Nature-enhancing design of scour protection for monopiles in the North Sea

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by

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Cover image: The North Sea as seen from space (NASA, 2003)

Preface

As a civil engineering student in the field of hydraulic structures I had, even though I found it interesting, little knowledge about ecology. This study, in which the technical design of a scour protection and the impact of this design on marine life was the main focus, allowed me to expand my knowledge in the field of ecology and to combine this with the knowledge that I gathered during the past six years of my study, resulting in this MSc-thesis. However, I could not have done this without the help of many people and will therefore take a moment to thank them.

First of all I want to express my gratitude to my supervisor at Witteveen+Bos, Tom Wilms, who shared his insights, provided valuable feedback, and gave helpful advice on multiple occasions. I also want to thank the rest of my thesis committee; Mark van Koningsveld, Gregory Smith, Bas Hofland, and Remment ter Hofstede for their feedback on my presentations and their shared insights.

Another group of persons I want to thank is that of my family and friends, who motivated me and distracted me when necessary. A special thanks to my wife Magriet, who supported me throughout my whole study.

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Abstract

A combination of the growth of the offshore wind energy sector and the decline in both species richness and species abundance in the North Sea has inspired the goal to use the scour protection in wind farms as a means to enhance marine life. Present research has focused on general changes which are to be applied to benefit marine life. However, it lacks practical applications of changes to the design of the scour protection and fails to quantify the expected effects of these changes.

In this study the extend to which marine life in the North Sea can be enhanced through improvements to the scour protection design for monopiles in wind farms is researched by comparing the habitat suitability in three situations (North Sea in absence of wind farms, North Sea with wind farms and scour protections as currently designed, and wind farms with enhanced scour protections) for four indicator species (Atlantic cod, European lobster, flat oyster, and the Ross worm). For the third situation (the enhanced scour protections), several habitat enhancements as well as some stock enhancements have been proposed and their expected effects and costs have been studied.

The availability of hard substrate and the absence of (seabed disturbing) fisheries is what makes wind farms suitable compared to a sandy sea bed. These habitats can be further improved by using a large and narrow grading to provide shelter and stable attachment material and by placement of additional elements such as piles of rock, (concrete) tubes, and shell filled nets. Species which are not likely to successfully colonize the wind farm, such as the European lobster and flat oyster, are to be introduced by humans through stock enhancements.

Extended abstract

In the past years the offshore wind energy sector has experienced an ongoing growth due to the renewable energy goals set by the members of the European Council in an attempt to limit the emissions of greenhouse gasses. This growth is expected to continue as the deadline of these goals approaches.
Many wind turbine foundations are monopiles. These monopiles have a scour protection to prevent the development of a scour hole near the the monopile, which would threaten their stability. Although the scour protection, which often consists of quarried rock, is not a naturally occurring material in the North Sea, it is beneficial to many species and to biodiversity in general.

The effect of a scour protection on marine life and the possibilities to design the scour protection in a way that benefits marine life have been studied in the past. However, this research lacks practical applications of changes to the design of the scour protection and fails to quantify the expected effects of these changes.

The objective of this study is to determine how the design of scour protections around monopiles in the North Sea can be adapted to create suitable habitat for marine life and to quantify the effects of these changes.
The following research question is formulated:

To what extent can marine life in the North Sea be enhanced through improvements to the scour protection design for monopiles in wind farms?

The steps that precede the answer to this question are:

- Setting up a framework which consists of:
  - General information about wind farms in the North Sea and specific information about a reference wind farm.
  - A description of the physical environment in the North Sea and in the reference wind farm.
  - Information on scour protection design and specifically about the scour protection design in the reference wind farm.
  - General information about species in the North Sea, the reasoning behind the selection of four indicator species, and information about these species.
- Analyzing the suitability of the North Sea in absence of wind farms for the selected indicator species.
- Analyzing the suitability of the North Sea for the selected indicator species with wind farms and scour protections as currently designed.
- Analyzing the potential for nature enhancement with improved scour protections.

Setting up a framework

The framework is used to present information which serves as a basis on which the answers to the research question(s) are founded.

Wind farms in general and the reference wind farm
Currently about 12,800 MW of offshore wind capacity is installed in the North Sea and it is expected that in the near future this will increase with another 24,400 MW. Most of these wind farms will be constructed relatively close to the coast in waters up to 40 m in depth with monopiles as foundations. Reference wind farm 'Gemini' is one of the recently constructed wind farms and is located about 80 km north of the coast of Groningen. It consists of two plots of 75 wind turbines with a combined capacity of 600 MW. The turbines are supported by monopiles with a base diameter of 7.1 m and surrounded by a scour protection consisting of a 1-3" filter layer and a 3-9"HD armour layer (" stands for *inch*, which is 2.54 cm).

Physical environment
The North Sea is a shallow sea which in many places is not deeper than 80 m and is shallower in the South than in the North. The Southern part of the North Sea is also more sheltered from higher waves. Currents show an anti-clockwise direction throughout the whole North Sea with smaller scale currents going either in clockwise or anti-clockwise direction. Most of the North Sea seabed consists of soft substrate in the form of sand or mud. Some hard substrate is present: natural hard substrate in the form of gravel, pebbles, and boulders, and artificial hard substrate in the form of shipwrecks, artificial reefs, and foundations and scour protections for oil and gas platforms and wind turbines.
The physical environment in the reference wind farm can be described as follows: Water depths between -37 m LAT and -28 m LAT with a sandy seabed, current velocities usually below 0.7 m/s and significant wave heights which commonly are below 3 m but can be as large as 10 m in the most extreme storm conditions.

Scour protection design
A scour protection is constructed to keep a potential scour hole far enough away from the monopile to safeguard its stability. Quarried rock is the most common type of scour protection and is usually constructed in multiple layers. The scour protection in the reference wind farm consists of two layers: a 1-3" filter layer to prevent winnowing, which has a diameter of 4.25 times the pile diameter, and a 3-9"HD armour layer to resist the hydrodynamic forces induced by currents and waves, which has a diameter of 3 times the pile diameter. This results in a total of 388 m^3 of armour layer material and 362 m^3 of filter layer material and a covered area of 733 m^2 per scour protection.

Species
There are more than a thousand different species in the Dutch part of the North Sea which can not all be researched due to limited time and information available. Four species (Atlantic cod, European lobster, European flat oyster, and Ross worm) are selected because they are very different from each other, native to the North Sea, threatened or of high commercial value, and because they interact with the seabed in various ways. The juvenile Atlantic cod finds shelter on the seabed in holes and crevices while the adults forage on species that occur on and around the seabed. The European lobster finds shelter on the seabed in holes and crevices, the juveniles to shelter from predators and currents and the adults to shelter from currents. The European flat oyster prefers to settle on present oyster reefs or on the shells of other bivalves but is also known to use rocks and other hard substrate to attach to. The Ross worm requires a hard substrate to settle on before building its tube out of sand and shell fragments that are stirred up from the seabed. The occurrence and survival of these species depend on several factors: food abundance; suitable substrate for shelter and settlement; currents which transport food and oxygen but can also hinder the species; fishing, which extracts species and can destroy the present substrate; predators; water depth; competition for food and space; minimum number of species required to obtain a healthy population; a mobility which might hinder the distribution of the species over a larger area; and soil composition.

An analysis of the suitability of the North Sea in absence of wind farms
In general it can be said that (seabed disturbing) fisheries and the lack of suitable substrate in the form of rock and shells are the largest inhibiting factors for the four species in the North

Sea. The Atlantic cod is the most likely indicator species to recover when fishing is strictly regulated. Both the European lobster and the flat oyster are unlikely to spread throughout the North Sea without human intervention due to their limited mobility. Little is known about the Ross worm, but as long as seabed disturbing fisheries destroy their reefs and no hard substrate is present to build new reefs there is little chance of recovery for this species.

An analysis of the suitability of the North Sea with wind farms with basic scour protections

The construction of a wind farm with hard substrate increases the food abundance locally (on the scour protection) with a factor 24 compared to a sandy seabed (Coolen et al., 2019), on wind farm scale this is a 4% increase compared to the situation before the construction of the wind farm.

The armour layer serves as a suitable substrate for juvenile cod which hide in the holes in the scour protection, but for larger species, such as the adult cod and the adult lobster, the holes in the 3-9"HD armour layer are too small.

The 1-3" filter layer is not stable enough to be used as a settling substrate for the flat oyster and the Ross worm (multiple layers are displaced during 1/1 year storm conditions). The armour layer is stable enough to be used by the flat oyster and Ross worm.

Fishing is currently not allowed within the wind farm or 500 m around it. This meanst that an area of 92.7 km^2 is closed for fishing in the reference wind farm, which is beneficial for all species. However, 92.7 km^2 is 0.018% of the North Sea and 0.163% of the Dutch part of the North Sea, from which can be concluded that locally (in the wind farm) the suitability with regards to fisheries has increased, but that on a larger level ((Dutch) North Sea) the change is insignificant.

Juvenile cod competes for shelter sites in the scour protection. A single armour layer is estimated to provide habitat for about 620 juvenile cod of 0.06 m in length, which translates to 93,000 in the whole wind farm. The lobsters, which are very territorial, are commonly found on hard substrate in densities between 1 and 20 per 100 m^2, resulting in a total of 7-154 lobsters per scour protection and 1,200-23,200 in all of the wind farm. However, the limited hole size in the scour protection prohibits the lobster from inhabiting the wind farm. The flat oyster competes with other species for settlement area, but no references are found that quantify densities.

The Atlantic cod is a very mobile species and the larvae of the Ross worm have a long pelagic stage during which the currents can transport them over long distances, allowing these two species to spread over all of the North Sea. This is not the case for the European lobster and the flat oyster, which are less mobile and not abundant enough to inhibit the distant wind farms successfully.

From this it can be concluded that wind farms with their scour protections as currently designed are beneficial for all four indicator species but that only the Atlantic cod and possibly the Ross worm will benefit from its construction. The European lobster and the flat oyster require human intervention to inhabit the wind farms in large numbers.

An analysis of the potential for nature improvement with enhanced scour protections

Three methods to enhance the populations of the indicator species are considered: Habitat enhancement; Stock enhancement; and Food enhancement.

<u>Habitat enhancement</u> aims at improving the habitat for the selected species and consists of changes to the scour protection design and the placement of additional beneficial elements.

- Changes to the scour protection design:
  - Increasing the grading size.
    This leads to larger holes in the scour protection and benefits cod and lobster. Additionally the scour protection will be more stable which benefits the oyster and Ross worm. The cost of this improvement is estimated to be similar to a common scour protection.
  - Narrowing grading width.
    This leads to slightly larger holes in the scour protection and benefits cod and lobster and can be done without any significant extra costs.

  - Changing the horizontal dimensions.
    This increases all beneficial factors of a scour protection but requires a lot of extra material and will therefore be costly. Increasing the armour layer area from 460 m^2 to 780 m^2 per pile (70% increase) would require an additional 300 m^3 of rock per pile (77% increase). Increasing the filter layer area from 770 m^2 to 1,170 m^2 per pile (52% increase) would require an additional 195 m^3 of rock per pile (54% increase). The armour layer provides larger holes than the filter layer while the filter layer provides suitable settling substrate for the Ross worm at its edges (assumed that the grading is large enough to be stable).

- Placement of additional beneficial elements:
  - Placement of 450 piles of rock of 1 metre in height throughout the wind farm.
    This creates extra hard substrate with holes and crevices which benefit cod and lobsters. Additionally the calm areas created by these piles allow for spat settlement while the turbulent areas are suitable for the Ross worm.
  - Placement of 900 rocks of 1 metre diameter throughout the wind farm.
    This creates extra hard substrate which benefit cod and lobsters by providing food. Additionally the calm areas created by these rocks allow for spat settlement while the turbulent areas are suitable for the Ross worm. This solution has been judged to be financially unfeasible since these rocks are rare and thus difficult to acquire.
  - Placement of 450 (concrete) tubes on the scour protection.
    This creates holes which serve as shelter for large cod and lobsters. Additionally the surface of the tubes serves as a hard substrate to which various species can attach.
  - Placement of 450 shell-filled nets on the scour protection.
    This creates 2,800 m^2 suitable settling substrate for oyster spat on which a total of approximately 20,000 oysters can grow.

Stock enhancement aims at increasing the abundance of the selected species by introducing species which have been reared or cultivated somewhere else. This can be done for the European lobster and the flat oyster, which are limited in their mobility and therefore do not easily reach a wind farm by themselves.
The lobster stock enhancement consists of releasing 40,000 hatchery reared lobsters of 0.005-0.007 m (stage IV and V) over the course of four years. This is estimated to lead to a self sustaining population of approximately 10,000 lobsters in the short term, and a population between 1,200 and 23,200 lobsters in the long term (assuming that the scour protection provides enough shelter). The cost of this enhancement is estimated to be €287,500.
The oyster stock enhancement consists of releasing 49,000 oysters of different ages (and thus sexes) in broodstock cages with clean empty shells as settling material. This is estimated to lead to a self sustaining oyster population of approximately 29,000 oysters in the short term and, when successful, a population of $8.3*10^6$ - $46.4*10^6$ oysters in the long term. The costs of this enhancement is estimated to be €955,000.

Food enhancement aims at increasing the amount of food available for the selected species. This can be done by letting fishermen discard their bycatch within the wind farm. However, it is estimated that this solution is not feasible.

Conclusion and recommendations
Marine life in the North Sea can be enhanced through the improvements which are listed above. The extent to which each improvement enhances marine life differs. By implementing several of the improvements into the scour protection design, and by stock enhancements for the European lobster and the flat oyster it is possible that a wind farm such as Gemini in the long term provides a suitable habitat for thousands to tens of thousands of Atlantic cod and European lobsters, millions to tens of millions of flat oysters, and more than 20,000 m^2 of Ross worm reefs.
It is recommended to verify the validity of the proposed solutions. The validity can be tested

with a pilot study or with multiple pilot studies in which several different scour protection designs are applied in a wind farm (or multiple wind farms) and by implementing stock enhancements for the lobster and oyster. Requirements regarding these improvements is then to be included in future tenders.

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Symbol	Unit	Description
a_b	m	Horizontal wave amplitude at the seabed
C	$\sqrt{m}/s$	Chézy coefficient
CL	m	Lobster carapace length
D_{50}	m	Median rock diameter
D_X	m	The diameter at which X% of the sample's mass is comprised of rocks with a diameter less than this value
D_{n50}	m	Median nominal rock diameter
D_{nX}	m	The diameter at which X% of the sample's mass is comprised of rocks with a nominal diameter less than this value
D_{pile}	m	Diameter of the monopile
f_c	$-$	Current friction factor
f_w	$-$	Wave friction factor
F	m	Start point
g	m/s^2	Gravitational acceleration
h	m	Water depth
H_{m0}	m	Significant wave height
H_s	m	Significant wave height
H_{max}	m	Maximum wave height
H	m	Wave height
H_X	m	The diameter at which X% of the sample's holes have a diameter less than this value
k_r	m	Nikuradse roughness
L	m	Wave length
m	$-$	Shape factor
N_{pores}	$-$	Number of pores in a volume of a grading
P_{80}	$-$	Slope factor
r	m	Radius of the scour hole
S	m	Equilibrium scour depth
TL	m	Total lobster length
T_p	s	Peak wave period
T_{02}	s	Zero crossing wave period
T_w	s	Wave period
U_c	m/s	Current velocity
U_w	m/s	Horizontal wave induced flow velocity
Δ	$-$	Relative stone density
ρ_w	kg/m^3	Density of water
τ_c	N/m^2	Current induced bed shear stress
τ_{cr}	N/m^2	Critical bed shear stress
τ_m	N/m^2	Mean bed shear stress
τ_{max}	N/m^2	Maximum bed shear stress
τ_w	N/m^2	Wave induced bed shear stress
φ	$degree$	Friction angle of the soil
ϕ	rad	Angle between the wave and current direction
Ψ_{cr}	$-$	Critical Shields parameter

1 Introduction

1.1. Context

1.1.1. Growth of offshore wind energy sector

It is widely known and agreed upon that the climate is changing rapidly, and that humans are the cause of this accelerated global warming (Cook et al., 2016). In an attempt to limit the increase of global average temperature 174 states and the European Union (195 states in total) signed the Paris Agreement in which they agreed to '*Holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change*' (United Nations, 2015). As a follow-up the European Council has committed to generate 27% of its total energy generation through renewable energy sources by 2030 (European Council, 2014). This commitment by the European Council has translated itself into goals set by its members. The Dutch government for example has set goals in its coalition agreement to reduce the emission of greenhouse gasses by 49% compared to 1990 levels before 2030, which partially must be realized by the construction of more offshore wind farms (VVD et al., 2017).
Not only the Netherlands is aiming to increase its offshore wind capacity (from 4.5 GW in 2023 to 11.5 GW in 2030 (Wiebes, 2018)), also the UK (Department of Energy & Climate Change, 2011), Germany, Denmark and Norway are looking to build more offshore wind turbines in the North Sea.

1.1.2. Reduction of ecological wealth

The North Sea has experienced a decline in both species abundance and species richness over the last decades. This is mostly due to fishery and to bottom trawling in particular (Marine Information Network, 2011). Apart from catching (shell)fish faster than they can reproduce, bottom trawling also disrupts or destroys the substrate that many species require. The oyster beds for example, which used to cover large parts of the North Sea sea bed (as can be seen in Figure 1.1) have almost completely disappeared and with it a substantial amount of hard substrate and species which lived on and around these oyster beds.

1.1.3. Ambition for change

Hard substrate provides habitat for species that are unable to establish populations on sandy seabeds (Smaal et al., 2017; Lengkeek et al., 2017; Van Duren et al., 2017; Coolen et al., 2018). The scour protection for monopiles, which is there to keep a potential scour hole far enough away from the monopile, is a form of (artificial) hard substrate which can benefit the requirements of these species. Thus far however, the scour protection has been designed taking into account only technical and financial aspects. Recently the Dutch government added a requirement in the tenders for new offshore wind farms to '*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*' (Ministry of Economic Affairs, 2014). This requirement has caused engineering companies and contractors to research methods to incorporate nature-enhancing aspects into the design of scour protection.

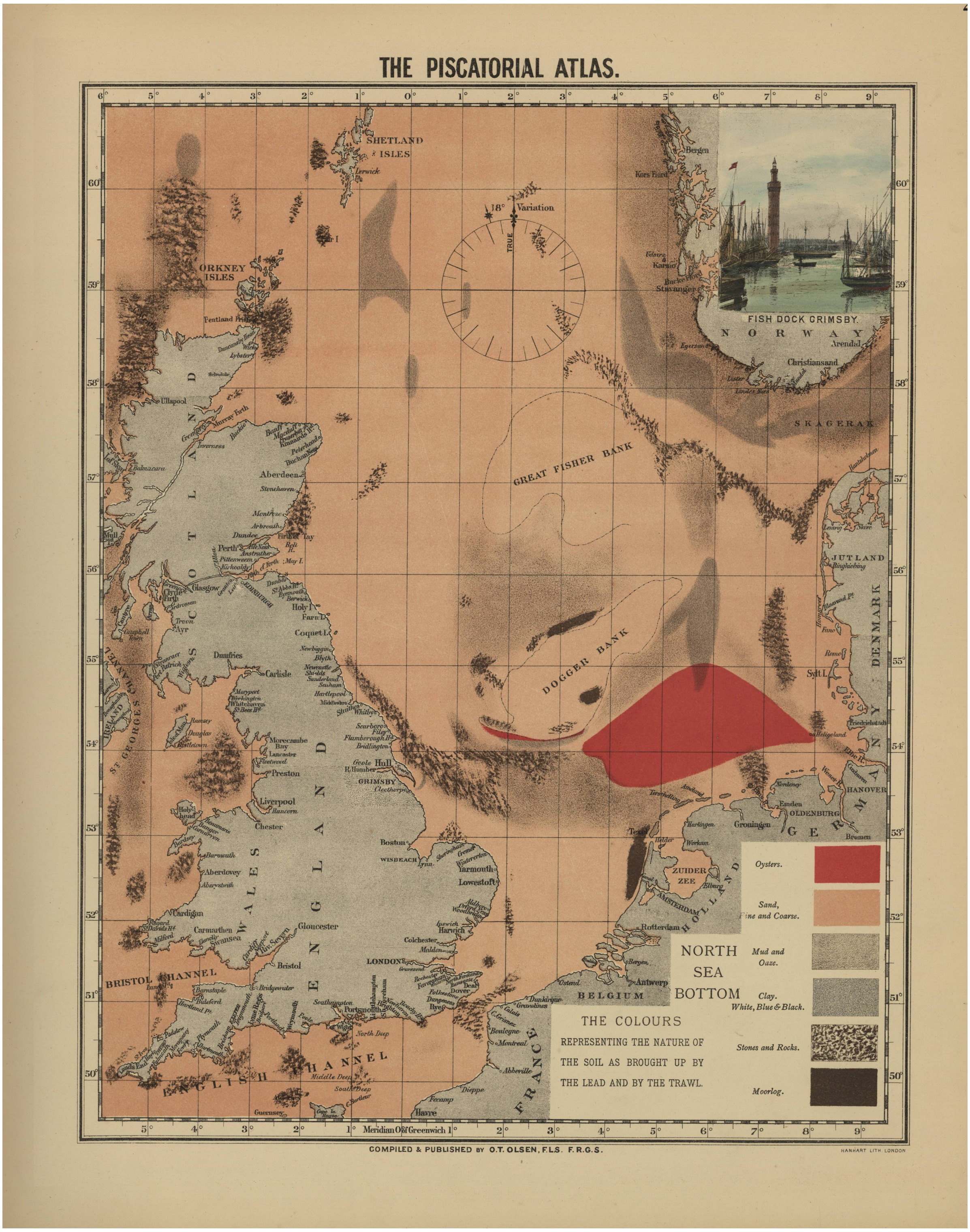


Figure 1.1: The presence of oyster beds in 1883, red on the map (Author: Olsen, 1883)

1.2. Problem description

The need to design nature-enhancing scour protection arises from the desire to obtain a healthy ocean for future generations and to comply with imposed requirements. Engineering companies and contractors tend to optimize the design of scour protections with respect to cost and technical requirements only, without taking into account possibilities regarding nature-enhancement. The reasons that engineering companies and contractors do not include the nature-enhancing aspects in the scour protection design are:

- The lowest offer wins.
  Enhancing nature by changing the scour protection design incurs costs for the engineering companies and contractors without increasing the chance of winning the tender and is therefore often left out of the design.
- Lack of knowledge about:
  - which species to focus on in the North Sea.
    Researching all species is not possible, but certain species might have habitat requirements which benefit other species as well and are therefore more efficient to research.
  - the requirements of the species in the North Sea.
    Each species has different requirements regarding its habitat and this information is often not readily available.
  - how the design of a scour protection can be altered to accommodate the needs of certain species.
    Several parameters of the scour design can be adjusted to enhance the scour protection for nature. Little knowledge is present about which parameters are to be changed and how these parameters are to be changed to comply with the species requirements while still complying with the technical requirements. There is also little knowledge of additional elements which might be beneficial to certain species.
  - the expected benefits.
    Having a rough quantitative estimate on the effects that the changes to a scour protection have, is necessary to know whether it is worth it to invest in further research.
  - the implications of these solutions on the cost of the scour design.
    Engineering companies and contractors need to know what the expected cost will be before this is included in their tenders.

1.2.1. Present knowledge

Multiple research projects have studied the effect of hard substrate on biodiversity, species abundance, and marine life in general and partially fill the knowledge gaps mentioned above. A summary of the present research regarding the influence of hard substrate in wind farms on marine life is presented below.

General

Multiple research projects have studied the effect of hard substrate on biodiversity, species abundance, and marine life in general (see Table C.1 and Table C.2 in Appendix C for an overview of all reviewed documents).
The general consensus is that hard substrate is more beneficial for biodiversity than a sandy sea bed.
The effect of wind farms on marine life has been studied as well, although most wind farms do not allow the study of long term effects since most wind farms are less than 10 years old.

State of the art

Lengkeek et al. (2017) wrote a report which provided guidelines for the eco-friendly design of scour protection structures around monopiles to enhance ecological functioning. It focused on two umbrella species: Atlantic cod and European flat oyster. The report resulted in four design variables for optimised scour protection:

- Adding larger structures to provide shelter/holes for large mobile species
- Adding more small-scale structures to create more small-scale holes, attachment substrate, and settlement substrate.
- Providing or mimicking natural (biogenic) chemical substrate properties to facilitate species.
- Active introduction of specimens of target species to enhance establishment of new populations.

Additionally to these design variables some example materials, specifications for implementation, and a cost overview were presented. A standardized approach for deployment and monitoring was provided as well.

A second research, by Smaal et al. (2017), on opportunities for the development of flat oyster populations on existing and planned wind farms in the Dutch section of the North Sea followed the report of Lenkeek. It focused on identifying the sites in the Dutch section of the North Sea that offer the best potential for flat oyster introduction and reintroduction experiments. The conclusions drawn from this study were:

- Crucial habitat factors for the development of flat oyster beds in wind farms are sea bed dynamics, sediment composition, suspended particle levels in the water column, and the possibility of successful recruitment.
- Phythoplankton, salinity, and oxygen content have no limiting effect.
- Predation and competition are important factors but it is impossible to say to what extend.
- Zee-energie and Buitengaats, Borssele, and Luchterduinen are suitable wind farms for oyster reintroduction.
- Empirical testing in pilot studies and experiments is necessary.

A third research, by Coolen et al. (2019), consisted of a desk-study on the positive impact of rocks in offshore wind farms on hard substrate associated benthic macrofauna and fish. This study was done by combining data from scour protections and soft sediment seabed monitoring and resulted in the following conclusions:

- Total epibenthic species richness may double when scour protection is introduced.
- Epibenthic biomass in the area covered by scour protection directly around a turbine increases by a factor 24.
- The Dutch edible crab population may increase with 50 million individuals, an increase of 880% of the population on the sandy sea bed.
- Fish may increase with hundreds of thousands of Atlantic cod, an many millions of smaller reef-species such as rock gunnel and goldshinny wrasse.
- Connectivity between populations of benthic species rises after the construction of wind farms but quantification is challenging due to differences in reported larval duration and lack of reported travel distances.

A research by Van Duren et al. (2017) on ”possibilities and knowledge gaps pertaining to hard substrate in relation to ecological added value” examined how natural structures native to the North Sea could be restored and how the ecological condition of the North Sea could be improved by using artificial hard substrate. It made a distinction between the placement of artificial hard substrate and ’nature-inclusive design’. It described the habitats of reef building species such as the flat oyster, the Ross worm, the honeycomb worm, sandmason worm, and Northern horse mussel and drew up a set of criteria for projects which aimed at restoration of the natural environment or on nature-inclusive building:

- Focus on species and structures that are native to the Dutch section of the North Sea.
- Where possible, let nature do the work.
- Minimise the need to use non-native material.
- Reduce the probability of introducing exotic species.
- Formulate clear objectives and evaluate them effectively.

One of the most important conclusions from this study was that the seabed must be relatively undisturbed, in other words no seabed-disturbing activities such as sand extraction, dredging, fishing (including shrimp fishing) should take place. This means that wind farms are particularly suitable in this regard. Another important finding was that greater diversity in habitat will also provide greater diversity in the biotic communities established in it.

1.2.2. Missing knowledge

These above mentioned reports all focus on how the scour protections as currently designed influences or benefits marine life and provide some general advice on how to improve the scour protection design for nature. However, none of them provide estimates of the effect that the proposed improvements can have.

1.3. Interest

Governments from the countries which surround the North Sea have all drawn up a Marine Strategy which focuses on the protection, preservation and restoration of the marine environment, where sustainable use of the North Sea is also guaranteed (European Commission, 2003). Wind farms are part of that Marine Strategy because they influence the marine environment. By creating nature-enhancing scour protection these wind farms have a smaller negative impact or even a positive impact on the environment. Solutions to the problems described in 1.2 are therefore valuable to a government since they give a better indication of the expected impacts of the wind farms and allow the governments to set more precise guidelines for the design.

The engineering companies and contractors that design the scour protection for the wind farms in the North Sea have to follow the requirements that are given by the governments to win the tenders for the wind farms. Filling the knowledge gaps listed in 1.2 therefore is valuable to them since it makes compliance with the imposed requirements more feasible.

1.4. Research objectives

1.4.1. Objective

The main objective of this study is to combine ecological and technical knowledge to improve the scour protection design for monopiles in the North Sea so that it does not only protect the sea bed against scour but also enhances marine life. This main objective is split into the following sub-objectives:

1. Determining indicator species in the North Sea and their habitat requirements.
2. Determining the suitability of the North Sea for these indicator species.
3. Determining the suitability of a scour protection as currently designed for these indicator species.
4. Providing viable nature enhancing improvements to the scour protection and their costs and benefits.

1.4.2. Research questions

The main objective is translated into the following research question:

To what extent can marine life in the North Sea be enhanced through improvements to the scour protection design for monopiles in wind farms?

To answer this research question the following sub-questions, dealing with the sub-objectives listed in 1.4.1, need to be answered first:

1. On what species in the North Sea should this study focus and what are the requirements of these species?
2. Is the North Sea in absence of wind farms suitable for these species?
3. What are the requirements for a cost-efficient scour protection and are these scour protections suitable/sufficient for the selected indicator species?
4. What changes are needed to improve the habitat for the selected indicator species, what are the expected effects on nature, and what will be the costs of these changes?
5. What additional actions are needed to achieve enhancement of the marine life when changes to the habitat are not sufficient?

1.5. Research scope

The scope of this research is limited due to limited time and resources. This section provides an overview of the scope and provides justification for the choices that were made:

- North Sea ⇔ Seas in general
  The research is limited to the North Sea. The main reason for this constraint is that the countries surrounding the North Sea are front runners in the field of building nature-inclusive, and thus have the biggest advantage by this research.
- Small selection of species ⇔ All species
  The research is limited to a small selection of relevant species. This choice is made based on the idea that when the habitat is suitable for a limited number of so-called indicator species it will also be suitable for a lot of other species.
- Monopiles ⇔ All kinds of support structures
  The majority of the wind turbines in the North Sea is supported by monopiles, therefore no other support structures will be considered.
- Scour protection ⇔ Rest of construction
  Only the scour protection is taken into account. The rest of the construction (monopile, transaction piece, J-tube etc.) is not considered. This choice is made to exclude the effects that changes to the monopile have on the dynamic behaviour of the monopile.
- Hypothetical situation ⇔ Scale and real life situations
  This study will be limited to hypothetical situations to avoid expensive scale tests and tests in real life.
- Precision in cost estimates
  Due to the technical background of the author of this study less attention is paid to the financial aspect of the problem at hand.
- Compliance with policies
  Due to the technical background of the author of this study less attention is paid to the legislative aspect of the problem at hand.
- Effect on tendering procedure
  The tendering procedure is shortly discussed in the framework but the effect that the proposed changes have on the tendering procedure are not further discussed.

1.6. Approach

To answer the research questions listed in 1.4 several steps are to be made.

1.6.1. Setting up the framework

The first step is to set up a framework. This framework describes the current situation in the North Sea and provides the available knowledge on the indicator species which are selected. It also provides information on a reference wind farm which is used to provide numbers for quantification and in subsequent chapters serves as a base-case to which suggested changes are compared. The goal of this framework is to provide all the required information in a coherent way as input for the rest of the study, this is visualized in Fig. 1.2.

1.6.2. Analyzing the suitability of the North Sea in absence of wind farms

The second step is to analyze the suitability of the North Sea in absence of wind farms. This is done by comparing the requirements of the selected indicator species with the physical environment in the North Sea as it was described in the framework.

1.6.3. Analyzing the suitability of scour protections as currently designed

The third step is to analyze the suitability of scour protections as they are currently designed. This is done by comparing the requirements of the selected indicator species with the physical environment within a wind farm as it was described in the framework.

1.6.4. Analyzing the potential for nature enhancement with improved scour protections

The fourth and last step is to provide potential improvements to the scour protection design and to assess the expected effect and cost of these improvements.

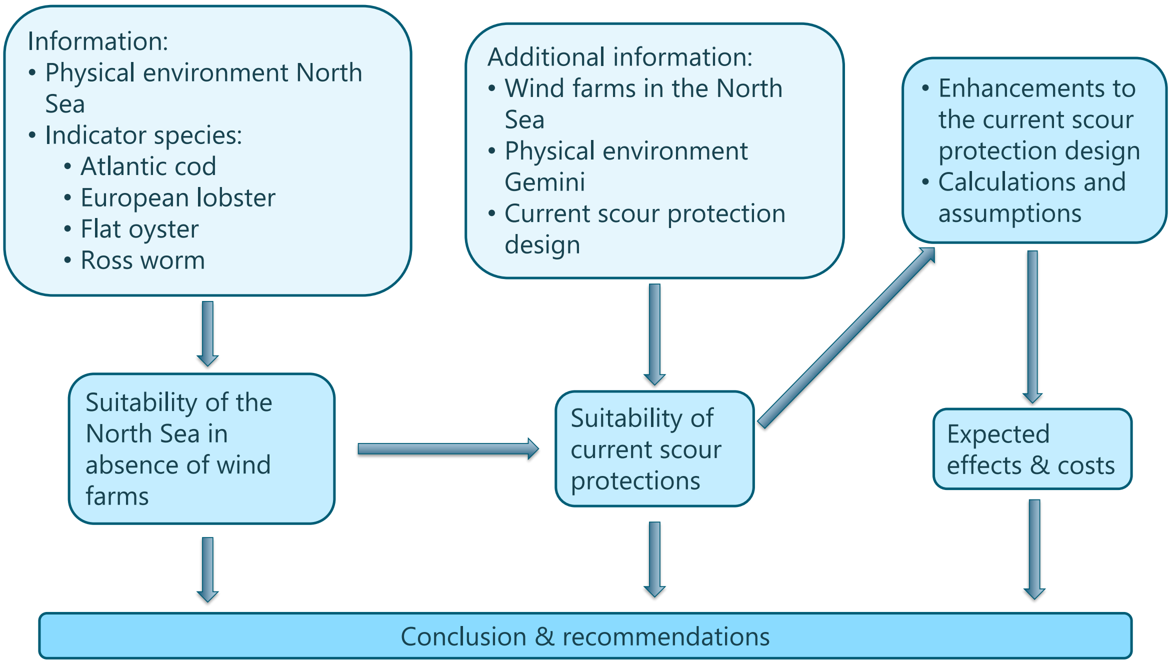


Figure 1.2: The approach to answering the research question

1.7. Document outline

Chapter 1 introduces the subject of this study by providing context about the study. It describes the present knowledge, the knowledge gaps, and provides a problem description. Subsequently it lists the research objectives and the scope to which this research is limited. Finally it provides an insight in how the research objectives are to be realized.
Chapter 2 reviews the relevant available literature on the subject and provides a framework which will be used in subsequent chapters. Section 2.2 treats the location of the wind farms in the North Sea, the types of foundations used, the installation methods and the tendering procedure. Subsequently, this section also contains general information about the reference wind farm. Section 2.3 contains information on the physical environment in both the North Sea in general and in the reference wind farm in particular. In section 2.4 the reason for a scour protection and the design requirements are given after which the design process and design of the scour protection of the reference wind farm are presented. Section 2.5 contains some general information about North Sea species and the selection process of four indicator species which are described in the subsequent subsections.
Chapter 3 presents the assessment of the suitability of the North Sea for the selected species in absence of wind farms. This is done for each of the four selected indicator species by listing their requirements regarding promotional and inhibiting factors and comparing these to the habitat that the North Sea provides.
Chapter 4 presents the assessment of the suitability of the North Sea for the selected species assuming that wind farms are present in the North Sea. In this chapter the reference wind farm is used to express the suitability quantitatively. It does so for each of the four selected indicator species.
Chapter 5 presents enhancements to the scour protection as it is currently designed. These enhancements are split up in three subjects and treated in the following sections: 5.2 Habitat enhancements, 5.3 Stock enhancements, and 5.4 Food enhancements after which sections 5.5 and 5.6 discuss their expected results and costs. The following section in this chapter, section 5.7, provides an example of a scour protection design in which several of the enhancements have been implemented. This chapter is concluded with a summarizing conclusion.
Chapter 6 concludes with a discussion about the validity of the proposed solutions and assumptions, provides a conclusion on the study, and gives recommendations on future research and implementation.

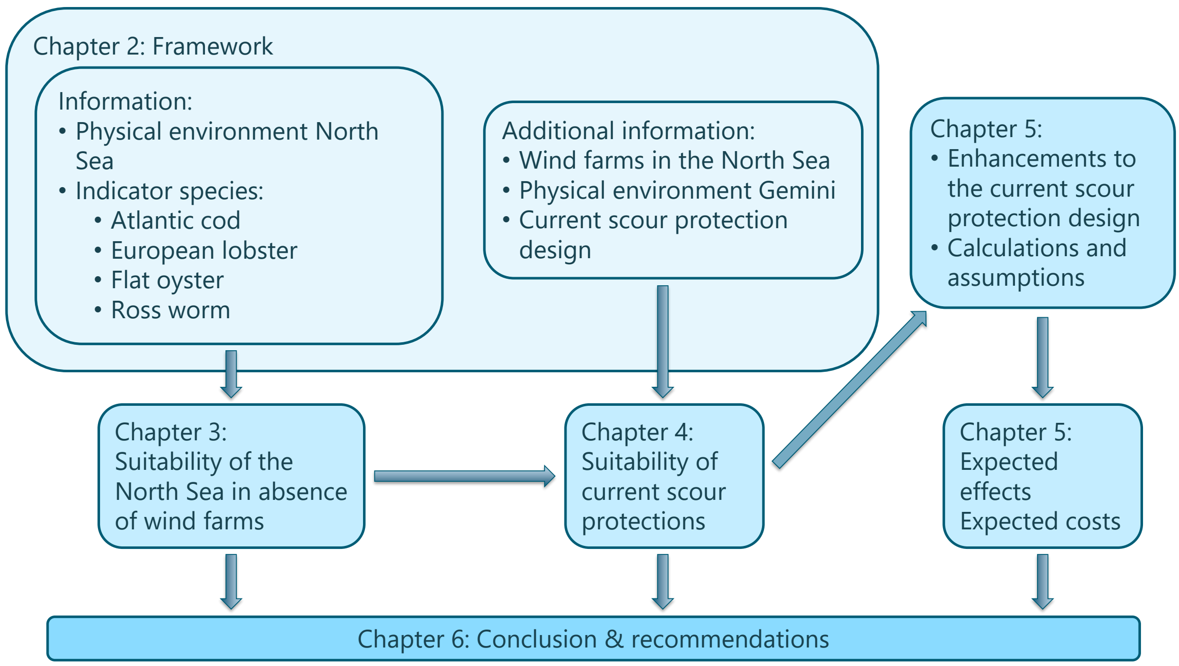


Figure 1.3: The study outline visualized

2 Framework

2.1. Introduction

In this chapter a framework is presented which provides the reader with the required information regarding the North Sea, wind farms in general, a reference wind farm, and four indicator species. Figure 2.1 shows how this information ties into the rest of this research.

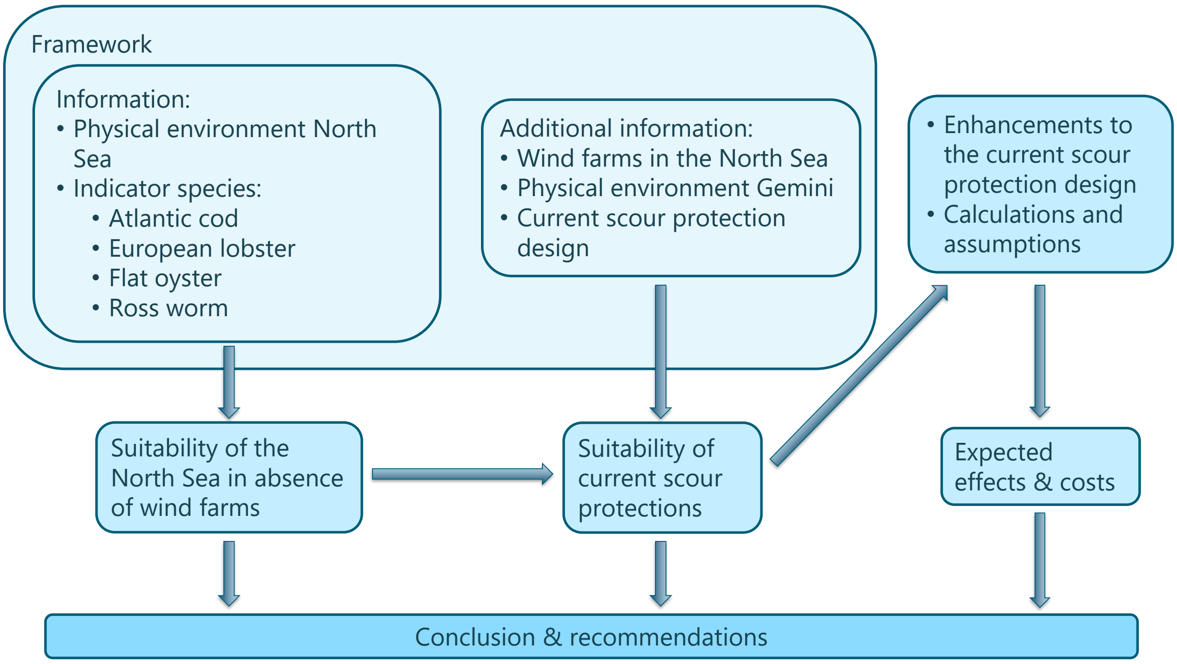


Figure 2.1: The function of the framework within the research

The first part of section 2.2 describes the location of wind farms in the North sea and provides some general information about the types of foundations used, the construction methods and the tendering procedure. The second part describes the location, design, and construction method of a reference wind farm. This information is used to assess the suitability of scour protections as they are currently designed in Chapter 4.
Section 2.3 describes the physical environment in the North Sea, treating location, bathymetry, seabed soil composition, artificial hard substrate, currents and waves, temperature and salinity, and, in Chapter 3, is used to assess the suitability of the North Sea in absence of wind farms. Section 2.3 also describes the physical environment in the reference wind farm and aids in Chapter 4 in the assessment of the suitability of scour protections as they are currently designed.

