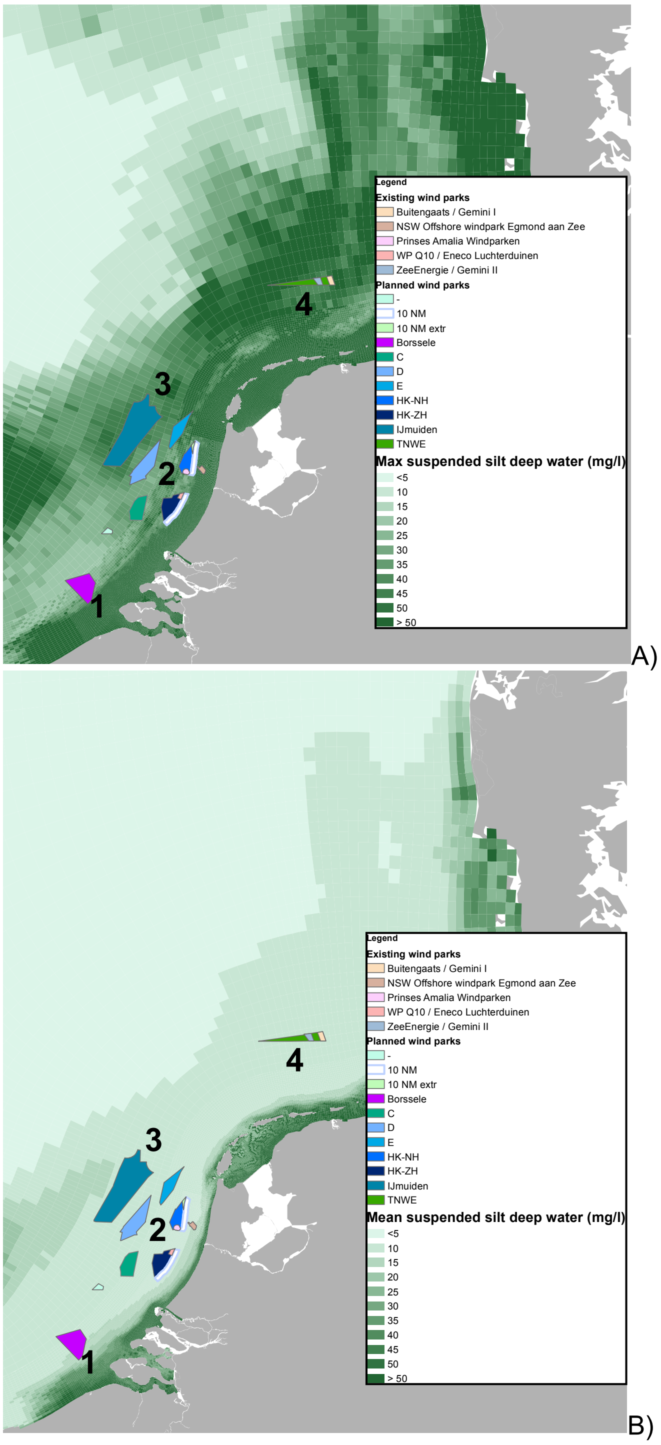

Figure 7.5 Suspended silt in the lower water layers. A) maximum, B) average (Source: van der Kaaij et al. in prep.)

Table 7.1 provides an overview of relevant physical parameters for species settlement at the different wind farm locations.

Table 7.1 Overview of physical parameters associated with wind farm locations (WEG: Wind Energie Gebied: Wind Farm Zone) and their relative priority for analysis in the present study (appointed by Ministry of Economic Affairs, with the highest priority two or three stars for applying the outcome of this study). Bed shear stress was modelled with the ZuNo-DD model based on Delft3D (van der Kaaij et al. in prep.) Current speed was modelled with Delft 3D-FLOW.

Location	**Specified**	**Priority**	**surface Current speed (m/s)**	**Bottom shear stress** (τ in Newton/m²)	**Average Depth** (m)	**Surface min-max Temp range** 2003-2007 (°C)	**Nitraat Surface** (mmol/m3) (Gem. 2015 Dec)
(A) WEG “IJmuiden Ver”	IJmuiden ver	*	1.1	5.2	-28.0	4- 17.6	8.2
(B) WEG “Borssele”	Kavel I	***	1.1	3.4	-27.0	4 - 18.6	8.1
	Kavel II	***					
	Kavel III	***					
	Kavel IV	***					
	Kavel V	**					
(C) WEG “Hollandse Kust”	Zuid (Kavel I + II)	**	-	6.0	-23.0	3 - 19	10.4
	Zuid (Kavel III + IV)	**					
	Noord (Kavel I + II)	**		6.7			
	resterende locatie (1)	*		5.6			
	resterende locatie (2)	*					
	resterende locatie (3)	*					
	resterende locatie (4) (meest zuidelijk)	-					
(D) WEG “Ten noorden van de Waddeneilanden”	Resterende locatie (1)	*	0.8	5.6	-34.0	3 - 19	8.4
	Resterende locatie (2)	*					

In addition to differences on a regional scale with respect to physical parameters, there are gradients within a wind farm location as well. For example, there can be differences in the degree to which a sand wave will go through a location. This however is also taken into account when deciding on the optimal locations for a wind turbine, making sure monopile is not situated at the crest or trough of a sand wave. Furthermore, there can be differences in bed shear stress and the addition of structures such as monopiles and wind turbines add to these changes. Closer to the turbine, the currents will be stronger and consequently make the conditions less optimal for ecological development. Such elements need to be considered when optimising the design of a monopile with artificial substrate added for ecological enhancement. Ideally, the design will be aimed at the outer edges of the scour protection around a monopile where conditions are more favourable.

7.2 Conditions and native species (groups)

The ability of species to occur and potentially thrive at the artificial hard substrate to be installed at wind farm locations is in part determined by the physical parameters described in paragraph 7.1. Relatively little species-specific information on their physical boundary conditions is available to be able to assess the potential of species to occur in certain locations based on their preferences. Generally, species can optimally occur at locations with low amounts of suspended sediment and clear waters. Clearer waters generally contain more food and especially at high current speeds this will facilitate growth of filter feeding benthos, given that the substrate is appropriate as well. When food availability is relatively high, higher tropic levels such as fish species are more likely to be attracted to the area as well.

Locations rich in suspended sediment might be too dynamic for some species. However, there are also species that are known to prefer high amounts of suspended matter in the water column, such as the reef building *Sabellaria*. These target values are however specified for the reef building *Sabellaria* and not specific for the singe worms that could occur on hard substrate.

Smaal *et al.* (in prep.) have interpreted historic maps of flat oyster populations in the North Sea to estimate their tolerability for bottom shear stress. It showed that the flat oyster prefers bed shear stress of 0.25-0.6 N/m^2.

As described, differences in dynamics of the sediment with respect to bottom shear stress and sand waves can differ both between regions and within the wind farms themselves. This is something to consider when deciding upon optimal locations within the wind farm for the enhancement of ecological potential of artificial hard substrate.

7.3 Technical requirements scour protection wind farms

In order to better understand the technical requirements of a scour protection, this section will address the hydrodynamic load patterns around a monopile, the need for a scour protection, a brief overview of the different options and construction methods that are available and the solutions that have been adopted so far in the Dutch wind farms.

7.3.1 Scour and the need for a scour protection

When a structure is installed in an offshore environment, the flow (combined action of currents and waves) must divert around the structure. A schematic overview is presented in Figure 7.6. Due to flow contraction, the flow velocity will increase. To provide a rough estimate: according to the ‘simplified’ potential flow theory, the flow velocity can double close to the sides of the pile. Besides flow contraction, also different turbulent structures (vortices) will develop. Due to the vertical velocity gradient in the approach flow, a pressure gradient will develop at the upstream side of the pile. Because the pressure is larger higher up in the water column, a down flow will develop. When this down flow hits the seabed, it spirals off around both sides of the pile. The vortex that develops has the shape of a horseshoe and is therefore named “horseshoe vortex”. This vortex is the main driver of the scour process around a cylindrical pile. It typically extends up to one pile diameter from the pile.

At the downstream side of the pile, alternating vortices will develop when the flow is shed off the pile. These vortices have a vertical axis and are named lee-wake vortices. Although the mean flow velocities in the leeside of the pile are close to zero, the velocity and pressure fluctuations can still be significant.