Section 2.4 describes the general scour protection design after which in the second part of the section the design for the reference wind farm is provided. Both parts form part of the basis for Chapters 4 and 5.

The fourth and last section provides some general information on North Sea species and lists selection criteria which are used in the subsequent subsection to select four indicator species. These four species are the Atlantic cod, the European lobster, the European flat oyster, and the Ross worm, and will be described in this order. The information on these species is used in all subsequent chapters to assess the suitability of the North Sea, the scour protections as currently designed, and the improvements for these species.

2.2. Wind farms

This research focuses on the scour protections of wind farms in the North Sea. The following section therefore provides information on wind farms in the North Sea, their locations, the types of foundations that are commonly used and the construction method(s). Subsequently the relevant information about the reference wind farm Gemini is provided.

2.2.1. Wind farms in the North Sea

Since the construction of the first offshore wind farm 'Vindeby' in 1991, consisting of 11, 450 kW turbines in 4 m deep water 2 km off the coast of Norway, many offshore wind farms have been constructed and more are planned as can be seen in Table 2.1.

Table 2.1: Data on wind farms in the North Sea (Sources: www.4coffshore.com & www.thewindpower.net)
Planned MW is calculated from 'Partial Generation', 'Under construction', 'Pre-Construction' and 'Consent Authorised'.

Country	# of OWF's	# of turbines	Total capacity (MW)	planned MW
United Kingdom	23	1,128	4,590.4	14,763
Norway	1	1	2.3	26
Denmark	5	183	414.5	735
Germany	17	997	4,646.5	4,115
The Netherlands	4	289	957.0	3,644
Belgium	8	274	1,185.9	1,075
France	0	0	0.0	0
Total	58	2,872	11,796.6	24,358

Locations

The North Sea is divided over the following countries: The United Kingdom, Norway, Denmark, Germany, The Netherlands, Belgium and France. Of these countries only France has not constructed any wind farms in the North Sea. There are 47 wind farms with more than 10 wind turbines in the North Sea. Most of these wind farms are located relatively close to the coast where the water is relatively shallow so the material and transport costs are not as large as for the wind farms further from the coast. In general new wind farms are planned further from shore than previously, as can be seen in figure 2.2 (the planned (lighter coloured) wind farms are further away from the coast than the already constructed wind farms (darker coloured)).

Types of foundations

There are several types of foundations used to support the wind turbines. The most frequently used type is the monopile which is used for 81.7% of all installed substructures in Europe (Pineda, 2018). These monopiles are, as the name indicates, a single steel pile which is hammered or drilled into the sea bed and obtains its stability from the horizontal soil resistance. The reason that monopiles are used is their relative low cost and the ease with which they are made. If the water is too deep (leading to disproportional large diameters) or if the soil is too hard, other types of foundations, such as tripods, jackets, gravity based foundations and floating foundations are used. These are shown in figure 2.3.

Tripods, tripiles, and jackets are quite similar to each other in the sense that they all consist of multiple elements which are interconnected and anchored into the soil. The reason to use these constructions is to realize the larger bending resistance that is necessary in deeper water.

Another type of foundation is the gravity based foundation which, unlike the above mentioned types, does not penetrate deep into the soil but instead obtains its stability from the weight of the (concrete) foundation.

Floating foundations are seldom used, but might become more common in the future when the presence of deep water makes other types of foundation impossible, for instance along the coast of Norway.

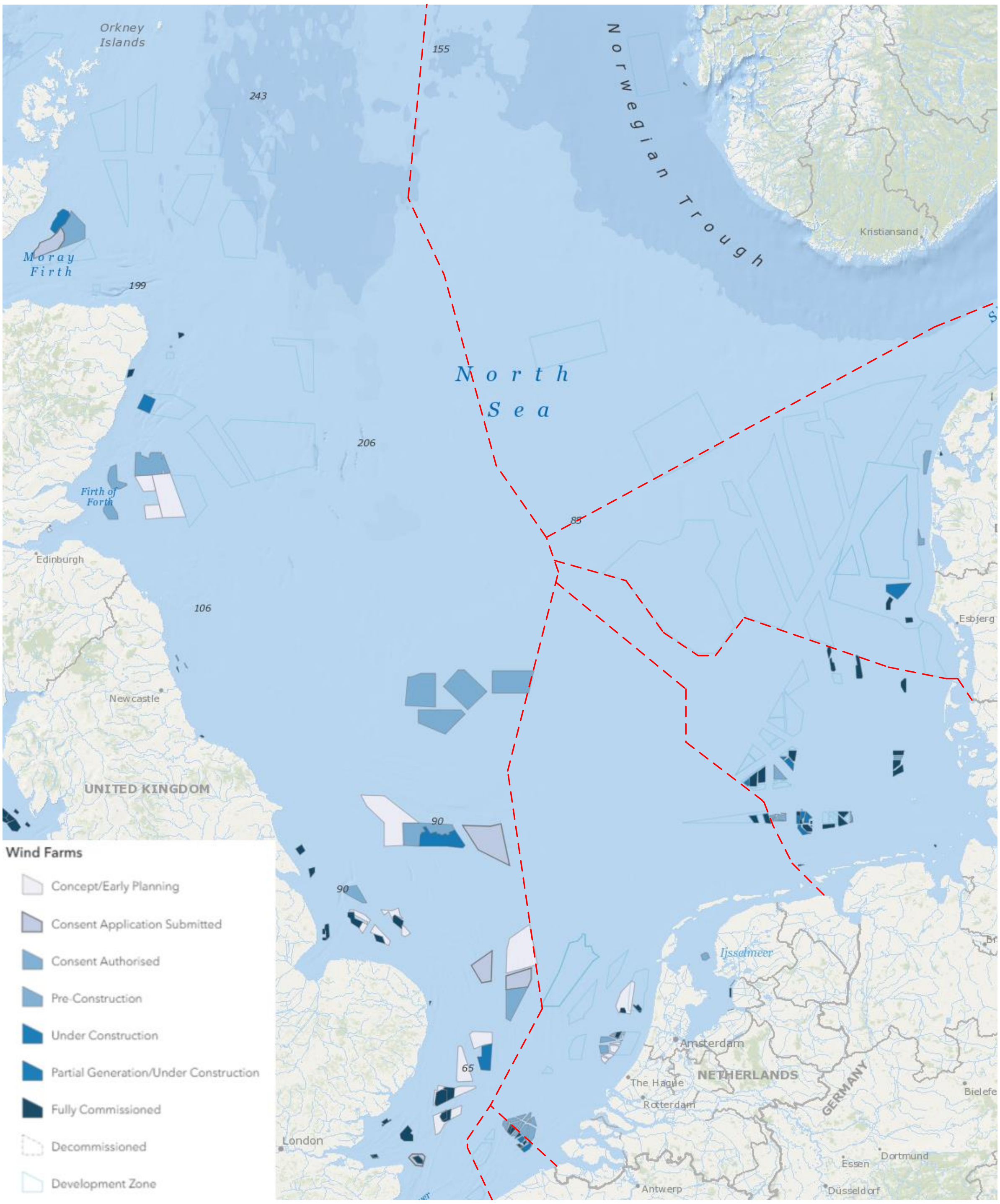


Figure 2.2: Wind farms in the North Sea
(Source: https://www.4coffshore.com/offshorewind/)

Construction methods

This report focuses on monpiles. Their construction starts with the placement of the filter layer. This filter layer should be stable over the time that it takes to install the wind turbine and the armour layer (which can take several months or longer due to weather conditions in the winter), this is to avoid the extra costs of replacing the washed away filter layer material. The state of the filter layer should be checked before continuing to the next step, this can be done with divers, ROV's, or acoustic surveys. After this check the monopile is hammered or

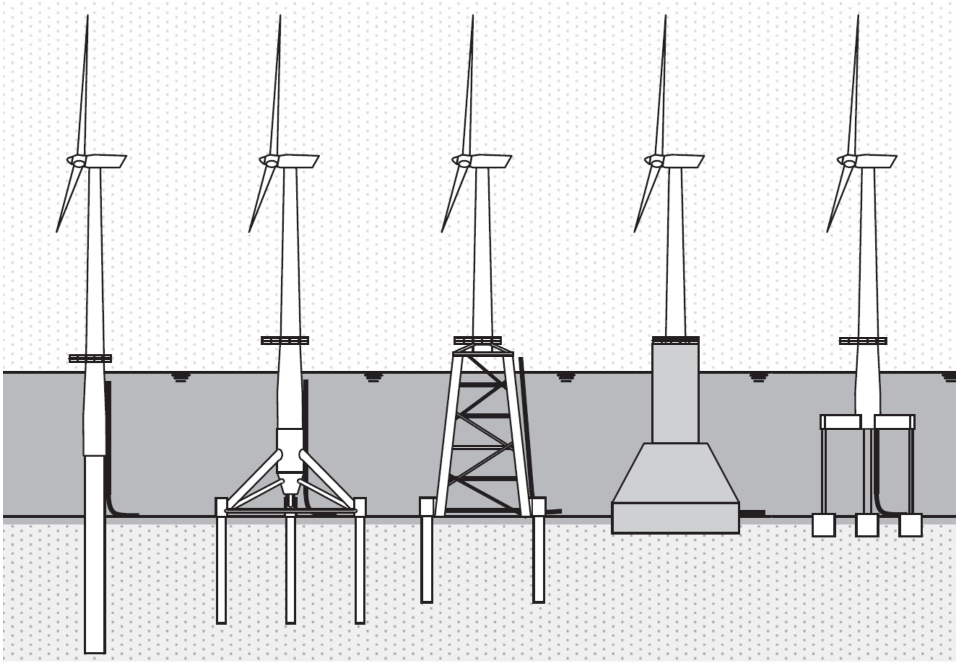


Figure 2.3: Foundation types, from left to right: monopile, tripod, jacked, gravity based, floating. (WIT transactions on State of the Art in Science and Engineering, Vol 44, ©2010 WIT Press)

drilled through the filter layer into the soil up to a predefined depth with the help of a crane (on a jack-up vessel or pontoon), a mold to keep the monopile in place, and a pile-driver. Once this is done, the transition piece is installed and connected to the monopile using a grout injection, this transaction piece also enables secondary structures such as the J-tube, a boat landing, and a platform to be constructed. The next step is to place the armour layer consisting of larger rocks with the aid of a fallpipe vessel or side stone dumper after which the rest of the of the wind turbine (tower, nacelle, and rotor blades) is installed. These last two steps can also be done in a different order, but the first method is preferred.
In some cases it is decided to design the scour protection with only one (wide) grading, serving as both filter and armour layer, which is easier to install and does not have the issue of having to construct a thin filter layer. In this case, dependent on the thickness of the pile and the dimensions of the individual stones in the grading, the sequence in which the scour protection and the pile are installed can vary. If the stones are too large to hammer or drill the pile through the layer into the soil, the pile is installed first, causing a scour hole surrounding it. This scour hole is then back-filled with as consequence that the amount of required rock is increased. If the individual stones are not too large compared to the pile, the scour protection is installed first after which the pile is hammered or drilled trough the scour protection into the soil.

Tendering procedure
The tender procedure of an offshore wind farm differs per country and can take many forms. Several items can be decided on to create a tender which best fits the situation (European Wind Energy Association, 2015).
A *centralized approach*, in which public authorities select the site and openly provide information to all interested parties, and a *decentralized approach*, in which developers propose sites and compete for public support, are both used by the different countries surrounding the North Sea. The centralized approach puts the emphasis on the ability of the government to determine the right site, but also allows the government to plan the grid connection of multiple wind farms centrally. On the other hand a decentralized approach allows the government to focus on other matters such as the administrative procedures that are involved in this project.
Material pre-qualification criteria (safeguarding material qualities), *financial pre-qualification*

criteria (to make sure only financially healthy companies participate) and *penalties* (to have an incentive to deliver on promises) are implemented to ensure that only credible developers participate in the tender and that the winner of the tender will be committed to complete the project as promised. The right balance between ensuring sufficient participation and competition and ensuring the completion of the project is found by carefully defining these pre-qualification criteria. Too strict criteria will deter investors from the tender while weak criteria might reduce the likelihood that the project will be completed.
Bidders can be rewarded with a fixed payment for the installed capacity, *Remunerating capacity (EUR/MW)*, or with a fixed payment for the produced power *Remunerating energy (EUR/MWh)*. Of these two options the latter is better suited since it rewards efficiency and maximization of wind production.
The *price-finding mechanism*, in which the price and tender winner is found has three forms. In the *sealed bid* closed bids are submitted by the developers and the lowest bid wins the tender. A second option is the *iterative process* in which the price is established by lowering the price from a certain level till only one developer is willing to accept the price or by starting from zero and increasing the price (limited to a certain ceiling) till the first developer is willing to accept the price. A combination of these methods, although more complex, is also possible with a iterative process in the first tender to find a price range followed by a closed bid in the following round to decide on the tender winner.

2.2.2. Wind farm Gemini

The wind farm Gemini is chosen as reference project because it was commissioned in the end of 2016 and can thus be assumed to be representative for future wind farms. Additionally it is located in an area where multiple other wind farms are planned to be constructed.

Location

The wind farm Gemini is located at 54°02’13”N 5°57’54”E, about 80 km north of the coast of Groningen. This location is, as can be seen from Figure 2.4, relatively close to the coast where the wind speeds are higher than at most other locations this close to the coast.
There are 46 wind farms with more than 10 wind turbines in the North Sea, Gemini itself excluded. The closest of these wind farms is the German wind farm Veja Mate which is located only 32 km away from Gemini. The furthest wind farm is the Aberdeen Offshore Wind Farm which is located off the east coast of Scotland at a distance of 612 km from Gemini. The mean distance of the wind farms in the North Sea to Gemini is 257 km.

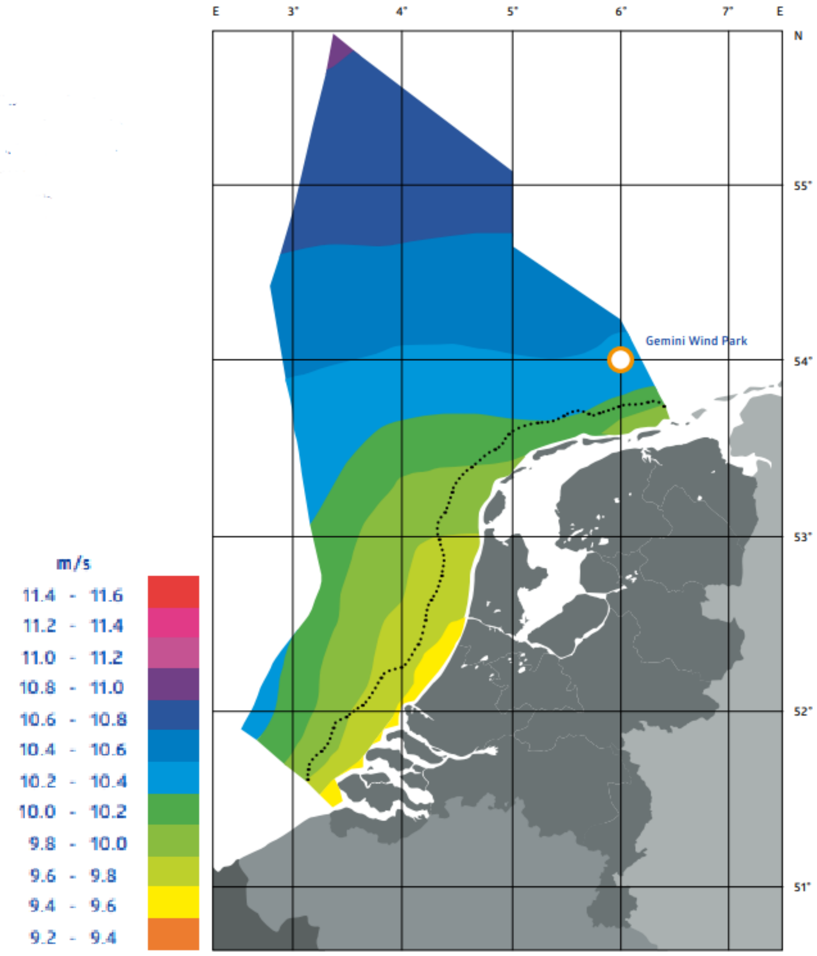


Figure 2.4: The location of wind farm Gemini on the Dutch part of the North Sea (Author: Haag, 2015)

Design

The wind farm consists of two plots, ZeeEnergie and Buitengaats for the western and eastern plot respectively (see figure 2.5), of 75 Siemens wind turbines of 4 MW each and a total capacity of 600 MW. Two offshore high-volgtage substations transform the power produced by the turbines from 33kV to 220 kV after which it is transferred to the mainland via the export cable.

The monopiles have base diameter of 7.1 m and contain a conical section in which the diameter of the monopile decreases from 7.1 m at 4.5 m above the sea bed to a diameter of 5.5 m at 29.7 m above the sea bed.
To protect the sea bed around the monopiles against scour a scour protection is constructed which consists of two layers. The filter layer, composed of 1-3” rock, is 0.5 m thick and is constructed in a circle with a diameter of 4.25 times the pile diameter around the monopile. The armour layer, composed of 3-9” high density rock, is 0.5 m thick and is constructed in a circle with a diameter of 3 times the pile diameter around the monopile. The edges of both layers have a slope of 1:2. A cross-section of this design can be found in Figure 2.17 in section 2.4.2.

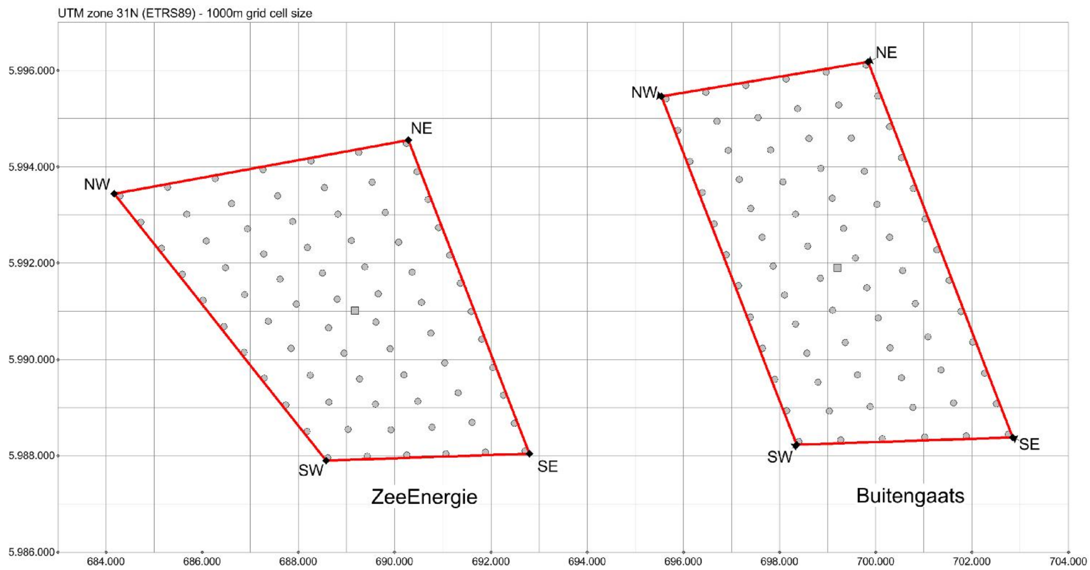


Figure 2.5: The layout of wind farm Gemini with ZeeEnergie on the west side and Buitengaats on the east side (Author: Gemini, 2014).

Construction method
The filter layer and armour layer are constructed by a flexible fallpipe vessel. After installation of the filter layer the monopiles are hammered through the scour protection with aid of an offshore installation vessel which is jacked above sea level during this process. The armour layer is constructed after installation of the monopiles.

2.3. Physical environment

The physical environment affects the species that live in the North Sea and has an influence on the design of the scour protection. This section therefore describes the physical environment in the North Sea and in the reference wind farm Gemini.

2.3.1. Physical environment North Sea

Location

The North Sea is located in the northern part of Europe and bordered by the UK mainland, the Orkney and Shetland islands, Norway, Denmark, Germany, the Netherlands, Belgium and France. It is directly connected to the Atlantic in the north and indirectly by the Strait of Dover in the southwest. The North Sea is also connected to the Baltic Sea in the east, via the Kattegat and the Danish straits and its surface area is about 525,000 km^2. The above named states all have ownership over part of the North Sea, Belgium and France own a small area. The North Sea has commercial value by providing fishing grounds, a shipping zone which is connected to large rivers that run deep into the mainland of Europe, and through its oil and gas reserves beneath the sea bed. In recent years the offshore wind energy market has emerged and has started to become more and more demanding on the space that it requires.

Bathymetry

The physical geography differs over the different parts of the North Sea. In general the northern part is deeper than the southern part and only few parts of the North Sea are more than 100 m deep (see Figures 2.7 and 2.8), one of them being a deep trench which runs parallel to the Norwegian coast. In the south many smaller banks and sand dunes are present, see table 2.2 for their definitions and indication for their morphodynamic time-scales and figure 2.6 for their location in the North Sea. A bigger bank, the Doggersbank, is located in the middle of the North Sea, as can be seen in figure 2.8.

Table 2.2: Marine bedforms in the North Sea
Source: (Van Dijk et al., 2011)

Bedforms	Wavelength [m]	Height [m]	Orientation [degrees to tidal current]	Morphodynamic time [order of years]
Offshore sand banks	1,000-10,000	5-50	0-30	Centuries
Long bed waves	1,000-2,000	1-10	60	Centuries
Sand waves	100-1,000	1-10	90	Years-decades
Mega-ripples	7-40	< 1	90	Hours

Seabed soil composition

Almost the entire North Sea seabed consists of either fine sand or mud. Along the coast of the UK patches of pebbles are present and the Doggersbank consists of coarse sand. The southern side of the trench along the Norwegian coast is lined with patches of gravel and pebbles. An estimated total of 20% of the North Sea is covered in coarse sands, gravels, and rocks (Coolen, 2017; EMODnet, 2019). Using benthic monitoring data from box corer samples taken in the Dutch offshore zone in 2014-2015 by Rijkswaterstaat, Coolen et al. (2019) calculated the average biomass in the Dutch North Sea to be 13.8 g ash free dry weight (AFDW) per m^2 and assumed the AFDW to weigh 10.5% of the wet weight. From this the average wet weight biomass is calculated to be 131 g/m^2.

Artificial hard substrate

Artificial hard substrate in the North Sea consists of around 1,300 oil and gas platforms with their infrastructure (OSPAR, 2018), scour protection for support of close to 3,000 structures for wind turbines (see table 2.1), rock berms as protection for pipelines and cables, more than 25,000 shipwrecks (Lettens, 2019), and some artificial reefs.

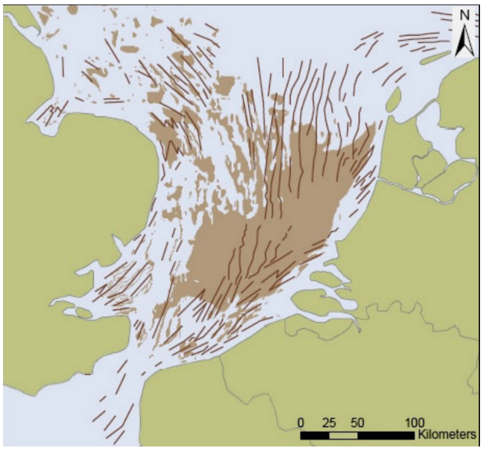


Figure 2.6: Presence of sand waves (brown area) and sand banks (dark lines) in the North Sea (Author: Roos and Hulscher, 2007).

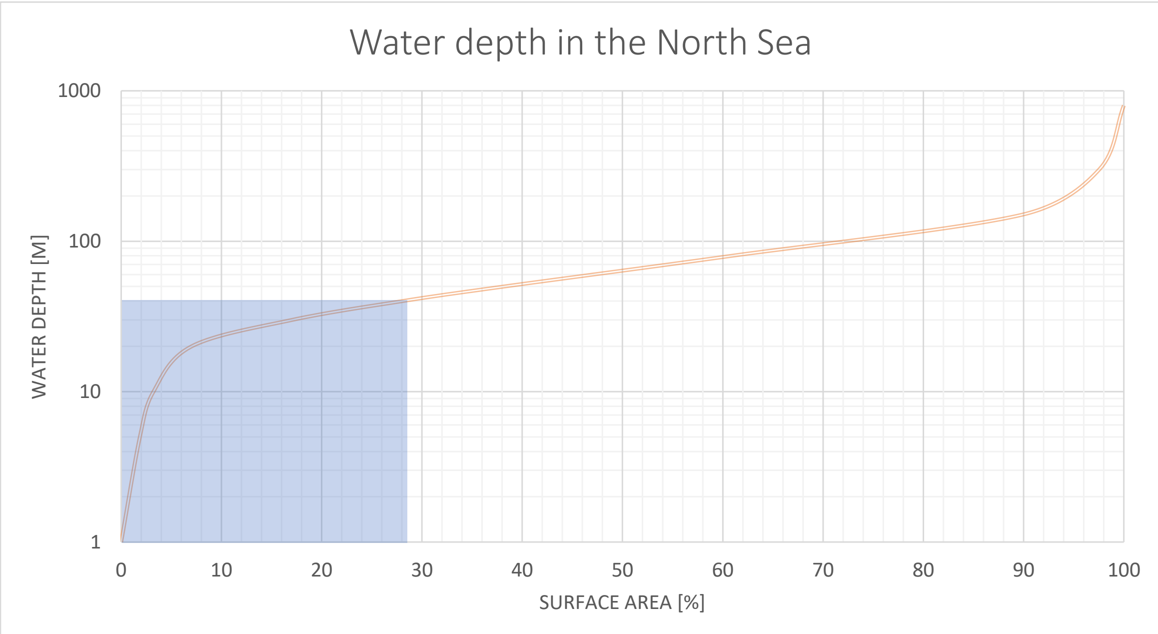


Figure 2.7: Water depth in the North Sea as function of area. The shaded area shows the water depth up to which wind farms are commonly constructed (40 m). Data from Helmholz-Zentrum Geesthacht (2018a).

Currents and waves

Most of the water entering the North Sea enters from the North Atlantic into the upper part of the North Sea (between Schotland and Norway) while a smaller, warmer and more saline flow of water enters through the English channel in the southern part of the North Sea. An (almost) negligible flow of water enters the North Sea from the Baltic Sea which has a low salinity. The flow out of the North Sea follows the Norwegian coast, resulting in a flow in the North Sea which in general is anti-clockwise with some smaller local circulation patterns which can be either clockwise or anti-clockwise (Paramor et al., 2009). The mean flow in much of the North Sea is weak, typically 0.02-0.05 m/s (Thorpe, 2012).
Significant wave heights are largest in the open northern North Sea where they show a strong variability. In the southern more shallow regions the significant wave heights and their variability are much smaller.

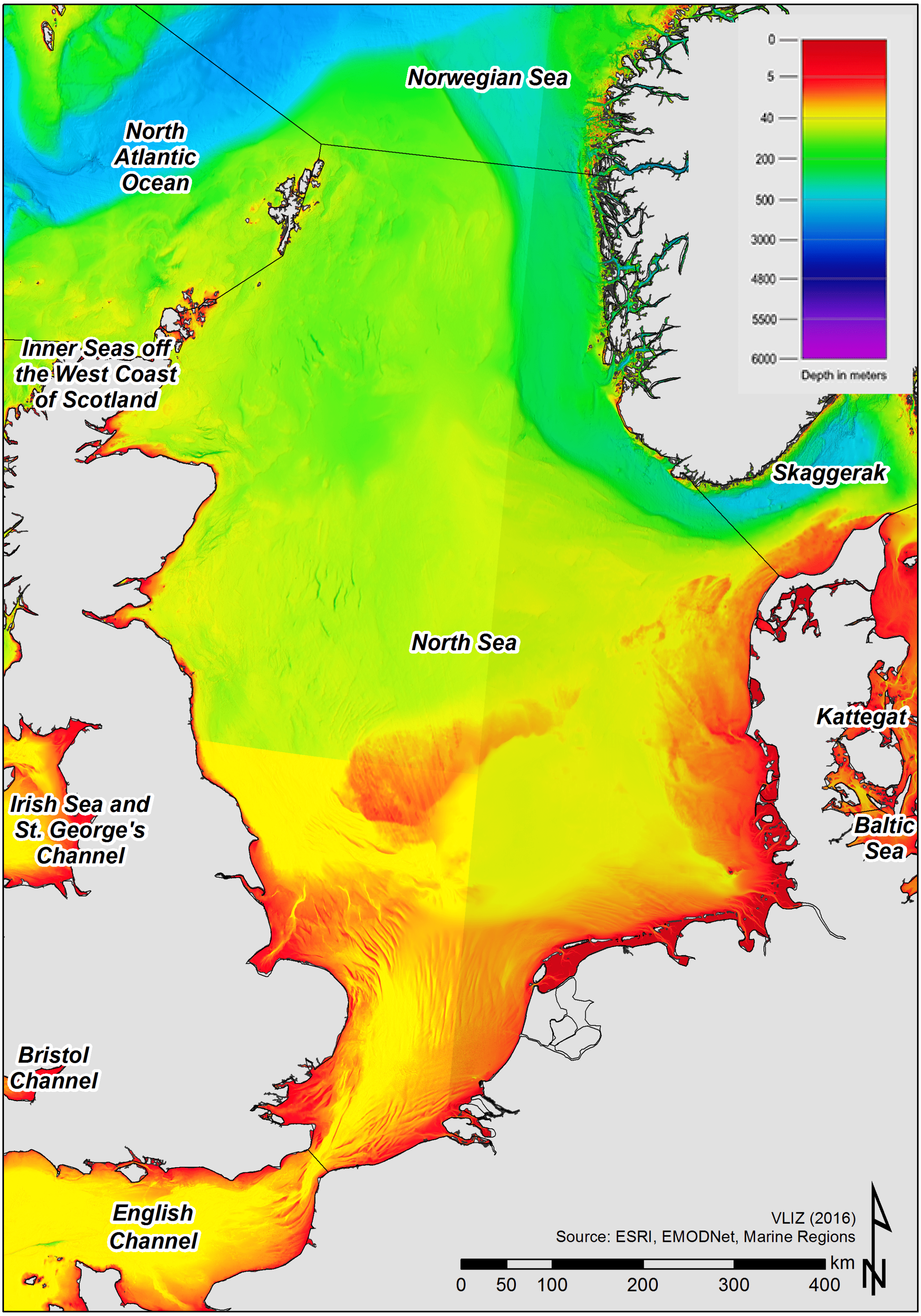


Figure 2.8: Bathymetry of the North Sea (Marineregions.org, author: De Nauwere, Nathalie)

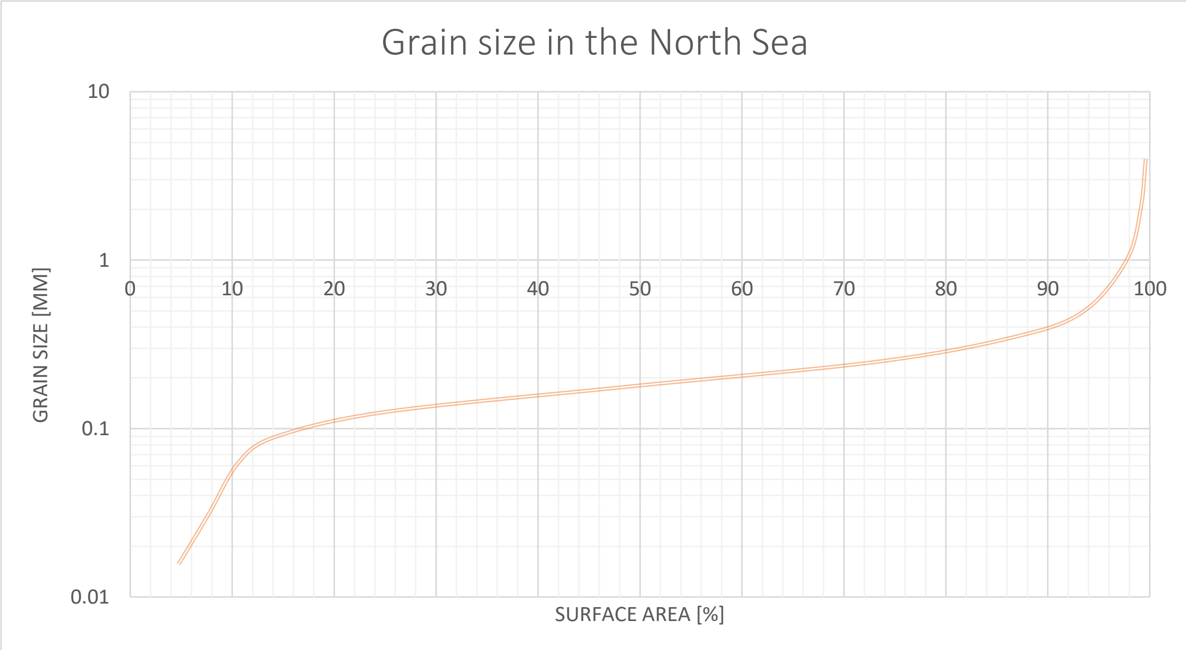


Figure 2.9: The grain size distribution in the North Sea (40.000 km^2 unknown) as a graph. Data from Helmholz-Zentrum Geesthacht (2018b).

Temperature and salinity

The surface temperature follows a much stronger annual cycle than the seabed temperature, this is explained by parameters that influence them. The surface water is influenced by heating by the sun, heating or cooling by the wind, and by mixing with deeper water due to storms or tidal currents. The water at the seabed of the sea on the other hand is only influenced by the mixing with the surface layer. Both surface and seabed temperature have been increasing since 1970 (Quante et al., 2016).

The surface temperature is lowest in January and averaging 8 $^\circ C$ while the average surface temperature in the warmest month, August, is about 16 $^\circ C$. Important to note is that the difference between the highest and lowest temperature is the largest for the shallower south-eastern part of the North Sea.

The seabed temperature in the northern part of the North Sea fluctuates less than in the shallower southern part where waves and currents mix the water layers.

Away from the influence of fresh water input from the European rivers and the less saline Baltic Sea the salinity typically ranges between 34‰ and 35‰. Closer to these influences the salinity decreases to 28‰ (Quante et al., 2016).

2.3.2. Physical environment Gemini

The information in this section is gathered from the (unpublished) report (Van Oord, 2014) that was provided by Van Oord to the writer of this study.

Bathemety

The water depths within ZeeEnergie are between -32.44 m LAT and -36.72 m LAT, for Buitengaats this is between -28.51 m LAT and -35.65 m LAT.

Seabed soil composition

The layer of the seabed is described for ZeeEnergie as follows: 'Very loose to loose, locally silty, silica fine to medium SAND, with shell fragments, locally with organic matter, locally with a thick bed of silt at the bottom. Locally medium to coarse sand.'
The top layer of the seabed is described for Buitengaats as follows: 'Very loose to loose silica fine to coarse SAND, with many shell fragments, locally with pockets of silt, locally medium dense, locally consisting of firm to stiff SILT'. The comment for this layer is that it is locally absent but present in most parts of the site. The layer underneath this top layer sometimes protrudes through and consists of 'Medium dense to very dense, locally slightly gravelly, locally sitly, sillic fine to medium SAND, with shells and shell fragments, with traces of organic matter, locally with pockets and thin laminae to thick beds of silt and clay'.
Some sand banks are present in the area (see Figure 2.6). These sand banks are very long and high, but travel very slow (see Table 2.2).

Currents and waves

Currents

The largest flow velocities occur for currents from the east and (slightly less) the west as can be seen from figure 2.10.

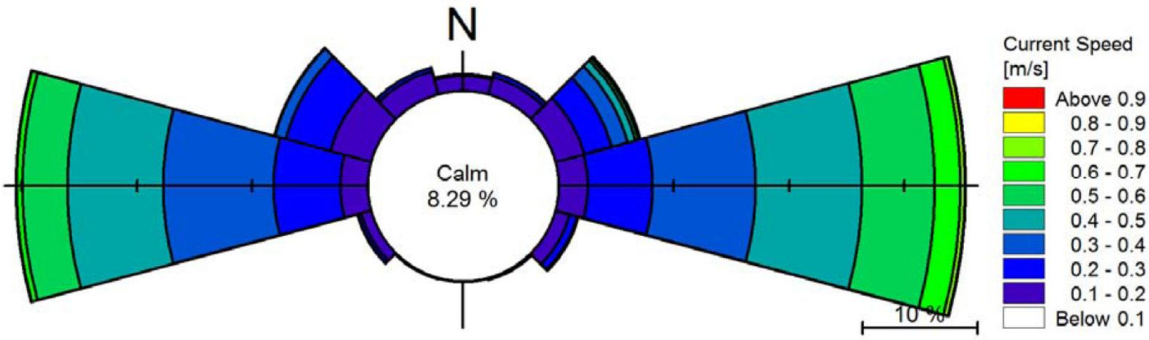


Figure 2.10: Current rose for wind farm Gemini.
Source: Van Oord (2014)

The extreme currents with their corresponding return periods are given in table 2.3

Waves

The largest waves come from the south-west to north, as can be seen from figure 2.11.
The extreme waves with their corresponding return periods are given in table 2.4.

Temperature and salinity

The water temperature within the wind farm ranges during the year between 3.3 °C and 18.9 °C with a mean of 11.0 °C. The salinity ranges between 30.8‰ and 34.9‰ with an average of 33.8‰.

Table 2.3: Flow velocities in wind farm Gemini
Source:Van Oord (2014)

Return Period (years)	Current speed (m/s)		
	Depth-averaged	Surface	1 m above seafloor
1	0.87	0.99	0.6
5	0.97	1.11	0.67
10	1.02	1.17	0.7
25	1.08	1.23	0.74
50	1.12	1.28	0.77
100	1.17	1.34	0.8

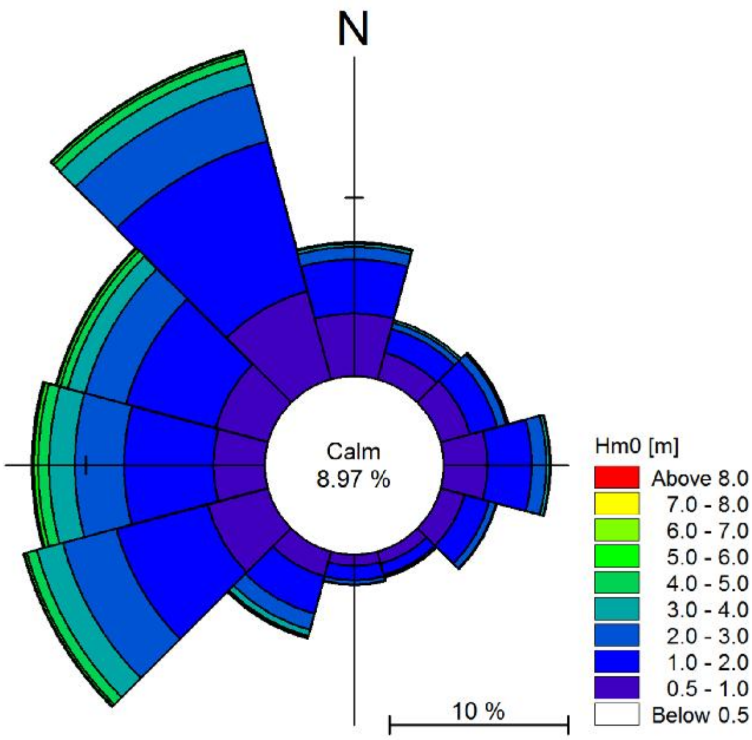


Figure 2.11: Wave rose for wind farm Gemini.
Source: Van Oord (2014)

Table 2.4: Wave heights in wind farm Gemini
Source: Van Oord (2014)

Return Period (years)	Significant wave height H_{m0} [m]	Maximum wave height H_{max} [m]	Zero crossing period T_{02} [s]	Peak period T_p [s]
1	7.30	13.8	9.0	11.5
5	8.20	15.4	9.5	12.2
10	8.60	16.2	9.7	12.4
25	9.20	17.2	10.1	12.9
50	9.50	17.8	10.2	13.1
100	9.90	18.5	10.4	13.3

2.4. Scour protection

This section describes the general scour protection design and provides the scour protection design for the reference wind farm Gemini. This information is subsequently used in Chapter 5 to estimate the quantitative effects of potential changes to the scour protection.

2.4.1. General scour protection design

Hydrodynamic forces on the seabed caused by both waves and currents are amplified when a structure such as a monopile is present. These amplified hydrodynamic forces can induce local scour at the base of the monopile when the shear stress on the bed becomes too large and can lead to scour holes with a depth of up to twice the pile diameter (see Figure 2.12). Usually a value of 1.3 times the pile diameter is assumed (Det Norske Veritas AS, 2013).

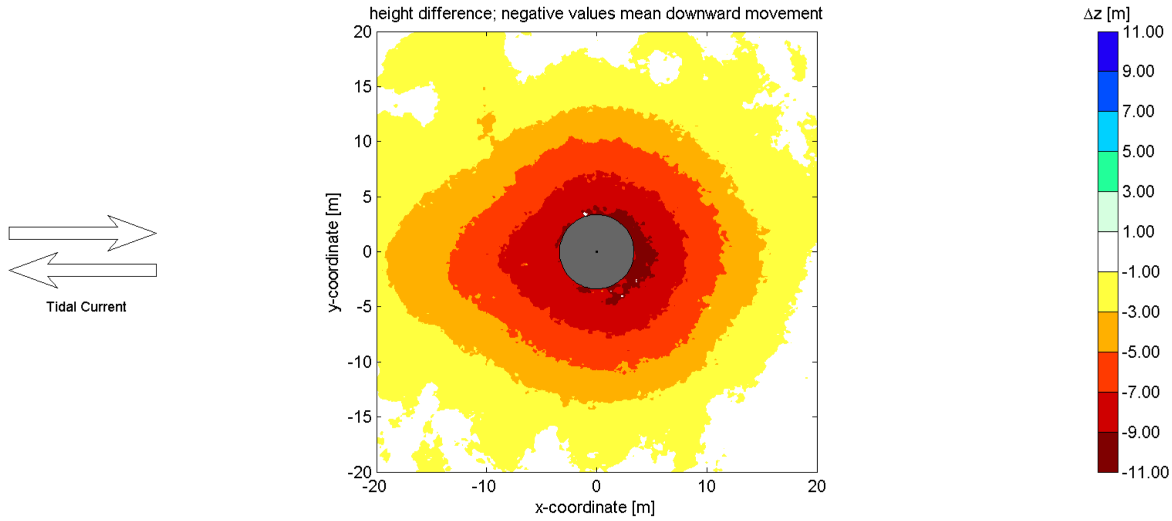


Figure 2.12: The scour hole that developed around the monopile on an unprotected seabed in the scale model. Source: Van Oord (2014)

The reason for scour protection

Both wind and water contribute to the horizontal forces which are exerted on the monopile. To resist both the horizontal forces and the overturning moment created by these forces, the monopile is hammered or drilled into the sea bed to obtain enough horizontal soil resistance. The danger of scour near a monopile is that the part of the monopile that is supported by the soil, and thus by the resisting forces, becomes smaller. When the scour hole becomes too deep and the resisting forces too small compared to the loads, the monopile becomes unstable.
One way to prevent the development of a scour hole adjacent or close to the monopile is by constructing a scour protection which keeps the bed level constant.

Types of scour protection

There are multiple types of scour protection which differ in size, shape, material properties, complexity, the effort it takes to obtain and place them etc. The most common scour protection is quarried rock which comes in different gradings and densities.

Requirements

The most important function of the scour protection is to keep the scour far enough away from the monopile during its lifetime. If the scour protection fails to do so the monopile will fail as described before. There are 4 ways in which the scour protection can fail (De Vos et al., 2012):

- by erosion of the top layer caused by the flow, possibly leading to scour near the structure (Figure 2.13a);

- by loss of subsoil through the scour protection, which may lead to sinking of the top layer in the bed. This can be an iterative process, eventually leading to scour holes near the construction (Figure 2.13b);
- due to the edge scour, which originates from the abrupt change in roughness between the scour protection and the bed, stones may disappear at the edge of the scour protection, leading to an undersized scour protection (horizontal dimensions) (Figure 2.13c);
- when the scour hole at the edge is to steep, a resulting flow slide may damage the scour protection from the (Figure 2.13d).

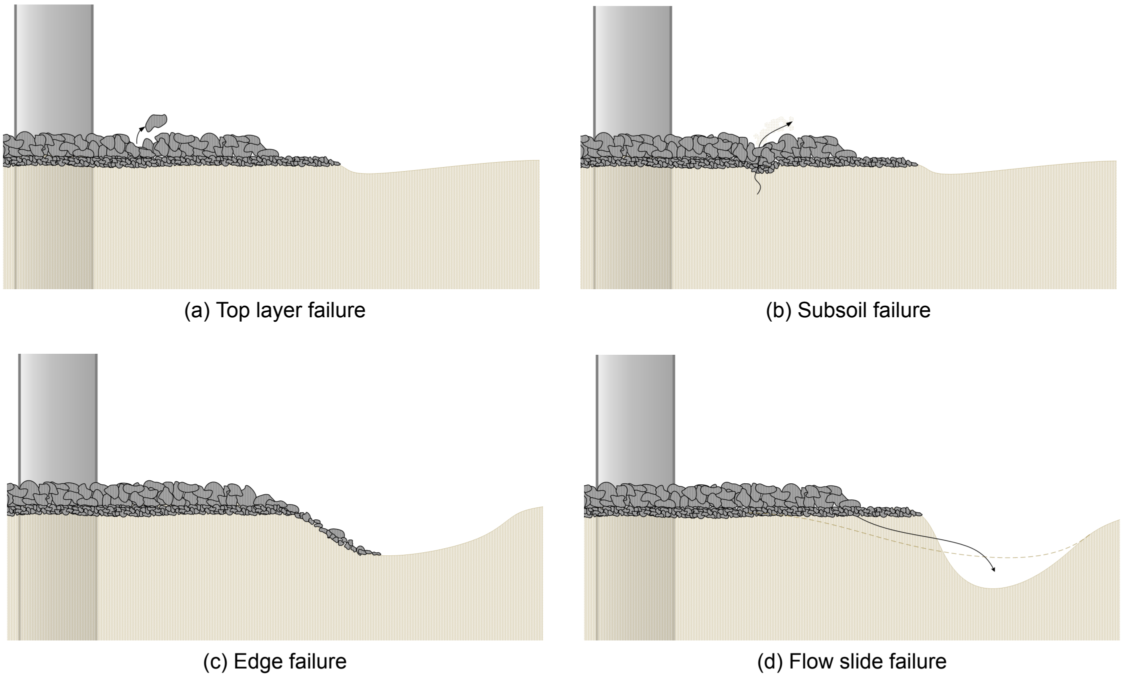


Figure 2.13: Failure modes for a scour protection.

To prevent these failure mechanisms, both the armour layer as well as the filter layer(s) of the scour protection must not fail (armour stability and filter stability). It is also necessary for the scour protection to be flexible enough to follow the sea bed lowering at the edges of the scour protection without completely failing (flexibility).
Armour stability refers to the stability of the top layer against the hydraulic loads. Armour stability is derived from the weight of the individual stones. To derive the required stone diameter the Shields criteria is used: 'When the current induced bed shear stress τ_c exceeds the critical bed shear stress τ_{cr}, the stones of the armour layer will move' (Schiereck and Verhagen, 2016). The bed shear stress for a steady and uniform flow is defined as:

$$\tau_c = \frac{1}{2}\rho_w f_c U_c^2 \qquad [N/m^2] \quad (2.1)$$

In which:

ρ_w	density of water	$[kg/m^3]$
f_c	friction factor of the bed	$[-]$
U_c	current velocity	$[m/s]$

The dimensionless friction factor f_c of the bed can be calculated as follows:

$$f_c = \frac{2g}{C^2} \qquad [-] \quad (2.2)$$

In which:

g	gravitational acceleration	$[m/s^2]$
C	Chézy coefficient	$[\sqrt{m}/s]$

This Chézy coefficient can be calculated to be:

$$C = 18 * \log\left(\frac{12 * h}{k_r}\right) \qquad [(m/s)^{0.5}] \quad (2.3)$$

In which:

k_r	Nikuradse roughness	$[m]$
h	water depth	$[m]$

The Nikuradse roughness is usually equal to several times the characteristic stone diameter. Not only a steady and uniform flow induces a bed shear stress, waves do so as well. This wave shear stress is oscillatory and has an amplitude τ_w:

$$\tau_w = \frac{1}{2}\rho_w f_w U_w^2 \qquad [N/m^2] \quad (2.4)$$

In which:

f_w	wave friction factor	$[-]$
U_w	horizontal velocity amplitude	$[m/s]$

There are several methods proposed to calculate f_w of which the method given by Soulsby is often used:

$$f_w = 0.237 * \left(\frac{a_b}{k_r}\right)^{0.52} \qquad for \quad a_b > 0.636 k_r \qquad [-] \quad (2.5)$$

In which:

a_b	horizontal wave amplitude at the seabed	$[m]$

The horizontal velocity amplitude U_w can be, for monochromatic waves and undisturbed flow, be derived with linear wave theory as:

$$U_w = \frac{\pi H}{T_w}\frac{1}{sinh(\frac{2\pi h}{L})} \qquad [m/s] \quad (2.6)$$

In which:

H	wave height	$[m]$
T_w	wave period	$[s]$
L	wave length	$[m]$

Since most seabeds around monopiles experience current induced bed shear stress as well as wave induced bed shear stress, it is necessary to combine these two to obtain the actual bed shear stress. For this Soulsby compared the mean and maximum bed shear stress during a wave cycle and derived two equations based on a data set of 131 points:
The mean shear stress

$$\tau_m = \tau_c\left[1 + 1.2\left(\frac{\tau_w}{\tau_c + \tau_w}\right)^{3.2}\right] \qquad [N/m^2] \quad (2.7)$$

and the maximum shear stress

$$\tau_{max} = \left[(\tau_m + \tau_w \cos(\phi))^2 + (\tau_w \sin(\phi))^2\right]^{1/2} \qquad [N/m^2] \quad (2.8)$$

In which ϕ is the angle between the wave and current direction.
The flow around a monopile however is different from the unrestricted flow and thus the presence of the monopile should be taken into account. This is done by introducing amplification factors about which there still is a lot of uncertainty (see also Appendix B). With these amplification factors the actual bed shear stress is found. This is used to calculate the required median rock diameter (Schiereck and Verhagen, 2016):

$$D_{50} = \frac{\tau_{bed,max}}{\Psi_{cr}\rho_w \Delta g} \qquad [m] \quad (2.9)$$

Filter stability refers to the ability of the scour protection to prevent material from escaping from within the protection itself or from the layer underneath. The following three design formulas aid in securing this (Schiereck and Verhagen, 2016):

- $\frac{d_{15U}}{d_{85L}} < 5$ Which dictates that the diameter of the smaller stones in the upper layer, d_{15U}, must be less than 5 times the size of the larger stones in the lower layer, d_{85L}. When this rule is followed, the larger stones in the lower layer will be blocked by the smaller stones in the upper layer.
- $\frac{d_{60}}{d_{10}} < 10$ Which dictates that the larger stones, d_{60}, within a layer should be smaller than 10 times the size of the smaller stones ,d_{10}, in that same layer. When this rule is followed, the larger stones will not be so large that they are unable to block the smaller stones in that same layer.
- $\frac{d_{15U}}{d_{15L}} > 5$ Which dictates that the smaller stones in the upper layer, d_{15U}, should not be bigger than than 5 times the size of the smaller stones in the lower layer,d_{15L}. This rule is to prevent pressure build-up by requiring that the upper layer should be more permeable than the lower layer.

Flexibility refers to the ability of the scour protection to follow the sea bed lowering at the edges of the scour protection without completely failing. This is often done by extending the horizontal dimensions of the filter layer. The extent to which the scour protection needs to extend in horizontal direction is the subject of discussion. Matutano et al. (2013) researched this subject and found six different recommendations for the extent of the scour protection (measured from the edge of the pile) ranging between 2D and 4.5D, in which D is the pile diameter. However, in the paper by Matutano et al. (2013), scour protection extension and erosion extension are used interchangeably. Det Norske Veritas AS (2013) provides a formula to calculate the radius r of the scour hole with formula 2.10 and recommends to extend the scour protection over the same length. Using scale model tests to determine the horizontal extend of the scour protection can lead to other values, in wind farm Gemini for example, the scour protection extends over only 1.6D (Van Velzen et al., 2014).

$$r = \frac{D}{2} + \frac{S}{\tan\varphi} \qquad [m] \quad (2.10)$$

In which:

S	equilibrium scour depth	$[m]$
φ	friction angle of the soil	$[degree]$

Common design
A common design for a rock scour protection around a monopile (see Figure 2.14) consist of the following elements:

- Armour rock grading

- Filter layer(s) grading
- Layer thickness
- Horizontal dimensions of the scour protection

The grading (size range and distribution of sizes) of armour rock follows from the bed shear stress which is caused by waves and currents. The grading of the filter layer(s) follows from the filter rules which are discussed above and the thickness of each layer is dependent on the rock size in that layer ($2 * D_{50}$ and at least $0.3[m]$). The horizontal dimensions follow from a combination of the scour hole depth at the end of the scour protection and the dynamic response of the wind turbine. If the effect of the scour hole is too large then the horizontal dimensions should be increased.

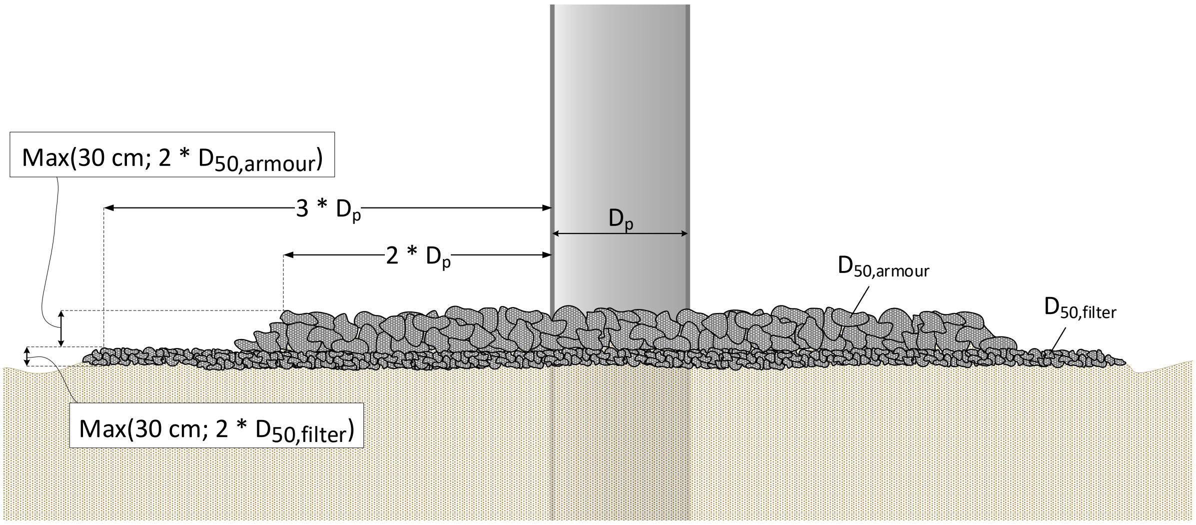


Figure 2.14: Typical design of a scour protection

2.4.2. Scour protection Gemini

The wind farm Gemini is chosen as reference project because it was commissioned in the end of 2016 and can thus be assumed to be representative for future wind farms. Additionally it is located in an area where multiple other wind farms are planned to be constructed.

Design requirements

The design lifetime of all the components of the wind farm is 25 years, this is also the case for the scour protection. As a result the scour protection is designed to withstand a storm with a return period of 50 years (Van Velzen et al., 2014). However, due to the fact that the filter layers are exposed in the time between their installation and the installation of the scour protection, it is necessary for the filter layer to be able to resist the hydraulic forces that can occur during that time. It is possible that the armour layer is only constructed after a winter has passed, therefore the filter layer should be able to withstand a storm with a return period between 1 and 10 years.

Calculations

The scour protection has been designed using physical modelling (Van Velzen et al., 2014) instead of the calculations provided in 2.4.1. Four filter layers (see Table 2.5) and five armour layers with a 1-3” filter layer underneath (see Table 2.6) were tested. The normal density gradings have a density of 2,650 kg/m^3 while the high density (HD) gradings have a density of 2,950 kg/m^3.

Table 2.5: Tested filter gradings
Source: Van Oord (2014)

Stone grading	d_{15}		d_{50}			d_{85}		d_{85}/d_{15}	
	min	max	min	mean	max	min	max	min	max
1-3”	0.029			0.047		0.066		2.28	
2-8”	0.061			0.111		0.168		2.75	
3-9”	0.081	0.110	0.125	0.1525	0.180	0.173	0.215	2.14	1.95
3-9” HD	0.081	0.110	0.125	0.1525	0.180	0.173	0.215	2.14	1.95

Table 2.6: Tested armour gradings
Source: Van Oord (2014)

Stone grading	d_{15}		d_{50}			d_{85}		d_{85}/d_{15}	
	min	max	min	mean	max	min	max	min	max
10-60 kg	0.206		0.258	0.285	0.311	0.376		1.83	
11-67 kg HD	0.206		0.258	0.285	0.311	0.376		1.83	
10-200 kg	0.198	0.249	0.346	0.397	0.447	0.440	0.590	2.22	2.37
40-200 kg	0.324		0.402	0.432	0.461	0.556		1.72	
45-223 kg HD	0.324		0.402	0.432	0.461	0.556		1.72	

The filter layers have been tested on winnowing, edge-scour, and stability while the armour layer has been tested on stability only. Also the effect of the scour protection on the surrounding sea bed has been researched.

Results

Of the four tested filter gradings the 1-3” filter prevented winnowing while the larger layers have shown to experience sinking immediately around the pile. Larger filter layers such as the 2-8” and 3-9” prevented winnowing only when applied in thick enough layers. This however is costly due to the significantly larger rock volumes.
The stability tests for the filter layers (see Table 2.7 and Figure 2.15) showed that the 1-3” filter layer deformed in the order of 0.2 m (±5 layers) near the pile after a 1/1 year storm

condition and that the sea bed became exposed after a 1/10 year storm condition. The expected maximum deformation of the 1-3” filter layer is at least 0.50 m (±10 layers). The maximum deformation of the 2-8” filter layer after a 1/1 year storm condition is expected to be 0.4 m (±4 layers) while the 1/10 and 1/50 year storm conditions resulted in exposure of the sea bed at the downstream side of the monopile. The 1/1 year storm conditions for the 3-9” grading resulted in a deformation of 1-2 layers (1-2 layers more at the downstream side) while the 1/10 year storm conditions removed approximately 3 layers. The deformation of the 3-9” HD grading is negligible during both the 1/1 and 1/10 year storm conditions.

Table 2.7: Results of testing the filter layer
Source: Van Oord (2014)

Grading	Performance during 1/1 and 1/10 year storm conditions
1-3”	Good filter properties, severe movement during storm conditions
2-8”	Marginal filter properties, significant movement during storm conditions
3-9”	Poor filter properties, marginal movement during storm conditions
3-9”HD	Poor filter properties, little to no movement during storm conditions

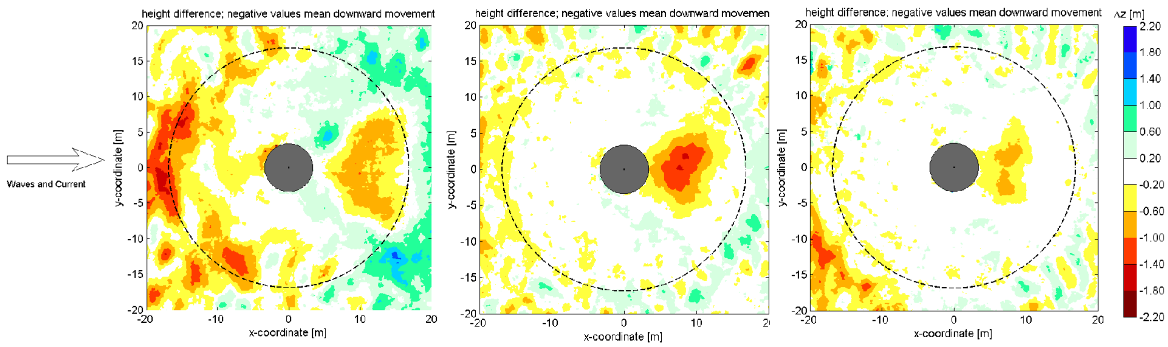


Figure 2.15: The difference in bathymetry for the test of the 1-3” layer (left), the 3-9” layer (middle), and the 3-9”HD layer (right).
Source: Van Oord (2014)

The stability tests for the armour layers (see Table 2.8) showed that the 11-67 kg HD, 10-200 kg, 40-200 kg, and 45-223 kg HD layers were all dynamically stable during 1/50 year storm conditions in which a deformation of 1-2 layers is expected (see figure 2.16 for the deformation in test conditions). The 3-9” stone grading was marginally stable but could be dynamically stable if more rock layers are applied. From these results and field experience in other parks it is assumed that a slightly larger grading of 60-300 kg HD would be stable with little stone movement.

Table 2.8: Results of testing the armour layer
Source: Van Oord (2014)

Grading	Performance during 1/50 year storm conditions
60-300 kg	Dynamically stable, little to no stone movement, low monitoring frequency
45-223 kg HD	Dynamically stable, 1-2 layers displaced, intermediate monitoring frequency
40-200 kg	Dynamically stable, 1-2 layers displaced, intermediate monitoring frequency
10-200 kg	Dynamically stable, 1-2 layers displaced, intermediate monitoring frequency
11-67 kg HD	Dynamically stable, 1-2 layers displaced, intermediate monitoring frequency
3-9”	Marginally stable, large stone movement, frequent monitoring frequency

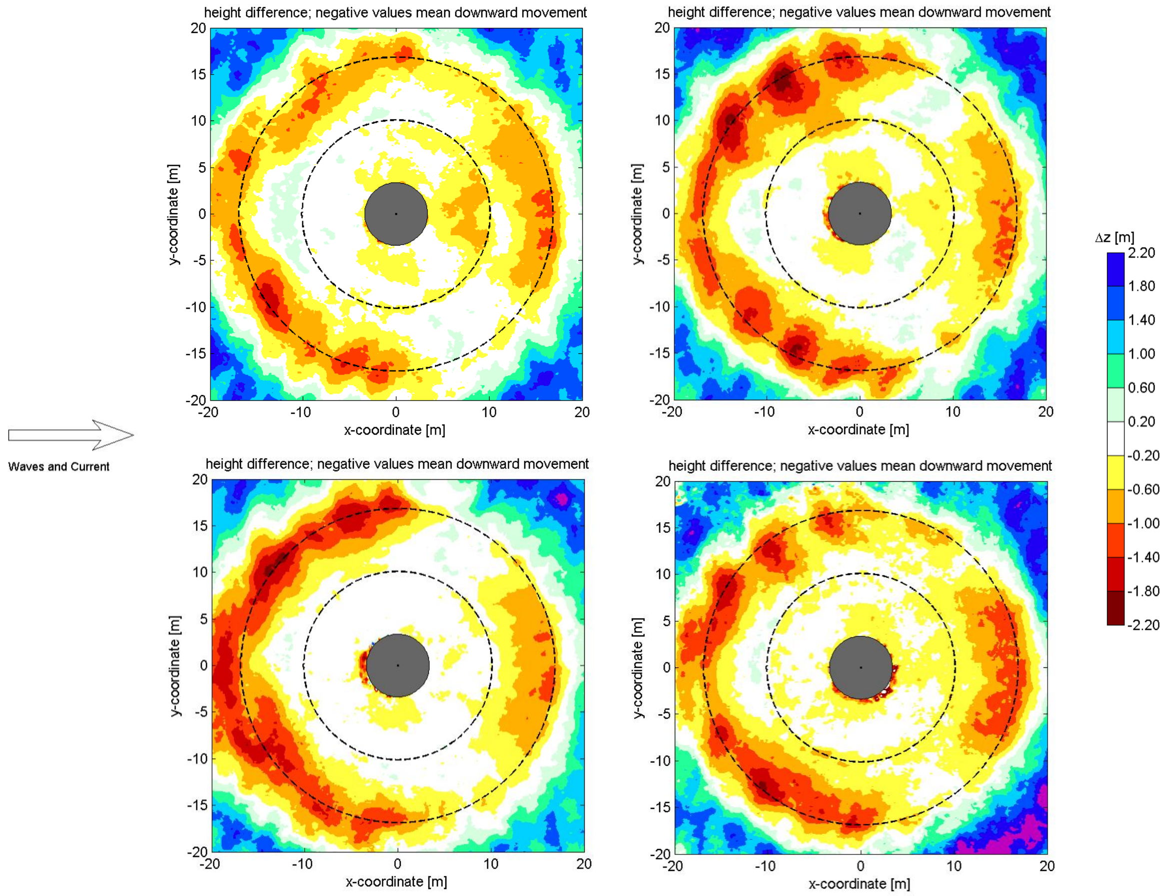


Figure 2.16: The difference in bathymetry for the test of the 10-200 kg armour grading (top left), the 40-200 kg armour grading (top right), the 11/67 kg HD armour grading (bottom left), and the 45/223 kg HD armour grading (bottom right) after subsequently 1/1 year, 1/10 year, and 1/50 year storm conditions. All contain a 1-3" filter layer with 1 m thickness. Source: Van Oord (2014)

Design

Three different potential scour protection designs are proposed by Deltares of which the following has been used (see Figure 2.17 and Figure 2.18):

- A 1-3" filter layer with a minimal thickness of 0.5 m, a diameter of at least 4.25 times the pile diameter, edge slopes not steeper than 1:2, and at least 2 m of free surface between the upper edge of the filter layer and the lower edge of the armour layer.
- A 3-9" HD armour layer with a minimal thickness of 1 m, a diameter of at least 3 times the pile diameter, edge slopes not steeper than 1:2, and at least 1 m of free surface at the top side.

This provides a hard substrate surface for which the areas are shown in Figure 2.18. In total it is calculated that about 388 m^3 of armour layer and 362 m^3 of filter layer is required per monopile (58,200 m^3 and 54,300 m^3 for all monopiles). The total area of added hard substrate is 773 m^2 per monopile and thus about 116,000 m^2 for the whole wind farm.
The precise size of the holes in the scour protection is unknown, but Buijs (2015) approximated the pore size distribution in his MSc-thesis using a medical CT scanner and imaging software after which he fitted the results to a Rosin Rammler distribution and obtained the following equation:

$$f(x, P_{80}, m, F) = 1 - e^{\ln(0.2)*\left(\frac{x-F}{P_{80}}\right)^m} \qquad for \quad x > F \qquad [m] \quad (2.11)$$

In which:

$P_{80} = \left(-2.13 * \phi * \frac{D_{85}}{D_{15}} + 13.2\right) * \frac{D_{50}}{25}$	determines the slope of the distribution	$[-]$
$m = \left(-0.533 * \phi * \frac{D_{85}}{D_{15}} + 2.29\right)$	determines the shape of the distribution	$[-]$
$F = (27.5 * \phi - 3.35) * \frac{D_{50}}{25}$	determines the start point of the distribution	$[m]$
$\phi(= 0.37)$	porosity	$[-]$

and in which the pore size is defined as $D_{pore} = [Volume_{pore}]^{1/3}$ (see Figure 2.19).

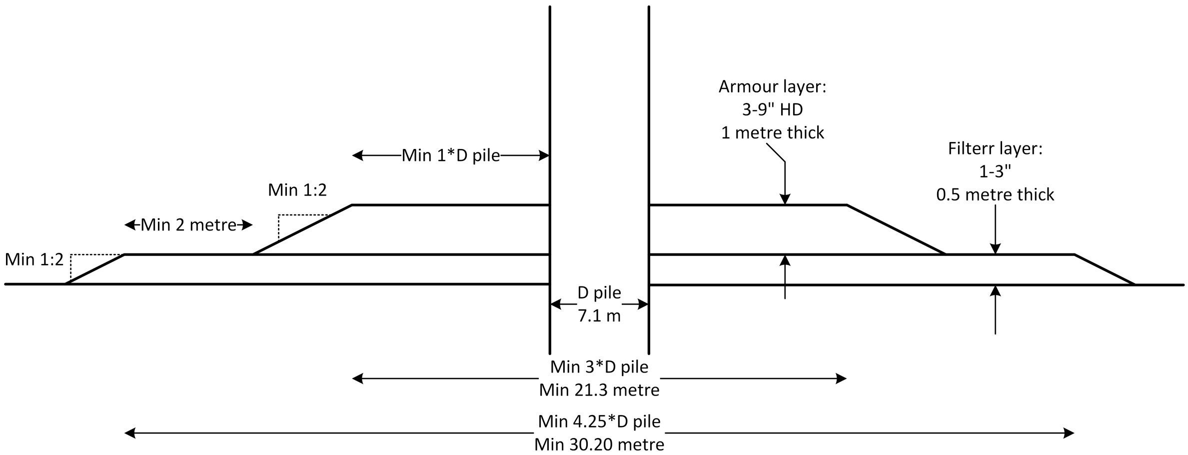


Figure 2.17: The scour protection design for wind farm Gemini (drawing not to scale)

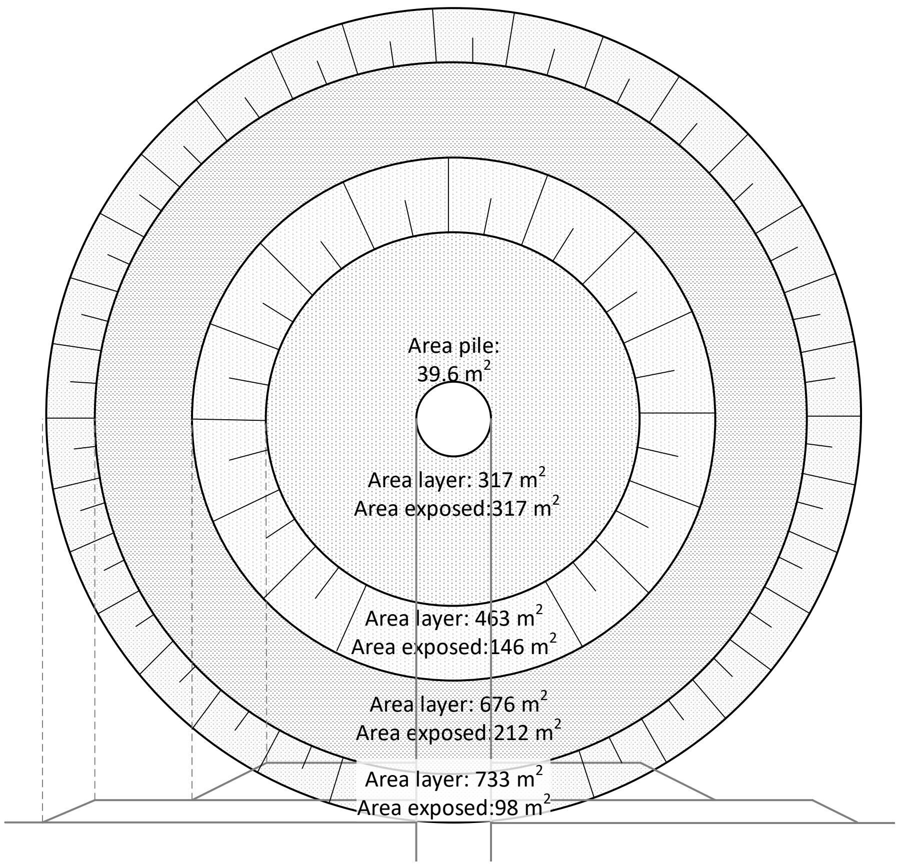


Figure 2.18: The areas of the scour protection design for wind farm Gemini (drawing not to scale)

Buijs (2015) also approximated the number of pores in a volume V of scour protection with the following formula:

$$N_{pores} = 1.81 * \left(\frac{D_{85}}{D_{15}}\right)^{0.25} * \frac{V * (1-\phi)}{D_{50}^3} \qquad [-] \quad (2.12)$$

Using these formulas it can be calculated that the armour layer of the scour protection for a single pile in wind farm Gemini contains bout 150,000 holes of different sizes for which the approximated distribution is given in Figure 2.20 and an explanation for how to read the graph in the Intermezzo that follows.
It should however be noted that the constant value of the porosity used here (ϕ = 0.37) is actually not a constant but instead depends on the size, shape, and uniformity of the rocks in the grading. This was not included by Buijs in this formula and will therefore also not be included in this study. Another point of attention is that this approximation was made on a limited number of scans and therefore is not exact.

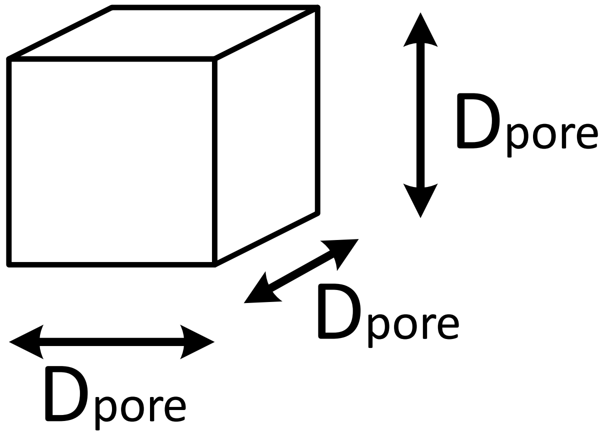


Figure 2.19: The definition of the pore size D_{pore}

Intermezzo: How to read the pore-size distribution graph
The pore-size distribution graph is used multiple times in this document and since it might not be straightforward how to read this graph it is explained in this section.
The x-axis lists the pore-size diameter in [m], the y-axis lists the fraction of the pores that is larger than a certain value.
The horizontal red line is drawn at a value of 0.5 on the vertical y-axis, the place where it touches the pore-size distribution curve (blue) shows via the vertical red line the pore-size diameter that is larger than 50% of the pores, in this case about 0.087 m.
This approach is valid in the other direction as well. Start on the horizontal x-axis at a value of 0.06 m (green line) and go up till the pore-size distribution line (blue) is reached, that point shows via the horizontal green line what fraction of the holes is larger than this value, in this case about 0.89, or 89%.
Alternatively one can pick a point on the pore-size distribution curve and read the point the following way: (y-axis value) of the pores in this grading is larger than (x-axis value).

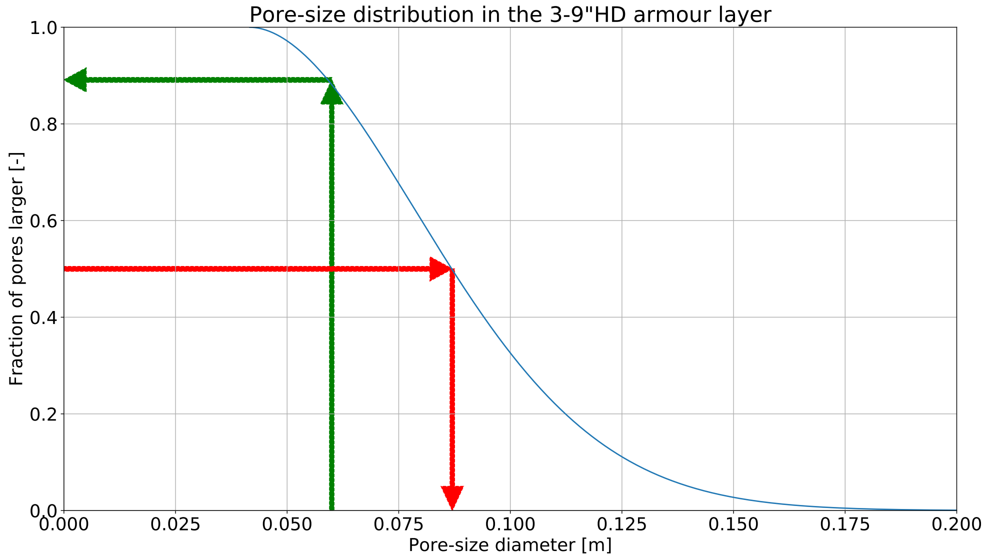


Figure 2.20: The pore-size distribution in the 3-9” HD armour layer. After Buijs (2015).

2.5. Species

2.5.1. North Sea species

The list of species occurring in the Dutch section of the North Sea (Bos et al., 2016) gives a good indication of the type of species that are present in the shallow parts of the North Sea (see also Figure 2.21). This list is based on the species listed in the 'Nederlands Soortenregister' (Dutch species register) and has been complemented with species from different databases and literature. From this list the following information is obtained: There are a total of 1,106 different species (excluding birds) living in the Dutch part of the North Sea of which 556 are categorized as occurring in the coastal zone (0-20 m) and 839 as occurring offshore (0-60 m), two categories which do not exclude each other. Another division is made between benthic species occurring on hard substrate (519) and benthic species occurring on soft substrate (810). A third relevant characteristic is whether the species is native or exotic. For the species occurring in the Dutch part of the North sea 1,032 are categorized as native and 71 (6.4%) as exotic, for the three remaining species this characteristic has not yet been determined.

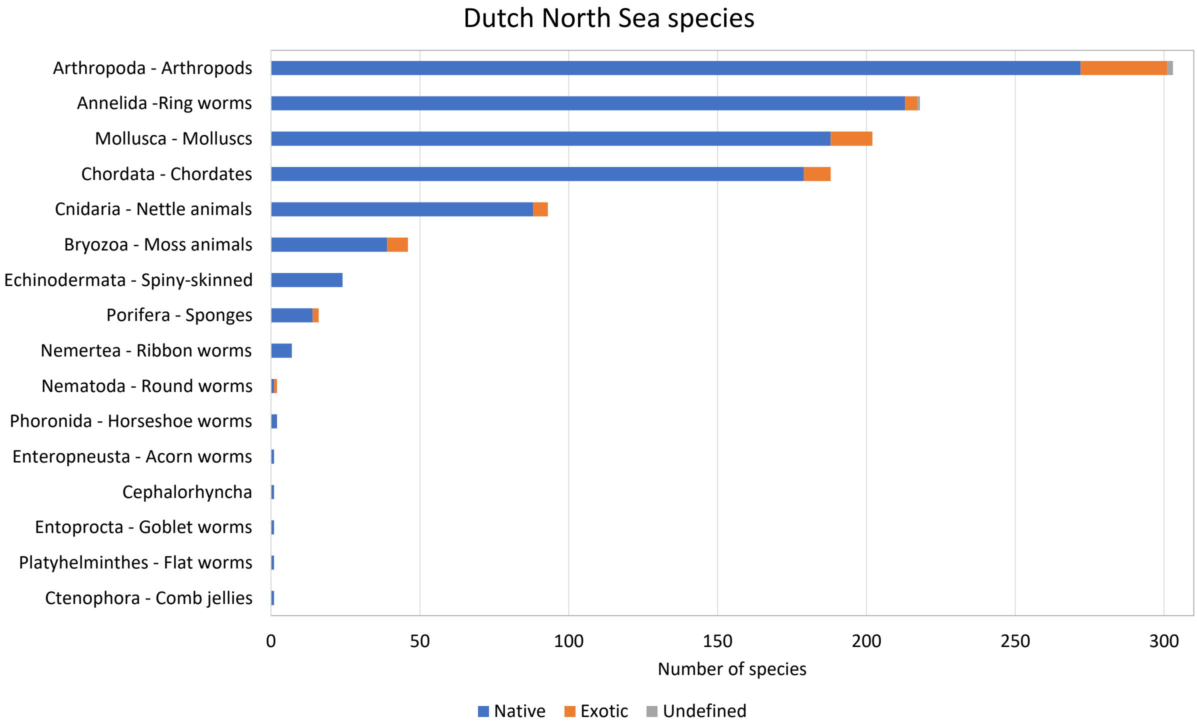


Figure 2.21: Species in the Dutch part of the North Sea
(Adapted from Soortenlijst Nederlandse Noordzee (Bos et al., 2016) with exclusion of birds)

Species mentioned in literature

Multiple research projects have taken place regarding the influence of offshore wind farms on North Sea species and the possibilities that the hard substrate provides. One of the most extensive research projects was commissioned by the Dutch ministry of Economic Affairs and aimed to give an overview of possibilities and knowledge gaps regarding hard substrate in relation to ecological added value. The objective of this study was to provide input for the national policy on "Building with North Sea nature". This resulted in three extensive reports, the first regarding reefs in general (Van Duren et al., 2017), followed by a report on eco-friendly scour protections in offshore wind farms (Lengkeek et al., 2017), and a final report analyzing the opportunities for the development of flat oyster populations in wind farms (Smaal et al., 2017), a subject that is related to a previous feasibility study on the restoration of flat oyster beds in the Dutch part of the North Sea which was also commissioned by the Dutch ministry of Economic Affairs (Smaal et al., 2015).
Over the last decade several researchers from different countries have researched similar

subjects. These research projects all focus on offshore wind farms in the North Sea and/or on the hard substrate that is present in the form of scour protection, natural hard substrate or other. Table C.1 gives an overview of some of the papers and reports that have been published in relation with this subject and the area and species that were targeted in the research.