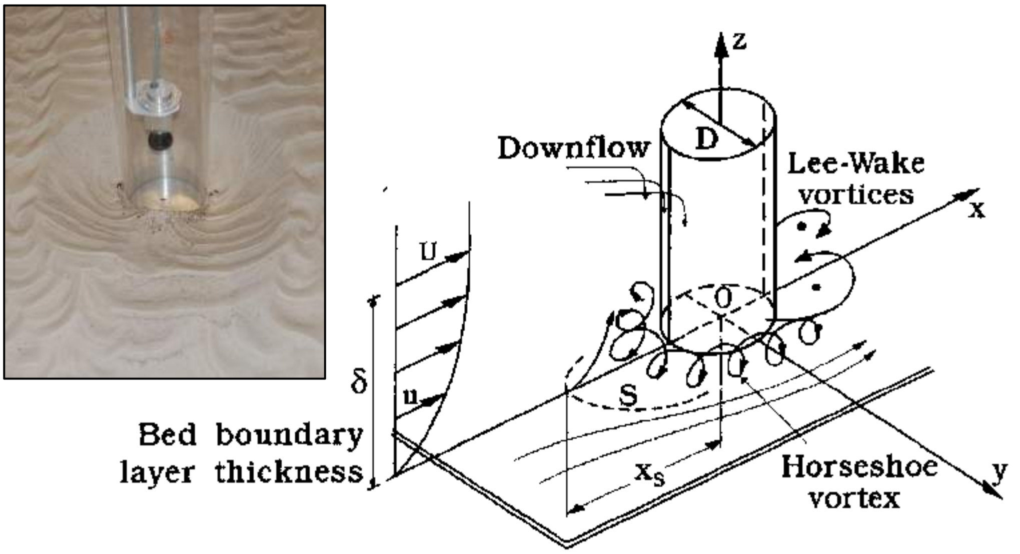

Figure 7.6 Flow pattern of a current flowing around a cylindrical pile (Sumer and Fredsøe, 2002); (upper left) a scour hole in a scale model test with a (transparent) monopile.

Because of the increased flow velocities and turbulent vortices, the bed shear stresses increase around the foundation. As a consequence, the sediment transport capacity increases and local erosion (scour) will develop. In principle, both wave-dominated conditions (e.g. during storms) and current-dominated conditions (during ‘normal’ tidal conditions without significant waves) can cause scour development. However, for most structure shapes (monopiles, jackets, GBS) current-only or current-dominated conditions will create the deepest scour holes, while wave-dominated conditions will partially backfill the scour holes. This can be explained by the fact that the imbalance between sediment transport close and far away from the foundation will be much larger under current conditions, because the horseshoe vortex can hardly develop under oscillating wave conditions.

The scour depth that will develop around a monopile is illustrated in Figure 7.7 (Raaijmakers *et al.* 2013). The scour depth is presented as a dimensionless value: the scour depth S is divided by the pile diameter D. To be conservative long time series of relevant hydrodynamic input conditions were used to obtain conservative 95% non-exceedance values for the scour depth.

Since scour development is most sensitive to the magnitude of the (tidal) current velocity, this Figure also shows that the current velocities are strongest in the southern part of the Netherlands (e.g. the Borssele zone) and gradually reduce towards Hollandse Kust (noord) and the zone Ten noorden van de Waddeneilanden.

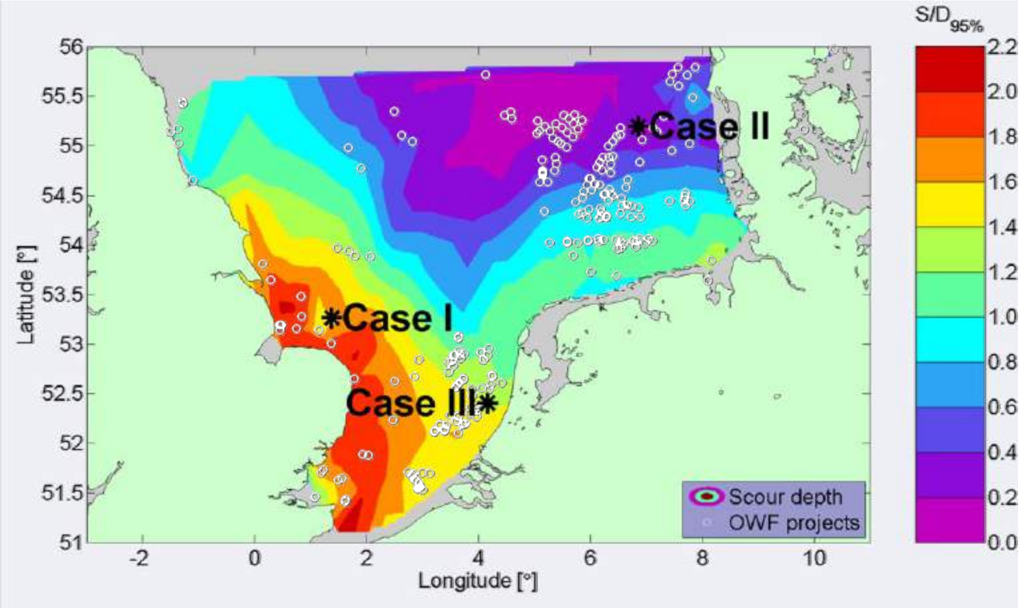

Figure 7.7 Map showing predicted dimensionless scour depth $(S/D_{pile})_{95\%}$ *for monopiles in the southern North Sea, illustrating that the flow velocities are decreasing in magnitude from south to north in front of the Dutch coast.*

A designer of offshore wind turbine foundations always should decide whether he chooses to protect the foundation against scour by installing a scour protection, or whether he adjusts the pile design by increasing the pile length and wall thickness. This decision is based on comparing the costs for installing scour protection against the costs for additional steel. An example of such a ‘decision map’ is presented in Figure 7.8 (Raaijmakers *et al.* 2013). This map shows that in the southern part of the Netherlands (Wind Farm Zones Borssele and Hollandse Kust (zuid)) installing a scour protection will be more cost-efficient. The more northerly wind farm zones (Hollandse Kust (noord) and Ten noorden van de Waddeneilanden) are around the break-even point, because the costs for additional steel consumption in case scour is allowed will exceed the costs for installing a scour protection. This break-even point will shift northward when wind turbines are getting bigger and monopile diameters are getting larger. Note that at present almost all existing monopile foundations (even the ones in the northern part of the German Bight) are equipped with a scour protection, since the prevailing guidelines still contain very conservative formulae to calculate the scour depth.

Different foundation types will require alternative decision making on the most efficient scour mitigation strategy. Foundations that are of the sit-on-bottom type (e.g. Gravity Base Structures: GBS) or are only shallowly penetrating the seabed (e.g. Suction Bucket Jackets: SBJ) will need a scour protection in most cases, whereas piled jackets can handle much more scour and will not have a scour protection in most cases. So, where this study only focuses on scour protection around monopiles ecologically friendly scour protections could also be applied around GBS and SBJ.

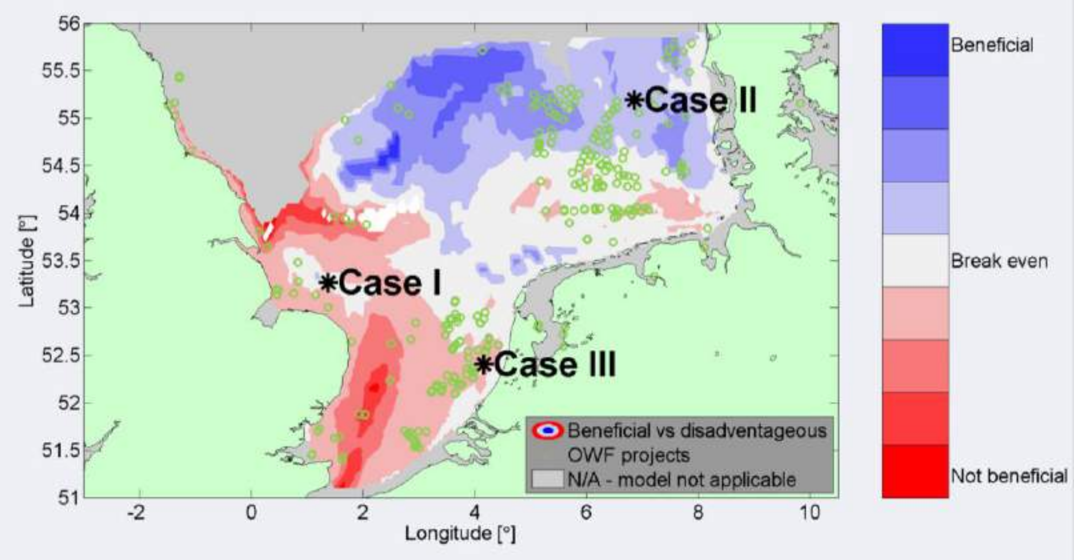

Figure 7.8 Map showing the areas where a scour protection is most needed (red areas) and where it can be considered to omit the scour protection (blue) note that this map is valid for 6m monopiles. For larger monopiles and turbine sizes the northern Dutch wind farm areas which are now grey will also become red.