Policies regarding the North Sea and North Sea species

The European Habitats Directive, adopted in 1992, aims to promote the maintenance of biodiversity, taking account of economic, social, cultural and regional requirements and initiated the Natura 2000, a network of nature protection areas in the territory of the European Union (European Council, 1992).

The Marine Strategy Framework Directive (MSFD) was created in 2008 to safeguard the environmental status of the marine environments across the EU. This directive obliges every European Member State to draw up a Marine Strategy which must focus on the protection, preservation and restoration of the marine environment, where sustainable use of the North Sea is also guaranteed, and must consist of a status description of the marine environment based on eleven descriptors: biodiversity, exotic species, commercial fish stocks, food web, eutrophication, soil floor integrity, hazardous substances, hazardous substances in fish, litter, and energy supply (European Commission, 2003).

2.5.2. Selection of indicator species

Not all the species mentioned in 2.5.1 can be researched in the time available. Therefore a limited number of species is selected which are different from each other in their interaction with the wind farm, their requirements, their way of living and their type. Each of these species will serve as a measure of the suitability of the environmental conditions for its own type of species and thus is an indicator species.

Selection criteria and considerations

The following criteria are used to decide on which species will be selected to be the indicator species.

- **Criterion:** The selected species must be different from each other.
  Consideration: Due to limited time it should be avoided to spend time on multiple species which are similar.
  Decision: Figure 2.21 shows the species that are present in the Dutch section of the North Sea. These species are divided based on their phylum (taxonomic category below kingdom). By selecting a species from each of the four largest phyla 82% of all the species are represented with regards to their phylum.

- **Criterion:** The selected species must be native to the North Sea.
  Consideration: Species which are not native to the North Sea (invasive species) can be harmful for native species and are therefore unwanted.
  Decision: Invasive species are not considered.

- **Criterion:** The selected species must have a small population compared to previous levels or be of commercial value.
  Consideration: Species whose populations have not declined are not considered since these species do not require stimulation as much as more threatened species.
  Decision: Species which are not listed as Critically Endangered, Vulnerable, Near Threatened, or Conservation Depend on the IUCN Red List of Threatened Species (Figure 2.22) or are not on the the OSPAR List of threatened and/or declining species and habitats, will not be considered unless they have significant commercial value.

- **Criterion:** The selected species must interact with the sea floor.
  Consideration: Species which do not interact with the sea floor are not relevant when considering changes to a scour protection.
  Decision: Species which do not interact with the sea floor are not considered.

- **Criterion:** The number of selected species must be small but not too small.
  Consideration: Due to limited time not all species which remain after considering the previous criteria can be studied. A minimum number of species is to be taken into account to make sure that there remain enough possibilities.
  Decision: Not more than 5 and no less than 3 species will be selected for further research.

Figure 2.22: Classes which are used by the IUNC to classify the status of species.
EX: **Ex**tinct, **EW**: **E**xtinct in the **W**ild, **CR**: **Cr**itically Endangered, **EN**: **En**dangered, **VU**: **Vu**lnerable, **NT**: **N**ear **T**hreatened, **LC**: **L**east **C**oncern.

Selected species

Based on the given criteria the following species have been selected (see Table 2.9):

- The Atlantic cod, a benthopelagic fish species which has been listed as vulnerable after the population collapsed due to over-fishing and has significant commercial value.
- The European lobster, a decapod (ten-legged) crustacean which belongs to the family of Nephropidae (clawed lobster) and is a highly priced commercial catch and considered a luxury food in many countries.
- The European flat oyster, a bivalve mollusc which in the 19^{th} covered large areas in the North Sea but has now almost completely disappeared.
- The Ross worm, a reef building worm which lives in a tube made of shell fragments and coarse sand cemented together with mucus.

In selecting these four species the criteria are fulfilled. Additionally these four species represent four different types: 1) the Atlantic cod is a swimming species which uses the whole water column and is able to travel large distances, 2) the European lobster is bound to the sea floor and travels shorter distances, 3) the European flat oyster is attached to the hard substrate on the sea floor and does not travel once attached, and 4) the Ross worm builds its own habitat out of soft substrate and does not move once it has started building.

Table 2.9: Selected species

Species	**Phylum**	**Status**	**Native**	**Interaction with sea floor**
Atlantic cod	Chordates	IUCN: Vulnerable	Yes	Adults forage Juveniles find shelter
European lobster	Arthropods	Commercially valuable	Yes	Possibility for shelter
European flat oyster	Molluscs	OSPAR: Threatened	Yes	Attachment
Ross worm	Ring worms	OSPAR: Threatened	Yes	Builds reefs from sand

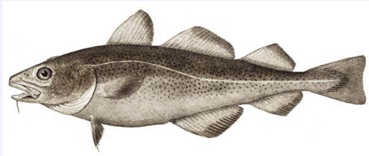
2.5.3. Atlantic Cod - Gadus morhua

General information

Appearance

The Atlantic cod can be recognized by it's three large dorsal fins, its two anal fins, the barbel under the lower jaw and its disproportionately large head. Their colour varies depending on their environment, ranging from a light yellowish-green to a darker reddish-green. Their back and head are often spotted and dark while their belly is more pale and shows little spots. A distinctive lateral line is often present from the pectoral fins to the tail.

Atlantic cod



Scientific classification

Kingdom:	Animalia
Phylum:	Chordata
Class:	Actinopterygii
Order:	Gadidformes
Family:	Gadidae
Genus:	Gadus
Species:	Gadus morhua

Distribution

Figure 2.23: Distribution of the Atlantic cod.
Author: Aotearoa

Size

Atlantic cod can grow to up to 2 m in length and almost 100 kg in weight, common length however is about 1 m for grown adults with an average mass of 40 kg.

Distribution

This species occurs in the North Atlantic and Arctic, from Nova Scotia in the west, along the coast of Greenland, Iceland, the UK, into the North Sea, along the coast of Norway all the way into the Barents Sea in the east, although migrations of individual schools are usually limited to 200 km.

Behaviour

During the day the adult cod swims in schools about 30-80 m above the sea bed, at night it feeds individually on invertebrates and fish, including young cod (Froese and Pauly, 2018).

Preferences

The juvenile cod (<0.31 m) prefers shallow sublittoral waters (10-30 m) with complex habitats which provide protection from predators. Adult cod prefer deeper (up to 600 m deep), colder waters (Froese and Pauly, 2018). Cod is able to tolerate very low salinities (<10‰) but prefers salinities between 28-35 ‰ (FAO, 2019a).

History

For many years the Atlantic cod has been an extremely important source for fishery up until the 1990's, when the cod fisheries collapsed due to overfishing. After this collapse the fishing continued but a rebuilding plan was agreed upon by the European Commission in 2004. Since the historical low level of spawning stock biomass in 2006 the population has slowly recovered and by 2013 the limit reference point for spawning stock biomass was surpassed (ICES, 2018).

Life cycle

Reproduction

And average female Atlantic cod caries around 500 ripe eggs per gram body weight. The size of these eggs increases with the age of the fish and larger eggs have a larger chance of survival than smaller eggs (Trippel, 1998). Spawning can occur year round for Atlantic cod but peak levels occur in winter and spring. This spawning is an annual happening which takes place within a three month period anywhere in the water column (ICES, 2004).

Life cycle
The life cycle of Atlantic cod consists of four stages. The Atlantic cod starts as buoyant pelagic eggs, located in harbours, bays, and offshore banks. After two to three weeks the eggs hatch and enter the second stage, the larval stage, which lasts up to 3 months (at 8°C). This stage is followed by the juvenile stage , in which the cod stays near the sea bed till it is about 0.06m in length. The male and female cod reach reproductive maturity at respectively 1.7 to 7 years and 1.7 to 5.4 years. Length at first maturity is 0.31-0.74 m. Their average lifespan is about 16 years.

Promotional and inhibiting factors
Promotional factors
Factors which are beneficial to the Atlantic cod are:

- Food abundance.
  Enough food must be available. During the larval stage cod feeds on zooplakton, as juveniles shrimp and other small crustaceans are consumed and as adults they feed on anything available, including smaller cod (Froese and Pauly, 2018).
- Suitable substrate.
  Heterogeneous habitat and vertical structures are favorable for shelter against predators. Especially during the first four years of their life (Laurel et al., 2003a,b, 2004). Cod stays near the bed till they are at least 0.06 m in length (Tupper and Boutilier, 1995a). The catch per unit effort (CPUE) is significantly higher on gravel and rocky seabed than on sand (Wieland et al., 2009), indicating that hard substrate is more beneficial to cod than sand.
- Currents.
  Currents transports the cod during its larval stage and transports oxygen into the shelter, therefore the presence of a current is required for the cod.

Inhibiting factors
Factors which inhibit the occurrence of Atlantic cod are:

- Fishing.
  Fishing is a large inhibiting factors for Atlantic cod above the age of 0 (>0.2 m) (Daan, 1974). The fishing mortality at ages 2-4 was 0.44 in 2017 (ICES, 2018), which means that 44% of the cod of age 2-4 years was caught.
- Predators.
  Juvenile Atlantic cod is at risk of being eaten by larger fish such as grey gunnards. This risk decreases with increasing size (Walker and De Oliveira, 2015).
- Water depth.
  The water depth is associated with the amount of light penetration, the water temperature, the current, and the availability of food, which are all to some extent important for cod during its lifetime. The larvae float near the surface while the juvenile cod is commonly found between 10-30 m water depths. The adult cod can be found up to a depth of 600 m (Froese and Pauly, 2018).
- Competition.
  Competition is mainly an issue for the demersal juvenile cod which competes with other cod for shelter sites (Tupper and Boutilier, 1995b). For grown pelagic cod competition is only an issue at very large population sizes when resources become scarce.
- Minimum population.
  In theory only one male and one female cod are required to continue a population, however, for a healthy population a larger population is required. Research has shown that for a long-term stable and effective population a minimum of $\pm$1,000 cod is required (Poulsen et al., 2006).

- Currents.
  Cod is not hindered by currents, but very strong currents can tire the cod.

- Mobility.
  Migrations of individual schools of cod are usually limited to about 200 km (Froese and Pauly, 2018). For the cod that lives near the seabed and uses shelter the home range (maximum distance moved in any direction from the shelter site) has been recorded in a research and found an exponential relation between the length of cod and the home range (Tupper and Boutilier, 1995b), starting from about 20 m^2 at 0.05 m length to about 200 m^2 at 0.2 m length.

- Soil composition.
  This is not an inhibiting factor for the Atlantic cod.

Current situation

The International Council for the Exploration of the Sea (ICES) has drawn up an extensive report on the status of the Atlantic cod in which advice is given on the fishing opportunities and is summarized as follows: ”Fishing mortality (F) has declined since 2000, but remains above F_{MSY}. Spawning-stock biomass (SSB) has increased from the historical low in 2006, but is still below MSY $B_{trigger}$. Recruitment (age 1) since 1998 remains poor.” (ICES, 2018). Figure 2.24 provides some graphs as aid.
F_{MSY} is the fishing mortality consistent with achieving Maximum Sustainable Yield (MSY), in this case that means that at this rate the fishing is not sustainable.
The Spawning-stock biomass (SSB) is the total weight of all sexually mature fish in the stock. As noted in the report this is still below MSY $B_{trigger}$, which is a biomass reference point that triggers a cautious response within the ICES MSY framework.
The recruitment is the amount of fish added to the exploitable stock each year due to growth and/or migration into the fishing area. The recruitment (age 1) is the amount of fish that reach the age of 1.
Based on this information it can be concluded that, even though recovering, the Atlantic cod is still under pressure.

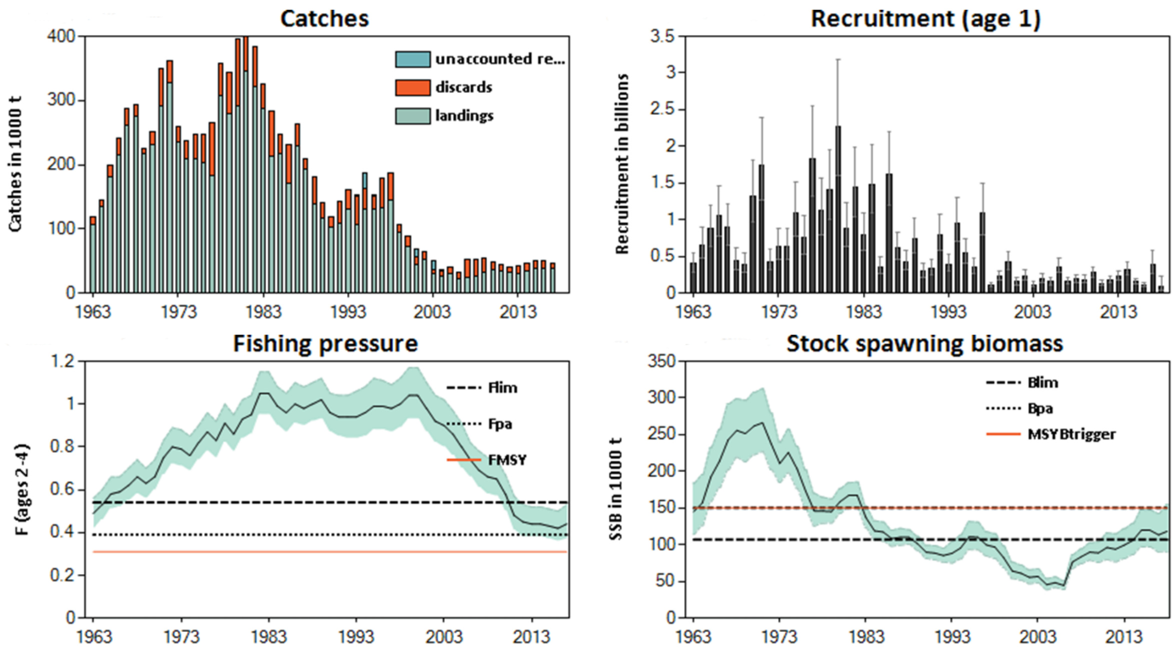


Figure 2.24: Cod in the North Sea. Summary of the stock assessment. Catches are assessment estimates. Only positive unaccounted removals are plotted. Shaded areas (F,SSB) and error bars (R) indicate 95% confidence intervals (ICES, 2018).

The most recent complete information available in this report is from the year 2017-2018. Of this year the most important figures are the following:

- The Spawning-stock biomass in this year was $113.5 * 10^6$ kg. A small part of this number lives in the southern half of the North sea and a larger part in the northern half and in the Skagerrak/Kattegat (Sea between Norway and Denmark).
- The fishing mortality (F) for the ages 2-4 was 0.44, which means that 44% of the number of fish in that year is taken by fisheries.
- The Recruitment (age 1) was $386 * 10^6$. This number however varies a lot (in 2016-2017 it was $110 * 10^6$).

2.5.4. European lobster - Homarus gammarus

General information

Appearance

The European lobster is a decapod (ten-legged) crustacean and belongs to the family of Nephropidae (clawed lobster). It has two large pincers of which one is slightly larger than the other, the larger one is used for crushing and the smaller one for cutting. While alive the lobster has a blue color, while the better known red color only appears when the lobster is cooked.

Size

Through molting (shedding their old exoskeleton and growing a new one) the European lobster grows throughout its whole life. However, the frequency of this molting, and thus its growth rate, diminishes over time. Lobsters usually do not exceed a length of 0.5 m. The total length of the lobster is about 2.8 times the carapace length (Rozemeijer and Wolfshaar, 2019), which is measured from the rear of the eye socket to the rear of the carapace.

Distribution

This species occurs along almost all of the European coasts, excluding the Baltic, probably due to lower salinity and extremer temperatures (Prodohl et al., 2006).

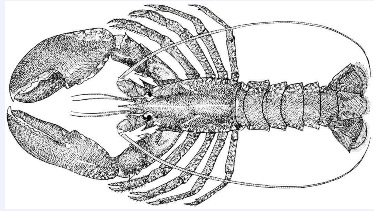
Behaviour

The diet of the European lobster, who hunts mainly at night, consists of hermit crab, whelk, polychaeta worms, blue mussels, and occasionally animal carcasses (van der Meeren, 2013). This species typically stays within 2 km from their home (The National Lobster Hatchery, 2017) but distances as large as 15.7 km have been reported (Jensen et al., 1994).

Preferences

The lobster can be found at a depth between 0 and 150 m, but usually not deeper than 50 m. It prefers rocky shores, reefs, and cobble and boulder fields (Bannister and Addison, 1998). The availability of shelter has a positive influence on the size composition of the lobster population (Howard, 2007). The lobster is limited in its ability to find food by strong currents and thus prefers weaker flows (Howard and Nunny, 1983).

European lobster



Scientific classification

Kingdom:	Animalia
Phylum:	Euarthropoda
Subphylum:	Crustacea
Class:	Malacostraca
Order:	Decapoda
Family:	Nephropidae
Genus:	Homarus
Species:	Homarus gammarus

Distribution

Figure 2.25: Distribution of the European lobster. ©FAO

History

The European lobster is highly valued as a seafood product and has been heavily targeted by fisheries which has lead to diminishing populations. Regulation thus far have been limited to minimum catching sizes (0.085 m carapace length in Dutch, Belgian, and German waters, 0.087 m in British waters, and 0.088 m in Norwegian waters (Rozemeijer and Wolfshaar, 2019)), the prohibition of catching berried female lobsters (European Council, 2006), and V-notching, which is the marking of female species to give them an opportunity to reproduce.

Life cycle

Reproduction

Reproduction takes place during summer after which the eggs are held on the pleopods (five pair of swimming limbs attached to the abdomen) where they hatch the next summer.

Life cycle
After hatching the larvae enter a pelagic phase which lasts about 2 to 3 weeks depending on the water temperature. During these weeks the larvae develop into meta-larvae and settle to the seabed. Research has shown that no successful larval development is possible at temperatures below 14°C and that larval survival increases from 9% at 14°C to 80% at 22°C, while duration of larval development decreases correspondingly from 26 to 13 days (Schmalenbach and Franke, 2010). It is estimated tht only 0.005% of the hatchling lobsters survive the planktonic phase to reach the benthic phase (Rozemeijer and Wolfshaar, 2019). Knowledge about the early benthic phase (between 0.005 and 0.02 m carapace length) is lacking, and information on the juvenile stage (up to 0.045 m carapace length) is scarce. In the laboratory environment (The National Lobster Hatchery, 2017) it was found that the juveniles, once settled, burrow into the seabed where they spend approximately 2 years, seldom moving. The preferred habitat ranges from coarse sand to fine shingle, although burrowing in cohesive mud has also been observed. After this burrowing stage, in which they eat marine worms and other animals like small crabs and urchins till their carapace length is about 0.015 m, they leave their burrows for crevices and holes in rocky substrate. Maturity is, again depending on water temperature, reached after 5-8 years after which the male on average reaches the age of 31, with a maximum of 42 $\pm$ 5 years while the females reach a significantly higher average (54) and maximum (72 $\pm$ 9) age (Sheehy et al., 1999).

Promotional and inhibiting factors
Promotional factors

- Food abundance.
  The diet of lobsters consists of hermit crab, whelk, polychaeta worms, blue mussels, and occasionally animal carcasses (van der Meeren, 2013), species that are often found on hard substrate.

- Suitable substrate.
  Lobsters are known to use holes and crevices as shelter from predators and currents (Langhamer et al., 2009; Langhamer and Wilhelmsson, 2009).

- Currents.
  Currents transport oxygen into the holes and crevices in which the lobster takes shelter.

Inhibiting factors
Factors which inhibit the occurrence of lobster are:

- Fishing.
  Due to its commercial value the lobster is heavily targeted (FAO, 2019b).

- Predators.
  Juvenile lobsters are at risk of being eaten by predators while larger lobsters are vulnerable to predators during molting.

- Water depth.
  Water depth influences oxygen levels, light penetration and temperature which in turn have an influence on lobsters. Lobsters are found in water depths between 0-150 m, but do commonly not occur deeper than 50 (The National Lobster Hatchery, 2017).

- Competition.
  Lobsters are highly territorial (FAO, 2019b). J.W.P. Coolen noticed that no more than two or three lobsters were present at a shipwreck which was large enough for many more (personal observation). However, (Jensen et al., 1994) caught in three years from 1990 till 1992 respectively 35, 25, and 54 lobsters on an artificial reef which consisted of 8 piles of reef units (1 m high, 4 m across) spread over an area of 30 by 10 metres at 10 m depth, on which was concluded that the most likely number of animals within the 8 reef units is about 50, which can be translated into 17 lobsters per 100 m^2 for the whole area or 39 per 100 m^2 hard substrate. Schmalenbach (2009) reported in her thesis that

0-3 lobsters per 100 m^2 were counted by divers while swimming transects (mean: 1.4 ± 1.2 lobsters per 100 m^2). Rozemeijer and Wolfshaar (2019) listed six different average densities that he found in literature. These values ranged from 0.00037 lobsters per 100 m^2 for the total water surface of the Oosterschelde, to 26.7 lobsters per 100 m^2 on an artificial reef. These numbers vary greatly which makes it difficult to say with certainty what lobster densities are realistic.

- Minimum population.
  It is unknown what the minimum population size for successful reproduction is.

- Currents.
  Lobsters will only come out of their shelter to forage/hunt when the current is not too strong. A current velocity of 0.27 m/s was found to reduce the lobster mobility in a wave flume and when the current velocity is higher than 0.6 m/s they can get carried away (Howard and Nunny, 1983).

- Mobility.
  Lobster is a species which seldom travels further than a few hundred metres a day and stays within 4 km of its territory for periods up to a year, the few lobsters that travel further than 15 km probably do so to find new territories (Jensen et al., 1994). The larvae are mobile during their pelagic state during which they are transported by the current over distances of up to 100 km (Rozemeijer and Wolfshaar, 2019). Below the age of 2 the lobster buries in the sand and does seldom move. Krone and Schröder (2011) argued that lobsters can reach all of the North Sea by using wrecks, offshore wind farms and other hard substrates like oil and gas platforms as steppingstones.

- Soil composition.
  Juveniles prefer coarse sand to fine shingle to burrow in, but burrowing in cohesive mud has also been observed (The National Lobster Hatchery, 2017).

Current situation
Little is known about the current situation of the lobster stocks in the North Sea. Several countries in which lobster fishery is common such as the UK and Scotland have assessed their near-shore stocks, but a North Sea wide assessment is lacking.

2.5.5. European flat oyster - Ostrea edulis

General information

Appearance

The European flat oyster is a bivalve mollusc with an oval-shaped shell of which one valve is concave and attched to the substrate, the other is rougher and flat and serves as a lid.

Size

The diameter of the European flat oyster can grow up to 0.22 m but is often smaller.

Distribution

The flat oyster occurs naturally around the coast of Europe with exception of the Baltic Sea and will be found to a depth of 80 m. Densities are highest around the coast of northern France, Belgium and the Netherlands.

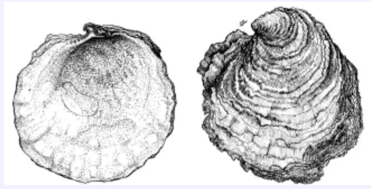
Behaviour

The flat oyster is a filter feeder which adjusts its gaping depending on the conditions (Nielsen et al., 2017). Research has showed that effective growth is achieved when the the amount of chlorophyll exceeds 0.5 µg/l (Yildiz et al., 2011) and that 1.68 µg/l is the optimal concentration for reproduction (Millican and Helm, 1994).

Preferences

The water depth is an important factor for the oyster, since it is related to the available oxygen and availability of food. Oysters need to be covered with water to feed since they are filter feeders but at too large depths the amount of oxygen is lower and the light penetration, which influences the presence of algae, is reduced.
Flow velocity is another important factor since it influences both the settlement and the supply of food and oxygen. A small flow velocity benefits the settlement of oysters while an absence of flow velocity will lead to starvation of the oyster.

Flat oyster



Scientific classification

Kingdom:	Animalia
Phylum:	Mollusca
Class:	Bivalvia
Order:	Ostreoida
Family:	Ostreidae
Genus:	Ostrea
Species:	Ostrea edulis

Distribution

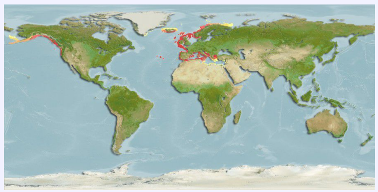


Figure 2.26: Distribution of the flat oyster.
Source: www.aquamaps.org

History

The over-exploitation in the 18th and 19th century and the impact of two parasitic epizooites in the 1970s and 1980s (Linley et al., 2007) has drastically reduced the flat oyster population after which it remained small up to this date (FAO, 2019c).

Life cycle

Life cycle & reproduction

Flat oysters switch gender multiple times in their lifetime. The female oyster produces, depending on her size, 1-3 million eggs which are fertilised and mature while still in her shell. After 7-10 days, having already grown two shells, the larvae leave the safety of the shell and enter a pelagic larvae-stadium which lasts 8-14 days. This phase is followed by the settling of the larvae in which they cement themselves to the hard substratum. The dispersal distance is on average 1 km (distances up to 10 km are possible under favorable conditions (Berghahn and Ruth, 2005)). The shells of other oysters, either living or dead, are a preferred substrate for oyster spat (probably due to the calcium that these shells contain) this makes oyster bed development a self-reinforcing process (Kamermans et al., 2018). When settled, the flat oyster starts its life as a male, becomes mature after three years, and changes to being female after spawning. The average life span of the European flat oyster is about 6-10 years, but may reach in excess of 15 years (Perry and Jackson, 2017). During their lifetime the flat oyster is firmly attached to the substrate and thus will not move unless it is broken from the substrate forcefully or when the substrate itself is moved.

Promotional and inhibiting factors

Promotional factors

Factors which are beneficial to the flat oyster are:

- Food abundance.
  Oysters get their food by filtering it from the water. For effective growth at least 0.5 µg chlorophyll per liter is required (Yildiz et al., 2011) while the optimum amount of chlorophyll is 1.68 µg/l (Millican and Helm, 1994). Figure 2.27 shows the long-term averge chlorophyll concentration in the upper 10 metres of the water column.

- Suitable substrate.
  Substrates on which oysters are already present are the preferred substrate to settle on for oyster spat, most likely because of the chemical cues that play a role in this (Rodriguez-Perez et al., 2019). The shell (fragments) of other bivalves such as the invasive alien Pacific oyster (Crassotrea gigas) or the blue mussel (Mytilus edulis) are a suitable substrate for the flat oyster as well (Christianen et al., 2018; Kamermans et al., 2018). In absence of shell (fragments) other hard substrates such as boulders or wrecks are also used as settling substrate. The substrate needs to be stable enough so that the oysters do not get crushed by the rocks to which they are attached or which surround them.

- Currents.
  A current which supplies both oxygen and nutrients is necessary (Perry and Jackson, 2017; Lapègue et al., 2006) this current is still beneficial at current velocities of up to 0.8 m/s (Pogoda et al., 2011).

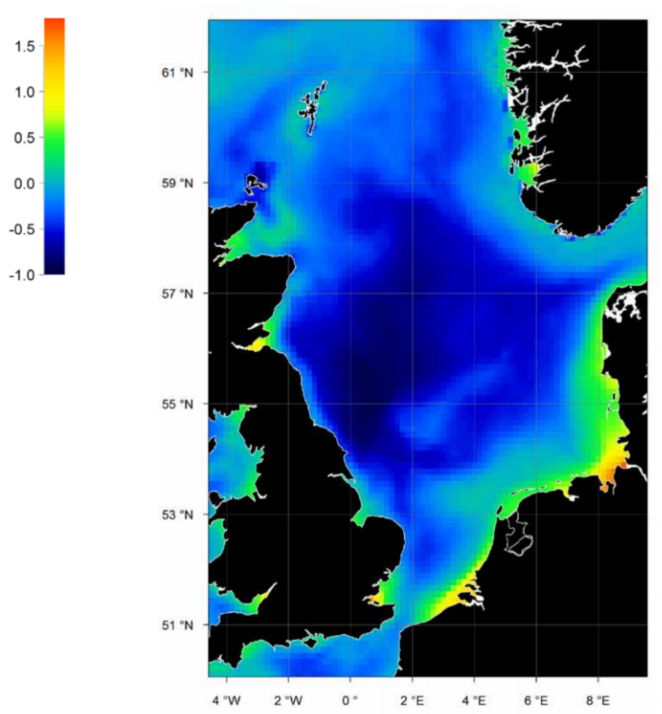


Figure 2.27: Long-term average chlorophyll concentration in the upper 10 metres of the water column in µg/l using a logarithmic scale with 0 = 1 µg/l and 1 = 10 µg/l (Herman et al., 2015)

Inhibiting factors
Factors which inhibit the occurrence of flat oyster are:

- Fishing.
  Using bottom disturbing fishing methods such as bottom trawling, destroys oyster beds and other hard substrate. Figure 2.28 shows the bottom trawl fishing intensity in the North Sea between 2010 and 2012.

- Predators.
  Due to their thin shell young oysters smaller than 0.03 m are vulnerable to predation by for example the common starfish, the common whelk, the dog whelk, the green shore crab and especially members of the family of predatory sea snails (*Muricidae*) (Gercken and Schmidt, 2014).

- Water depth.
  Water depth influences oxygen levels, light penetration and temperature. These all influence the oyster. Oysters are usually not found below 80 m water depth.

- Competition.
  The flat oyster has to compete with several other species for settlement area (e.g. the common slipper limpet) and food (e.g. the invasive Pacific oyster) (Gercken and Schmidt, 2014).

- Minimum population.
  A minimum amount of oysters is required for the spat to settle successfully and for the oyster bed to survive (Smaal et al., 2017), both male and female oysters are required for this. (Smaal et al., 2017) estimated that these oysters need to produce a minimum of 50 larvae per square metre to achieve recruitment but does not provide a minimum number of oysters to achieve this and instead claims that this depends on the age structure, density, the number of larvae produced, and the water motion. (Smyth et al., 2009) demonstrated that a flat oyster population in Strangford Lough recovered to over a million species even though only 1200 were counted in 2003.

- Currents.
  Oyster spat is not able to settle in strong currents (Korringa, 1940). Flow velocities between 0.25 and 0.60 m/s have been reported to be optimal, with flow velocities higher than 0.6 m/s making a site unsuitable for spat settlement and flow velocities lower than 0.25 m/s making it sub-optimal due to the higher sedimentation rate (Smaal et al., 2017).

- Mobility.
  The larvae of flat oysters disperse while they are pelagic, usually about 1 km while distances of up to 10 km are possible under favourable conditions (Berghahn and Ruth, 2005) although a larger travel distance of 43 km has also been suggested by (Coolen et al., 2019) based on the 10 day pelagic stage and a mean flow velocity of 0.05 m/s (Thorpe, 2012). However, general consensus is that oysters have a strong homing range. The oyster larvae have one attempt at settling and do not move once settled.

- Soil composition.
  Oysters can not survive when covered in sand. Sand waves which cover an oyster for an extended period of time will lead to the death of the oyster. A large part of the population (50%) will die when buried for 7 days (Colden and Lipcius, 2015). Oysters filter suspended matter from the water, the phytoplankton serves as food, but inorganic matter is of no use and will reduce their capacity for growth (Smaal et al., 2017) therefore a soil with small particles is unfavourable.

- Diseases.
  Several diseases threaten the flat oyster of which the most dangerous is considered to be Bonamiosis, caused by *Bonomia ostrae* (Gercken and Schmidt, 2014). Especially

oysters up to the age of two are susceptible to infection while only the older individuals show the symptoms. Marteiliosis, caused by the parasite *Marteilia refringens*, is another dangerous disease.

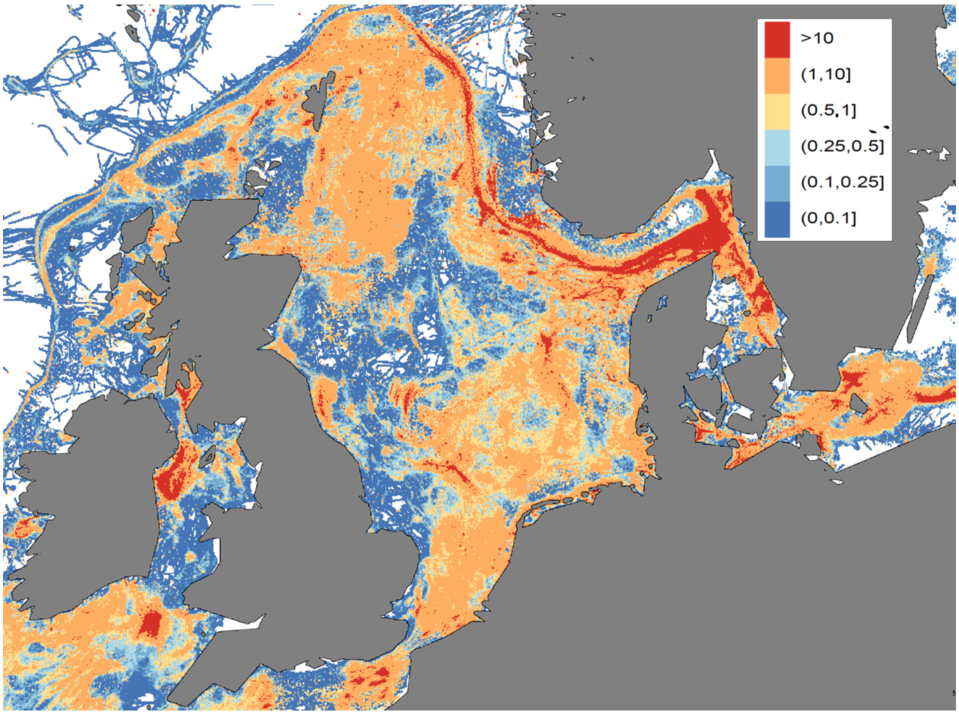


Figure 2.28: Bottom trawl fishing intensity in the North Sea between 2010-2012
Source: Benthis

Current situation

The oyster beds which in the 19th century covered large areas in the North Sea (Olsen, 1883) have disappeared due to diseases and over-exploitation. After that these oyster populations were too small to reproduce successfully (Gross and Smyth, 1946) and at this moment the oyster has almost completely disappeared from the North Sea (De Vooys et al., 2004).
Several reports however have reported on individual oysters (OWEZ wind farm (Bouma and Lengkeek, 2012), Princess Amalia Wind Farm (Coolen et al., 2018; Glorius and Jak, 2017), oil platforms in the UK and ship wrecks in on the Dutch Continental Plat (Jager, 2013; Schild et al., 2017)), on small patches of flat oysters and even a complete oyster beds (6.8 ± 0.6 m^{-2} at the 'Voordelta' in the Netherlands (Christianen et al., 2018), at Ljimford in Denmark (Gercken and Schmidt, 2014), at Grevelingen in the Netherlands (Schild et al., 2017), at Solent in England (Schild et al., 2017) and at Strangeford Lough in Ireland (Smyth et al., 2009)).

2.5.6. Ross worm - Sabellaria spinulosa

General information

Appearance

The Ross worm is a polychaete worm which lives in a tube made of shell fragments and coarse sand. This tube is attached to the substrate over its entire length while only the worm's head extrudes from the opening of the tube when feeding. Bristles are growing on its head which the Ross worm can use to close the top side of the tube.

Size

Ross worms are less than 0.02 m long, but construct tubes up to 0.1 m in length. However, at greater densities (up to 9,500 species per m^2) competition for space results in overlapping and may cause the tubes to be build outwards, away from the substratum. This way, in favourable conditions, it can form reefs of several metres across and 0.6 m in height.

Distribution

The Ross worm is naturally common around the British Isles, but is also found throughout the rest of the north-east Atlantic and has even been reported to occur in the Indian Ocean (Pearce, 2014).

Behaviour

Due to its attachment to the substrate there is not much to note about the behaviour of the Ross worm. It feeds by extending its feeding tentacles to catch plankton and hides in its tube from predators such as the pink shrimp, shore crab, and the shanny (Pearce, 2014).

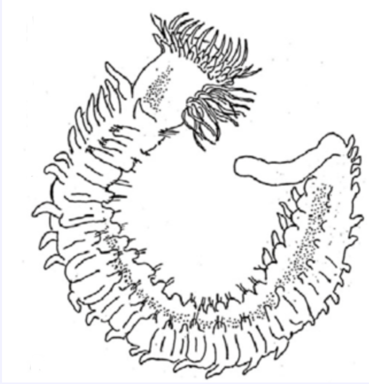
Preferences

The Ross worm requires sand grains to construct the tube in which it lives, coarse sand is therefore a necessity, but also turbulence to suspend sand and shell particles. It prefers a living or old colony to settle on, but can also use bedrock, cobbles, gravel or shell fragments as anchorage points. The Ross worm is usually not found in waters deeper than 50 metres, but it is known that it can occur in deep water (>1,000 m) as well.

History

The Ross worm was once common in the Wadden Sea (Riesen and Reise, 1982), but shrimp fisheries have played a large role in the destruction and disappearance of these colonies (Reise and Schubert, 1987). Other sources blame coastal eutrophication (Vorberg, 2000).

Ross worm



Scientific classification

Kingdom:	Animalia
Phylum:	Annelida
Class:	Poluchaeta
Subclass	Palpata
Order:	Canalipalpata
Suborder:	Sabellida
Family:	Sabeariidae
Genus:	Sabellaria
Species:	Sabellaria spinulosa

Distribution

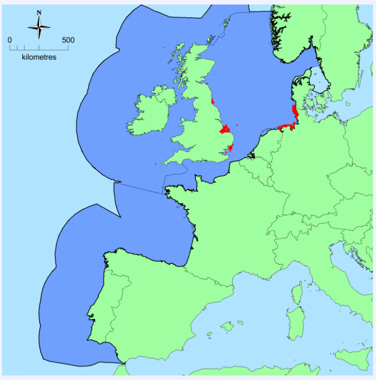


Figure 2.29: Distribution of the Ross worm.
Source: Eionet

Life cycle

Reproduction

The Ross worm releases its gametes (a specialised sex cell that fuses with another gamete of the opposite gender) during spawning events. The frequency and timing of these events is largely unknown but it is assumed that it takes place early in the year when the sea is still cold. These fused gametes spend between 6 and 8 weeks as larvae before they settle and start building tubes (Wilson, 1970). The preferred settling substrate is a living or old colony or, if that is not present, another type of hard substrate.

Life cycle

Its typical life span is likely to be equal to the similar Sabellaria alveolata, which is about 9 years.

Promotional and inhibiting factors

Promotional factors

- Food abundance.
  The Ross worm is a filter feeder which relies on suspended sediments for feeding and building materials.

- Suitable substrate.
  To build a tube the Ross worm needs coarse sand and shell fragments. Clay and silt are not suitable. A hard substrate such as rock or existing reefs is required for settlement after which it can spread over soft substrate (Maddock, 2008) provided that enough sand and shell fragments are suspended (Pearce, 2014).

- Currents.
  The building of the tube is done by catching sand and shell fragments out of the water and cementing these to the existing part of the tube. Without a turbulent current no sand and shell fragments are present in the water (Pearce, 2014). Colonies have been found in areas with current velocities in the range of 0.5 m/s to 1.0 m/s (Gibb et al., 2014) and Davies et al. (2009) managed to distribute sediment rain from an airlift throughout a tank at a water flow velocity of 0.07 m/s, indicating that the Ross worm could exist in habitats with a water flow above this velocity. Tillin (2010) developed a statistical model for the Ross worms congener *Sabellaria alveolata* from which she derived that the optimal mean current speed for sabellariids ranges from 0.5-1.22 m/s.

Inhibiting factors

- Fishing.
  Bottom disturbing fishing methods such as the shrimp fishery destroys the reefs build by the Ross worm (Vorberg, 2000).

- Predators.
  The Ross worm is an important component in the diet of the pink shrimp, shore crab and the shanny (Pearce, 2014).

- Water depth.
  The Ross worms depth range extends from very shallow inter-tidal environments to the bathyal zone and thus does not appear to be an inhibiting factor (Pearce, 2014).

- Competition.
  There is little evidence that the Ross worm is significantly impacted by competitors, although it is possible that the slipper limpet and the Pacific oyster are a potential threat in terms of competition for food and space (Tillin et al., 2018).

- Minimum population.
  Unknown

- Currents.
  Strong currents don't seem to be an issue, but without a current the Ross worm is not able to feed or build, it requires at least 20 g m^{-3} of suspended material in the water (Davies et al., 2009).

- Mobility.
  The Ross worm is only mobile during its 6-8 week long larval state during which it is transported by currents. Using the calculation method which was suggested by Coolen et al. (2019) with a mean flow of 0.05 m/s (Thorpe, 2012) a dispersal distance of 180 to 240 km is possible. After that it is fixed to the sea bed (Wilson, 1970).