7.3.2 Scour protection alternatives

Figure 7.9 (Left) An example of a scale model test for scour protection consisting of loose rock: a top layer of red and blue rock (armour layer) and a bottom layer of black rock (filter layer); (right) an example of a scale model test for scour protection consisting of frond mats (artificial seaweed)

Once it is decided that a scour protection is required, the designer should choose between different alternatives. The most commonly applied scour protection method is a protection consisting of a few layers of rock. The knowledge level and field experience is most extensive for this method. However, alternatives exist that are based on concrete block mattresses, geotubes or geocontainers, artificial seaweed, rock-filled bags and even nets filled with old car tyres. Figure 7.9 shows two scale model tests for a two-layer rock protection (left) and a protection consisting of frond mats (or artificial seaweed).
Every scour protection method should fulfil the technical requirements of a scour protection:

1. External stability
2. Internal stability
3. Flexibility

The first requirement of "external stability" refers to the stability of the top layer against the hydraulic loads. In the case of a scour protection consisting of loose rock, this would mean that the rocks need to be sufficiently heavy to resist the wave- and current-induced flows that are amplified by the presence of the structure. These rocks have an armouring function and are therefore referred to as "armour layer". For this armour layer two different external stability approaches can be followed, see Figure 7.10. In the left picture, a statically stable scour protection is depicted, which means that the armour rocks will remain stable under hydraulic conditions up to the design condition (for a wind turbine foundation typically a storm with a return period of 50 years). In the right picture a dynamically stable scour protection is presented. According to this design concept, armour rocks are allowed to move under the larger waves and even deformation is allowed as long as the underlying filter layer does not become exposed. The current design practice aims at further optimising this dynamic design concept, which allows for smaller and hence cheaper rock grades in the armour layer, but also implies that rocks close to the pile can move quite heavily.

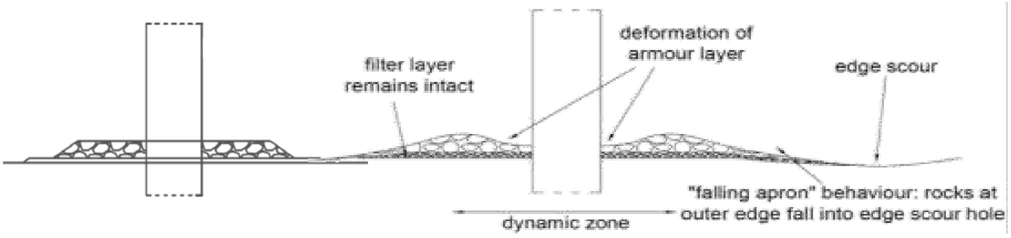

Figure 7.10 (Left) A statically stable scour protection; (right) a dynamically stable scour protection that can deform to some extent.

The second requirement refers to the ability of the scour protection to prevent material escaping from within the protection itself or from the layer underneath. In the case of a rock protection, this would result in the need of at least one filter layer consisting of smaller rocks to prevent the escaping of seabed sediment ("winnowing" or "suction removal" of sediment) that should be placed underneath the armour layer. The requirement of internal stability also refers to each individual layer itself. The smaller particles in a rock grade should not be able to escape from the rock layer. This means that the larger particles in a rock grade should not become much larger than the smaller particles in a rock grade. This is indicated by the grade width, often expressed by the ratio of D_{85} (the rock diameter of which 85% of the rock volume will be smaller) and D_{15} (the rock diameter for which 15% of the rock volume will be smaller). A practical rule-of-thumb tells that the grade width (D_{85}/D_{15}) should not become larger than 10-12. Or expressed alternatively: the larger particles in a grade should not become more than ~10 times larger than the smaller particles. This rule-of-thumb should be obeyed by all rock layers. As a consequence, it is not allowed to put large cobbles directly on the seabed, since that would cause a washout of the underlying seabed sediment. But it is also not allowed to mix very large cobbles with small gravel material, because then this layer itself will not be internally stable: or in other words, the smaller gravel particles will then be eroded from in between the larger cobbles.

The third requirement refers to flexibility. Even when you protect the seabed directly surrounding the seabed, still erosion of the seabed surrounding the scour protection can occur. This is referred to as edge scour (see also right picture in Figure 7.10 and Figure 7.11) and is caused by a pair of “contra-rotating vortices” that will develop downstream of the scour protection with respect to the dominant flow condition. Off the North Sea coast the flood velocities are dominant over the ebb velocities, causing edge scour to occur north-east of the scour protection.

Seabed lowering may also be related to autonomous large-scale morphological processes (e.g. migrating sand waves or tidal channels). For both cases, the scour protection should be able to follow this seabed lowering at the edges by deforming without completely failing. For a rock protection, this would result in filter rocks rolling down and protecting the side slope of the edge scour hole. This is referred to as “falling apron behaviour” (right picture in Figure 7.10). The commonly applied solution for rock protections to obey the flexibility-criterion is to increase the extent of the filter layer to allow for some sacrifice of filter rocks to the falling apron.

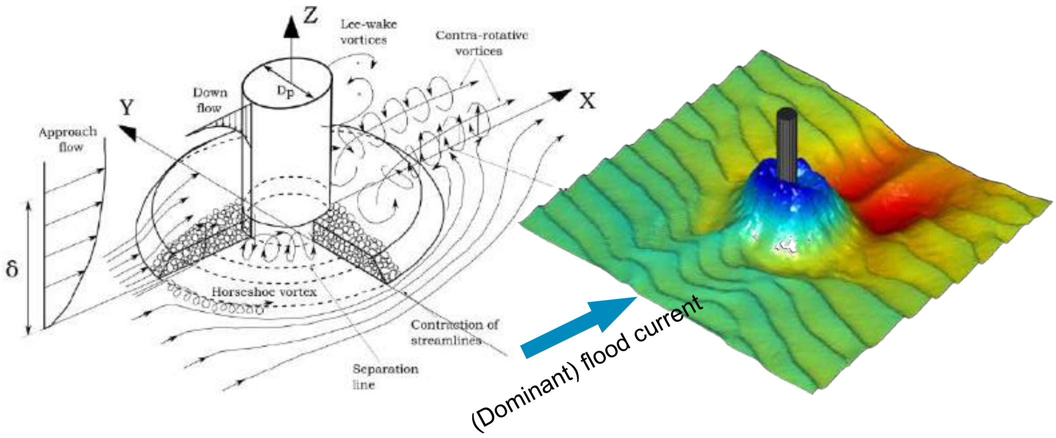

Figure 7.11 (Left) Flow patterns around a monopile with a scour protection; (right) example of edge scour that developed around a monopile with scour protection in Egmond aan Zee OWF.

In case of seabed lowering due to autonomous large-scale morphological processes, the seabed lowering may become too severe to adopt this “falling apron”-approach. The left picture of Figure 7.12 shows a part of wind farm zone Borssele where a pattern of sand waves (up to 8m high) is overlying a pattern of sand banks. The preferred method for wind farm design would be to locate the wind turbines in the sand wave troughs to limit the potential seabed lowering. If this is not feasible, a scour mitigation method needs to be developed that can deal with large seabed lowering. In the right picture of Figure 7.12 a scour protection method for very morphodynamic areas is illustrated that is based on 1) first predict and allow scour development; 2) at the right time install a single wide rock grade inside the scour hole (to benefit from the sheltered position) and with a sufficiently large extent; 3) monitor seabed lowering and falling apron behaviour in the following years and 4) perform maintenance whenever required.

For these locations, the requirements on the dimensions of the rocks are very tight and provide not much room for modifications. This is mainly due to the fact that a single wide grade need to fulfil all three main requirements within one rock grade, which are in essence contradictory: external stability asks for larger rocks, while internal stability puts limits on the rock sizes. To overcome this contradiction often a higher rock density is chosen (e.g. eclogite with a solid rock density of >3000 kg/m^3 instead of the more common granite with a rock density of ~2650 kg/m^3).

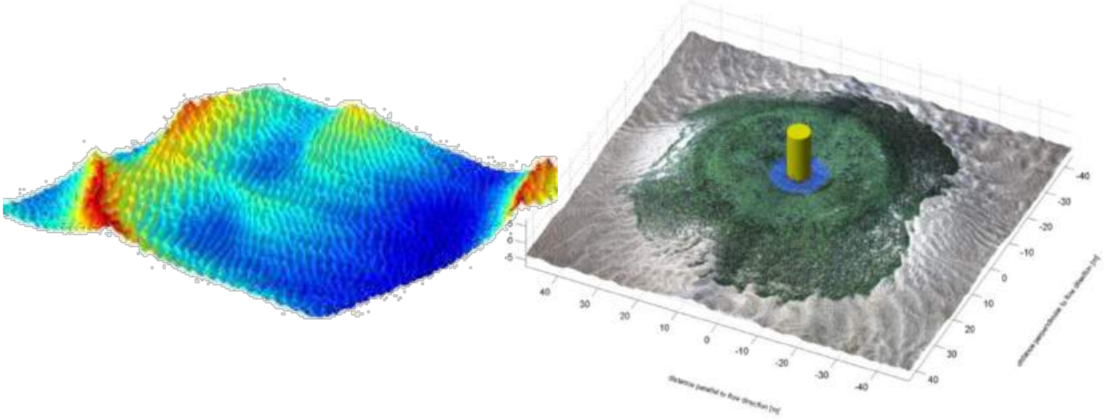

Figure 7.12 (Left) Bathymetry (North Sea bottom topography) in a part of Borssele Wind Farm Zone, showing sand waves overlying a pattern of sand banks (vertical scale is exaggerated); (right) scale model test of a scour protection that experiences a lowering of the surrounding seabed to simulate monopiles that are installed in a morphodynamic seabed such as Borssele.

7.3.3 Applied scour protection solutions in Dutch wind farms

Table 7.2 describes the adopted scour mitigation strategies that have been adopted in the Dutch offshore wind farms so far. All wind farms have scour protections with a larger and a smaller rock grade. The differences are related to the installation order and the ease of construction offshore. For the first Dutch wind farm, a (mildly) dynamic scour protection was designed, which resulted in a rock grade with a median grain size of about 40-45 cm. Since this rock grade was considered too large to drive the monopile through, the armour rocks were installed after installation of the monopile. This is a rather expensive and time-consuming and expensive method in offshore conditions. The second wind farm (Prinses Amalia) experimented with driving the monopiles first and then install first the cable and then the rock layers in the scour holes that developed around the monopile. The armour rocks could be dimensioned smaller, because the rocks were located more sheltered against the hydraulic loads. The drawback of this solution is that the monopile still needs to be extended, resulting in additional steel costs.

The current trend that was already followed in Luchterduinen and GEMINI is to further optimise the rock size of the armour grade. Besides reducing the costs for the grade itself, the main advantage of these smaller rocks is the fact that monopiles can be driven through both rock layers. This allows for efficient installation of the scour protections with large dedicated rock installation vessels (fall pipe vessels), which can manoeuvre freely, since the monopiles are not yet installed.

Besides this trend towards smaller rock grades, some wind farms are already equipped with single grade protections. These grades can also be installed prior to monopile installation; the smaller rock stability is often compensated by installing a larger layer thickness or by allowing some winnowing of seabed sediment through the scour protection.

An interesting concept could be to consider the use of a larger single grade that does no longer fulfil the seabed winnowing criteria. With this concept, some seabed lowering has to be allowed, but this solution may be the optimum between rock stability, ease of construction, costs for rock material and installation, a slight increase in steel consumption, while providing larger pore volumes in between the rocks for ecological purpose.

Table 7.2. Applied scour protection solutions in Dutch North Sea wind farms; ND and HD refer to normal density and high density rock. OWEZ: Offshore Wind Egmond aan Zee; PAWP Prinses Amalia Wind Park; LUD Luchtterduinen.

Wind Farm	Year	Applied or estimated rock grades	Installation Order	Edge scour (outside scour protection)	Morphodynamic seabed?
OWEZ	2006	Coarse armour grade (60-300kg ND) and 1-3” filter grade	1. filter layer 2. monopile 3. cables 4. armour layer	Almost in equilibrium: ~2.5-3m	Hardly
PAWP	2007	Medium coarse armour grade (10-200kg ND) and a coarse filter grade (2-8”)	1. monopile 2. scour development 3. cables 4. cushion layer (filter) 5. armour layer	Almost in equilibrium: ~1m	2 areas of sand waves, rest is ~stable
LUD	2015	Medium coarse armour grade and a 1-3” filter grade	1. filter layer 2. armour layer 3. monopile 4. cables (with cable protection)	Still developing, expected to be in the order ~2-2.5m	Completely covered with sand waves
GEMINI	2016 / 2017	Smaller armour grade (D_{50} = ~0.15m ND or HD) and a 1-3” filter grade	1. filter layer 2. armour layer 3. monopile 4. cables (with cable protection)	Still developing, expected to be in the order ~1-2m	Relatively stable seabed

Finally, some typical dimensions are presented for the currently adopted optimised designs. The extent of the armour layer is typically 3-4 times the pile diameter (measured at the top: so neglecting the side slopes of the armour layer). A typical armour layer thickness is 1-1.5m. The filter layer underneath typically has an extent of 5-6 times the pile diameter with a layer thickness between 0.4 and 0.8m.

8 Potential output ecological functioning

8.1 Ecology on currently used scour protection

In general, existing scour protection in wind farms for each monopile consists of a circular area with a diameter of at least four to six pile diameters (with pile diameters of 4-10 metres) of hard substrate rubble. This is an interesting substrate for various species due to its habitat complexity and the crevices between the stones (van Duren *et al.* 2016). “The scour protections will introduce new types of sub-littoral structures and increase the heterogeneity in the area. The introduced habitat will be suitable for colonization by a variety of marine invertebrates and attached algae. The hard bottom structures may act both individually and collectively as an artificial reef.” (Leonhard & Pedersen 2005).

The development of benthic communities on two Dutch and one Danish wind farms (monopiles and scour protection layer) in the North Sea has been described (Bouma & Lengkeek 2012; Vanagt *et al.* 2013; Leonhard & Pedersen 2005). In these studies, two methods were used: a qualitative method, using video footage and pictures, and a quantitative method, collecting several small rocks and bringing these to the surface in order to sample organisms present on rocks of the scour protection layer. Professional divers were used in conducting both methods.

8.1.1 Offshore wind farm Egmond aan Zee (OWEZ)

Information from Bouma & Lengkeek 2012:

Technical

The offshore wind farm Egmond aan Zee is located 10 to 18 km off the coast of Egmond aan Zee. The farm exists of 36 wind turbines in 27 km^2. The water depth within OWEZ varies between 15 to 20 metres (relative to LAT). Around the base of the monopiles a scour protection layer was installed with a diameter of approximately 25 metres, which consists of a filter layer of small sized rock and a top layer of heavier rock grade (§7.3.3).

Biodiversity

A total of 55 species were identified, of which a total of 35 species were identified on the scour protection layers (24 in 2008 and 18 in 2011) (Appendix B). Samples were collected from the scour protection of three turbines, two and five years after construction. In 2011, eight new species were recorded compared to 2008. A total of 14 species recorded in 2008 were not identified in 2011 and four distinct crustacean species were distinguished that were grouped during the analysis in 2008. Like September 2008, there were no clear differences between the hard substrate communities on rocks collected from the scour protection layers of the three different turbines.