- Soil composition.
  High levels of mud and silt might clog the feeding apparatus (Wells, 1970).

Current situation

Extensive Sabellaria spinulosa reefs as were once present in the North Sea have disappeared, but throughout almost all of the North Sea small patches and lonely species can still be found (see figure 2.30). Jager (2013) for example reported the presence of Sabellaria spinulosa on artificial reefs, in wind farms on the Dutch continental shelf, in wind farms and on a wreck on the Belgian continental shelf (e.g. Thornton Bank (Kerckhof et al., 2010)), and on the Cleaver Bank. The presence of S. spinulosa in the Princes Amalia wind farm, several North Sea platforms, and on the Borkum Reef Ground was reported by Coolen and Jak (2018). More extensive reefs were reported of the coast of south-eastern UK (Pearce et al., 2011; Jenkins et al., 2018) and in the German part of the North Sea (Van Duren et al., 2017). Bouma and Lengkeek (2012) reported the presence of Sabellaria spinulosa in the Horns Rev wind farm.

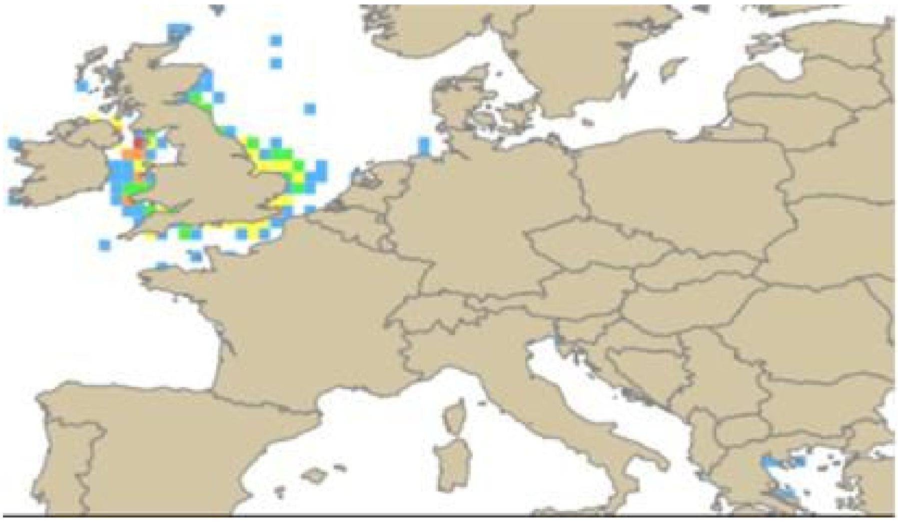


Figure 2.30: Known locations of Sabellaria spinulosa reefs
(Source: http://www.coastalwiki.org/wiki/File:S._spinulosa_.jpg)

2.6. Conclusion

The presented framework shows that the present wind farms and those wind farms that are planned to be built are mostly located in the (shallower) southern part of the North Sea and that the most frequently used type of foundation for these wind farms is the monopile. The reference wind farm (Gemini) is one of these wind farms and is located about 80 km north of the coast of Groningen and consists of 150 wind turbines of 4 MW each. The monopiles are surrounded by a scour protection consisting of a 0.50 m thick 1-3” filter layer with a diameter of 4.25 times the pile diameter and an 1.00 m thick 3-9”HD armour layer with a diameter of 3 times the pile diameter. Both of these layers have been tested using physical modeling and have shown to be dynamically stable during extreme storm conditions.

The physical environment in the North Sea shows a difference between the northern part and the southern part. The northern part of the North Sea in general is deeper, colder, exposed to higher waves with a stronger variability, and contains fewer man-made structures than the southern part of the North Sea. The sea soil composition does not show such a clear distinction between the northern part and the southern part, although sand waves and sand dunes are mainly present in the most southern part.

The four selected indicator species (Atlantic cod, European lobster, European flat oyster, and Ross worm) are selected because they are very different from each other, native to the North Sea, threatened or of high commercial value, and because they interact with the sea bed in different ways. The juvenile Atlantic cod finds shelter on the sea bed in holes and crevices while the adults forage on the species that occur on and around the sea bed. The European lobster finds shelter on the sea bed in holes and crevices, the juveniles to shelter from predators and currents and the adults to shelter from currents. The European flat oyster prefers to settle on present oyster reefs or on the shells of other bivalves, but is also known to use rocks and other hard substrate to settle on. The Ross worm requires a hard substrate to settle on before building its tube out of sand and shell fragments that are stirred up from the sea bed. The occurrence and survival of these species depend on several factors: Food abundance; suitable substrate for shelter and settlement; currents which transport food and oxygen but can also hinder the species; fishing, which extracts species and can also destroy the present substrate; predators; water depth; competition for food and space; minimum number of species required to obtain a healthy population; a mobility which might hinder the distribution of the species over a larger area; and soil composition.

3

Suitability of the North Sea in absence of wind farms

3.1. Introduction

This chapter assesses the suitability of the North Sea in absence of wind farms for the indicator species which were presented in Chapter 2. This is done qualitatively at first and where possible quantitatively. Per species a table is presented which lists the requirements of the species, the qualitative suitability of the North Sea in absence of wind farms with regards to inhibiting and promoting factors, and a quantification of this suitability. Additionally a conclusion is drawn on the overall suitability of the North Sea for each of the indicator species.

3.2. Atlantic cod

Section 2.5.3 described the promotional and inhibiting factors which influence the Atlantic cod to a certain degree. Table 3.1 summarizes the requirements of the Atlantic cod regarding each of these factors and provides the qualitative suitability of the North Sea in absence of wind farms. In the column on the right the suitability is made qualitative where possible. References to where this information comes from can be found in 2.5.3.

Conclusion on the suitability of the North Sea for Atlantic cod

The North Sea is suitable for the Atlantic cod and has opportunities for the population to grow, but is limited herein by fisheries and the lack of shelter for juveniles.
Quantifying this suitability is difficult due to the many factors involved. Knowing that the spawning-stock biomass in 2017-2018 was $113.5 * 10^6$ kg and assuming that the average mass of a grown cod is 40 kg however provides grounds to assume that the number of cod which are able to reproduce is about $2.8 * 10^6$. Given that the area of the North Sea is $525 * 10^9$, the average density of cod per m^2 in the North Sea is $5.3 * 10^{-6}$, which in a wind farm with a surface of $67.6 * 10^6$ m adds up to ± 360 cod. This is however a very low estimate as the weight of the average cod will be lower than 40 kg.

Table 3.1: Analysis of the suitability of the North Sea for Atlantic cod in the absence of wind farms.

Factor	Requirements	Qualitative suitability	Quantitative suitability
Food abundance	Zooplankton during larval stage. Small crustaceans during juvenile stage. Anything edible during adult stage.	There is plenty of food available in the North Sea for the population of the Atlantic cod to grow but more food would speed up this process.	The average biomass (which can serve as food) is 0.131 kg/m^2.
Suitable substrate	Habitat with a great variability in material and with vertical structures is favourable for shelter against predators.	Due to the disappearance of hard reefs in the North Sea there is a very limited amount of hard substrate present in the North Sea, this limits the survival of the benthopelagic juvenile cod.	About 20% of the North Sea consists of hard substrate and is thus suitable substrate. There are also more than 25,000 shipwrecks and about 1,300 platforms which can be used as shelter by the juveniles.
Currents	The presence of a current (>0.05 m/s) is required.	Almost everywhere in the North Sea currents are present which are capable of distributing oxygen throughout the water.	The complete North Sea is about 525,000 km^2, which is all suitable regarding minimum current velocity.
Fishing	Complete absence of fisheries is optimal.	Fishing limits the survival of Atlantic cod above the age of 1 and puts a heavy pressure on the populations.	44% Of the cod of age 2-4 was caught in 2017.
Predators	As little as possible predators is optimal.	Predators such as the grey gunnards and larger cod are present and feed on (juvenile) cod.	No information found to quantify this factor
Water depth	10-30 m for juvenile cod.10-600 m for adult cod.	Almost all of the North see is in the range of suitable depth for the Atlantic cod.	Area of North Sea: 525,000 km^2. Area shallower than 10 m: 16860 km^2. Area between 10-30 m: 72,500 km^2. Area deeper than 600 m: < 5,000 km^2
Competition	Fewer cod per shelter site is beneficial for juveniles. Fewer cods in general is beneficial for the food availability for adult cod.	The populations are small, so competition for food is not an issue. Competition for shelter sites is an issue due to the lack of shelter sites.	Thousands of wrecks, 184 offshore rigs and several (artificial) reefs provide a limited amount of shelter to juvenile cod. Food is available but not abundant.
Critical mass	Minimum population of ±1,000 cod.	There are multiple cod populations which are large enough to successfully expand.	This is not an inhibiting factor for the Atlantic cod.
Currents	Not too extreme (> 2 m/s for extended period of time >6 hours) since this will tire the cod.	Except for a few places in the North Sea the currents are nowhere strong enough to be an issue for the Atlantic cod.	525,000 km^2 of North Sea with low enough currents.
Mobility	Individual schools migrate over distances of about 200 km during their lifetime.	The Atlantic cod species is able to spread over all of the North Sea although individual schools are not able to.	The North Sea is about 1,000 km from North to South and 600 from East to West. Individual schools will not travel over all of the North Sea. 525,000 km^2 is about equal to 16 circles with 200 km diameter.
Soil composition	Not applicable	This is not an inhibiting factor for the Atlantic cod.	This is not an inhibiting factor for the Atlantic cod.

3.3. European lobster

Section 2.5.4 described the promotional and inhibiting factors which influence the European lobster to a certain degree. Table 3.2 summarizes the requirements of the European lobster regarding each of these factors and provides the qualitative suitability of the North Sea in absence of wind farms. In the column on the right the suitability is made qualitative where possible. References to where this information comes from can be found in 2.5.4.

Conclusion on the suitability of the North Sea for European lobster

Several places in the North Sea are suitable for the European lobster, but still a large area is unsuitable. J.C. Coolen created a map (Figure 3.1) witch shows the relative suitability of the North Sea for European lobster (relative suitability means that areas with a higher score are more suitable than areas with a lower score, it does not mean that an area with a high score is perfect or an area with a low score is unsuitable). The places that are not suitable for the European lobster are those places where hard substrate, which provides shelter, is missing. Another reason why not all of North Sea in its current state is suitable for the European lobster is the distance between suitable habitats which is too large for adult lobsters to reach.

Quantifying the suitability of the North Sea for the European lobster is not possible with the currently available information. However, it can be said that the places in which shelter is not present are unsuitable for the lobster and will therefore have almost no lobster present.

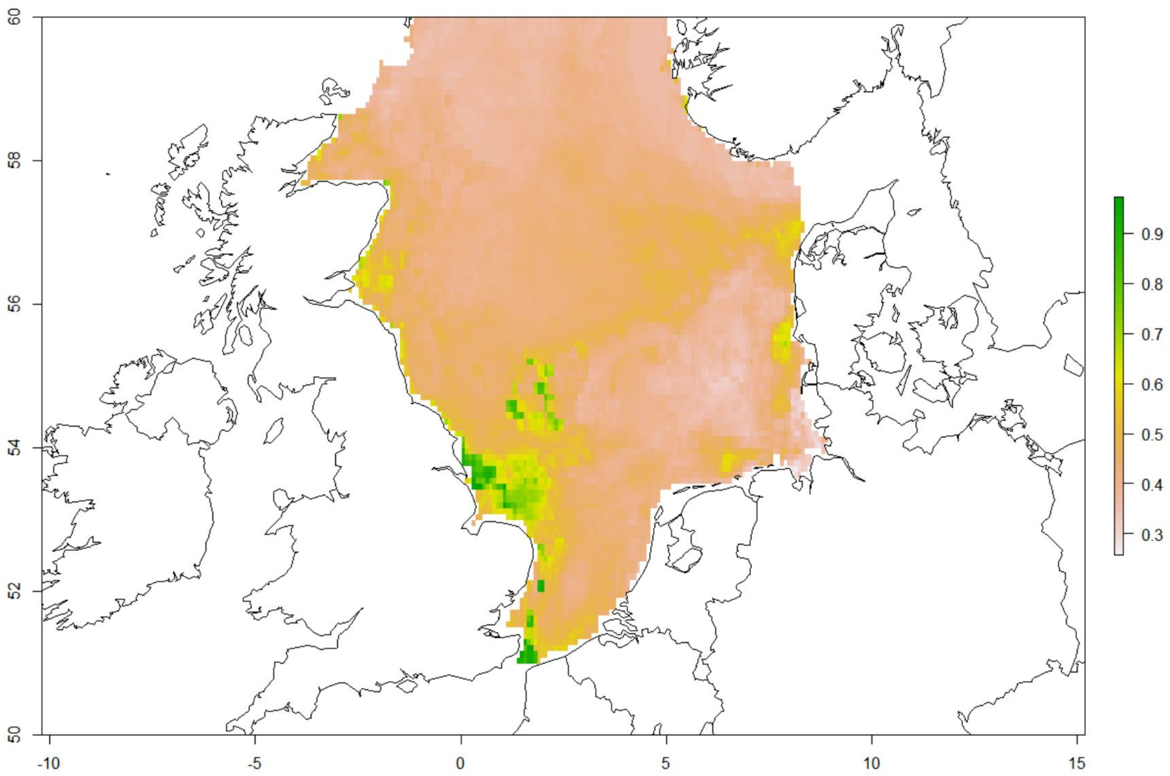


Figure 3.1: The relative suitability of the North Sea for the Eurpean lobster *Homarus gammarus*.
Source: J.C. Coolen

Table 3.2: Analysis of the suitability of the North Sea for European lobster in the absence of wind farms.

Factor	Requirements	Qualitative suitability	Quantitative suitability
Food abundance	Lobsters eat animals which are associated with hard substrate.	Food abundance is not a limiting factor on the growth of the lobster population.	The average biomass (which can serve as food) is 0.131 kg/m^2.
Suitable substrate	Holes and crevices are required as shelter against currents and predators.	Due to the disappearance of hard reefs in the North Sea there is a very limited amount of hard substrate present in the North Sea, this limits the survival of the European lobster. Although there are suitable shipwrecks, oil/gas platforms and (artificial) reefs present.	More than 25,000 ship wrecks, 1,300 offshore rigs, several (artificial) reefs, and some rocky coast can accommodate many lobsters locally, while other parts of the North Sea are less suitable.
Currents	The presence of a small current (>0.05 m/s) is required for the lobster.	Almost everywhere in the North Sea currents are present which are capable of distributing oxygen throughout the water.	The complete North Sea is about 525,000 km^2, which is all suitable regarding minimum current velocity.
Fishing	Complete absence of fisheries is optimal.	Lobster fisheries have diminished due to the decreased lobster stocks, however, it still is a relevant inhibiting factor.	No information found to quantify this factor.
Predators	As little as possible predators is optimal.	Predators are present and feed on lobsters.	No information found to quantify this factor.
Water depth	Optimal water depth is less than 50 m, but depths up to 150 m are possible.	Almost all of the North see is in the range of suitable depth for the European lobster.	Area of North Sea:Area between 0-50 m: 200,000 km^2 between 50-150 m: 270,000 km^2
Competition	Lobsters are highly territorial and thus require a large enough habitat. It is not likely that more than 6 lobsters are present per habitat (0-20 lobsters per 100 m^2).	There are few suitable habitats and the competition for these habitats is severe.	There are more than 25,000 shipwrecks (150,000 lobsters) and about 1,300 platforms (7,800 lobsters) which can be used as habitat, about 20% of the North Sea consists of hard substrate and could thus also be used as habitat.
Critical mass	The critical mass is unknown.	The locations on which multiple lobsters are present are suitable for reproduction.	No information found to quantify this factor.
Currents	Too strong current hinder the lobster in its mobility, it has been estimated that the maximum current velocity that the lobster can withstand is 0.27 m/s.	Not all of the North Sea is suitable for the European lobster due the the currents that can occur.	It is unknown what areas of the North Sea are unsuitable due to the strong currents.
Mobility	Habitats within 10 km from each other for adult lobsters. Habitats that can be reached in the 2-3 week pelagic stage.	Certain areas in the North Sea are not likely to be reached by the lobster.	The far offshore areas in the North Sea will not be reached by the lobster.
Soil composition	Juveniles prefer coarse sand to fine shingle to burrow in, cohesive mud can also be used.	Large parts of the North Sea are suitable, but this is only relevant if shelter sites are nearby to inhabit after this phase, this combination is very scarce.	No information found to quantify this factor.

3.4. European flat oyster

Section 2.5.5 described the promotional and inhibiting factors which influence the flat oyster to a certain degree. Table 3.3 summarizes the requirements of the flat oyster regarding each of these factors and provides the qualitative suitability of the North Sea in absence of wind farms. In the column on the right the suitability is made qualitative where possible. References to where this information comes from can be found in 2.5.5.

Conclusion on the suitability of the North Sea for flat oyster

Most of the North Sea is unsuitable for the flat oyster due to the lack of (stable) substrate in the form of rock or other bivalves. Additionally the seabed disturbing fisheries destroy the present habitats and the short pelagic larval stage of the oyster prevents it from reaching the habitats. Human intervention is therefore required.

It is estimated that there is a small number of individual oysters present in the North Sea and that there are some small oyster beds as well (as was shown in 2.5.5), but most parts of the North Sea will have no oysters present at all.

Table 3.3: Analysis of the suitability of the North Sea for the flat oyster in the absence of wind farms.

Factor	Requirements	Qualitative suitability	Quantitative suitability
Food abundance	Oysters are filter feeders who require at least 0.5 µg chlorophyll per liter and thrive at an optimum amount of chlorophyll of 1.68 µg/l.	The chlorophyll levels in the North Sea change significantly during the year and are largest during the spring. Almost all of the North Sea, except for possibly the centre of the North Sea contains enough chlorophyll for oysters to grow or at least survive.	525,000 km^2 is suitable for the flat oyster.
Suitable substrate	Present oyster beds are the preferred substrate but shell fragments of other bivalves are suitable too. Other hard substrate such as rock is less suitable but occasionally is used as well.	Oyster beds have almost completely disappeared everywhere in the North Sea. Shells of other bivalves are present in most other locations, but their stability and abundance varies.	It is unknown what parts of the North Sea are suitable habitat with regards to substrate.
Currents	The presence of a small current is required for the oyster to distribute oxygen, a current of 0.25 m/s is required for large enough sedimentation rates.	Almost everywhere in the North Sea currents are present which are capable of distributing oxygen throughout the water.	No information found to quantify this factor.
Fishing	Complete absence of seabed disturbing fisheries is optimal.	Seabed disturbing fisheries are still present in large parts of the North Sea.	The North Sea is unfit as habitat for oyster except for a few places where (artificial) hard substrate makes bottom trawling impossible.
Predators	As few as possible predators is optimal.	Predators are present and feed on oysters.	It is unknown what parts of the North Sea are suitable habitat with regards to predators.
Water depth	Optimal water depth is less than 80 m.	Almost all of the North see is in the range of suitable depth for the European lobster.	Area of North Sea:Area between 0-80 m: 320,000 km^2
Competition	The oyster competes for both settlement area and food with for example the common slipper limpet and the Pacific oyster.	These species occur in the North Sea and thus compete with the flat oyster which is disadvantageous for the flat oyster.	No information found to quantify this factor.
Critical mass	A minimum amount of 50 oyster spat per square metre is required to settle successfully with an estimated total of a few hundred oysters.	Few oyster populations of this size are present in the North Sea, none of them are likely to expand.	The oyster populations in the North Sea are too small and too few to be successful.
Currents	Spat can't settle in currents higher than 0.6 m/s and currents lower than 0.25 m/s are sub-optimal with regard to sedimentation rate.	Not all of the North Sea is suitable for the flt oyster due the the currents that can occur.	No information found to quantify this factor.
Mobility	Dispersal of oyster larvae is usually about 1 km with distances of up to 10 km under favourable conditions although distances of up to 43 km have also been reported as feasible.	It is unlikely that the oyster will successfully spread and settle over the whole North Sea due to the short dispersal distances and the lack of suitable settling substrate.	Distribution over the whole North Sea is very unlikely without human intervention.
Soil composition	Sand waves can bury and kill the flat oyster and are therefore unwanted.	Sand waves are only present in the southern part of the North Sea.	About 10% of the North Sea is covered by sand waves, most between the Netherlands and the UK.

3.5. Ross worm

Section 2.5.6 described the promotional and inhibiting factors which influence the Ross worm to a certain degree. Table 3.4 summarizes the requirements of the Ross worm regarding each of these factors and provides the qualitative suitability of the North Sea in absence of wind farms. In the column on the right the suitability is made qualitative where possible. References to where this information comes from can be found in 2.5.6.

Conclusion on the suitability of the North Sea for the Ross worm

Several places in the North Sea are suitable for the Ross worm but most are unsuitable due to a lack of suitable substrate. J.C. Coolen created a map with depicting the relative suitability of the North Sea for the Ross worm. The largest inhibiting factors for the Ross worm are the bottom disturbing fisheries and the lack of suitable substrate.

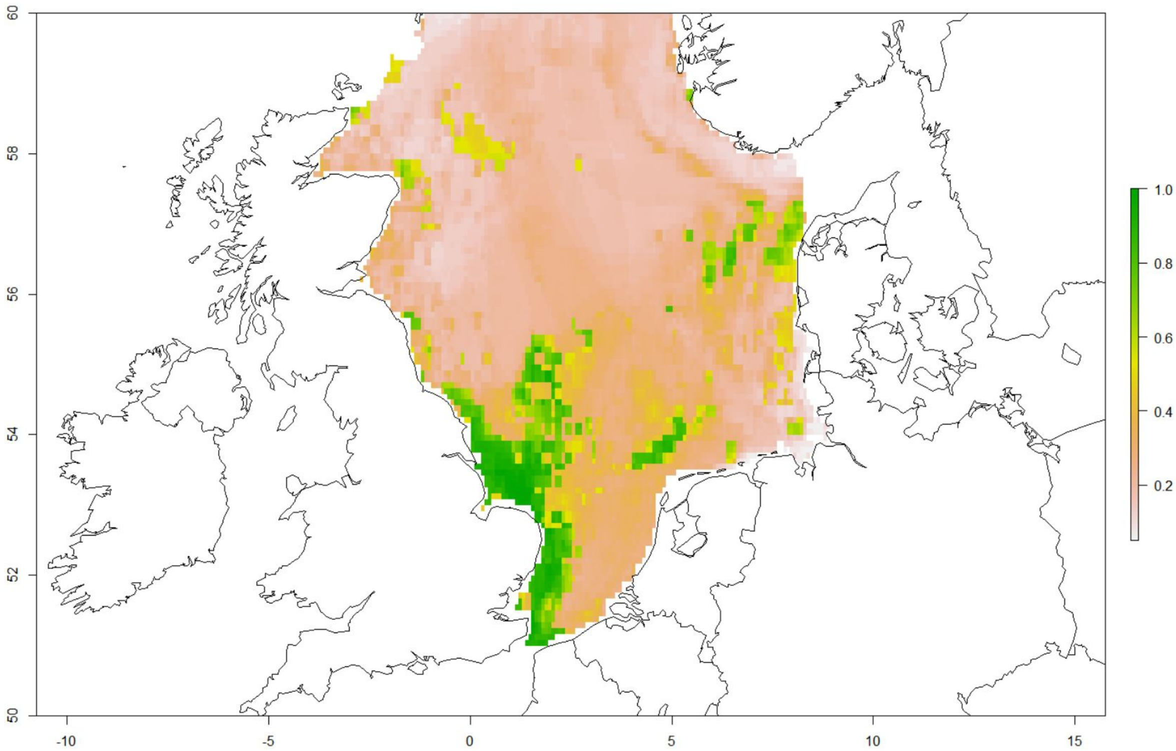


Figure 3.2: The relative suitability of the North Sea for the Ross worm *Sabellaria spinulosa*.
Source: J.C. Coolen

Table 3.4: Analysis of the suitability of the North Sea for the Ross worm in the absence of wind farms.

Factor	Requirements	Qualitative suitability	Quantitative suitability
Food abundance	Ross worms are filter feeders and require at least 20 g m^{-3} of suspended material in the water.	Parts of the North Sea are suitable with respect to food abundance.	No information found to quantify this factor.
Suitable substrate	The Ross worm requires sand and shell fragments to build its tube and a hard substrate such as rock to settle on.	Rock in combination with sand and shell fragments is almost nowhere present in the North Sea except for along the south eastern coast of the UK.	Only the waters around the south eastern coast of the UK are suitable habitat.
Currents	The presence of a (turbulent) current is required for the Ross worm to suspend sand and shell fragments. The minimal current velocity is 0.07 m/s while the optimal mean current speed is found to be 0.5-1.22 m/s.	There are places in the North sea where this is the case.	No information found to quantify this factor.
Fishing	Complete absence of seabed disturbing fisheries is optimal.	Seabed disturbing fisheries are still present in large parts of the North Sea.	The North Sea is unfit as habitat for the Ross worm except for a few places where (artificial) hard substrate makes bottom trawling impossible and a few rocky patches on the east coast of the UK.
Predators	As few as possible predators is optimal.	Predators such as the pink shrimp, shore crab and the shannyare present and feed on the Ross worm.	It is unknown what parts of the North Sea are suitable habitat with regards to predators.
Water depth	All depths are possible, but influence of waves can be beneficial for turbulence and thus too deep is not suitable.	Almost all of the North see is suitable regarding depth for the Ross worm.	525,000 km^2 of the North Sea is suitable habitat with regards to water depth.
Competition	The common slipper limpet and the Pacific oyster might compete with the Ross worm for food and space.	The common slipper limpet and the Pacific oyster occur in the North Sea and compete with the Ross worm for food and space.	No information found to quantify this factor.
Critical mass	It is unknown what the critical mass of a Ross worm population is.	The suitability of the North Sea with respect to critical mass is unknown.	No information found to quantify this factor.
Currents	Strong currents are not an issue for the Ross worm.	The Ross worm is nowhere limited by strong currents in the North Sea.	525,000 km^2 of the North Sea is suitable habitat with regards to maximum current velocities.
Mobility	Dispersal of the larvae is takes place over a 6-8 week period during which the currents transport the larvae.	Mobility is not an inhibiting factor for the Ross worm due to its long pelagic larval stage.	Mobility is not an inhibiting factor for the Ross worm.
Soil composition	High levels of mud and silt might clog the feeding apparatus.	Most parts of the North Sea have only a small mud content (<10%) and are thus suitable for the Ross worm.	Almost all of the North Sea, except for the Oyster Ground, the Fladen Ground, and the Norwegian Trench are suitable, see Figure D.1 and Figure D.2 for the locations.

3.6. Conclusion

In general it can be said that (seabed disturbing) fisheries and the lack of suitable substrate in the form of rock and shells are the largest inhibiting factors for the four species in the North Sea. The Atlantic cod is most likely to recover out of these four indicator species when fishing ss strictly regulated. Both the European lobster and the flat oyster are unlikely to spread over the North Sea without human intervention due to their limited mobility and the lack of sufficiently large source populations. Little is known about the Ross worm, but as long as seabed disturbing fisheries destroy their reefs and no hard substrate is present to build new reefs there is little chance of recovery for this species.
Table 3.5 shows the relative suitability of the North Sea for the four indicator species. This table serves as a way to compare the effects of the changes, and is not based on calculations, it should therefore only be used as a visual guide.

Table 3.5: Relative suitability assessment (scoring from 0 (very unsuitable) to 5 (very suitable)) for the North Sea (NS). The empty columns are filled in in subsequent chapters.

	NS	WF + SP	WF + ESP	WF + SP + SE	WF + ESP + SE
Atlantic cod	2	-	-	-	-
European lobster	1	-	-	-	-
Flat oyster	0	-	-	-	-
Ross worm	1	-	-	-	-
Total	4	-	-	-	-

4

Potential for nature improvement with basic scour protection

4.1. Introduction

At present there are wind farms with scour protections located in the North Sea, and although these scour protections have not been designed to benefit marine life, they have an influence on the species that are present in these parts of the North Sea.
This chapter aims to quantify both the positive and negative influences of the wind farms on the four selected indicator species. The Gemini wind farm will serve as a reference case. Section 4.2 starts with an overview of the conclusions from related research. Subsequently section 4.3 describes the changes to the promoting and inhibiting factors qualitatively after which these changes are quantified in section 4.4. Section 4.5 concludes the chapter.

4.2. Related research

Over the last decade several researchers from different countries have researched the influence of offshore wind farms and other hard substrate in the North Sea and reported on the changes that they noticed. Table C.2 gives an overview of the papers and reports that have been published in relation with this subject and the area and species that were targeted in the research.
In general it can be concluded that wind farms with a scour protection have a positive effect on both biodiversity and species abundance. Older hard substrate, such as ship wrecks and platforms have an even larger positive effect, which is attributed to their longer life and even more to their structural complexity.
The following points are taken from these documents:

- The amount of species present on a scour protection depends on many factors (as listed in 2.5) and can not solely be attributed to the scour protection design.
- Colonization reaches equilibrium after 4-6 years during which the population changes from large numbers of few species to fewer numbers of many species (Jager, 2013).
- All hard substrate gets covered by marine life in far larger numbers than the surrounding soft sea bed (Leonhard et al., 2011; Bos et al., 2014; Krone et al., 2017).
- Concrete foundations have a biodiversity similar to other foundation types (Kerckhof et al., 2010) and there is a large overlap in communities on steel and rock and between wind farms and platforms (Coolen et al., 2018).
- Mytilus edulis (Blue mussel) is able to spread over large parts of the North Sea during its larval stage (Coolen and Jak, 2018).

4.3. Qualitative changes to the promoting and inhibiting factors

This section assesses the qualitative changes that the presence of a wind farm inflicts on the promoting and inhibiting factors based on available literature.

4.3.1. Qualitative changes to the promoting factors

Food abundance

Hard substrate allows for a larger biodiversity and a higher biomass than a sandy sea bed (De Mesel et al., 2015). The construction of a scour protection will therefore increase the food abundance (in the form of biomass) for the Atlantic cod and European lobster. The food abundance for oysters (microalgae and phytoplankton) and the Ross worm (phytoplankton) is not affected by the construction of a scour protection.

Suitable substrate

The construction of a scour protection introduces hard substrate in the form of rock. This increases the heterogeneity of the sea bed and adds vertical variability which benefits the survival of juvenile cod (Laurel et al., 2003a,b, 2004).
Lobsters also benefit from the hard substrate due to the holes and crevices which are present in the scour protection and serve as shelter from predators and strong currents (Langhamer et al., 2009; Langhamer and Wilhelmsson, 2009). Research has shown that a substrate in the form of cobble is far more favourable for the lobster than sand or corralline algae (Linnane et al., 2000).
Although a newly constructed scour protection does not contain any existing oyster beds or patches of other (dead) bivalves, it provides a form of hard substrate which can be used by the flat oyster to settle on. Additionally, other bivalves such as the blue mussel are likely to colonize the scour protection (as was shown in 4.2) and can provide suitable settling substrate for the flat oyster (Christianen et al., 2018; Kamermans et al., 2018).
The Ross worm benefits from the scour protection as it requires a hard substrate near a sandy seabed to settle on before spreading over the soft surrounding substrate (Maddock, 2008).

Currents

A scour protection changes the flow pattern, induces turbulence and creates areas with higher or lower flow velocities than the undisturbed flow velocity (see appendix B). The presence of low flow velocity areas can provide cod and lobster with resting places when the flow velocities at other places on or above the scour protection are high (Howard and Nunny, 1983). The low flow velocity areas also allow oyster spat and the larvae of the other three species to settle calmly after their pelagic stage (Korringa, 1940; Smaal et al., 2017). The Ross worm needs material such as sand and shell fragments and a (turbulent) flow to suspend this material to build its tube. The areas on and around the scour protection which previous to the construction of the scour protection did not meet the requirements regarding the suspended material in the water column might meet these requirements after construction due to the increased flow velocity and turbulence, making it suitable habitat for the Ross worm (Pearce, 2014; Davies et al., 2009).
The presence of the monopile affects the currents as well. Just behind the pile an area develops in which the flow velocity is lower than in the undisturbed area, this area allows the cod to rest.

4.3.2. Qualitative changes to the inhibiting factors

Fishing

Currently the policy is that fishing within a wind farm and 500 m around it is not permitted (Mockler et al., 2015). Cod benefits from this fishing free zone since fishing is one of its main causes of death above the age of 0 (Daan, 1974). Lobster, oysters and the Ross worm benefit from this since their habitat does not get destroyed within the wind farm by seabed disturbing fisheries.

Predators

The construction of a scour protection is likely to increase the number of species which feed on the cod (adult cod, grey gunnards), lobster, oyster (common star fish, common whelk, dog whelk, green shore crab, members of the family of predatory sea snails), and Ross worm (pink shrimp, shore crap, shanny).

Water depth

The construction of a scour protection does not change the water depth, therefore this inhibiting factor is not changed by the construction of a wind farm. However, it should be kept in mind that wind farms with monopiles and a scour protection are usually built in waters less than 40 m deep.

Competition

The construction of a scour protection does change the competition between each of the species internally and externally. However it is not possible with the available information to predict how the competition will be changed due to the complexity of the system. Lobsters for example are very territorial (FAO, 2019b) and the construction of a scour protection will increase the availability of suitable habitat which will attract more lobsters which will compete with each other for this habitat. Therefore the number of lobsters may rise while the competition stays the same.

Minimum population

The construction of a scour protection will not change the required or present minimum population. The species of which the population is already sufficiently large to reproduce successfully, such as the cod, will benefit from the scour protection while other species, such as the flat oyster, are not likely to colonize the scour protection without human intervention.

Currents

Apart from the benefits that a scour protection brings with regards to currents there are also negative aspects induced by the construction of a scour protection. All species require oxygen to some extent, this can only be transported if a current is present. Some areas of the scour protection might be so sheltered from all currents that the phenomenon of oxygen depletion can occur which makes these areas unsuitable to live in. The opposite is also a possibility, in which the currents are increased to such a high value that lobsters are washed away or experience hindered mobility (Howard and Nunny, 1983) and oyster spat is unable to settle (Korringa, 1940; Smaal et al., 2017).

Mobility

The construction of a scour protection can decrease the inhibiting mobility issues by increasing the number of habitats and thereby decreasing the distance between individual habitats. This may have only a small effect on mobile species such as the cod and the Ross worm, but for other species such as the lobster and the flat oyster, which are less mobile, this can make a large difference.

Soil composition

The construction of a scour protection locally raises the sea bed level and in that sense provide a safer habitat than the sea bed on which burying by sand is a threat. Additionally the presence of the scour protection and monopile increases the flow velocities and helps to keep the scour protection free of sand. This way the construction of a scour protection benefits immobile species such as the flat oyster and the Ross worm.

4.4. Quantitative changes to the promoting and inhibiting factors

In this section several of the factors which were discussed qualitatively in 4.3 are quantified for wind farm Gemini. Not all of the factors are quantified and those that are quantified not all are quantified for each of the species. This is done to prevent repetition and unsubstantiated assumptions.

4.4.1. Quantitative changes to the promoting factors

Food abundance

The area of hard substrate around a single mono-pile in wind park Gemini is 773 m^2, and thus for the 150 wind turbines that are present a total of $116 * 10^3$ m^2 of hard substrate is introduced (see 2.2.2) which will facilitate a higher biomass and thus a larger potential food abundance. Coolen et al. (2019) calculated the average wet weight biomass in the North Sea to be 0.131 kg/m^2 and calculated the wet weight biomass on the foundations of two wind farms (Offshore Wind Farm Egmond aan Zee (OWEZ) and Princes Amalia Wind Farm (PAWF) with respectively 12 samples at 18 m depth and 5 samples at 23 m depth) and two gas platforms (L13-A and K9-A with respectively 3 samples at 22 m depth and 3 samples at 32 m depth). The average wet weight for these samples was 3.2 ($\pm$7.4) kg/m^2 (gamma distribution since biomass is always ≥ 0), which is 24 times more than the average value (0.131 kg/m^2). The area of the complete wind farm is $67.6 * 10^6$ m^2 and the area of hard substrate in this wind farm is $116 * 10^3$ m^2, or 0.17% (see Figure 4.1). This means that the amount biomass in the wind farm is 104.2% of the amount that it would be without scour protection, or an increase of 4.2%. When considering the complete North Sea ($525 * 10^9$ m^2) the increase due to one wind farm is 0.0005%. Knowing that the reference wind farm produces 600 MW of the total installed capacity of 11,800 MW, or about 5%, and assuming that the amount of hard substrate per MW is equal for all wind farms, the total increase in biomass in the North Sea due to wind farms is about 0.01%. These estimates are conservative, since it is assumed that the area of hard substrate in a scour protection is equal to the area covered by the scour protection. This is not the case, since the scour protection is not a flat surface but instead is an uneven area with surface area between the stones as well. The amount of hard substrate area can therefore be expected to be several times larger than is assumed in the calculations above.

Table 4.1: The expected increase in biomass shown on different scales. The relative increase is calculated compared to the situation in which the total surface would be soft substrate. Based on the Gemini wind farm.

Scale	Total area [m^2]	Biomass if area is soft substrate [kg]	Hard substrate after construction scour protection [m^2]	Biomass on hard substrate [kg]	Biomass on remaining soft substrate [kg]	Total biomass [kg]	Amount of biomass relative to situation without hard substrate [%]
m^2	1	0.131	1	3.2	0	3.2	2,443
Wind farm	$67.6 * 10^6$	$8.9 * 10^6$	$116 * 10^3$	$371.2 * 10^3$	$8.9 * 10^6$	$9.2 * 10^6$	104
North Sea + 1 wind farm	$525 * 10^9$	$68.8 * 10^9$	$116 * 10^3$	$371.2 * 10^3$	$68.8 * 10^9$	$68.8 * 10^9$	100.0005
North Sea + all wind farms	$525 * 10^9$	$68.8 * 10^9$	$2.3 * 10^6$	$7.3 * 10^6$	$68.8 * 10^9$	$68.8 * 10^9$	100.01

Suitable substrate

Different aspects of the scour protection are of importance for the four indicator species. The Atlantic cod and the European lobster benefit from the holes and crevices in the scour protection which serve as protection against predators and strong currents (during storms some rocks might displace, but it is unlikely that a mobile species like cod or lobster will be killed by this). The flat oyster and the Ross worm benefit from the hard substrate which serves as a stable hard substrate to which they can attach (assuming a large enough amount of rocks are stable).

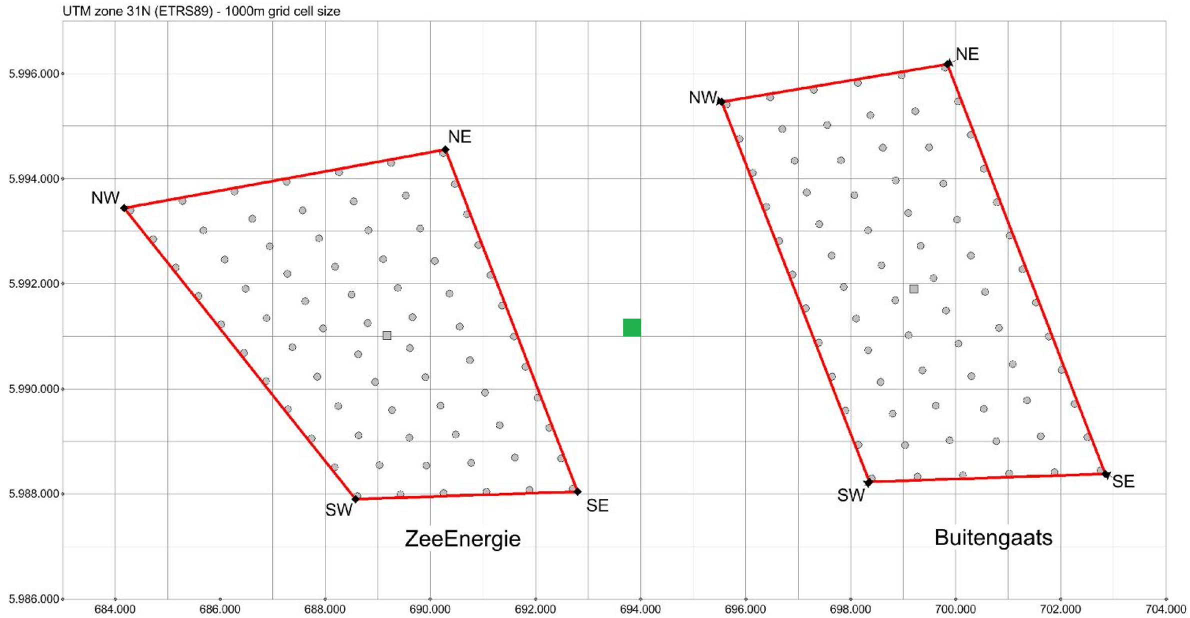


Figure 4.1: The total area of scour protection (green square) within the wind farm.