Densities of marine organisms on the scour protection were high. Anemones (all species combined) reached densities of circa 2,500 individuals per m^2, approximately 2.5 times higher than on the monopiles, where they reached densities of circa 1,000 per m^2. Starfish (both species combined) reached densities of circa 180 individuals per m^2. The covering percentages of the sea mat and small crustaceans varied between 60-100% and 30-50% respectively. It should be noted that the extrapolation to densities per m^2 are subject to large error margins due to the low number of samples collected and the high variation between the samples. Therefore, these densities should be regarded as indicative only.

Non-indigenous species

The inventory of non-indigenous species within OWEZ includes those occurring on scour protections and monopiles. Several non-indigenous species have been identified in the 2008 and 2011 assessments including the titan acorn barnacle (*Megabalanus coccopoma*), the acorn barnacle (*Balanus perforatus*), the Australasian barnacle (*Elminius modestus*), the slipper limpet (*Crepidula fornicata*), the Pacific oyster (*Crassostrea gigas*), the skeleton shrimp (Caprella mutica), the small crustacean *Jassa marmorata*, the hairy crab (*Pilumnus hirtellus*) and the marine splash midge (*Telmatogeton japonicus*), see appendix B.

8.1.2 Prinses Amalia Wind Farm (PAWF)

Information from Vanagt & Faasse 2011 & Vanagt et al. 2013:

Technical

The Prinses Amalia Wind Farm is located 23 km off the coast of Velsen. The wind farm exists of 60 wind turbines in 14 km^2. The water depth within PAWF varies between 19 to 24 metres (relative to LAT). Around the base of the monopiles a scour-protection layer is installed with a diameter of approximately 15 m. This scour-protection consists of rock dump of various dimensions. The scour protection was installed inside the scour hole that was allowed to develop after monopile installation and therefore has a more sheltered position compared to the scour protection in OWEZ (§ 7.3.3). The rock sizes could be chosen to be smaller because of this more sheltered position.

Biodiversity

A total of 110 species were identified, of which a total of 49 species were identified on the scour protection layers (49 in 2011 and 42 in 2013). Therefore, the total number of species found in the scour protection layer is considerable higher than those found in OWEZ (35 species). Four wind turbine generators (WTG) were sampled at both sides of the monopile (NNE and SSW), three and four years after construction. In 2013, four new species were recorded compared to 2011.

Densities of epifouling species were three to 10 times higher, while biomass was similar to double the value found in 2011. In 2013 only a limited amount of small scour protection rocks was collected, due to the accumulation of mud between the rocks, which is a consequence of the more sheltered position inside the scour hole. Comparable to 2011, *Conopeum reticulum* was the most abundant bryozoan species present on the scour protection rocks, sometimes reaching well over 50% cover. On the video footage, several mobile organisms were identified between the rocks: *Asterias rubens, Cancer pagurus, Necora puber* were found in both studies and additional *Psammechinus miliaris* (2011), *Pagurus bernhardus* (2013) and *Pholis gunnellus* (2013). Very obvious was the large density of empty mussel shells close to the monopiles.

The rapid colonisation of the PAWF by high species numbers of certain taxonomical groups indicates a high biodiversity potential. In three years, the wind farm was been colonised by 75% (6 of 8) of the native Anthozoa species (sea anemones and soft corals) and a considerable number of Bryozoa species, among which some very rare and new ones. The distance of the wind farm to the coast is relatively high, which means that colonisation by species without a dispersive stage may take more time. Nevertheless, several of these slow dispersers (Amphipoda, Isopoda, Ascidiacea) were found. Some of them (*Idotea pelagica, Gitana sarsi, Stenothoe tergestina*) have not been recorded from wind farms in the area before.

Rare species

After only three years the wind farm was colonised by a diverse community including several rare species, some species unrecorded from the area and some species not recorded from other wind farms in the area. Several species of Bryozoa were found that are rare or very rare along the eastern seaboard of the Southern Bight of the North Sea.

The polychaete ross worm *Sabellaria spinulosa* constructs hard tubes of sand grains and may aggregate to form reefs. *Sabellaria* reefs used to be present in the international Wadden Sea but disappeared during the last century (Nehring, 1999). *S. spinulosa* has become a much less common species after the disappearance of the reefs. Hard substrates on sandy bottoms in areas of strong currents have the potential to attract *Sabellaria* larvae and facilitate reef formation. *Sabellaria* reefs are known to develop diverse species communities (Jones, 1998 in Nehring, 1999). During this survey, only separate individuals of the ross worm were found, but the authors didn’t exclude that reef formation will take place in the future.

8.1.3 Horns Rev (Denmark)

Information from Leonhard & Pedersen 2005:

Technical

The offshore wind farm Horns Rev in Denmark is located 14 to 20 km off the coast of Blåvands Huk (Denmark) in the east North Sea. The farm exists of 80 wind turbines in 27,5 km^2. The water depth within Horns Rev varies between 6.5 to 13.5 metres. A scour protection layer was installed with a diameter of approximately 25 metres, which is approximately 1.3 m in height above the original seabed. It consists of a protective rock cover, 0.8 m in thickness, of large stones up to 55 cm in diameter (armour rock). A filter layer (rock grade 30-200 mm) is installed below the armour layer, which extends up to 4 m beyond the armour layer.

Biodiversity
A total of 111 invertebrate species of epifauna were identified, of which a total of 54 species were identified on the scour protection layers. Samples were collected from stone blocks at all six turbine scour protection sites, before, during and after construction.

Seven dominant species on the scour protection constituted more than 98% of the total abundance and between 46% and 97% of the total biomass registered at all surveys. From 2003 to 2005, a considerable increase in abundance was found. This was most obvious for the autumn surveys and was largely a consequence of an increase in the abundance of *Jassa marmorata.* Locally, *Jassa marmorata* could be found in densities up to 238,000 ind./m^2. At most turbine sites, sea anemones contributed with a substantial biomass. The coverage of the sea anemones on the scour protection at greatest depths was up to 70%, whereas the coverage at the sites with shallower water was less than 25%. Further increasing significance was found in the biomass contribution of dead man's fingers (*Alcyonium digitatum*). *Alcyonium digitatum* was also more frequently represented at turbine sites at deeper waters.

In the transect surveys, no significant differences between the NNE and SSW transects were found. In general, as in the quantitative samples, statistical differences were found between the stations close to the monopile and stations at the edge of the scour protection. Close to the edge of the scour protections, no statistical differences were shown between stations across the zones with different size of stones.

8.1.4 Biodiversity of scour protection vs. other hard substrates

The biodiversity of both artificial and natural reefs is high. In total, the list of species observed on the wind farm scour protection, shipwrecks and the Cleaver Bank includes over 500 species. Since the Cleaver Bank surveys included soft sediment fauna as well, it is clear that shipwrecks contain the most species within the artificial reef overview. The numbers of species reported here are in the same order as the 417 North Sea reef species van Moorsel (2014) reported using, in part, different datasets. The richer reefs also include the highest absolute numbers of policy-relevant species as well as numbers of non-indigenous species, while the relative number of non-indigenous species is highest for the OWEZ and PAWF wind farms (Table 8.1).

Table 8.1 Total species observed on different reef structures, including number of samples taken per study, total observed policy-relevant species and non-indigenous species observed (Bouma & Lengkeek 2012; Vanagt & Faasse 2011; Vanagt et al. 2013; van Moorsel 2003; Leonhard & Pedersen 2005; Bos et al. in prep.; AquaSense unpublished data 2015). Background information (justification and status of species) "policy-relevant" and "non-indigenous" species are listed in Appendix A.

	Total species	**Sample size**	**Policy- relevant species**	**Non-indigenous species**
OWEZ scour protection	29	12	0 (0%)	5 (17%)
PAWF scour protection	56	13	2 (4%)	6 (11%)
Wreck study BuWa	283	87	20 (7%)	27 (10%)
Cleaver Bank survey Aquasense	83	172 (50 hamon + 122 ROV)	6 (7%)	3 (7%)
Cleaver Bank survey Ecosub	292	62	13 (4%)	13 (4%)
Horns Rev 1 scour protection	54	72	2 (4%)	5 (9%)

8.2 Expected added value of optimised designs

From the analysis in §8.1.3 it is clear that only a small portion of the potential number of species that can occur on hard substrates has been observed on existing wind farm scour protection. In addition, some priority species have not been observed and others have been observed in very low numbers. The gap between what is observed on wind farm scour protection to date and what is observed on other hard substrates, indicates the potential for improvement. Not to the full extent however, because not all determining factors for species distribution can be manipulated by optimising scour protection design.

An important note is that colonisation of new substrates, and the development of a mature and diverse epifaunal community, will take time. The monitoring period should be at least 10 years and evaluation of success should not be finalised within a shorter period of time.

8.2.1 Biodiversity

The total number of species observed on Dutch offshore wind farm scour protection to date is 71. The numbers of species per study found on other gravel and rock/rubble-type of hard substrate comparable (including Cleaver Bank and other scour protection) reached 292, and on shipwrecks 283. This illustrates the large potential for improvement.

It is impossible to predict accurately how many species can be added by optimising the scour protection design, however, considering that:

- The maximum number of species observed in studies on hard substrates in the Netherlands is four times that observed on scour protection to date;
- Conventional scour protections have not been designed for ecological purposes;
- As a consequence: Habitat complexity, variability, stability and durability are not as optimal as they can be.

It can be expected that the number of native species inhabiting the scour protection can be increased substantially when eco-friendly design principles are implemented.

8.2.2 Umbrella species

Atlantic cod is reported to occur near the scour protections and wind turbine foundations of the current Dutch offshore wind farms. It is expected however, based on field observations of shipwrecks and other artificial structures (Lengkeek *et al.* 2013a, b), and around restored rocky reefs (Stenberg *et al.* 2015), that optimising the scour protection design can further improve the local Atlantic cod habitat. In current wind farms, Atlantic cod may be attracted to the hard substrates mostly to feed, but adequate shelter for large Atlantic cod is not available. Providing adequate shelter is expected to result in higher Atlantic cod abundance and/or a more complete size distribution with occurrence of both juveniles and large adults. Furthermore, providing adequate shelter is expected to result in increased abundance of several other large mobile species (§3.4).

European flat oysters once formed substantial biogenic reefs on the North Sea seabed. They are currently rare in the North Sea, and the only living reef in the DCS (Dutch Continental Shelf) is reported from the coast near Zeeland consisting of a mixture of both European flat oysters and Pacific oysters. A few individuals of European flat oyster have been reported in current Dutch offshore wind farms, but in very low numbers (1 or 2 specimens per wind farm). Establishing or reintroducing an oyster reef on a wind farm location is expected to be feasible based on Smaal *et al.* (in prep.) and would be an important step towards active nature-restoration on the North Sea. To achieve successful reintroduction with an established population as a result, the habitat characteristics can be optimised (chemical properties and stability) and active reintroduction of a source population will be necessary.

8.3 Risk of non-indigenous species

Several different definitions can be used to assess whether a species is non-indigenous and invasive. Here, definitions described by Lodge *et al.* (2006) are followed:
A species is indicated as non-indigenous when it occurs outside its native range due to human influence. Non-indigenous species are considered invasive when the species causes or is likely to cause net harm to the economy, environment, or human

health. Here, only the presence of non-indigenous species is considered without information on their (potential) invasiveness.

8.3.1 General occurrence non-indigenous species

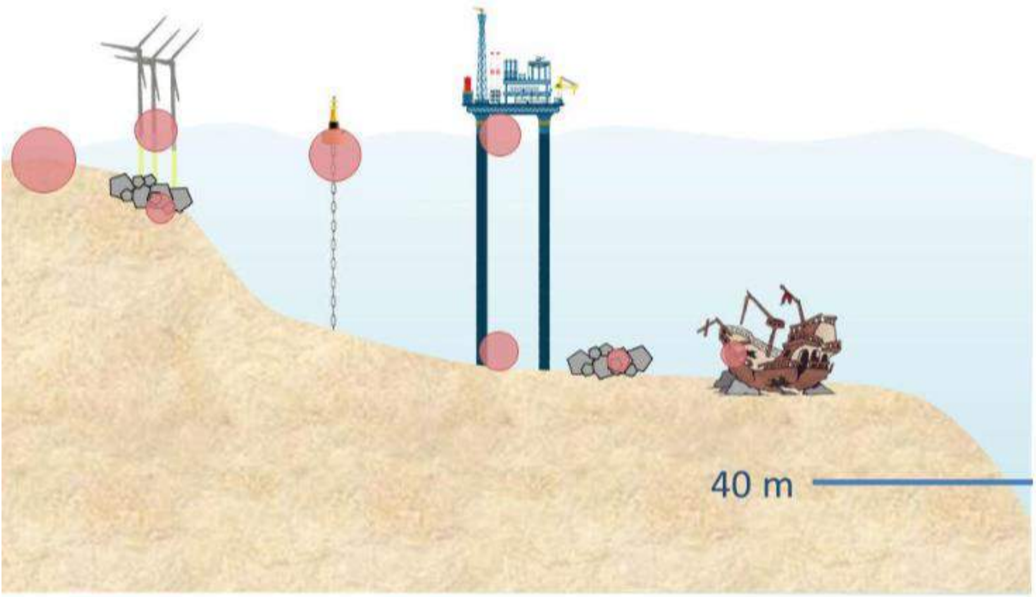

Figure 8.1. Non-indigenous species on hard substrates in the North Sea. Size of the circle is a relative indication of the numbers of non-indigenous species found on a specific substrate (from van Duren et al. 2016).

The spread of non-indigenous species in the North Sea is difficult to slow down since most species and especially the non-indigenous species that are known for their invasive behaviour, can travel long distances in their pelagic larval stage or, for example *Caprella mutica*, by utilising floating objects as rafts (Thiel & Gutow 2005). However, their spatial distribution within the North Sea shows a distinct pattern. Figure 8.1 (from van Duren *et al.* 2016) shows a graphic indication of the relative occurrence of non-indigenous species on artificial hard substrates in the North Sea. This schematic picture shows the highest numbers of hard substrate related non-indigenous species (several dozen) are expected along the coast in shallow waters (intertidal area and shallow depths) on floating objects and especially in marinas. In general, fewer non-indigenous species are expected further offshore. Along the coast hard substrate related non-indigenous species are expected on shellfish reefs (Pacific oyster reefs) and dykes (Gittenberger *et al.* 2010). The highest diversity of non-indigenous species off shore are found on floating objects such as buoys, followed by the intertidal area and area just below the low water mark in wind farms and on the legs of production platforms. In deeper water, few non-indigenous species are observed and particularly on artificial hard substrates such as wrecks. On natural hard substrates, such as stones, rocks and gravel of the Cleaver Bank, non-indigenous species are rarely observed (Van Moorsel 2014). Long term expectations using scour protection around older oil and gas platforms and the rocks in the Borkum Reef grounds are that amount of non-indigenous species that will sustain a population on offshore scour protection is limited. Ways to mitigate unintended facilitation of non-indigenous species can be summarised as 1) preventing transportation of living material 2) preventing installation of artificial substrates that are floating, distributed near the coast or in shallow water 3) prefer natural materials such as rocks over artificial material 4) not enhancing Pacific oyster reefs.

8.3.2 Non-indigenous species on rocky scour protection

To evaluate the risk of colonisation of offshore subtidal rocks by non-indigenous species, the list of known benthic species present on rocks in Dutch wind farms OWEZ and PAWF (Bouma & Lengkeek 2012; Vanagt & Faasse 2011; Vanagt *et al.* 2013), rocks around platforms (Coolen *et al.* 2017) and on rocks in the Borkum Reef grounds (Coolen *et al.* 2015) was cross-referenced with the list of native and non-indigenous species (Bos *et al.* in prep.). The Cleaver Bank records are not included here since these data also hold benthic soft bottom species.

Of a total of 124 species, 105 were confirmed to be indigenous, 7 were confirmed to be non-indigenous (Table 8.2) and for 12 species no data on status was available (Table 8.3). All the non-indigenous species on BRG were also observed in the wind farm. Within the list of species without status, *Sabellaria spinulosa* and *Balanus balanus* are unclear. Van Duren *et al.* (2016) included *Sabellaria spinulosa* as an indigenous species.

It is clear that non-indigenous species are certain to colonise the scour protection of newly installed wind farms. Whether these species can also be considered invasive, and therefore problematic, was not evaluated here.

Table 8.2 Overview of non-indigenous species on scour protection (WF=wind farm, PF=platform, BRG=Borkum Reef Grounds).