Suitability for cod
The precise size of the holes in the scour protection is unknown, but (Buijs, 2015) approximated the hole-size distribution and the number of holes in a volume of scour protection as was shown in section 2.4.2. Using those formulas it can be calculated that the armour layer of the scour protection for a single pile in wind farm Gemini contains 82,000 holes with a minimal diameter of 0.06 m (the length at which the juvenile cod leaves the safety of the sea bed). Not all of these holes are accessible from the outside, therefore it is assumed that only the top layer with a thickness of one D_{85} stone (= 0.194 m) is accessible. This leaves 94.3 m^3 of armour layer with 36,000 holes of which 33,500 with a minimal diameter of 0.06 m per scour protection. Using the same method to calculate the number of accessible holes in the filter layer gives about 305,000 accessible holes, but almost none are larger than 0.06 m in diameter. This has been visualized in figure 4.2.
The largest 5% of the holes (H_{95}) in the filter layer are 0.04 m in diameter or larger and provide shelter for the smallest of the cod while the largest 5% of the holes (H_{95}) in the armour layer are 0.14 m in diameter and therefore provide shelter for both the bottom-dwelling cod as well as some larger cod.

Suitability for lobster
Using the formulas provided by Buijs (2015) which give the pore size distribution based on the used grading, and the data on carapace length (CL) obtained from Schmalenbach (2009) (Helgoland population) and Skerritt et al. (2012) (UK east coast population) as well as the relation between CL and total length (TL) from this first paper ($TL = (CL + 0.0055)/0.3727$, all in m), provides some insight in the suitability of the 3-9”HD armour layer as shelter for lobsters. Figure 4.3a shows the hole size distribution of the armour layer that is used in the reference wind farm (red line with left axis values) as well as the carapace length of two populations (orange bars for UK east population and blue bars for Helgoland population). The carapace length is converted to total length using the formula given above and is plotted in the same graph as the hole size distribution in figure 4.3b. This figure (4.3b) shows how only the smallest lobsters benefit from some of the larger holes in the armour layer. However, this is under the (possibly invalid) assumption that a hole of exactly the lobster length is suitable for the lobster.

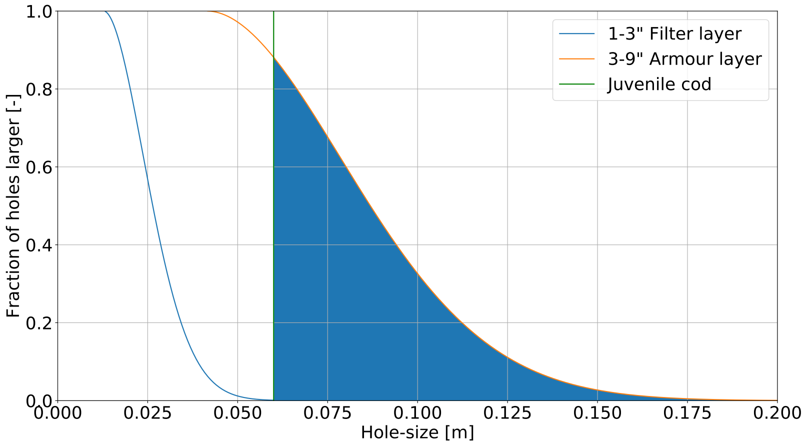
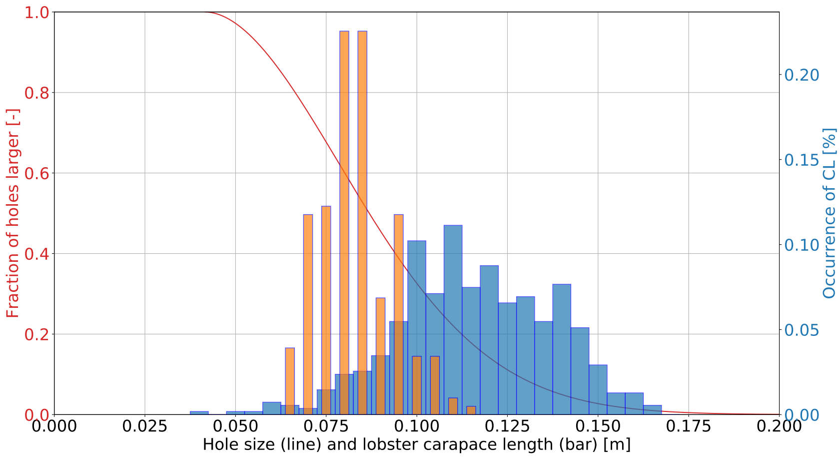
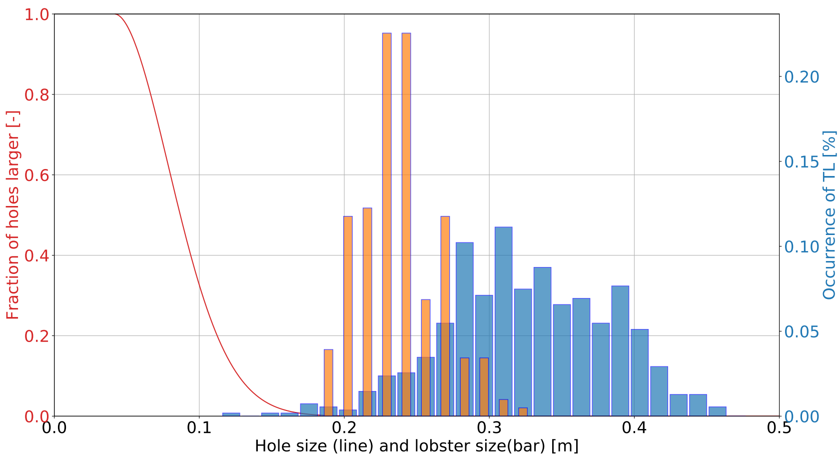


Figure 4.2: The hole size distribution for the filter (blue) and armour (orange) layers with the green vertical line indicating the size at which juvenile cod leaves the safety of the sea bed. The blue area indicates the suitable part of the layers.



(a) 3-9”HD compared to CL



(b) 3-9”HD compared to total length

Figure 4.3: Hole size distribution of the 3-9”HD armour layer (red line) and boxplot of carapace length (a) and total lenght (b) with the UK east coast population in orange and the Helgoland population in blue.

Suitability for oysters and Ross worms

The stability of the scour protection is of importance for the flat oyster and the Ross worm. Moving stones can damage or kill these species and should therefore be prevented. As the test results which are presented in table 2.7 and table 2.8 showed, the 1-3” filter layer shows severe movement ($\geq$ 5 layers) during 1/1 and 1/10 year storm conditions, making it an unsuitable substrate for the oyster and Ross worm. However, if given the time to develop, these species might stabilize the filter layer by connecting the individual stones. The 3-9”HD armour layer showed little to no movement ($\leq$ 1 layers) during 1/1 and 1/10 storm conditions and is therefore more suitable as substrate. During 1/50 year storm conditions the 3-9” HD layer is only dynamically stable. This however is not an issue since storms of this magnitude usually occur with enough time in between to allow the populations to recover.

Currents

The scour protection and monopile will create areas in which the current is smaller than in the undisturbed area, which provides cod and lobsters with resting places. Quantifying the extent of these areas and the effect that they have is not possible with the currently available information.

The beneficial influence of a scour protection and monopile for the Ross worm is found in the increased turbulence around the edges of the scour protection as is seen in Figure B.1. This increased turbulence suspends the sand and shell particles that the Ross worm requires for the construction of its tube. It is assumed that a band of d m width with its centre on the edge of the filter layer is affected positively by this turbulence. This creates a suitable habitat A_{rw} for the Ross worm with an area that is given by:

$$A_{rw} = \pi(r + \frac{1}{2}d)^2 - \pi(r - \frac{1}{2}d)^2 = 2\pi dr \qquad [m^2] \quad (4.1)$$

In which:

r	distance from the pile center	$[m]$
d	width of the band suitable for the Ross worm	$[m]$

Assuming d = 1 m, translates in case of the reference wind farm to 101 m^2 of suitable substrate for the Ross worm per monopile and 15,200 m^2 in the complete wind farm.

4.4.2. Quantitative changes to the inhibiting factors

Fishing

Fishing is not allowed within a wind farm and 500 metres around it. For Gemini this would mean that an area of 92.7 km^2 is closed to fishing, which is 0.018% of the North Sea and 0.163% of the Dutch North Sea. This is for 150 monopiles in a single wind farm. At present there are 2,872 wind turbines present in all of the North Sea, which is 19 times as many as are present in the reference wind farm. Assuming that the area closed to fishing per wind turbine is on average equal to that of the reference wind farm, it can be estimated that 0.345% of the North Sea is closed for fishing due to the construction of wind farms.

Predators

The number of predators is assumed to increase with the same amount as the other species based on expert judgement.

Water depth

The water depth is not changed by the construction of a scour protection, however, monopiles are only used in waters which are not too deep, as deep water leads to disproportional large pile diameters. Therefore it can be assumed that the water depth in a wind farm is less than 40 m. This makes wind farms suitable for all for species.

Competition

Juvenile demersal cod competes for shelter sites (Tupper and Boutilier, 1995b). The construction of a scour protection adds shelter sites and therefore decreases the competition for shelter sites. Tupper and Boutilier (1995b) found an exponential relation between home range and the length of the juvenile cod. From the data points that were plotted in their research the relation was found to be the following:

$$Homerange = 0.7314 * e^{0.3028*Length} \quad [m^2] \quad (4.2)$$

According to this formula the armour layer of the scour protection (which has holes large enough for the juvenile cod) provides habitat for 622 juvenile cod of 0.06 m in length. Expanding this to the whole wind farm (150 turbines with scour protection) results in habitat for about 93,000 cod smaller than 0.06 m.

Lobsters are known to be very territorial (FAO, 2019b). Based on the research listed in 2.5.4 it is assumed that the number of lobsters present on a scour protection will range between 1-20 per 100 m^2, resulting in a total of 7-154 lobsters per scour protection and 1,200-23,200 in a wind farm with 150 monopiles. However, this is only the case when there is shelter available, which is not the case in the reference wind farm.

The flat oyster competes with other species for settlement area. These other species are assumed to increase with the same amount as the other biomass. The Ross worm does not experience any significant competition.

Minimum population

Krone et al. (2017) researched the mobile demersal megafauna at common offshore wind turbine foundations in the German Bight (North Sea) two years after deployment. In this research the average number of Atlantic cod detected on the footprint areas (1,050 m^2) of a monopile was 17. Assuming this same density to occur in the reference wind farm with a scour protection area of 773 m^2 allows us to calculate the expected number of cod per monopile to be 13 and in the whole wind farm to be 1,900. It therefore can be assumed that Atlantic cod will be present in the wind farm in large enough numbers to form a healthy population (Atlantic cod needs >1,000 individuals to successfully reproduce). It must be noted that the number of cod found for competition is far larger (93,000 cod), this however looked at juvenile cod smaller than 0.06 m, it is therefore assumed that the total number of cod in the wind farm will be between 1,900 and 93,000. The lobster and the flat oyster need to be introduced by humans in large enough numbers to reach the minimum population while the Ross worm could settle on in the wind park by itself but would be helped by human intervention.

Currents

The inhibiting effects of the currents on the selected indicator species are enhanced by the presence of the scour protection and monopile (this is further explained in Appendix B). The increased flow velocities near the pile can hinder the lobster in its mobility, however, the lobster can move away from the pile or hide between rocks when the flow velocities near the pile become too large. The flat oyster is not able to move away from the monopile and can therefore not avoid the increased flow velocities. The flow velocities are not constant and vary in time with the change of tide and wave height. The largest problem that the oyster experiences is that the increased flow velocity and turbidity prevents the oyster spat from settling. It is impossible to predict what the flow velocity will be at the moment that the oyster spat is present in the wind farm, therefore it is assumed that the area within a distance of 0.5*D_{pile} is not suitable for oyster spat settlement. For a monopile with a diameter of 7.1 m this an area of about 120 m^2, which is about 15% of the scour protection.

Mobility

As was shown in section 2.2 the distance of the reference wind farm to the other wind farms in the North Sea with more than 10 wind turbines ranges between 32 and 612 km with a mean of 257 km. Figure 4.4 shows a histogram of the number of wind farms that have the nearest wind farm at a certain distance (blue bars), and the number of wind farms that have

the 4th nearest wind farm at a certain distance (orange bars). The vertical lines indicate the mobility of several species, the solid lines indicate the distance that the species itself is estimated to travel, and the other lines (dashed or dot-dashed) indicate the distance that the larvae of certain species are estimated to travel.
The lobster, which usually stays within a range of about 15 km will not spread from one wind farm to another, while distribution within a wind farm is very likely. The larvae of lobsters are transported up to 100 km, which allows them to reach multiple wind farms in the North Sea. However, it should be kept in mind that larvae reaching a wind farm might not be enough to establish a healthy population.
Both the flat oyster and the Ross worm are immobile species who's populations only spread through their larvae. The larvae of the flat oyster are, due to their short pelagic stage, not likely to spread between wind farms while distribution within a wind farm is very likely. The larvae of the Ross worm have a significantly longer pelagic stage which allows them to spread over much larger distances and reach most of the North Sea using other wind farms as stepping stones.

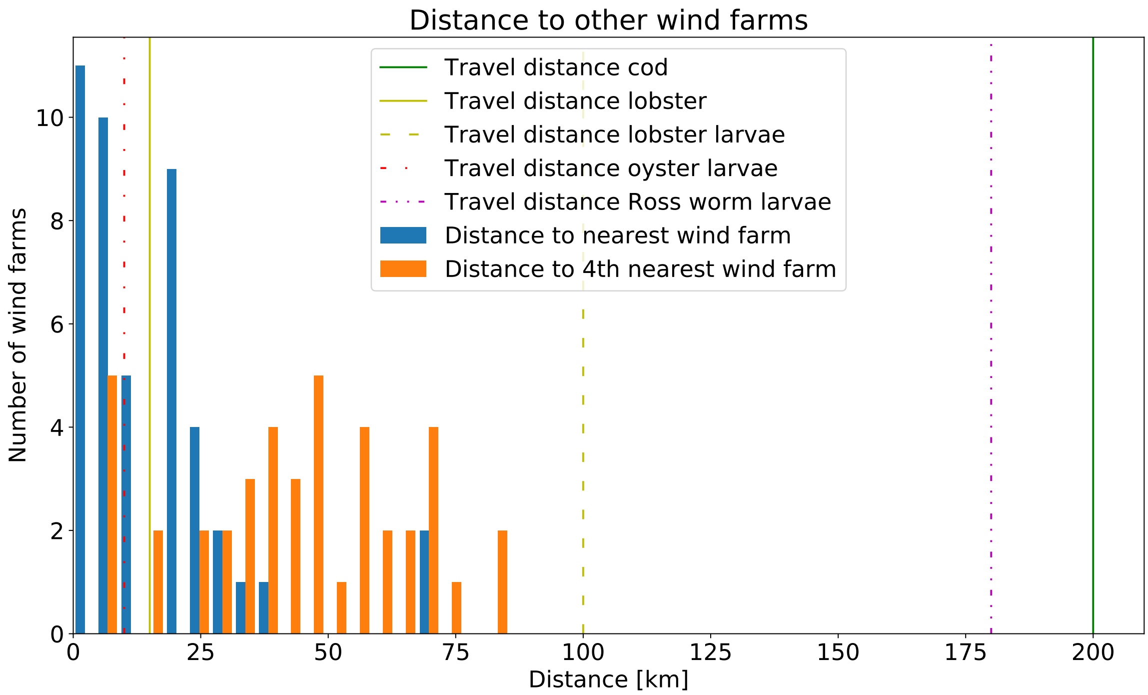


Figure 4.4: Distance to neares wind farm and fourth nearest wind farm of wind farms in the North Sea with more than 10 wind turbines

Soil composition
This can not be quantified with the found information.

4.5. Conclusion

The general conclusion is that the addition of hard substrate and the absence of (seabed disturbing) fisheries are the main reasons why wind farms in the North Sea are beneficial to the indicator species.
Due to the absence of fisheries the fishing mortality drops, which means that more species survive for a longer time, giving them the chance to reproduce. Another benefit of the absence of fisheries is that the reef building species such as the flat oyster and Ross worm can build their reefs undisturbed without having their habitat destroyed.
The presence of hard substrate increases the food abundance and creates shelter for lobsters and cod against currents and predators. The flat oyster spat can attach to the present hard substrate or to bivalves which grow on the hard substrate. The Ross worm benefits from the increased turbidity which suspends the sand particles and shell fragments that it requires to build its tube and from the hard substrate to which it can attach before building its tube.
However, several factors are still preventing the indicator species from inhabiting the wind farms and its scour protections.
The size of the holes in the scour protection are dependent on the grading size and width, in the case of the reference wind farm the holes are too small to be used as shelter by adult lobster.
The filter layer is not stable enough under storm conditions, which makes is less suitable for the Ross worm to build its tube on.
Additionally, even if the habitat for the indicator species would be optimal, their presence is not certain as their mobility might prevent them from reaching the wind farm. This is a problem for the lobster, which has a short travel distance and larvae which spread no further than 100 km, and for the oyster, which is immobile and has larvae which spread no further than 10 km.
In a wind farm as currently designed the population of Atlantic cod is estimated to increase from 360 (see Section 3.2) to 1,900-93,000 (see Section 4.4.2).
The population of European lobsters is estimated to stay very small due to the lack of suitable shelter for larger lobsters and due to the lack of a sufficiently large source population.
The population of flat oysters is estimated to stay very small due to the lack of a sufficiently large source population.
There is a possibility that the Ross worm will settle in the wind farm, which could result, according to Formula 4.1, in $\pm 15,000$ m^2 of Ross worm reefs.

Table 4.2 shows the relative suitability of the North Sea and for a wind farm with a scour protection for the four indicator species. This table serves as a way to compare the effects of the changes, and is not based on calculations, it should therefore only be used as a visual guide.

Table 4.2: Suitability assessment (scoring from 0 (very unsuitable) to 5 (very suitable)) for the North Sea (NS) and for wind farms (WF) with a normal scour protection(SP)

	NS	WF + SP	WF + ESP	WF + SP + SE	WF + ESP + SE
Atlantic cod	2	4	-	-	-
European lob-ster	1	2	-	-	-
Flat oyster	0	2	-	-	-
Ross worm	1	3	-	-	-
Total	4	11	-	-	-

5

Potential for nature improvement with enhanced scour protection

5.1. Introduction

Chapter 4 showed how the construction of scour protections around mono-piles in the North Sea changed the potential for nature improvement compared to the situation without wind farms as described in Chapter 3. There still is room for improvement by stimulating the promotional factors and by discouraging the inhibiting factors. There are three strategies to enhance the populations further: 1) Habitat enhancement, which aims to change the habitat such that it is more suitable for the selected species, this can be done by a) changing the design of the scour protection and/or b) applying additional elements, 2) Stock enhancement, which aims at increasing the abundance of the selected species by introducing species which have been reared or cultivated somewhere else, and 3) Food enhancement, which aims at increasing the amount of food available for the selected species. The first strategy is worked out in section 5.2 while the second and the third strategy are worked out in respectively sections 5.3 and 5.4. Sections 5.5 and 5.6 provide estimates of respectively the results and the cost of these enhancements and are followed by an example design for the reference wind farm in section 5.7.

5.2. Habitat enhancements

Chapter 3 showed that the largest inhabiting factors for the indicator species are the lack of suitable substrate for shelter and attachment, the presence of (seabed disturbing) fisheries, and the limited mobility of the European lobster and flat oyster (the Ross worm is a species which does not move when settled, but has a long pelagic larval stage and is therefore considered mobile). The construction of a wind farm adds hard substrate in the form of a scour protection which in general increases the suitability for the indicator species. The fishing free zone is also very beneficial. However, as chapter 4 showed, a standard scour protection does not benefit the indicator species optimally. This section focuses on the enhancement of the habitat by changes to the scour protection design and the placement of additional materials. The assumptions on what is beneficial for each of the species are based on the information in 2.5.

5.2.1. Changes to the scour protection design

Several changes to the scour protection design are possible to enhance the habitat while still complying with the design requirements.

Adjusting grading size and width

For increased shelter

Formula 2.11 from 2.4.2 shows that larger gradings create larger holes in the scour protection. These larger holes benefit the juvenile cod and the lobster who use these holes to shelter from currents and predators (visualized in Figure 5.1).

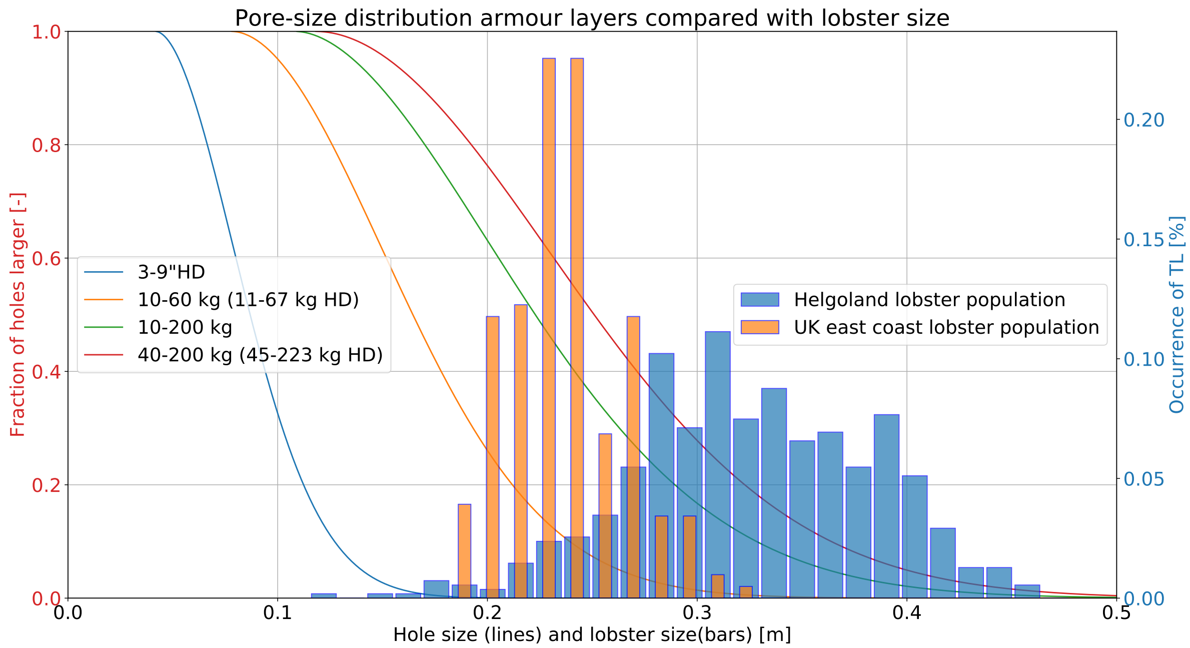


Figure 5.1: The pore size distribution for four armour gradings (lines against left y-axis) compared to the lobster size (bars against right y-axis) of two populations, the Helgoland population (Schmalenbach, 2009) in blue and a UK east coast population (Skerritt et al., 2012) in orange.

Table 5.1 lists the number of holes per grading and some characteristic dimensions. From this it can be concluded that all four armour layers are suitable for juvenile cod, which require hiding places up to a length of 0.06 m. Lobsters, which in general are smaller than 0.5 m (as can be seen in figure 5.1 as well) do not benefit from all gradings. Since lobsters are territorial and therefore do not occur in large numbers on a scour protection a few holes of the right size per scour protection will be sufficient as shelter. Based on this knowledge it makes sense to use the H_{95} (the size of a hole for which 95% of the holes are smaller, and thus 5% of the holes is larger) as a measurement for the suitability of the grading with respect to shelter for lobsters. Table 5.1 shows that a grading as small as 10-60 kg provides a

H_{95} of 0.263 m, which is large enough for a good part of the smaller UK east coast population but too small for the larger Helgoland population, which would need a 40-200 kg grading.

Table 5.1: Number of holes in the upper layer (thickness D_{85}) per armour grading. The H_X indicates the hole size for which X percent of the holes is smaller. The column 'Fitting HL/UK [%]' indicates the percentage of respectively the Helgoland population (HL) and the UK east coast population (UK) that fit in the H_{95}.

Grading	Upper layer volume $[m^3]$	Number of holes [-]	$H_{10}[mm]$	$H_{50}[mm]$	$H_{95}[mm]$	Fitting HL/UK [%]
3-9"	94.3	36,244	58	87	140	2/0
10-60 kg	177.6	10,169	110	164	263	10/75
10-200 kg	238.0	5,335	149	223	362	68/100
40-200 kg	255.3	4,133	169	251	399	87/100

Apart from using a larger grading to increase the hole size, a more narrow grading increases the hole size as well, although not as efficient as increasing the D_{50} while keeping the D_{15} and D_{85} the same, as can be seen in figure 5.2 and Table 5.2. Increasing the D_{50} however will most likely increase the D_{60} which in turn will affect the second filter rule that was listed in 2.4.1, This should be taken into account.

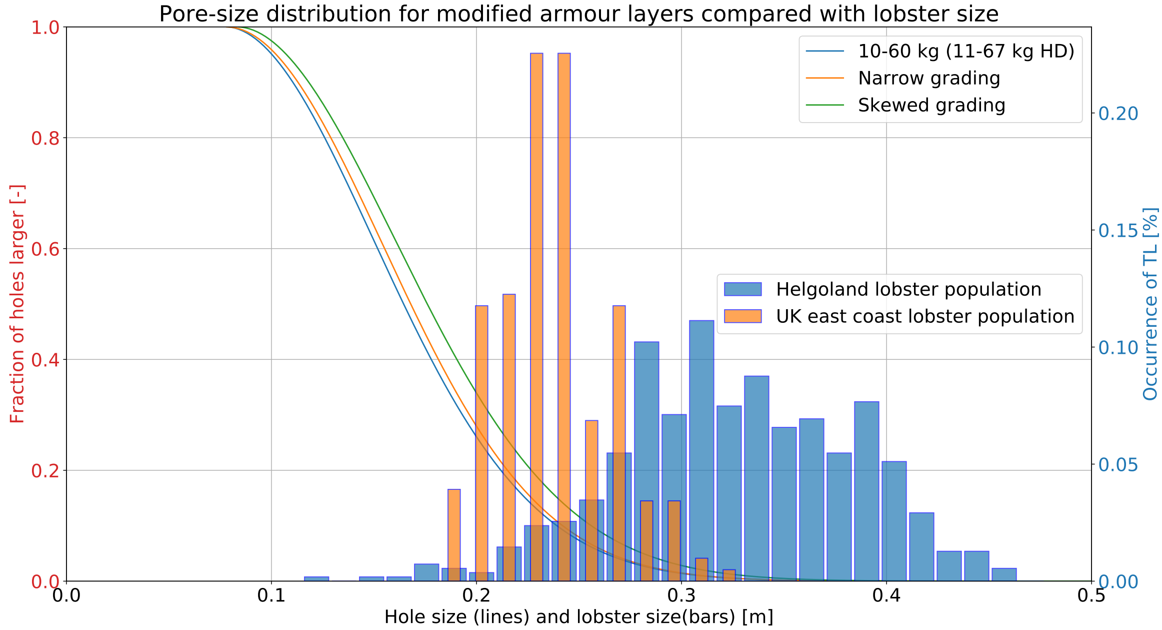


Figure 5.2: The pore size distribution for the 10-60 kg armour grading, the same grading but with D_{15} increased and D_{85} decreased with 20 mm (narrow grading), and the same grading with a D_{50} increased with 20 mm (skewed grading).

For increased stability

Increasing the stability of the stones for a more stable substrate makes it more suitable for species which otherwise would be damaged by moving stones. Increasing the armour layer from a 3-9"HD grading, which showed little movement during 1/1 and 1/10 year storm conditions, to a 11-67 kg HD layer makes the armour layer stable during these storms.

Changing the horizontal and vertical dimensions

For increased area of suitable substrate

Increasing the distance to which the scour protection extends horizontally increases the area of the scour protection. Increasing the horizontal extent from its old diameter D_{old} measured

Table 5.2: Hole size for normal grading, narrow grading, and skewed grading for the 3-9” and 10-60 kg armour layers.

Grading	D_{15} [mm]	D_{50} [mm]	D_{85} [mm]	H_{10} [mm]	H_{50} [mm]	H_{95} [mm]
3-9”	0.095	0.1525	0.194	0.058	0.087	0.14
3-9” Narrow	0.105	0.1525	0.184	0.059	0.088	0.141
3-9” Skewed	0.095	0.1625	0.194	0.062	0.093	0.149
10-60 kg	0.206	0.285	0.376	0.11	0.164	0.263
10-60 kg Narrow	0.226	0.285	0.356	0.112	0.167	0.264
10-60 kg Skewed	0.206	0.305	0.376	0.118	0.176	0.281

from the centre of the pile to a new diameter of D_{new} increases the area of hard substrate with $0.25 * \pi * (D_{new}^2 - D_{old}^2)$. The diameter for the armour layer and filter layer in the reference wind farm are respectively 3*D_{pile} and 4.25*D_{pile} or 21.3 m and 30.2 m. Increasing both these layers by 1*D_{pile} would increase the area of respectively the armour layer and the filter layer with 322 m^2 (+70%) and 399 m^2 (+52%). Important note: part of the increase in filter layer area can be canceled when the the armour layer covers part of this increase.

For increased length of edges
Increasing the distance to which the scour protection extends horizontally increases the length of the scour protection which borders the sandy sea bottom, this is the zone that is suitable for the Ross worm. The length increases with $\pi * (D_{new} - D_{old})$. Increasing the filter layer diameter by 1*D_{pile} will increase the edge length from 101 m to 123 m (+22%).

For increased vertical variability
Adding vertical variability is a method to create low-current areas. This can be done by creating piles of rock or dumping large rocks on the edges of the scour protection. The benefit of creating a pile of rocks is that it can be done by using the same type of rock as is used for the scour protection, which is easier to acquire. Another benefit is that the pile will contain holes which can serve as shelter for small animals. The benefit of using a few large rocks is that the placement is easier (no need for precise stacking, although a crane might be required) and that they are guaranteed to be stable. A risk of using few large rocks is that they might sink into the sea bed or create a scour hole which negatively affects the scour protection.
The pile is likely to be reshaped by waves and currents and it is assumed that it will become cone-shaped with slopes equal to those of the scour protection (1:2). For a pile of 1 m high this would mean that the base is circular with a diameter of 4 m and an area of $\pi*r^2 = \pi*2^2 = 12.57$ m^2. The total volume of rock required would be $1/3 * \pi * r^2 * h = 1/3 * \pi * 2^2 * 1 = 4.19$ m^3 while the exposed surface would be $\pi * r * \sqrt{r^2 + h^2} = \pi * 2 * \sqrt{2^2 + 1^2} = 14.05$ m^2.
The large rocks are assumed to be square. For a vertical height of 1 m a rock of slightly larger than this height is required to compensate for sinking into the scour protection. Assuming that this sinking is limited to 0.2 m means that a rock diameter of 1.2 m is required. These rocks are assumed to be square and have a volume of $D_{rock}^3 = 1.2^3 = 1.73$ m^3 and an exposed surface of $5 * D_{rock}^2 = 5 * 1.2^2 = 7.20$ m^2.
For further quantification it is assumed that either 3 piles of rock are placed per wind turbine, or 6 large rocks. The total increase of hard substrate for using rock piles or large rocks are respectively 6,300 m^2. and 6,500 m^2. However, it must be noted that these piles or rocks, when placed on the scour protection, will occupy a certain area, leading to a smaller increase in exposed area. The netto increase in exposed area per pile of rocks and per large rock are respectively $14.05 - 12.57 = 1.48$ m^2 and $7.20 - 1.44 = 5.76$ m^2, or a total increase in the wind farm of respectively 666 m^2 and 5,200 m^2.

5.2.2. Additional beneficial elements

Placing (concrete) tubes on the scour protection
Tubes provide shelter for both lobsters and cod. These tubes can be placed on the scour protection with aid of a crane and divers and should be stable during storm conditions to

avoid it being displaced or slammed against something causing them to break.
Various materials and dimensions can be used for these tubes. Murk (2018) proposed an idea of using concrete drainage tubes (0.2 m diameter, 1.0 m length), an idea that is also proposed by Lengkeek et al. (2017). The costs of these tubes are relatively low due to the low material and production costs. An estimate of the costs for various tubes is given in Table 5.3. and are based on a quick indication of the prices online. The largest costs are incurred by the transportation and placement. These costs are assumed to be €20,000 per day based on estimates by Sas et al. (2018). The total cost depends on the amount of tubes placed. Assuming to place two tubes of each size at each pile amounts to $(40 + 80 + 160) * 2 * 150 =$ €$84,000$ excluding placement costs. Assuming that it is possible to place these tubes in five days would bring the total cost of this enhancement to €184,000.

Table 5.3: Different dimensions of concrete tubes that can be used to create shelter for cod and lobster

Material	Length [m]	Diameter[m]	Weight[kg]	Price[€]
Concrete	1.00	0.20	124	40
Concrete	1.50	0.40	327	80
Concrete	2.00	0.60	624	160

Points of attention:

- The placement of these tubes is to be carried out carefully to avoid breaking.
- Securing the tubes to the sea bed is required to avoid displacement.
- The tubes should not sink into the soil, placement on the filter layer can avoid this.

Adding empty shells
Shells are a suitable substrate to settle on (Schild et al., 2017; Sas et al., 2018; Didderen et al., 2018a). Dumping empty shells on the scour protection is a method to add suitable settling substrate to the scour protection. The price of clean shell material is €100 per m^3 (Sas et al., 2018) of which 0.5 cm/m^2 should be sufficient. Covering all of the scour protections (116*10^3 m^2) with a 0.005 m thick layer of shells would amount to 580 m^3 of shells which would cost $58,000. However, a (large) portion of the shells would be washed away by the tide, making this an inefficient solution. One way to avoid this is by putting the shells in nets and dropping these nets (weighted down with rock or steel if necessary) on or around the scour protections. Deltares (2017) reported on the use of rock-filled mesh bags as scour protection which are commonly filled with rock of 50-200 mm, weigh 2-8 tons and have a diameter of 2-3 m. Assuming that the shell-filled nets are shaped as a cylinder with a 2 m diameter and a height of 0.5 m (see Figure 5.3) a single bag would have to be filled with 1.57 m^3 of shells and would have an exposed area of 6.28 m^2. Placement of three bags per monopile requires 700 m^3 of clean shell material and creates 2,800 m^2 of suitable settling substrate for oyster spat. However, without active oyster stock enhancement this improvement is useless.

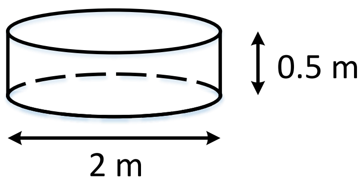


Figure 5.3: The definition of the net size.

The total costs consist of material costs and placement costs. At €100 per m^3 for shell material, the material costs for 450 shell-filled nets are €70,000 excluding the costs for the nets and the filling of the nets, these are assumed to be €50 per net. The placement costs are estimated to be €20,000 per day. Assuming that it is possible to place these nets in three days would bring the total cost of this enhancement to €152,500.

5.3. Stock enhancements

Atlantic cod is able to reach the wind farms in the North Sea by itself and therefore does not require active introduction. The European lobster and even more so the flat oyster are not able to colonize newly build wind farms without human intervention. The Ross worm is, due to its long pelagic stage able to reach newly build wind farms, provided that the present currents transport the larvae in the right direction. This section will therefore discuss the possibilities for lobster stock and oyster stock enhancements.

5.3.1. Lobster stock enhancement

Over the past decades multiple lobster stock enhancements have been carried out with varying success. These stock enhancements, in which hatchery-reared lobsters are released into the wild, differ from each other in the number of lobsters that are released and the age of these lobsters. It is common to repeatedly release either a large number (>5,000 at a time) of postlarvae (stage IV and V; carapace length = 0.005-0.007 m) or a smaller number (<1,000) of lobsters which have been reared in the laboratory for 5-8 months to stage XII+ (carapace length = 0.012-0.016 m) (Beal et al., 2002). Releasing large numbers of larger lobsters, which have a higher survival rate, is not feasible due to the large costs that this incurs.
Research has shown that raising postlarvae in a habitat with substrate and shelter as opposed to an empty tank, 'trained' the juvenile lobsters for the wild and led to survival rates which were 3 times higher (53% vs 18%) than 'untrained' juvenile lobsters (Agnalt et al., 2017). Other reported survival rates were 30-40% for 1 year old lobsters (Schmalenbach et al., 2011) and 50-84% for 7 month old lobsters (Bannister et al., 1994). The hatchery-reared female lobsters seem to have the same fecundity as wild lobsters (Agnalt, 2008).
As was calculated in 4.4 there is room in the wind farm for 1,200-23,200 lobsters provided that adequate shelter is available. To achieve this, assuming a survival rate of 30-50%, between 2,300 and 77,300 juvenile lobsters should be released.
Beal et al. (2002) estimated the costs of placing 20,000 stage V lobsters in nursery field containers to be $28,000 (200 cages of $45 each + 20,000 stage V lobsters of $0.85 each + 20,000 containers of $0.10 each). Additional costs from time required to load and deploy the lobsters was estimated to be $7,200 while costs of fuel, renting vessels etc. was not included in the estimate. An estimate of the costs is made for the example of a lobster stock enhancement in Table 5.4. The costs of the first 10,000 lobsters is estimated (after conversion from dollar to euro ($1 = €0.88) and correcting for inflation (1$ in 2002 is $1.42 now)) to be €17,500 (100 cages of €56 each, 10,000 stage V lobsters of €1.05 each, 10,000 containers of €0.13 each). The following years the cages can be reused which limits the costs to €12,000 each year. The labour costs of loading and deploying the lobsters is estimated to be €6,500. This amounts to a total of €79,500 (€53,500 for lobsters and material + €26,000 for labour) excluding the cost of fuel, renting vessels etc. These costs are assumed to be €26,000 per day as was reported by Sas et al. (2018) for the oyster stock enhancement (see section 5.3.2). Additionally it is assumed that the deployment will take 2 days each year, adding €208,000 to the cost which brings the lobster stock enhancement costs to a total of €287,500.

Table 5.4: Lobster stock enhancement example

Total amount of lobsters	40,000
Lobsters per year	10,000
Length (age)	0.005-0.007 m (stage IV and V)
Sex distribution	Evenly distributed
Method of introduction	Release above hard substrate at each pile

Points of attention:

- Distribution near the substrate is preferred to avoid predators during settlement.
- Distribution at one location only will not be efficient due to the high competition for shelter.

5.3.2. Flat oyster stock enhancement

The restoration of the flat oyster in the North Sea by stock enhancement is a subject of ongoing research. To successfully kick-start a population of flat oysters a disease free starting population is required. The minimum required population size is unknown, but the larger the population, the larger the chance that it is successful. A project in the Solent (UK) consisted of 9,000 oysters in broodstock cages attached to marinas and pontoons and seems to be successful in terms of survival, growth, and reproduction (Schild et al., 2017). Sas et al. (2018), assessing the possibility of a flat oyster pilot design in North Sea offshore wind farm, made the expert judgement that 20,000 oysters should be sufficient to kick-start a population. In the pilot for the restoration of the flat oyster in Borkum Reef Ground, 80,000 adult flat oysters were placed on the sea floor with a density of 10 oysters/m^2.
Another requirement for an oyster population to be successful is the presence of suitable settling substrate for the oyster spat, preferable clean empty shells such as mussel, cockle, Pacific oyster and flat oyster shells (Sas et al., 2018; Schild et al., 2017; Didderen et al., 2018b). An average layer thickness of 0.5 cm/m^2 is assumed to be sufficient.
For successful reproduction both male (<3 year) and female (>3 year) oysters are required.
Didderen et al. (2018b) reported higher survival for oysters in racks (40-80%) than for oysters placed directly on the sea floor (26%) and found the main factor influencing oyster survival to be duration of storage and size of the oysters at introduction.
Sas et al. (2018) estimated the costs of the pilot and reported the following numbers: €1,450 per rack in which oysters will be placed, €15 per cage and holder which hold the oysters in place (4 per rack), €3-15 per oyster (including keeping oysters alive at harbour), and €100 per m^3 clean shell material as settling substrate. Deployment, maintenance and monitoring activities were assumed to be €26,000 per day.

Table 5.5: Example of an oyster stock enhancement plan

Total amount of oysters	49,000
Distribution	1,000 oyster during pilot. 60 piles with 800 oysters per pile if pilot is successful.
Age	Half < 3 year, half > 3 year.
Sex distribution	Evenly distributed
Method of introduction	Broodstock cages (400 oysters per rack) on or around scour protection.
Additional requirements	Placement of 4 m^3 clean shells (mussel and/or cockle) per used pile.

Assuming a cost of €10 per oyster (including keeping oysters alive at harbour) this would amount to (excluding the 1,000 oyster pilot) a total cost of €695,000 excluding placement costs. These costs are composed of €490,000 for the oysters, €181,000 for the racks and cages, and €24,000 for the shell material. Additionally it is assumed that it will take a total of 10 days to complete the placement of the broodstock cages. This adds €260,000 to the costs and brings the total to €950,000.
Points of attention:

- Best time for oyster introduction is early spring, before may 15^{th}.
- The oysters should be taken without damaging the parent population.
- The oysters should be free of diseases and invasive alien species.
- Parasites such as *Marteilia refringens* and *Bonamia ostreae* should be avoided.