ScientificName_accepted	**WF**	**PF**	**BRG**	**Phylum**	**Family**
Monocorophium acherusicum	X	X	X	Arthropoda	Corophiidae
Monocorophium sextonae	X	X		Arthropoda	Corophiidae
Fenestrulina delicia	X			Bryozoa	Microporellidae
Smittoidea prolifica	X			Bryozoa	Smittinidae
Diplosoma listerianum	X		X	Chordata	Didemnidae
Diadumene lineata		X		Cnidaria	Diadumenidae
Crepidula fornicata	X		X	Mollusca	Calyptraeidae

Table 8.3 Overview of species without status (indigenous/ non-indigenous) on scour protection (WF=wind farm, PF=platform, BRG=Borkum Reef Grounds).

ScientificName_accepted	**WF**	**PF**	**BRG**	**Phylum**	**Family**
Phyllodoce longipes		X		Annelida	Phyllodocidae
Harmothoe fernandi		X	X	Annelida	Polynoidae
Subadyte pellucida		X		Annelida	Polynoidae
Proceraea prismatica			X	Annelida	Syllidae
Sabellaria spinulosa	X	X	X	Annelida	Sabellariidae
Balanus balanus		X	X	Arthropoda	Balanidae
Ischyrocerus anguipes			X	Arthropoda	Ischyroceridae
Cribrilina punctata		X		Bryozoa	Cribrilinidae
Garveia nutans			X	Cnidaria	Bougainvilliidae
Campanularia volubilis			X	Cnidaria	Campanulariidae
Corbula gibba		X		Mollusca	Corbulidae
Protosuberites epiphytum	X			Porifera	Suberitidae

9 Part II: Synthesis and discussion

The list of focal species is too broad and the information too sparse to design optimised scour protection for each species separately. By seeking a common ground for potential improvement for all species it may become feasible to increase the abundance of a significant amount of the focal species with limited effort. This may be attained by adding larger rocky substrates to scour protection or by increasing the area of seabed covered by gravel. By facilitating the umbrella species Atlantic cod and European flat oyster, and at the same time monitoring the overarching species groups ‘overall native biodiversity’ and ‘number of policy-relevant species’ more focal species may benefit on the long term. Although not all locations in all wind farms are suitable for European flat oysters, expectations are that selected locations within wind farms will be suitable for reintroduction of this keystone habitat altering species (Chapter 6).

Physical conditions can set the boundaries for the species expected to occur. Most species in the North Sea generally function well at circumstances with clear waters and high food availability, thus they prefer conditions that are not too dynamic. The analysis of physical conditions has focussed specifically on sediment dynamics and composition and bed shear stress and shows that the Southern part of the Dutch North Sea is mostly current dominated as opposed to the wave dominated conditions in the North. Wind Farm Zone (WFM) Borssele was shown to be relatively dynamic (relatively high sand waves, high average bed shear stress due to significant tidal currents) compared to the other planned wind farms.
‘Ten Noorden van de Waddeneilanden’ is a WFM that is relatively less dynamic (lower tidal current velocities and less mobile seabed), although it has a high maximum number of fine particles in the lower layers of the water column due to the relatively fine sediment composition. It is likely that these conditions only occur during larger storms when shear stress on the sediment increases.
Dynamics within a location can differ and need to be assessed when choosing optimal locations for artificial hard substrate in a wind farm. Focussing on the outer edges of the monopile might have more potential for ecological enhancement due to the stronger currents close to the monopile.

When placing wind turbine structures in the North Sea there is often a need to protect these structures against local erosion (scour) caused by increased flow velocities and turbulent vortices around the piles. Scour can develop in both wave-dominated and current-dominated conditions, but for monopiles current-dominated conditions cause the largest scour depths. Installing scour protection in the southern part of the Dutch North Sea at Borssele and the Hollandse Kust (zuid) is most cost beneficial, because tidal current velocities are most severe in the southern part of the Dutch North Sea. With increasing wind turbine sizes and monopile diameters, it is expected that also the more Northern locations will benefit beyond the break-even point from having scour protection. (Note that monopiles in existing wind farms almost all have scour protection because of too conservative guidelines that are now in the process of being updated).

There are different types of scour protection to choose from, however, they should all meet the requirements with respect to external stability, internal stability and flexibility. Conventional scour protections consist of two different layers of rock: an armour layer at the top with large rocks and a filter layer below with smaller rocks (Chapter 7).

The number of species on the conventional scour protection material that is currently deployed in the North Sea is relatively low compared to other artificial hard substrates. Therefore, the scour protection in Dutch offshore wind farm offers the potential for improving the ecology. Other hard substrates, such as shipwrecks, create a habitat for up to 283 species. Ecological improvements in scour protection can therefore stimulate overall native biodiversity, species richness and abundance of - policy-relevant - focal species in the North Sea.

Non-indigenous species will colonise the scour protection of newly installed wind farms. This has been observed on earlier studies in the OWEZ and PAWF. Longer term expectations from using scour protection around older oil and gas platforms and the rocks in the Borkum Reef grounds are that amount of non-indigenous species that will sustain a population on offshore scour protection is limited. To limit facilitation of non-indigenous species on offshore scour protection the transportation of living material and installation of floating objects should both be prevented, and the use natural materials such as rocks encouraged (Chapter 8).

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http://species-identification.org/species.php?species_group=mollusca&id=656

http://www.fishbase.org/summary/1349

http://www.fishbase.org/summary/2360

http://www.fishbase.org/summary/9198

http://www.iucnredlist.org/details/154644/0

http://www.marlin.ac.uk/species/detail/1560

http://www.marlin.ac.uk/species/detail/2002

http://www.marlin.ac.uk/species/detail/3

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http://www.fishbase.us/summary/speciessummary.php?id=2060
http://www.iucnredlist.org/details/161453/0
http://species-identification.org/species.php?species_group=sponges&id=251
http://www.iucnredlist.org/details/161626/0
http://www.fishbase.org/summary/5938
http://www.marinespecies.org/aphia.php?p=taxdetails&id=130888
http://www.marinespecies.org/aphia.php?p=taxdetails&id=132833
http://www.fishbase.org/summary/4326
http://www.fishbase.org/summary/4996
http://cvo-visserij.nl/wp-content/uploads/2015/11/Factsheet-Gladde-HaaiNL.pdf
http://www.iucnredlist.org/details/161691/0
http://www.fishbase.org/summary/4552
http://www.fishbase.org/summary/845
http://www.iucnredlist.org/details/161484/0
http://eol.org/pages/910773/overview
http://www.fishbase.org/summary/2535
http://www.fishbase.org/summary/2565
http://www.iucnredlist.org/details/6336/0
http://www.fishbase.org/summary/Galeorhinus-galeus.html
http://www.iucnredlist.org/details/11141/0
http://www.fishbase.org/summary/7617
http://www.iucnredlist.org/details/22563/0
http://www.efsa.co.uk/record/smooth.htm
http://www.iucnredlist.org/details/full/39358/0
http://www.fishbase.org/summary/2059