5.4. Food enhancements

Increasing the amount of available food in a wind farm is a method to make the wind farm more suitable for the selected species. Both the flat oyster and the Ross worm feed on microalgae and phytoplankton which makes food enhancements for these species near impossible. A way to increase the amount of available food in the wind farm for the Atlantic cod and the European lobster is by having fishermen discard their bycatch within the wind farm. In 4.4 it was calculated that the total biomass in the wind farm would be $9.2 * 10^6$ kg. To (temporarily) increase this with a significant amount (>10%), $920 * 10^3$ kg of bycatch is to be discarded by fishermen into the wind farm. IMARES (2014) reported that on average 40% of the catch in weight from demersal fisheries was discarded in the North Sea. For the years 2010, 2011, and 2012 this amounted to respectively $120 * 10^6$ kg, $206 * 10^6$ kg, and $121 * 10^6$ kg for all demersal fisheries in the North Sea combined. This means that to increase the amount of biomass in the wind farm by 10% between 0.45% and 0.77% of all bycatch in the North Sea is to be discarded within the wind farm. This however would increase the amount of biomass only temporarily (once per year), if this is to repeated monthly or even weekly the percentages rise to respectively 5.4-9.2% and 23.2-40.0%. This shows that this solution is not feasible.

5.5. Expected results

Where relevant, a distinction is made in short time results (within three years) and long term results (more than fifteen years).

5.5.1. Habitat enhancements

The habitat enhancements and their expected results are summarized below. Some of these enhancements will only be efficient when other enhancements are carried out as well. For example, adding empty shell in nets will create suitable settling substrate for oyster spat, but without a source population this will not lead to an increase of the oyster population.

- **Increasing the armour size**
  - Effect: Increase of hole size in armour layer and increase of rock stability.
  - Beneficiary: Cod and lobster benefit from the holes in the armour layer, oysters benefit from more stable substrate.
  - Expected result: Higher survival rate for cod, lobster, and oyster.
  - Quantified: Assuming the Helgoland lobster population to be most representative for the area, the used 3-9”HD armour layer does not create holes that are large enough. A 10-200 kg grading would provide holes for 68% of the population while a 40-200 kg grading would provide holes for 87% of the population. Cod benefits from all gradings, but larger gradings provide larger holes and thus creates shelter for the larger cod as well, this has not been further quantified. The 3-9”HD armour shows little to no movement during 1/1 and 1/10 year storm conditions, a larger armour layer is therefore not required with regards to stability.
- **Using a skewed grading**
  - Effect: Increase of hole size in armour layer.
  - Beneficiary: Cod and lobster benefit from the holes in the armour layer.
  - Expected result: Higher survival rate for cod and lobster.
  - Quantified: Using a skewed grading (increasing the D_{50} with 7%) increases the H_{95} (about 7%) and therefore provides limited benefits.
- **Increasing the armour layer horizontal extent**
  - Effect: Increase of armour layer area.
  - Beneficiary: All species who benefit from the armour layer benefit from a larger area of armour layer.
  - Expected result: All positive effects of the armour layer are increased with the same amount as the area.
  - Quantified: The positive effects increase with 70% when increasing the diameter of the armour layer from 3^*D_{pile} to 4^*D_{pile}.
- **Increasing the filter layer horizontal extent**
  - Effect: Increase of filter layer area and increase of the length of filter layer bordering the sand.
  - Beneficiary: All species who benefit from the filter layer benefit from a larger area of filter layer. The Ross worm benefits from the area of hard substrate bordering the sand.
  - Expected result: All positive effects of the filter layer are increased with the same percentage as the increase in area. The suitable settling area for the Ross increases with the same percentage as the increase in edge length.

  - Quantified: The positive effects of the filter layer increase with 52% when increasing the diameter of the filter layer from 4.25*D_{pile} to 5.25*D_{pile} assuming that the armour layer extent is not increased. The beneficial length of the edge for the Ross worm would in this case increase with 22%.

- **Placement of 450 1 m high piles of rock**
  - Effect: Increase of holes, increase of hard substrate, increase in both turbulent and calm areas.
  - Beneficiary: Cod and lobster benefit from the holes in the rock pile. All species who benefit from hard substrate benefit from a larger area of hard substrate. Cod, lobster, and oyster spat benefit from the calm areas.
  - Expected result: All positive effects of the hard substrate are increased with the same percentage as the increase of hard substrate area. Higher survival rate for cod and lobster. Higher survival rate and settling success for oyster spat.
  - Quantified: When placing these piles on the scour protection the amount of added hard substrate surface is 666 m^2, which is a 0.6% increase in hard substrate surface compared to the situation without these piles. Placing the piles on the sand bed would increase the hard substrate surface with 6,300 m^2, or 5.4%. However, in this case a filter layer beneath the pile would be required to avoid winnowing.

- **Placement of 900 1 m large rocks**
  - Effect: Increase of hard substrate, increase in both turbulent and calm areas.
  - Beneficiary: All species who benefit from hard substrate benefit from a larger area of hard substrate. Cod, lobster, and oyster spat benefit from the calm areas.
  - Expected result: All positive effects of the hard substrate are increased with the same percentage as the increase of hard substrate. Higher survival rate and settling success for oyster spat.
  - Quantified: 5,200 m^2 of hard substrate surface is added when the rocks are placed on the scour protection, which is a 4.5% increase in hard substrate surface. However, this hard substrate does not provide holes and crevices for shelter. Placing these rocks on the sand bed would increase the hard substrate surface with 6,500 m^2 or 5.6% but requires a filter layer to avoid it from sinking deep into the sea bed.

- **Placement of 450 (concrete) tubes on the scour protection**
  - Effect: Increase of holes and hard substrate.
  - Beneficiary: All species who benefit from hard substrate benefit from a larger area of hard substrate. Cod and lobster benefit from the large shelter sites that these tubes create.
  - Expected result: All positive effects of the hard substrate are increased with the same percentage as the increase of hard substrate area. Higher survival rate for cod and lobster.
  - Quantified: Habitat for 450 large cod and lobsters which allows the larger cod and lobsters to reproduce (larger cod and lobster produce more eggs (Trippel, 1998; Lavalli, 1999)). Without this shelter the lobsters would be washed away during storms.

- **Placement of 450 shell-filled nets**
  - Effect: Increase of suitable settling substrate for oyster spat.
  - Beneficiary: Oyster spat benefits from the presence of suitable settling substrate.
  - Expected result: Higher settling success for oyster spat.
  - Quantified: 2,800 m^2 of suitable settling substrate is created this way. Assuming that the oyster densities on these nets will be equal to the densities reported by Christianen et al. (2018) (6.8 ± 0.6 per m^2) the total number of oysters on the shell-filled nets will be about 20,000.

5.5.2. Stock enhancements

The lobster stock enhancement aims to increase the lobster population up to the capacity of the wind farm. This capacity of the wind farm has been calculated to be between 1,200 and 23,200 lobsters for which between 2,300 and 77,300 juvenile lobsters would have to be released.
The oyster stock enhancement aims to create a self sustaining oyster stock by placing 49,000 oysters of varying ages (and thus sexes) in broodstock cages in the wind farm. It is estimated that about 60% of the oysters will survive.

Short term

For the lobster stock enhancement as proposed in Table 5.4 the estimated short term results for the lobster population is a self sustaining population of about 10,000 lobsters (25% of the introduced population).
The oyster stock enhancement, if carried out as in Table 5.5, results in the short term in a self sustaining oyster population of about 29,000 oysters (60% of the introduced population).

Long term

In the long term the lobster population will grow up to the point where competition becomes the limiting factor. This will be when between 1,200 and 23,200 lobsters are present.
If the oyster stock enhancement is successful then the oysters can spread over all of the wind farm, attaching to all suitable substrate to form a flat oyster reef. Assuming that this population will reach the same density as was reported at the 'Voordelta' in the Netherlands (6.8 ± 0.6 m^{-2}) (Christianen et al., 2018) and covers all of the undisturbed area in the offshore wind farm (92.7 km^2), would result in a population of $630.6 * 10^6 \pm 5.6 * 10^6$ oysters. However, the oyster density reported by Christianen et al. (2018) was only found in shellfish patches and did not cover the entire area, the amount of oysters estimated above is therefore expected to be smaller. In a literature study by Gercken and Schmidt (2014) common abundances of 0.09-0.5 oysters per m^2 were reported. Assuming that these values are more realistic a total of $8.3*10^6$ - $46.4*10^6$ oysters can be estimated in the long term.

5.5.3. Food enhancements

Food enhancement can be a successful way to improve the suitability of a wind farm for Atlantic cod and European lobster, but, as was shown in 5.4, the amount of bycatch required to increase the amount of present food significantly is unrealistically large.

5.6. Expected costs

The expected costs are based on material cost and placement costs. The material costs for the quarried rock are based on rules of thumb provided by Witteveen+Bos (€22 per ton, or €36 per m^3, both for material, vessels, and placement costs). Below the costs have been estimated per improvement.

5.6.1. Habitat enhancements:

- Increasing the armour size: The costs do not increase when using a larger grading, however, a larger grading will at a certain point lead to a larger required volume due to the design rule that the layer should be at least 2 layers thick.
- Using a skewed grading: The cost of using a non-standard grading are not larger than for a standard grading.
- Increasing the armour layer horizontal extent: increasing the armour layer diameter with $1{*}D_{pile}$ requires 300 m^3 extra rock per pile at a cost of €10,800 which is 45,000 m^3 extra rock in total at a cost of €1,620,000.
- Increasing the filter layer horizontal extent: increasing the filter layer diameter with $1{*}D_{pile}$ requires 195 m^3 extra rock per pile at a cost of €7,000 which is 29,000 m^3 extra rock in total at a cost of €1,044,000.
- Placement of three 1 m high piles of rock per monopile: 1,900 m^3 extra rock in total at a cost of €68,400.
- Placement of six 1 m large rocks per monopile: These rocks are rare and therefore it is common to use concrete instead. This would lead to excessive use of concrete (which is harmful to the environment) and would require placement by crane due to their size. The placement of stones is therefore deemed to be financially unfeasible.
- Placement of 450 (concrete) tubes: €184,000.
- Placement of empty shells in nets: €152,500.

5.6.2. Stock enhancements:

- Lobster stock enhancement: €287,500.
- Oyster stock enhancement: €955,000.

5.6.3. Food enhancement:

- Discarding bycatch within the wind farm: price can not be estimated with the available information. However, to monthly increase the available biomass within the wind farm by 10% would require between 5.4-9.2% off all bycatch in the North Sea, meaning that a large number of vessels would have to take a large detour, which would be extremely costly.

5.7. Example improved design Gemini

A scour protection design for the reference wind farm is made in which several of the improvements are implemented (see Fig 5.4).
The scour protection consists of two layers:

- A 3-9"HD filter layer with a minimal thickness of 1 m, a diameter of at least 5 times the pile diameter with sections protruding up to 6 times the pile diameter, edge slopes not steeper than 1:2, and at least 2 m of free surface between the upper edge of the filter layer and the lower edge of the armour layer.
- A 40-200kg armour layer with a minimal thickness of 1 m, a diameter of at least 3.5 times the pile diameter, edge slopes not steeper than 1:2, and at least 1 m of free surface at the top side.

Additionally, 3 piles of rocks, 3 concrete tubes, and 3 shell-filled net are placed.
By increasing the filter layer size the stability is increased, which benefits the Ross worm, while simultaneously satisfying the filter rules ($\frac{d_{15U}}{d_{85L}} < 5$, $\frac{d_{60}}{d_{10}} < 10$, and $\frac{d_{15U}}{d_{15L}} > 5$). The increased filter layer thickness is required to avoid winnowing. A varying extent of the filter layer is implemented to increase the edge length of the filter layer, something that benefits the Ross worm.
The improved scour protection design is estimated to increase the number of cod from 1,500-93,000 to 3,000-240,000, the number of lobster from less than 1,000 to 2,000-36,000, the number of oyster from less than 1,000 to more than 20,000, and the area covered by Ross worm from 15,000 m^2 to 22,000 m^2. Table 5.6 provides an overview of the changes to the design and the estimated effects of the improved scour protection within the wind farm.

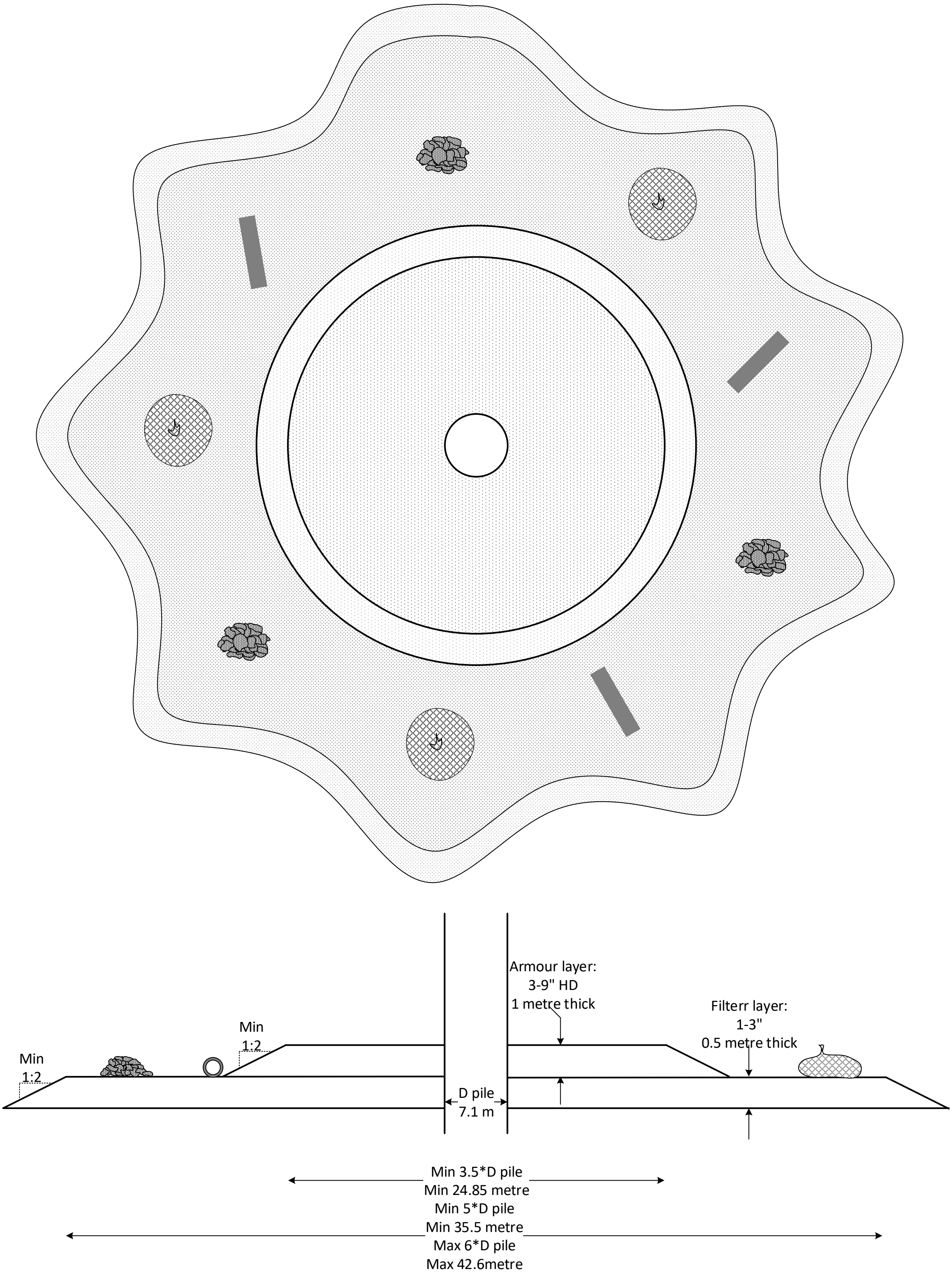


Figure 5.4: An example of how the scour protection for the reference wind farm could be designed to enhance marine life (drawing not to scale). Top of the picture show the scour protection as seen from above, the bottom picuture show a cross-section of the scour protection.

Table 5.6: Example of the changes for the improved design Gemini, based on the example design in this section
*cost of the concrete tubes and the shell-filled nets could be lower if placed simultaneously

Per pile	**Original design**	**Improved design**
Filter layer type	1-3”	3-9”HD
Filter layer thickness	0.5 m	1 m
Filter layer extent	15.1 m	17.8-21.1 m
Filter edge extent	17.1 m	19.8-23.1 m
Filter edge length	101 m	> 124-146 m
Filter layer volume	362 m^3	533-762 m^3
H_{95} Filter layer	0.04 m	0.14 m
Armour layer type	3-9”HD	40-200 kg
Armour layer thickness	1 m	1 m
Armour layer extent	10.7 m	12.4 m
Armour edge extent	12.7 m	14.4 m
Armour layer volume	388 m^3	528 m^3
H_{95} Armour layer	0.14 m	0.40 m
Entire wind farm		
Filter cost	$1,955,000	$2,888,000-4,115,000
Armour cost	$2,095,000	$2,851,000
Rock pile cost	-	$68,000
Concrete tubes cost*	-	$184,000
Shell-filled nets cost*	-	$153,000
Lobster stock enhancement	-	$288,000
Oyster stock enhancement	-	$955,000
Total cost	**$4,090,000**	**$7,387,000-8,614,000**
Estimated number of cod	1,500-93,000	3,000-240,000
Estimated number of lobster	<1,000	2,000-36,000
Estimated number of oyster	<1,000	>20,000
Estimated area covered by Ross worm	15,000 m^2	22,000 m^2

5.8. Conclusion

There are three strategies to improve nature compared to a scour protection as currently designed: 1) Habitat enhancement, which aims to change the habitat such that it is more suitable for the selected species, this can be done by a) changing the design of the scour protection and/or b) applying additional elements, 2) Stock enhancement, which aims at increasing the abundance of the selected species by introducing species which have been reared or cultivated somewhere else, and 3) Food enhancement, which aims at increasing the amount of food available for the selected species.

The Habitat enhancements consists of changes to the scour protection design and the placement of additional materials.

- Adjusting the grading size is an effective method to increase the size of the holes in the scour protection through which it creates shelter for cod and lobster. The cost of this enhancement is limited to an increase in required rock volume due to a possible increase in layer thickness or an additional layer.

- Using a more narrow grading (increase D_{15} and/or decrease D_{85}) or a skewed grading (increase only the D_{50}) increases the size of the holes in the scour protection with a small percentage (<10%) and is assumed not to incur extra costs unless the filter properties are affected to such an extent that an additional filter layer is required.

- Increasing the horizontal dimensions of the armour and/or filter layer increases all beneficial factors of a scour protection but requires a lot of extra material and will therefore be costly (€22 per extra ton of rock, which is about €36 per m^3).

- Increasing the vertical variability by placing piles of rocks or large rocks benefits cod and lobster by providing shelter and/or low current areas and could provide areas of low flow velocity which would allow oyster spat to settle successfully. This requires a significant amount of additional rock (450 piles of 1 m high require 1,900 m^3 of rock at a cost of €68,400) while creating limited benefits (0.6% added hard substrate (m^2) when placed on the scour protection and 5.4% added hard substrate (m^2) when placed on the sea bed, although this would require a filter layer).

- Placement of 450 large (concrete) tubes on or around the scour protection creates holes which serve as shelter for large cod and lobsters. Additionally the surface of the tubes serves as a hard substrate to which various species can attach. The costs of this solution is estimated to be €184,000.

- Placement of empty shells in nets creates suitable settling substrate for oyster spat. Estimated costs are €152,500.

The Stock enhancements aims at increasing the abundance of the selected species by introducing species which have been reared or cultivated somewhere else. The Atlantic cod is a very mobile species which can reach all wind farms in the North Sea without human intervention and therefore does not require a stock enhancement. The Ross worm produces larvae with a long pelagic stage which allows them to be distributed by currents throughout the North Sea and settling within the wind farms without human intervention. The lobster and especially the flat oyster are much less mobile and therefore need to be introduced into the wind farm to create a successful population.

- The lobster stock enhancement aims to increase the lobster population up to the calculated capacity of the wind farm (1,200-23,200 lobsters). This is done by introducing 40,000 juvenile lobsters (0.005-0.007 m (stage IV and V)) over the course of several years. The surviving part of this population is able to inhibit the wind farm successfully (given that shelter is available and adequate). The cost of this enhancement is estimated to be €287,500.

- The oyster stock enhancement aims to create a oyster population large enough to successfully reproduce and spread over all of the wind farm. The minimum amount of oysters required to achieve this is thought to be 20,000. Placement of 49,000 oysters (taking into account 60% survival rate) in broodstock cages and clean shell material as settling substrate throughout the wind farm is estimated to create a self sustaining population of about 29,000 oysters. In the long term the oyster spat could spread throughout all of the wind farm, settling on shells of flat oysters and other bivalves, resulting in a population of millions of oysters ($8.3*10^6$ - $46.4*10^6$). The cost of this enhancement is estimated to be €955,000.

Food enhancement aims at increasing the amount of food available for the selected species. Discarding bycatch caught by fishermen in the North Sea can be a method to achieve this. However, to significantly increase the amount of available food a very large number of vessels would have to take a detour, leading to extremely high costs. This method is therefore not deemed suitable.

Table 5.7 shows the relative suitability of the North Sea and of wind farms with or without enhancements. This table serves as a way to compare the effects of the changes, and is not based on calculations, it should therefore only be used as a visual guide.

Table 5.7: Relative suitability assessment (scoring from 0 (very unsuitable) to 5 (very suitable)) for the North Sea (NS), for wind farms (WF) with a normal scour protection(SP), for wind farms with an enhanced scour protection (ESP), for wind farms with a standard scour protection and stock enhancement (ESP), and for wind farms with an enhanced scour protection and stock enhancements

	NS	**WF + SP**	**WF + ESP**	**WF + SP + SE**	**WF + ESP + SE**
Atlantic cod	2	4	5	4	5
European lobster	1	2	3	2	5
Flat oyster	0	2	3	3	5
Ross worm	1	3	4	3	4
Total	4	11	15	12	19

The costs of these enhancements are not to be paid by the developer of the wind farm but instead should be paid for by their clients (governments, power supply company, or other) and is to be incorporated in the tendering procedure (see Section 2.2).
Before implementation of these improvements it should be checked thoroughly that they are compliant with all North Sea policies (see Section 2.5).

6

Discussion, conclusions, and recommendations

6.1. Discussion

6.1.1. Research problem and major findings

The objective of this study was to determine how the design of scour protections around monopiles in the North Sea can be adapted to create suitable habitat for marine species and to quantify the effects of these changes. This was done by assessing three different habitats: 1) The North Sea in absence of wind farms and their scour protections, 2) The North Sea with wind farms and the scour protections as currently designed, and 3) The North Sea with wind farms for which the scour protections are adapted to enhance marine life. These three different habitats were assessed for four different species: the Atlantic cod, the European lobster, the flat oyster, and the Ross worm.

The North Sea in absence of wind farms and their hard substrate does not allow any of the four species to thrive. The Atlantic cod can and does occur in the North Sea but its abundance is limited due to the presence of fisheries. Additionally there is a lack of shelter for the juvenile cod which depend on this shelter to survive their early years. The European lobster can occur in the North Sea but does so in small numbers, which is attributed to the lack of shelter. The flat oyster rarely occurs in the North Sea, its largest inhibiting factors are the lack of suitable setting substrate, the presence of seabed disturbing fisheries, and the lack of a larvae-producing source population. The Ross worm occurs on few locations in the North Sea, but most parts of the North Sea are disturbed by seabed disturbing fisheries and lack hard substrate to which the Ross worm larvae can attach.

The presence of wind farms and their scour protections as currently designed improve the situation for the four species significantly by providing hard substrate and an area that is closed to fisheries. The juvenile cod benefits from the holes between the rocks in the scour protection while the adults benefit from the increased amount of food that lives and grows on the rocks. The lobster however is not likely to benefit fully from the holes in the scour protection as these are (in the case of the reference wind farm) small and because source populations are often far away or small, preventing the lobster from successfully establishing a population in the wind farm. The flat oyster benefits from the absence of seabed disturbing fisheries within the wind farm, but suitable attachment material is still limited and larvae-producing source populations are often far away, which prevents the oyster from successfully establishing a population within the wind farm. The Ross worm benefits from the absence of seabed disturbing fisheries as well and is able to use the edge of the filter layer to attach to, where it builds its tube out of the suspended sand particles.

For the third habitat, the wind farm with adapted scour protections, three types of enhancements have been studied: 1) habitat enhancements, which aim to improve the habitat for the selected indicator species and is split up in changes to the scour protection design and the placement of additional materials, 2) stock enhancements, which aim to introduce self sustaining populations of lobster and oyster, species which are not able to reach the wind farm without human intervention, and 3) food enhancements, which aim to increase the availability of food. The largest improvement with regards to habitat enhancement is to use a larger grading, as this provides larger holes while only a limited amount of additional material is required. Increasing the distance over which the armour and filter layers extent is also expected to be very beneficial, although this requires significantly more material. Placement of additional materials such as piles of rocks and concrete tubes create more shelter and hard substrate while the placement of shell-filled bags provide suitable settling material for oyster larvae. The lobster and oyster stock enhancements consist of placing 40,000 juvenile lobsters (0.005-0.007 m (stage IV and V)) over the course of several years and placing 49,000 oysters in oyster racks in the wind farm. In the long term this is estimated to result in a lobster population of 1,200-23,200 lobsters and an oyster population which could be as large as 46 million species. Food enhancement is possible by discarding bycatch within the wind farm but has been shown to be unfeasible.

6.1.2. The relevance of the findings

These findings are relevant because they show that there are multiple methods to make a wind farm more suitable for marine life, that the costs of these improvements vary, and that species which are not able to reach a wind farm without human intervention need to be actively introduced. These findings provide guidelines on how to make a scour protection for a wind farm in the North Sea (more) suitable for marine life and give an estimate (which was previously lacking) of the expected effect and cost of these improvements.

6.1.3. Relation to similar studies

The research that precedes this study mainly focused on the effect that artificial hard substrate in general has on marine life and in some more specific studies on the possibilities of using the hard substrate in a wind farm to benefit marine life. However, this previous research only gave general advice on how to improve the scour protection without getting into detail about what specific changes should be implemented, what the estimated effect of these changes would be, and what these changes would costs. This study provides insights in what specific changes can be implemented and what the estimated effect and costs of these changes would be, and thereby sets the following step in a series of research on how to use artificial hard substrate in a wind farm to benefit marine life.

6.1.4. Limitations

There are some limitations to this study:

- **Number of species**
  This study focused on four different species, and although these species were chosen to represent many other species, it is likely that a number of species is not represented by the chosen indicator species. Improving the scour protection for these four species therefore does not mean that it is improved for all species.

- **Possible negative effects**
  Possible negative effects of the improvements have not been studied. It is possible that the proposed improvements also have a negative effect (e.g. a larger filter grading might prohibit the monopile from being hammered through the filter layer, leading to the monopile needing to be installed first, leading to the development of a scour hole which in turn leads to extra filter material needed to back-fill this hole).

- **Interaction between improvements**
  Individually the improvements are expected to benefit the indicator species to a certain degree, but it is unknown how these improvements interact with each other, some solutions might be detrimental to other improvements (e.g. placing shell-filled nets on the scour protection which creates suitable settling substrate for the oyster but also cuts off the entrances of the holes in the scour protection which would otherwise benefit cod and lobster).

- **Validity of assumptions**
  The results of this study are based on available literature and, where literature was lacking, assumptions have been made. These assumptions influence the outcome of this study while the validity of the assumptions is not guaranteed.
  - Assumption: Lobsters fit in a hole which have the same diameter as their length.
    Result: Based on this assumption a 40-200kg grading is large enough for the lobster.
    Sensitivity: Holes are never shaped like a perfect cube but are always longer in one direction than the other, meaning that the hole is always longer and narrower than the calculated hole diameter. This means that lobsters will likely fit in holes with a smaller diameter than their length, which in turn means that a smaller grading might still be suitable. However, it is also unknown how much extra space lobsters require. If this required extra space is large, then a larger grading is required.
  - Assumption: Placement cost for the concrete tubes and nets and the deployment of the lobsters and oysters for the stock enhancements range between €20,000 and €26,000. The duration of the placement of the concrete tubes and shell-filled nets are assumed to take respectively 5 and 3 days. The deployment of the lobsters and the oysters are assumed to take respectively 4 times 2 days and 10 days.
    Result: The placement costs of the improvements take up a significant portion of the total cost (25-70%)
    Sensitivity: The time required to place the additional elements or to deploy the stock enhancements is complicated to calculate and depends on many factors. It is possible that the cost of the enhancements (especially those for which placement/deployment costs take up a large percentage of the total cost) are significantly higher or lower than was assumed.
  - Assumption: Biomass is food.
    Result: Locally (on the scour protection) the food abundance increases with a factor 24.
    Sensitivity: The composition of the biomass is unknown. It is possible that the biomass on the hard substrate consists for a larger part of species which serve as food for the cod and lobster compared to the sandy sea, in which case the food abundance increases with more than a factor 24. The opposite is also possible, in which case the food abundance increases with less than a factor 24.
  - Assumption: There is no interaction between the wind farm and the surrounding area.
    Result: The species within the wind farm will not leave the wind farm to venture into an area where they could be caught by fisheries. Additionally, the wind farm will not serve as an oasis which attracts species from the surrounding area and lowers the amount of marine life there.
    Sensitivity: The venturing of species (especially mobile ones such as the cod) outside the wind farm is very likely to happen and the extraction of a large part of the cod population can harm the population significantly. The increase in biomass, and thus in food abundance, will attract species from the surrounding area. This has little influence on the outcome of this study but should be kept in mind.
  - Assumption: The formula proposed by Buijs (2015) is valid and the Helgoland lobster population is representative for all lobsters.
    Result: The holes in the 10-60kg grading are too small to be used by the lobster. The 10-200kg grading is more suitable and the 40-200kg even more so.
    Sensitivity: The number of data points used by Buijs was relatively small and the porosity was taken as a known value. This makes it likely that the actual pore size distribution is different from what is calculated. Only two lobster populations have been used and these two populations are very different in size distribution. The Helgoland population (consisting of larger lobsters) was used in this study as representative for the lobsters in the reference wind farm. If the UK east coast population (consisting of smaller lobsters) was used then the conclusion would have

been that the 10-60k grading would be large enough. This shows that the results are very sensitive to errors on the lobster size estimates.

- Changed flow patterns do not influence marine life negatively (except for oysters).
  Result: The area within 0.5*D_{pile} is not suitable for oyster spat settlement due to the increased flow velocity and strong turbulence. Other species are not influenced by this.
  Sensitivity: The high flow velocity and strong turbulence have an influence on the other species as well (e.g. through sandblasting or by displacing rocks) but it is uncertain to what extent. Mobile species such as the cod and lobster will be influenced to a lesser extent than immobile species such as the oyster and Ross worm, for these immobile species the changed flow patterns might be much more detrimental than was assumed in this study.

- **Source of information**
  The expected effects of the improvements have been quantified by using data which often was not generated for this study specifically. The quantified effects of the solutions are therefore rather crude.

6.2. Conclusions

The conclusions are presented as answers to the research questions. The main research question is answered first after which the research sub-questions, listed in section 1.4, are answered to provide backing of the answer to the main question. These answers (partially) fill the knowledge gap that was established in 1.2.

6.2.1. Main research question

Question: *To what extent can marine life in the North Sea be enhanced through improvements to the scour protection design for monopiles in wind farms?*

To increase the positive effect that a scour protection has on marine life (hard substrate gets covered by marine life in far larger numbers than a sandy sea bed (see Chapter 4)), several improvements to the scour protection design can be implemented (see section 5.2.1). The most effective improvement is to increase the area covered with hard substrate by increasing the length to which the scour protection extends from the monopile. To further improve the scour protection, a large grading can be used to create large holes in the scour protection which benefit species which require shelter such as the Atlantic cod and the European lobster. This improvement can be further optimized by using a skewed grading (e.g. larger D_{50}), leading to larger hole sizes.
Apart from changes to the scour protection itself, the suitability of a wind farm can be improved by the placement of additional elements (see section 5.2.2). The placement of rock piles for example increases not only the amount of hard substrate with its benefits, but also creates turbulent and calm areas which are beneficial to several species such as the flat oyster and the Ross worm. Placing concrete tubes of various sizes and nets filled with clean shells can provide respectively shelter areas for larger animals and suitable settling substrate for bivalves such as the flat oyster.
For certain species, such as the European lobster and the flat oyster, the improvement of the scour protection design with regards to habitat suitability is not enough to realise a population. This is mainly due to the absence of a large enough source population and can be resolved by stock enhancements (see section 5.3), which aim to increase the populations of these species to a size which is self sustainable and will, in the long term, spread further over the wind farm to make full use of its capacity.
The overall conclusion is that the scour protection for monopiles in the North Sea as currently designed already benefits several forms of marine life but that this positive effect can further be increased by changing the scour protection design, by placing additional elements, and by introducing source populations for immobile species. Implementing these changes is estimated to increase the number of cod, lobster, oyster, and area covered by Ross worm greatly (respectively from 1,500-93,000 to 3,000-240,000 (>100% increase), <1,000 to 2,000-36,000 (>100% increase), <1,000 to >20,000 (>2,000% increase), and 15,000 m^2 to 20,000 m^2 (33% increase)) at an extra cost of less than 5 million euro. This could create a diverse and rich oasis in the North Sea from where these species can spread over the rest of the North Sea. This expansion could be accelerated by implementing the improvements to multiple wind farms in the North Sea. However, for this to happen it is necessary that (seabed disturbing) fisheries around the wind farm are strictly regulated to prevent both excessive extraction of the species and destruction of vulnerable habitats.

6.2.2. Research sub-question 1

Question: *On what species in the North Sea should this study focus and what are the requirements of these species?*

Species selection

Four species from the four largest present phyla have been selected to be used as indicator species. These species were selected because they are all native to the North Sea, all threatened, vulnerable, or of high commercial value, and because they all interact with the seabed in a different way. These four indicator species are:

- The Atlantic cod (*Gadus morhua*) from the phylum of chordates. A fish native to the North Sea which is listed by the IUCN as vulnerable and interacts with the seabed by finding shelter as juveniles and by foraging as adults;
- The European lobster (*Homarus gammarus*) from the phylum of arthropods. A commercially valuable species native to the North Sea which uses the seabed to find shelter against currents and predators;
- The European flat oyster (*Ostrea edulis*) from the phylum of molluscs. A bivalve native to the North Sea and listed by OSPAR as threatened. The flat oyster attaches to suitable substrate on the seabed;
- The Ross worm (*Sabellaria spinulosa*) from the phylum of ring worms. A worm native to the North Sea and listed as threatened by OSPAR. The Ross worm lives in a tube which it builds from sand and shell fragments.

Species analysis

Both promotional factors (factors which promote the occurrence of a species in a habitat) and inhibiting factors (factors which inhibit species from occurring in a habitat) have been studied. Promotional factors that have been studied are food abundance, suitable substrate, and currents. Inhibiting factors that have been studied are fishing, predators, water depth, competition, minimum population, currents, mobility, and soil composition (in the case of the flat oyster diseases have been included in the inhibiting factors).

6.2.3. Research sub-question 2

Question: *Is the North Sea in absence of wind farms suitable for these species?*

Suitability of the North Sea in absence of wind farms

A large part of the North Sea has a limited suitability due to the lack of suitable substrate in the form of rock, which provides shelter for lobsters and juvenile cod and attachment material for the Ross worm, and in the form of shells as settling substrate for oyster spat. Additionally the presence of (seabed disturbing) fisheries further reduces the suitability. When fishing is strictly regulated, the Atlantic cod has a good chance of recovery. The European lobster and the flat oyster however are unlikely to spread over the North Sea (within short time) without human intervention due to their limited mobility and the lack of suitable substrate. The Ross worm could recover and spread over the North Sea if seabed disturbing fisheries are strictly regulated, but is unlikely to do so due to the lack of hard substrate to which it can attach.

6.2.4. Research sub-question 3

Question: *What are the requirements for a standard scour protection and are these standard scour protections suitable/sufficient for the chosen species?*

Scour protection analysis

Hydrodynamic forces caused by waves and currents are amplified due to the presence of a monopile, causing local strong turbulence that is capable of inducing scour at the base. This could lead to a scour hole which threatens the stability of the monopile. To prevent the development of such a scour hole, a scour protection is required, which is usually constructed from several layers of different sizes of rock. This scour protection needs to be stable (a limited number of rocks or rock layers is allowed to displace) and extend far enough to keep the scour hole away from the monopile.
Research has shown that scour protections in offshore wind farms have a positive effect on biodiversity and species abundance. The rocks get covered in marine life and the holes and crevices in the scour protection provide shelter against currents and predators.
For further quantification a reference wind farm, Gemini, was used. This is a wind farm with 150 wind turbines of 4 MW each, covering an area of $67.6 * 10^6$ m^2. The scour protection for the monopiles (7.1 m diameter) consists of two layers: a filter layer composed of 1-3" rock placed around the monopile as a circle with a diameter of 4.25*D_{pile} (30 m) and an armour layer composed of 3-9"HD rock with a diameter of 3*D_{pile} (21 m), both with slopes of 1:2. The total area covered by the scour protection is 773 m^2 per monopile and $116 * 10^3$ m^2 in total.

Suitability of scour protections as currently designed

The main reasons why scour protection in wind farms in the North Sea are beneficial for the selected indicator species, are the presence of hard substrate and the absence of (bottom-disturbing) fisheries.
Due to the absence of fisheries the fishing mortality drops, which means that more individuals survive for a longer time, allowing them to reproduce. Another benefit of the absence of fisheries is that the reef building species such as the flat oyster and Ross worm can build their reefs undisturbed without having their habitat destroyed.
The presence of hard substrate increases the food abundance and creates shelter for lobsters and cod against currents and predators. The Ross worm benefits from the increased turbidity which suspends the sand particles and shell fragments that it requires to build its tube, and from the hard substrate to which it can attach before building its tube.
In the reference wind farm however, the size of the holes in the scour protection are small and therefore not usable by adult lobsters, the filter layer is only dynamically stable during storm conditions which makes it less suitable attachment material for the Ross worm, and the European lobster and flat oyster have no large source population nearby and are not mobile enough to reach the wind farm in large numbers without human intervention.
It is estimated that only a few European lobsters and a small number of individual flat oysters will inhabit the wind farm and that the population of Atlantic cod will increase from ±360 to 1,900-93,000 while the Ross worm might settle within the wind farm and create ±15,000 m^2 of Ross worm reefs.

6.2.5. Research sub-question 4

Question: *What changes are needed to improve the habitat for the chosen species, what are the expected effects on nature, and what will be the costs of these changes?*

Potential improvements to the species' habitat

Several methods to improve the species' habitat are proposed:

- Increasing the armour size;
- Using a skewed grading;
- Increasing the armour layer horizontal extent;
- Increasing the filter layer horizontal extent;
- Placement of 450 1 m high piles of rock;
- Placement of 900 1 m large rocks;
- Placement of 450 (concrete) tubes;
- Placement of 450 shell-filled nets.

Expected effect

The expected effects are quantified based on the reference wind farm Gemini.

- Increasing the armour size: The currently used 3-9"HD armour layer does not provide holes that are large enough for adult lobsters. A 10-200 kg grading would provide holes for 68% of the population while a 40-200 kg grading would provide holes for 87% of the population.
- Using a skewed grading: Using a skewed grading (e.g. increase D_{50} by 7%) increases the H_{95} (with about 7%) and therefore provides some benefits.
- Increasing the armour layer horizontal extent: The positive effects (e.g. food availability and shelter) increase with 70% when increasing the diameter of the armour layer from $3*D_{pile}$ to $4*D_{pile}$.
- Increasing the filter layer horizontal extent: The positive effects of the filter layer (e.g. food availability and attachment material) increase with 130% (while the total area is increased with 52%) when increasing the diameter of the filter layer from $4.25*D_{pile}$ to $5.25*D_{pile}$ assuming that the armour layer is not increased. The beneficial length of the edge for the Ross worm would in this case increase with 22%.
- Placement of 450 1 m high piles of rock: When placing these piles on the scour protection the total amount of added hard substrate surface is 666 m^2, which is a 0.6% increase in hard substrate surface compared to the situation without these piles. Placing the piles on the sand bed would increase the hard substrate surface with 6,300 m^2, or 5.4%. However, in this case a filter layer beneath the pile would be required to avoid winnowing.
- Placement of 900 1 m large rocks: 5,200 m^2 of hard substrate surface is added when the rocks are placed on the scour protection, which is a 4.5% increase in hard substrate surface. However, this hard substrate does not provide holes and crevices for shelter. Placing these rocks on the sand bed would increase the hard substrate surface with 6,500 m^2 or 5.6% but requires a filter layer to avoid it from sinking deep into the sea bed. Rocks of this size are difficult to obtain, therefore concrete blocks are often used instead, making this an expensive solution. Additionally the production of concrete is detrimental to the environment. This option is therefore deemed to be unfeasible.