Appendix A Species list

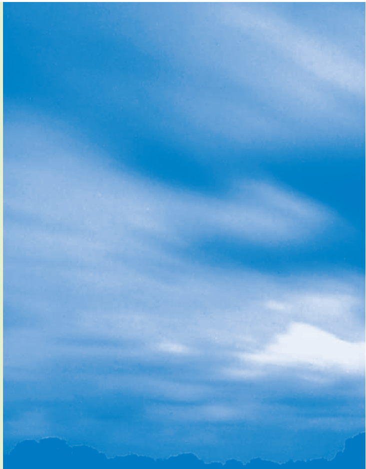
1. Scientific name	**2. Dutch common name**	3. English common name	4. Hard substrate	5. Intertidal only?	6. Coastal only?	7. Habitat Directive annex no.	8. N2000 area reference number	9. Typical species for habitat	10. Typical species for MSFD	11. Dutch policy document	12. OSPAR species NL	13. POLICY_HD_Annex_all	14. POLICY_HD_Annex_II	15. POLICY_HD_Annex_IV	16. POLICY_HD_Annex_V	17. POLICY_N2000_areas_for _species_YESNO	18. POLICY_N2000_areas_for_species_number	19. POLICY_N2000_Typical_species_H1170	20. POLICY_KRM_H1170 Riffen	21. POLICY_policy_NL_shark action plan	22. POLICY_Harbour Porpoise Conservation Plan	23. POLICY_policy_reintroduction European oyster	24. POLICY_OSPAR_species_relevant_for_NL	25. POLICY_Dutch_Red_Lists	26. POLICY_RedList_Status_long
Aequipecten opercularis	Wijde mantel	queen scallop	1	0	0			H1170										1							
Alcyonium digitatum	Dodemansduim	dead man's fingers	1	0	0			H1110C, H1170	H1170									1	1						
Alopias vulpinus	Voshaai	Thresher	0							Haaien actieplan										1					
Amblyraja radiata	Sterrog	Starry ray	0							Haaien actieplan										1					
Anguilla anguilla	Paling	Eel	0								1												1		
Aporrhais pespelecani	Pelikaansvoet	pelican's foot	1	0	0			H1170										1							
Arcopagia crassa	Stevige platschelp	blunt tellin	1	0	0			H1170										1							
Arctica islandica	Noordkromp	ocean quahog	0					H1110C			1												1		
Atherina boyeri	Kleine koornaarvis	big-scale sand-smelt	0																					1	Gevoelig (GE)
Belone belone	Geep	Garfish	0																					1	Bedreigd (BE)
Buccinum undatum	Wulk	Whelk	1	0	0			H1110ABC, H1140A, H1170										1							
Cetorhinus maximus	Reuzenhaai	basking shark	0							Haaien actieplan										1					

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Chone duneri	onbekend	unknown	1	0	0			H1170	H1170									1	1						
Symphodus melops	Zwartooglipvis	corkwing wrasse	1	0	1																			1	Gevoelig (GE)
Dasyatis pastinaca	Pijlstaartrog	Common stingray	1	0	0					Haaien actieplan										1					
Delphinus delphis	Gewone dolfijn	Atlantic Dolphin	0			IV						IV		1											
Dipturus batis	Vleet	common skate	0							Haaien actieplan	1									1			1	1	Verdwenen (VN)
Dosinia exoleta	Gewone artemisschelp	rayed artemis	1	0	0			H1170										1							
Gadus morhua	Kabeljauw	Cod	1	0	0			H1110C			1												1	1	Gevoelig (GE)
Galathea intermedia	Oprolkreeft	Squat lobster	1	0	0			H1170	H1170									1	1						
Galeorhinus galeus	Ruwe haai	Tope shark	0							Haaien actieplan										1					
Halichoerus grypus	Grijze zeehond	Grey seal	0			II, V	7, 113, 163, 164, 165, 166					II, V	1		1	1	6							1	Gevoelig (GE)
Haliclona (Haliclona) oculata	Geweispons	Mermaid’s glove	1	0	0			H1170										1							
Hippocampus guttulatus	Zeepaardje	Long-snouted seahorse	1	0	1						1												1		
Lagenorhynchus acutus	Witflankdolfijn	Atlantic White-sided Dolphin	0			IV						IV		1											
Lagenorhynchus albirostris	Witsnuitdolfijn	White-beaked dolphin	0			IV						IV		1											
Lamna nasus	Haringhaai	porbeagle	0							Haaien actieplan										1					
Lampetra fluviatilis	Rivierprik	river lamprey	0			II, V	7, 113, 163					II, V	1		1	1	3							1	Gevoelig (GE)
Leucoraja naevus	Grootoogrog	Cuckoo ray	1	0	0					Haaien actieplan										1					
Liparis liparis liparis	Slakdolf	sea snail	1	0	0			H1110AB																1	Kwetsbaar (KW)
Lipophrys pholis	Slijmvis	shanny	1	0	1																			1	Gevoelig (GE)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Lophius piscatorius	Zeeduivel	angler	0	0	0			H1170										1							
Merlangius merlangus	Wijting	Whiting	0					H1110BC																1	Gevoelig (GE)
Microstomus kitt	Tongschar	Lemon sole	1	0	0			H1110C																1	Gevoelig (GE)
Mustelus asterias	Gevlekte gladde haai	Starry smooth-hound	1	0	0					Haaien actieplan										1					
Mustelus mustelus	Gladde haai	Smooth-hound	1	0	0					Haaien actieplan										1					
Nucella lapillus	Purperslak	dog whelk	1	1							1												1		
Ostrea edulis	Platte oester	European flat oyster	1	0	0					Herintroductie Platte Oester	1											1	1		
Petromyzon marinus	Zeeprik	Sea lamprey	0			II	7, 113, 163				1	II	1			1	3						1	1	Gevoelig (GE)
Phoca vitulina	Gewone zeehond	Harbour seal	0			II, V	7, 113, 163, 164, 165, 166					II, V	1		1	1	6							1	Kwetsbaar (KW)
Phocoena phocoena	Bruinvis	Harbour porpoise	0			II, IV	7, 163, 164, 165, 166			Bruinvis beschermingsplan	1	II, IV	1	1		1	5				1		1	1	Kwetsbaar (KW)
Phrynorhombus norvegicus	Dwergbot	Norwegian topknot	1	0	0																			1	Gevoelig (GE)
Monia patelliformis	Manteldekschelp	ribbed saddle-oyster	1	0	0				H1170										1						
Raja brachyura	Blonde rog	Blonde Ray	1	0	0					Haaien actieplan										1					
Raja clavata	Stekelrog	Thornback skate / ray	1	0	0					Haaien actieplan	1									1			1	1	Bedreigd (BE)
Raja montagui	Gevlekte rog	Spotted ray	0							Haaien actieplan	1									1			1	1	Ernstig bedreigd (EB)
Raja undulata	Golfrog	Undulate ray	0							Haaien actieplan										1					
Raniceps raninus	Vorskwab	Tadpole-fish	1	0	0																			1	Bedreigd (BE)
Sabellaria spinulosa	Zandkokerworm	Ross worm	1	0	0			H1170	H1170									1	1						

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Scomber scombrus	Makreel	Mackerel	0																					1	Kwetsbaar (KW)
Scyliorhinus canicula	Hondshaai	Dogfish	1	0	0					Haaien actieplan										1					
Scyliorhinus stellaris	Kathaai	Nursehound	1	0	0					Haaien actieplan										1					
Simnia patula	'Gestreepte pegelhoren'; 'Stiefelslak'	unknown	1	0	0			H1170										1							
Spinachia spinachia	Zeestekelbaars	sea stickleback	0																					1	Verdwenen (VN)
Squalus acanthias	Doornhaai	Spurdog	0							Haaien actieplan	1									1			1	1	Ernstig bedreigd (EB)
Squatina squatina	Zee-engel	angelshark	0							Haaien actieplan	1									1			1		
Syngnathus typhle	Trompetterzeenaald	Broad-nosed pipefish	0																					1	Verdwenen (VN)
Trachinus draco	Grote pieterman	greater weaver	0																					1	Ernstig bedreigd (EB)
Trachurus trachurus	Horsmakreel	Horse mackerel	0																					1	Kwetsbaar (KW)
Trisopterus minutus	Dwergbolk	Poor cod	1	0	0																			1	Gevoelig (GE)
Tursiops truncatus	Tuimelaar	Bottle-nosed Dolphin	0			IV						IV		1										1	Verdwenen (VN)
Urticina felina	Zeedahlia	dahlia anemone	1	0	0			H1170	H1170									1	1						
Zoarces viviparus	Puitaal	Viviparous blenny	1	0	1			H1110A																1	Kwetsbaar (KW)
Alosa fallax	Fint	Twaite shad	0			II, V	7, 113, 163					II, V	1		1	1	3							1	Verdwenen (VN)
Osmerus eperlanus	Spiering	Smelt	0																					1	Kwetsbaar (KW)
Salmo salar	Atlantische zalm	Salmon	0			V					1	V			1								1		
Hippocampus hippocampus	Kortsnuitzeepaardje	short-snouted seahorse	1	0	1						1												1	1	Gevoelig (GE)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Coregonus oxyrinchus	Noordzeehouting	Houting	0			IV					1	IV		1									1	1	Gevoelig (GE)
Micrenophrys lilljeborgii	Noorse zeedonderpad	Norway bullhead	1	0	0			H1170										1							
Lithothamnion sonderi	onbekend	unknown	1	0	0			H1170	H1170									1	1						



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