- Placement of 450 (concrete) tubes: Habitat for large cod and lobsters which allows the larger cod and lobsters to reproduce (larger cod and lobster produce more eggs). Without this shelter the lobsters would be washed away during storms.
- Placement of 450 shell-filled nets: 2,800 m^2 of suitable settling substrate is created for a total of 20,000 oysters.

Expected costs
The expected costs of the proposed habitat enhancements are listed in Table 6.1.

Table 6.1: The estimated costs of the improvements to the species' habitat.
*Unless the amount of rock needed is increased due to increased layer thickness.
**Only the total costs are known, the distribution between material cost and other costs are unknown.
***Financially unfeasible

Improvement	Total cost	Material cost	Other costs
Increasing the armour size	0*	0*	0*
Using a skewed grading	0*	0*	0*
Increasing the armour layer horizontal extent	€1,620,000	Unknown**	Unknown**
Increasing the filter layer horizontal extent	€1,044,000	Unknown**	Unknown**
Placement of 450 1 m high piles of rock	€68,400	Unknown**	Unknown**
Placement of 900 1 m large rocks	n.a.***	n.a.***	n.a.***
Placement of 450 (concrete) tubes	€184,000	€84,000	€100,000
Placement of 450 shell-filled nets	€152,500	€92,500	€60,000

6.2.6. Research sub-question 5

Question: *What additional actions are needed to achieve enhancement to marine life when changes to the habitat are not sufficient?*

Additional actions
Apart from the habitat improvements listed under the previous research sub-question, stock enhancements and food enhancements are two more ways to achieve enhancement to marine life. A stock enhancement is required for species which are limited in their mobility and therefore not able to spread over the North Sea and reach wind farms without human intervention. The Atlantic cod is a very mobile species and the Ross worm produces larvae which are pelagic for multiple weeks in which they are transported by currents and able to reach large parts of the North Sea. However, the European lobster and flat oyster are much more limited in their mobility and therefore need to be actively introduced in a wind farm.

- Lobster stock enhancement: Releasing 40,000 hatchery reared lobsters of 0.005-0.007 m (stage IV and V) over the course of four years is estimated to lead to a self sustaining population of about 10,000 lobsters in the short term, and a population between 1,200 and 23,200 lobsters in the long term (assuming that the scour protection provides enough shelter). The costs of this enhancement is estimated to be €287,500 (€12-€240 per lobster).
- Flat oyster stock enhancement: Releasing 49,000 oysters of different ages (and thus sexes) in broodstock cages and placing clean empty shells as settling material is estimated to lead to a self sustaining oyster population of about 29,000 oysters in the short term and, when successful, a population of $8.3*10^6$ - $46.4*10^6$ oysters in the long term. The costs of this enhancement is estimated to be €955,000 (€0.02-€0.12 per oyster).

Increasing the amount of available food in a wind farm is only possible for the Atlantic cod and the European lobster (the flat oyster and Ross worm feed on microalgae and phytoplankton which can not be increased). Discarding bycatch by fishermen has been researched as a method of food enhancement, but was found to be impractical and too expensive if any significant effect is to be achieved.

6.3. Recommendations

This study focuses on possibilities to increase the positive effect that a scour protection has on marine life.

6.3.1. Recommendations for future research

Several aspects are still unknown or uncertain (as was mentioned in the section 6.1) and are recommended to be studied in the future.

- Research into more than the four selected indicator species.
- Research into the effect of the proposed solutions on other species.
- Research into the interaction of the proposed solutions.
- A more in depth research into the costs of the solutions.
- Research into the monetary value of the expected effect of each solution. This is composed of putting a monetary value on marine life and by researching how this can be extracted from the wind farm (e.g. through lobster fisheries or oyster farms).
- Verification of the validity of each solution before implementing it in a new wind farm and monitoring the effects when a solution is implemented, this can be done with a pilot or by implementing the solution in full.
- Compliance with policies and regulations regarding the North Sea and North Sea species should be further studied (e.g. what to do with additional placed elements after the design life time).
- Research into methods to implement requirements regarding nature-enhancement in the tenders.
- Research into the effect of the turbidity on marine life, as there is currently little information available about this subject.

6.3.2. Recommendations for implementation

As written above, the research into possibilities to improve the scour protection of a wind farm in the North Sea for marine life is not complete and requires further research before being implemented in each and every wind farm. It is recommended to implement some of the proposed solutions on a smaller scale to verify their validity. This could for example be done by implementing several of the solutions on half of the scour protections in a future wind farm and monitoring the marine life on both the enhanced scour protections and the 'normal' scour protection after which a comparison can be made to quantify the effect of the improvements.

6.3.3. Recommendations for nature inclusive design in general

This study focused on the possibilities of using the scour protection in an offshore wind farm in the North Sea for nature-enhancement and specifically on four species and the wind farm Gemini. Due to the increasing number of humans inhibiting the earth and interacting with nature, and the diminishing biodiversity and bio-abundance there will be an increased need to incorporate nature-enhancing solutions in man-made constructions. The approach used in this study is not only applicable in the case of scour protections for wind farms in the North Sea, but can be generalized to be used for other projects as well (e.g. a dam for hydroelectricity, a bridge over a canyon, a harbour near a nature reserve). This general approach has been visualized in Figure 6.1 and is recommended to be used when aiming to incorporate nature-enhancing solutions in man-made constructions.

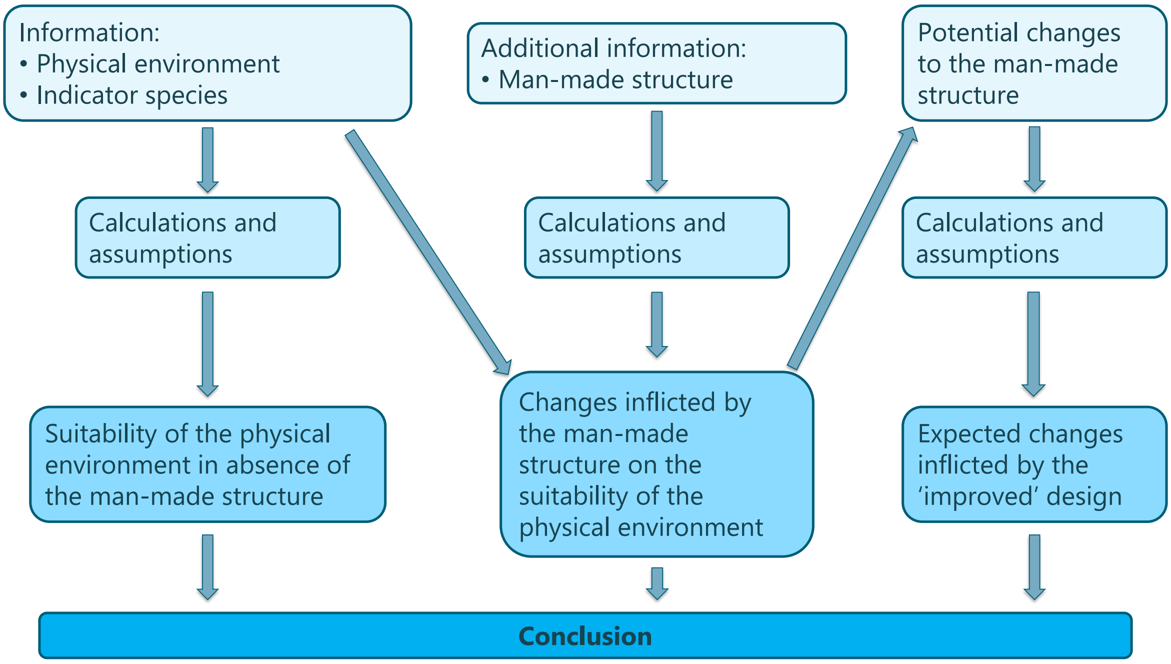


Figure 6.1: The general approach to design nature inclusive for different projects in different environments

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A

Glossary

Arthropod	An invertebrate animal having an exoskeleton, a segmented body, and paired jointed appendages (Dutch: Geleedpotige)
Benthic	Term referring to anything associated with or occurring on the bottom of body of water
Benthopelagic (species)	Living and feeding near the bottom as well as in the rest of the water column
Biodiversity	The variety of plant and animal life in a particular habitat
Chordate	An animal that is distinguished by the possession of a notochord at some stage during its development (Dutch: Chordadier)
Dorsal (fins)	Located at/on the back(side)
Epibenthic	Refers to organisms living on or just above the sea floor
Eutrophication	Excessive richness of nutrients in a body of water
Indicator species	A species which serves as a measure of the environmental suitability in a certain habitat
Invertebrate	An animal without a backbone or bony skeleton (Dutch: Ongewervelde)
LAT	Lowest astronomical tide
Mollusc	A soft-bodied invertebrate, usually wholly or partly enclosed in a calcium carbonate shell (Dutch: Weekdier)
Pectoral (fins)	Located at/on the chest
Pelagic	In the open sea, neither near the sea bed nor near the coast
Phylum	A principal taxonomic category that ranks above class and below kingdom, equivalent to the division in botany
Phythoplankton	Microscopic marine algae
ROV	Remote operated vehicle
Species abundance	Number of individuals per species
Species richness	Number of different species
Sublittoral	The environment beyond the low-tide mark which reaches depths of between 150 and 300 metres
Tender	The process whereby governments and institutions invite bids for large projects
Umbrella species	Species for which the protection of these species indirectly protects many other species in the same habitat
Winnowing	Fine material escaping through the spaces between coarser material due to flowing water

B Background information

Flow around a monopile
Figure B.1 shows the flow around a mono-pile and is explained below. The flow approaching the mono-pile sets up a pressure gradient on the upstream face of the pile between the low pressure near the sea bed flow and the high pressure in the flow above. This pressure gradient creates a downward flow along the front of the pile (Hoffmans and Verheij, 1997). The downward flow will hit the scour protection and is forced away from the pile, this creates a recirculating eddy, called the horseshoe vortex, which due to the approaching flow, is wrapped around the sides of the pile where it causes the flow velocity to accelerate. This flow is at its maximum at about $0.2 * D$ from the face of the mono-pile but can still have an influence at $4 * D$ for oscillatory flow.

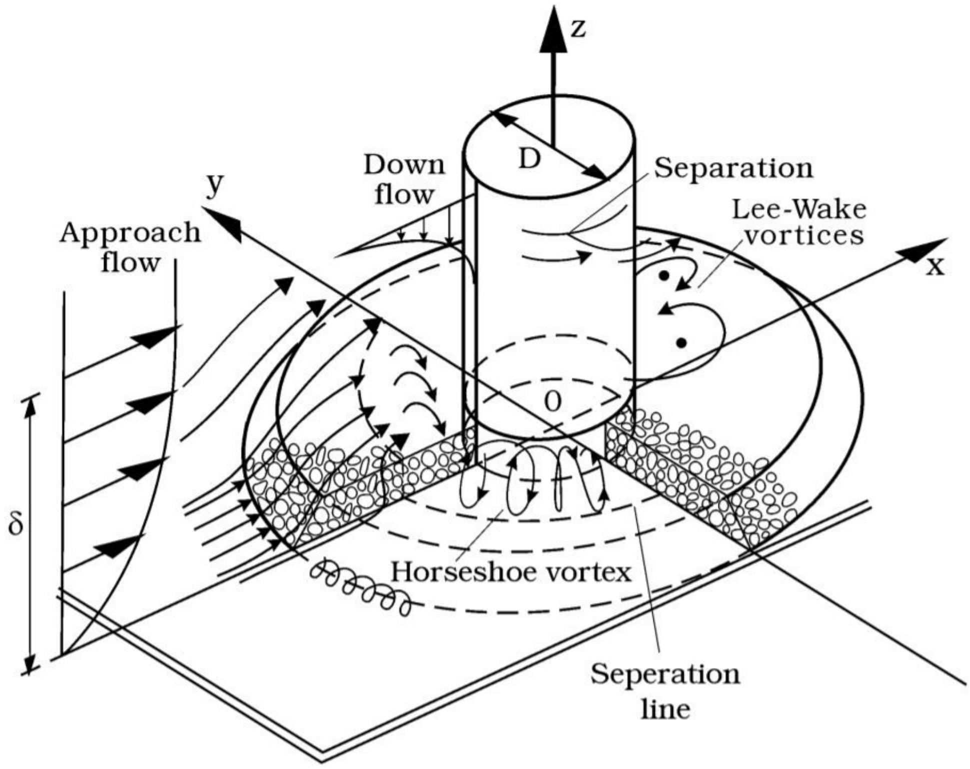


Figure B.1: Sketch of the flow around a monopile (Nielsen 2010)

The horseshoe vortex however only occurs in a steady current or due to waves that are large enough compared to the diameter D of the pile. The Keulegan-Carpenter (KC) number, which is a function of the pile diameter D, the amplitude of the bottom orbital velocity U_w and the wave period T_w, must be larger than 6 for the horseshoe vortex to be able to develop and is defined as:

$$KC = \frac{U_w T_w}{D} = \frac{H\pi}{D\sinh(kh)} \quad [-] \quad \text{(B.1)}$$

In which:

U_w	orbital velocity near the bottom	$[m/s]$
T_w	wave period	$[s]$
D	pile diameter	$[m]$
H	wave height	$[m]$
$k = 2\pi/L$	wave number	$[m^{-1}]$
L	wave length	$[m]$
h	water depth	$[m]$

When the KC number is smaller than 6, the waves are unable to create a horseshoe vortex because either the flow velocity near the bottom is too small (due to a large water depth for example), the wave period is too short, the pile diameter is too large, or a combination of these. When the KC number is too small the horseshoe vortex will only exist due to the steady state current.
At the lee-side of the pile vortex shedding occurs as result of the interaction between shear layers which detach from the sides of the pile when the KC number is larger than 6. The distance over which the vortex street extends $[L_v]$ is a factor of the diameter of the pile and increases linearly with the KC-number (Sumer et al., 1992):

$$L_v = 0.3\,KC * D \quad [m] \quad \text{(B.2)}$$

The disruption in the flow pattern leads to an increase in shear stress which is quantified by an amplification factor α (Sumer et al., 1992). The amplification factor α is defined as follows (De Vos et al., 2012):

$$\alpha = \frac{\tau_b}{\tau_{b,\infty}} \quad [-] \quad \text{(B.3)}$$

In which τ_b and $\tau_{b,\infty}$ are respectively the actual and the undisturbed bed shear stress.
Much research has been carried out regarding the amplification factor in case of a pile in a steady current. This is an idealized case which is not always valid in the open North Sea where waves are present as well.
Soulsby (1997) suggested a value of $\alpha = 2.2$ in the case of waves while Halfschepel (2003) reports a value of $\alpha = 2.25$ for waves with a KC number smaller than 6 and a value of $\alpha = 4$ in case of a steady current. Sumer et al. (1992, 2015) found values as high as $\alpha = 11$ for a steady current and $\alpha = 4$ near the pile for waves with a KC number up to $KC = 100$, the value of $\alpha = 11$ was also used by (Baykal et al., 2015). De Vos et al. (2012) uses an amplification factor of 2 on the velocity of a steady flow, which translates to an amplification factor of 4 for the shear stress.
In the reference wind farm the diameter D of the pile is 7.1 m while the bed level varies between -36.72 m LAT and -28.51 m LAT. Table B.1 shows that even for the conservative situation in which the bed level is taken as -28.51 m LAT, no horseshoe vortex will occur since $KC < 6$ (the KC value has been calculated for the significant wave height. In case of the maximum wave heights ($H_{max} = 13.8$ and $H_{max} = 15.4$ for respectively the $1/1$ year and $1/5$ year storm conditions) the KC number is larger than 6 (respectively 6.3 and 7.7)). This is understood better when considering the horizontal wave amplitude at the sea bed a_{max}, which is smaller than the pile diameter $D = 7.1m$ for all waves, making it impossible for the horseshoe vortex to develop. Sumer et al. (1992) found the scour depth to be almost nonexistent for KC numbers below 6 since both vortex shedding and the horseshoe vortex did not occur. However, a small shear-stress amplification ($\alpha < 2$) was found for small KC numbers, which agrees with Halfschepel (2003). Therefore a value of $\alpha = 2$ is assumed for $KC < 6$ and a value of $\alpha = 4$ is assumed for $KC > 6$.

Table B.1: KC numbers in the shallow part (-28.51 m LAT) of Gemini

$H_s[m]$	$T_p[s]$	$L[m]$	Water depth	$U_{max}[m/s]$	$a_{max}[m]$	KC
1	4.25	28	Deep	0	0	0.0
2	6.01	56	Deep	0.04	0.04	0.0
3	7.36	82	Transitional	0.3	0.35	0.3
4	8.50	105	Transitional	0.56	0.76	0.7
5	9.50	126	Transitional	0.84	1.27	1.1
6	10.41	143	Transitional	1.13	1.88	1.7
7	11.24	160	Transitional	1.42	2.55	2.3
8	12.02	174	Transitional	1.72	3.28	2.91
9	12.75	188	Transitional	2.01	4.08	3.61
10	13.44	201	Transitional	2.30	4.39	4.36

Louwersheimer (2007) assumed separate bed shear stress amplification factors for waves and currents in which he assumed the maximum bed shear stress amplification factor for waves K_w and the maximum bed shear stress for currents K_c to be respectively 4 and 11 as was found by Sumer et al. (2015) and formulated them as follows:

$$K_w = \left[1 + \left(\frac{0.5Dpile}{0.5D_{pile} + x}\right)^2\right]^2 \quad [-] \quad \text{(B.4)}$$

and

$$K_c = min\left\{11; 3.5\sqrt{D/x}\right\} \quad [-] \quad \text{(B.5)}$$

However, when $KC < 6$ the horseshoe vortex is not able to develop and the K_w value is overestimated. More realistic in this situation would be to use the α value proposed by (Halfschepel, 2003) and to changes the K_w formula to:

$$K_w = 1 + \left(\frac{Dpile}{D_{pile} + 0.5x}\right)^4 \quad [-] \quad \text{(B.6)}$$

which starts at $K_w = 2$ at the pile interface and diminishes relatively quickly to $K_w = 1$ further away from the pile ($K_w = 1.2$ at $x = D$).
The amplification factor for the current that Louwersheimer (2007) used starts at $K_c = 11$ and reaches a value of $K_c = 1$ at a distance of $12.25D$ from the pile and continues to decrease after reaching this point which is not the case in reality. Additionally both Halfschepel (2003) and De Vos et al. (2012) used an ampification factor of $\alpha = 4$ in the case of currents only. It therefore is assumed that the value of K_c is given by:

$$K_c = \left[1 + \left(\frac{4Dpile}{4D_{pile} + x}\right)^2\right]^2 \quad [-] \quad \text{(B.7)}$$

These formulas are then to be introduced into equations 2.7 and 2.8 to change them into:

$$\tau_m = K_c\tau_c\left[1 + 1.2\left(\frac{K_w\tau_w}{K_c\tau_c + K_w\tau_w}\right)^{3.2}\right] \quad [N/m^2] \quad \text{(B.8)}$$

and

$$\tau_{max} = \left[(\tau_m + K_w\tau_w\cos(\phi))^2 + (K_w\tau_w\sin(\phi))^2\right]^{1/2} \quad [N/m^2] \quad \text{(B.9)}$$

which results in an amplification factor as shown in figure B.2 (assuming τ_c and τ_w to be equal). This also agrees better with Raaijmakers (2009), who concluded that the dynamic zone, characterized by a lowering of the scour protection close to the pile, extended from the edge of the pile to $0.5D$ from the pile, which is also in agreement with the tests done for the reference wind farm (unpublished data).

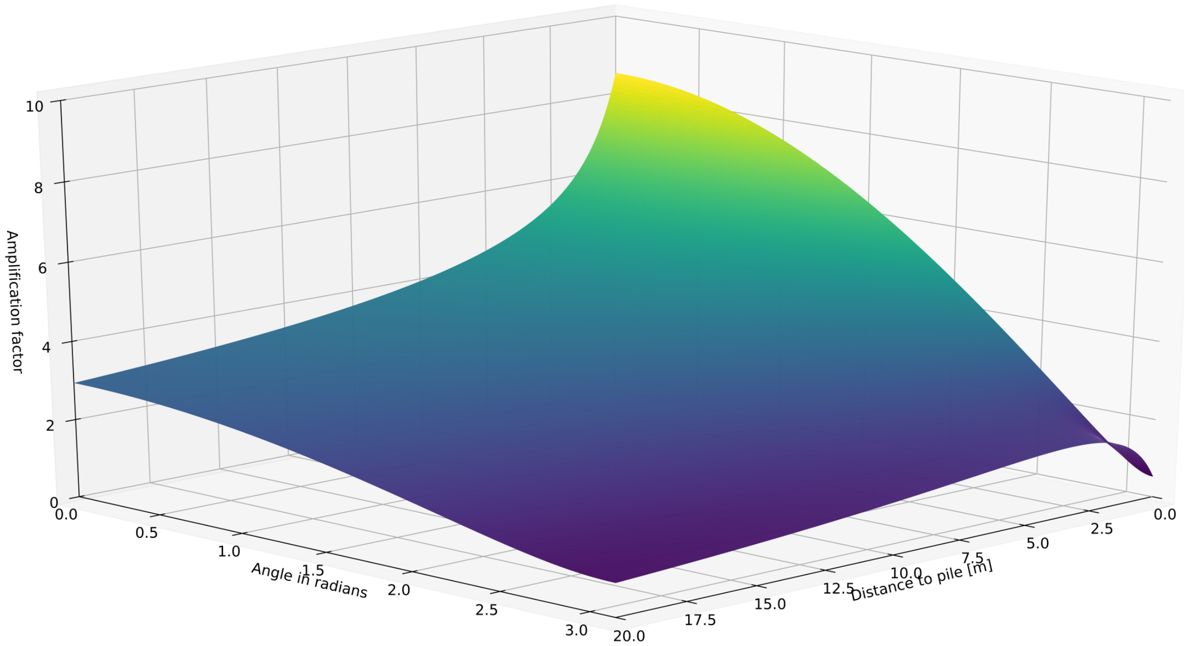


Figure B.2: Shear stress amplification factor under combined wave and current action for varying angles

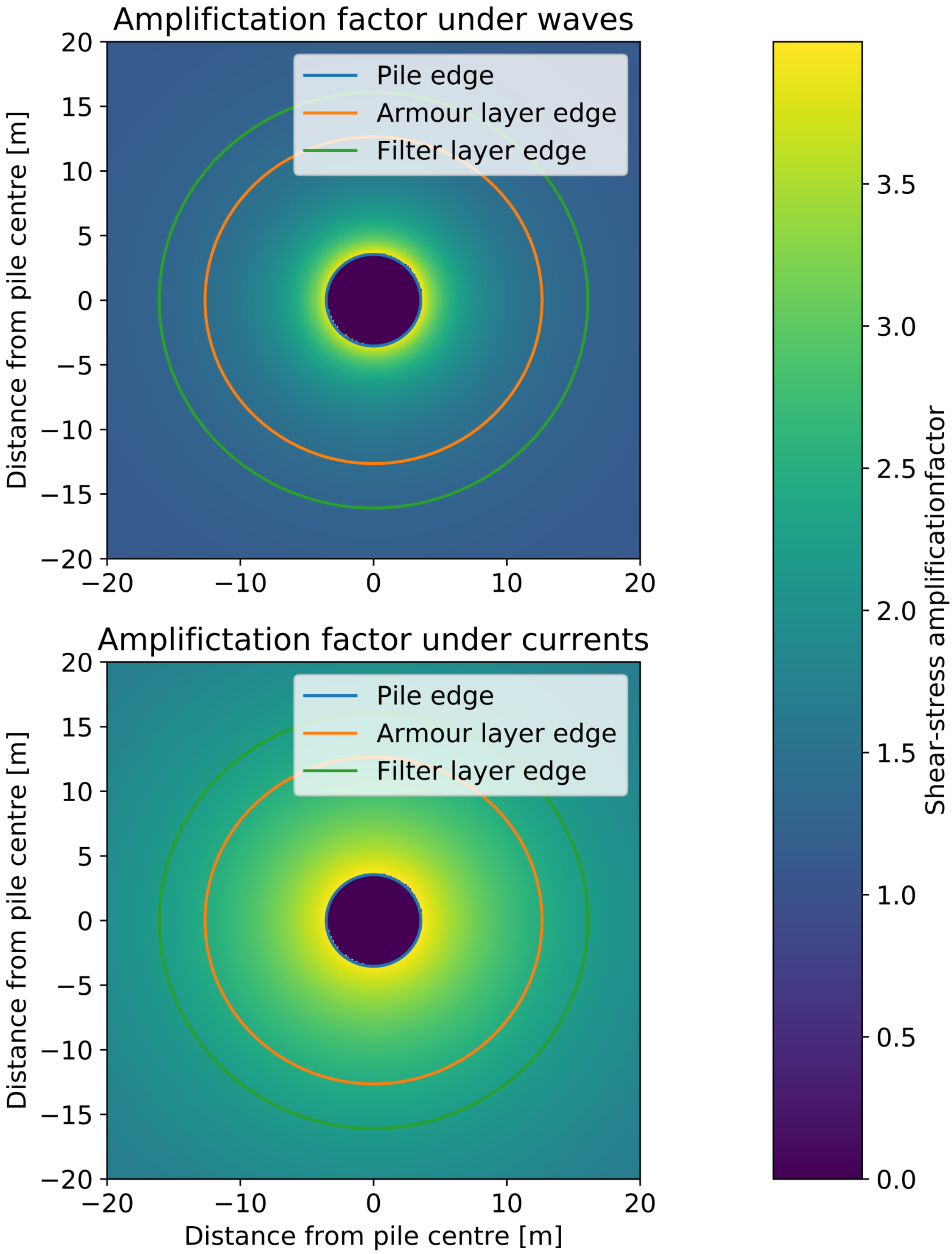


Figure B.3: Shear stress amplification factor for waves and current

C Tables

Table C.1: Reviewed documents

Name document	Year	Writer	Institution	Target area	Target species
Review of the reef effects of offshore wind farm structures and their potential for enhancement and mitigation.	2007	Linley et al.	PML Applications Ltd and the Scottish Association for Marine Science to the Department for Business, Enterprise and Regulatory Reform (BERR)	Windfarms in the UK	All
Local effects of blue mussels around turbine foundations in an ecosystem model of Nysted off-shore wind farm, Denmark	2008	Maar et al.	Journal of Sea Research	Windfarms in Denmark	Blue mussel
Early development of the subtidal marine biofouling on a concrete offshore windmill foundation on the Thornton Bank (southern North Sea): first monitoring results	2010	Kerckhof et al	International Journal of the Society for Underwater Technology	Windfarm Thornton Bank (Belgium)	General biofauling
Impact of OWEZ Wind farm on bivalve recruitment	2010	Bergman et al	Wageningen Imares	Wind farm OWEZ (the Netherlands)	Bivalves
Greening Blue Energy: Identifying and managing the biodiversity risks and opportunities of offshore renewable energy	2010	Wilhelmsson et al.	IUCN, Gland, Switzerland	Wind farms in general	All
Wrecks as artificial lobster habitats in the German Bight	2011	Krone et al.	Helgoland Marine Research	German Bight	Lobsters
Effect of the Horns Rev 1 Offshore Wind Farm on Fish Communities - Follow up Seven Years after Constructionn	2011	Leonhard et al.	DTU National Institute of Aquatic Resources	Horns Rev 1 (Denmark)	Fish

Name document	Year	Writer	Institution	Target area	Target species
Short-term ecological effects of an offshore wind farm in the Dutch coastal zone; a compilation	2011	Lindeboom et al.	IMARES, NoordzeeWind, Royal NIOZ, Bureau Waardenburg	Wind farm OWEZ (the Netherlands)	All
Benthic communities on hard substrates of the ofshore wind farm Egmond aan Zee	2011	Bouma et al.	Bureau Waardenburg	Wind farm OWEZ (the Netherlands)	Benthic species
Impact of OWEZ wind farm on the local macrobenthos community	2012	Bergman et al.	Wageningen Imares	Wind farm OWEZ (the Netherlands)	Macrobenthos
OSPAR threatened and/or declining species and habitats in the Netherlands	2012	Bos et al.	IMARES - Institute for Marine Resources & Ecosystem Studies	Dutch part of the North Sea	All
Offshore wind farms as productive sites for fishes?	2013	Van den driessche et al.	n/a	Windfarms in Belgium	Fish: Atlantic cod and pouting
Biodiversiteit kunstmatig hard substraat in de Noordzee (NCP)	2013	Jager Z.	Ziltwater	Dutch part of the North Sea	Hard substrate related species
Epifauna dynamics at an offshore foundation - Implications of future wind power farming in the North Sea	2013	Krone et al.	Marine Environmental Research	Offshore wind farms	Epifauna
Natuurwaarden Borkumse Stenen - Project Aanvullende beschermde gebieden	2014	Bos et al.	IMARES Wageningen UR	Borkumse stenen (the Netherlands)	Hard substrate related species
Feasibility of Flat Oyster (Osrea edulis) restoration in the Dutch part of the North Sea	2015	Smaal et al.	IMARES Wageningen UR	Dutch part of the North Sea	Flat oyster
Ecology-based bed protection of offshore wind turbines	2015	Buijs K.W.	TU Delft	Wind farms in general	European lobster, European cod, biodiversity in general
Succession and seasonal dynamics of the epifauna community on offshore wind farm foundations and their role as stepping stones for non-indigenous species	2015	De Mesel et al.	Royal Belgian Institute of Natural Sciences	Wind farms in the Belgian North Sea	Epifauna
Eco-friendly design of scour protection: potential enhancement of ecological functioning in offshore wind farms	2017	Lengkeek et al.	Deltares; Wageningen Univeristy & Research; Bureau Waardenburg	Dutch wind farms	Flat oyster and Atlantic cod
Flat oysters on offshore wind farms	2017	Smaal et al.	Wageningen University & Research	Dutch Wind farms	Flat oyster
Macrobenthos in offshore wind farms	2017	Jak R.; Glorius S.	Wageningen University & Research	Dutch, Belgian, Danish, UK, German wind farms	Benthic species

Name document	Year	Writer	Institution	Target area	Target species
Rich reefs in the North Sea	2017	van Duren et al.	Deltares	Dutch part of the North Sea	Hard substrate related species
North Sea Reefs - Benthic biodiversity of artificial and rocky reefs in the southern North Sea	2017	Coolen J.W.P.	Research School of the Socio-Economic and Natural Sciences of the environment	North Sea	Hard substrate related species
Mobile demersal megafauna at common offshore wind turbine foundations in the German Bight (North Sea) two years after deployment - increased production rate of Cancer pagurus	2017	Krone et al.	Marine Environmental Research	Wind turbines in the German Bight	Mobile demersal megafauna
Benthic biodiversity on old platforms, young wind farms, and rocky reefs	2018	Coolen et al.	ICES Journal of Marine Science	Dutch part of the North Sea	Hard substrate related species
European flat oysters on offshore wind farms: additional locations	2018	Kamermans et al.	Wageningen University & Research	Dutch wind farms	Flat oyster
Offshore Wind Farms as Potential Locations for Flat Oyster (Ostrea edulis) Restoration in the Dutch North Sea	2018	Kamermans et al.	MDPI; Sustainability	Dutch wind farms	Flat oyster
RECON: Reef effect structures in the North Sea, islands or connections?	2018	Coolen J.W.P.; Jak R.G.	Wageningen Marine Research	North Sea	Mythilus edulis; Jassa herdmani
Desktop study on autecology and productivity of European lobster in offshore wind farms	2019	Rozemeijer, M.J.C.; van de Wolfshaar K.E.	Wageningen Univeristy & Research	Offshore wind farms	Lobster

Table C.2: Related research

Name of the document	Writer	Target area	Conclusion
Review of the reef effects of offshore wind farm structures and their potential for enhancement and mitigation.	Linley et al. (2007)	All species in wind farms in the UK.	Wind farms have a positive effect on the edible crab, the European lobster and kelp. And in lesser extent on the blue mussel, pacific oyster and on finfish.
Colonisation of fish and crabs of wave energy foundations and the effects of manufactured holes. A field experiment.	Langhamer and Wilhelmsson (2009)	All species in the Lysekil Project, a wave energy on the Swedish west coast	Low densities of mobile organisms, significantly higher abundance of fish and crabs. Fish numbers not influenced by increased habitat complexity. Positive effect on the edible crab quantities. Negative effect on the prey of the edible crab.
Studies on the developmental conditions of the European lobster at the rocky island of Helgoland.	Schmalenbach (2009)	Lobsters on a rocky substrate in the German Bight.	Population size was estimated to be 25,000 lobsters, which is about 2% of its former size (1.5 million lobsters; about 5 lobsters per 100 m^2) in the 1930s. Population size seems to have decreased below a critical level where reproduction does not suffice to allow for a recovery of the population on its own. Release areas showed higher abundance of lobsters (1.4 per 100 m^2) than control areas (0.5 lobsters per 100 m^2), meaning that cultured lobsters show strong fidelity to their release site. Larvae developed successfully at temeratures above 14 °C. Newly hatched larva swam directly towards any light source. Lobsters should be reared in single compartments to increase survival rate. Carcasses of edible crbs are a suitable and valuable diet for lobsters. Juvenile lobsters can be reared withing 3 months to reach a total length of 3 cm (minimum release size) at a survival rate of 90%.
Early development of the subtidal marine biofouling on a concrete offshore windmill foundation on the Thornton Bank (southern North Sea): first monitoring results.	Kerckhof et al. (2010)	General biofauling on the concrete foundation of the Thornton Bank wind farm (Belgium)	Larger biodiversity than surrounding sand bed. Smaller biodiveristy than old shipwrecks. Similar biodiversity as other wind farms in the North Sea.
Impact of OWEZ Wind farm on bivalve recruitment.	Bergman et al. (2010)	Bivalves on the soft substrate in wind farm OWEZ (the Netherlands)	No differences were found between the densities of small-sized (>0.2 mm) bivalve recruits in OWEZ Wind farm and the 5 reference areas. For the larger recruits (>0.5 mm) differences in densities were found for two refference areas.
Wrecks as artificial lobster habitats in the German Bight.	Krone and Schröder (2011)	Lobsters on wrecks in the German Bight	Diving showed 1, 2, or 3 lobsters on 15.6% of the 64 investigated wrecks. Used-video data was not aimed at finding lobsters, expected is that the real percentage of lobster-inhibited wrecks is 2-3 times as high.
Effect of the Horns Rev 1 Offshore Wind Farm on Fish Communities - Follow up Seven Years after Construction.	Leonhard et al. (2011)	Fish in Horns Rev 1 (Denmark)	The introduction of hard substrate and higher complexity relative to the homogenous sand banks characteristic of the North Sea resulted in minor changes in the fish community and species diversity. The introduction of hard bottom substrate resulted in higher species diversity close to each turbine with a clear spatial (horizontal) distribution.

Name of the paper/report	Writer	Target area	Conclusion
Short-term ecological effects of an offshore wind farm in the Dutch coastal zone; a compilation.	Lindeboom et al. (2011)	All species in wind farm OWEZ (the Netherlands)	No short-term effects on the benthos in the sandy area between the piles. Hard substrate of the monopiles and the scouring protection led to the establishment of new species and new fauna communities. Bivalve recruitment was not impacted by the OWEZ wind farm. Species composition of recruits in OWEZ and the surrounding reference areas is correlated with mud content of the sediment and water depth irrespective the presence of OWEZ. Recruit abundances in OWEZ were correlated with mud content, most likely to be attributed not to the presence of the farm but to the absence of fisheries. The fish community was highly dynamic both in time and space. So far, only minor effects upon fish assemblages especially near the monopiles have been observed. Some fish species, such as cod, seem to find shelter inside the farm. Overall, the OWEZ wind farm acts as a new type of habitat with a higher biodiversity of benthic organisms, a possibly increased use of the area by the benthos and fish.
Benthic communities on hard substrates of the ofshore wind farm Egmond aan Zee.	Bouma and Lengkeek (2012)	Benthic species in wind farm OWEZ (the Netherlands)	The density of marine life on the scour protection was high. Densities of anemones were circa 2,500 individuals per m2 and densities of starfish circa 180 individuals per m2. The covering percentages of the sea mat and small crustaceans varied between 60-100% and 30-50% respectively.
Impact of OWEZ wind farm on the local macrobenthos community.	Daan et al. (2012)	Macrobenthos in wind farm OWEZ (the Netherlands)	Univariate comparison of the benthos community in the fishery-closed OWEZ Wind farm with that in six regularly trawled reference areas did not show any difference in total abundances, total biomass and total annual production in the 2011-survey, five years after the closure. Also multivariate species composition, biomass, and annual production in OWEZ did not differ from those in the reference areas.
On the biological connectivity of oil and gas platforms in the North Sea.	Thorpe (2012)	Biological connectivity of oil and gas platforms in the North Sea.	The M_2 tide results n a relatively rapid transfer of organisms between neighbouring platforms. 60% of platforms in the southern UK Sector are directly connected by tidal flows. The mean flow in most of the North Sea is typically 0.02-0.05 m/s.
Investigating the impact of offshore wind farms on European Lobster and Brown Crab fisheries.	Skerritt et al. (2012)	Lobster and crab in a demonstration wind farm and reference sites on the east coast of the UK.	A smaller population was present within the demonstration wind farm site than at the inshore 'control', while the average size of lobster was greater. Capture and recapture rates were to low for population modeling. The inshore site population was estimated to be 6,163 lobsters per km^2 (0.6 lobsters per m^2).
Epifauna dynamics at an offshore foundation. Implications of future wind power farming in the North Sea.	Krone et al. (2013)	Macrozoobenthos colonization on an offshore platform in the North Sea	The surface of the construction (1280 m^2)was covered by an average of 4300 kg biomass. This foundation concentrates on its footprint area (1024 m^2) 35 times more macrozoobenthos biomass than the same area of soft bottom in the German exclusive economic zone (0.12 kg m^2), functioning as a biomass hotspot.

Name of the paper/report	Writer	Target area	Conclusion
Aggregation at windmill artificial reefs: CPUE of Atlantic cod (Gadus morhua) and pouting (Trisopterus luscus) at different habitats in the Belgian part of the North Sea.	Reubens et al. (2013)	Atlantic cod and pouting in three different habitats in the Belgian part of the North Sea: windmill artificial reefs, shipwrecks and sandy bottoms.	population densities of both species were highly enhanced at the hard substrate habitats in comparison to the sandy sediments. The highest catch-per-unit effort values for both species were recorded around the WARs, which indicated distinct aggregation around the wind turbine foundations.
Biodiversiteit kunstmatig hard substraat in de Noordzee (NCP).	Jager (2013)	Hard substrate related species on ship wrecks, platforms, wind farms, artificial reefs. Dutch part of the North Sea	Colonization reaches equilibrium after 4-6 years. Wrecks are more species rich than wind farms, possibly to their larger age.
Natuurwaarden Borkumse Stenen - Project Aanvullende beschermde gebieden.	Bos et al. (2014)	Hard substrate related species on the Borkumse stenen (the Netherlands)	The hard substrate (gravel, rock and large stones) is 100% covered by typical hard substrate species and this area has the largest biodiversity and abundance.
Mobile demersal megafauna at common offshore wind turbine foundations in the German Bight (North Sea) two years after deployment - increased production rate of Cancer pagurus.	Krone et al. (2017)	Mobile demersal megafauna on offshore wind turbine foundations in the German Bight	Monopiles with scour protection were mostly colonized by typical reef fauna. They were inhabited by an average of about 5000 edible crabs Cancer pagurus (per foundation), which is more than twice as much as found at the foundation types without scour protection. Strong evidence was found that all three foundation types not only function as ag- gregation sites, but also as nursery grounds for C. pagurus.
Benthic biodiversity on old platforms, young wind farms, and rocky reefs.	Coolen et al. (2018)	Hard substrate related species in the Dutch part of the North Sea	Multivariate analysis showed a large overlap in communities on steel and rock and between the wind farm and platforms. The community changed over a gradient from deep rocks to shallow steel substrate, but no strong community differentiation was observed. Deep steel was more similar to natural rocks than shallow steel. When an artificial reef is intended to be colonized by communities similar to those on a natural reef, its structure should resemble a natural reef as much as possible.
RECON: Reef effect structures in the North Sea, islands or connections?	Coolen and Jak (2018)	Mythilus edulis and Jassa herdmani on eight Dutch and nine Danish offshore gas platforms in the southern North Sea	Mytilus edulis populations were present throughout the investigated area, showing that larvae are able to reach offshore locations. Larval transport by currents has probably contributed to the initial colonisation. Direct connectivity between some locations was also shown by the particle tracking models, although this could not be validated using genetic data. Possibly the distance between the studied locations is too large for direct larval exchange. There is hardly any connectivity of the populations of Jassa amongst the different sampling locations detected in this study. Apparently, once J. herdmani has colonized the hard substratum, it develops a distinct population, enabled by its short life-cycle and limited dispersal capacity.

D
Additional figures

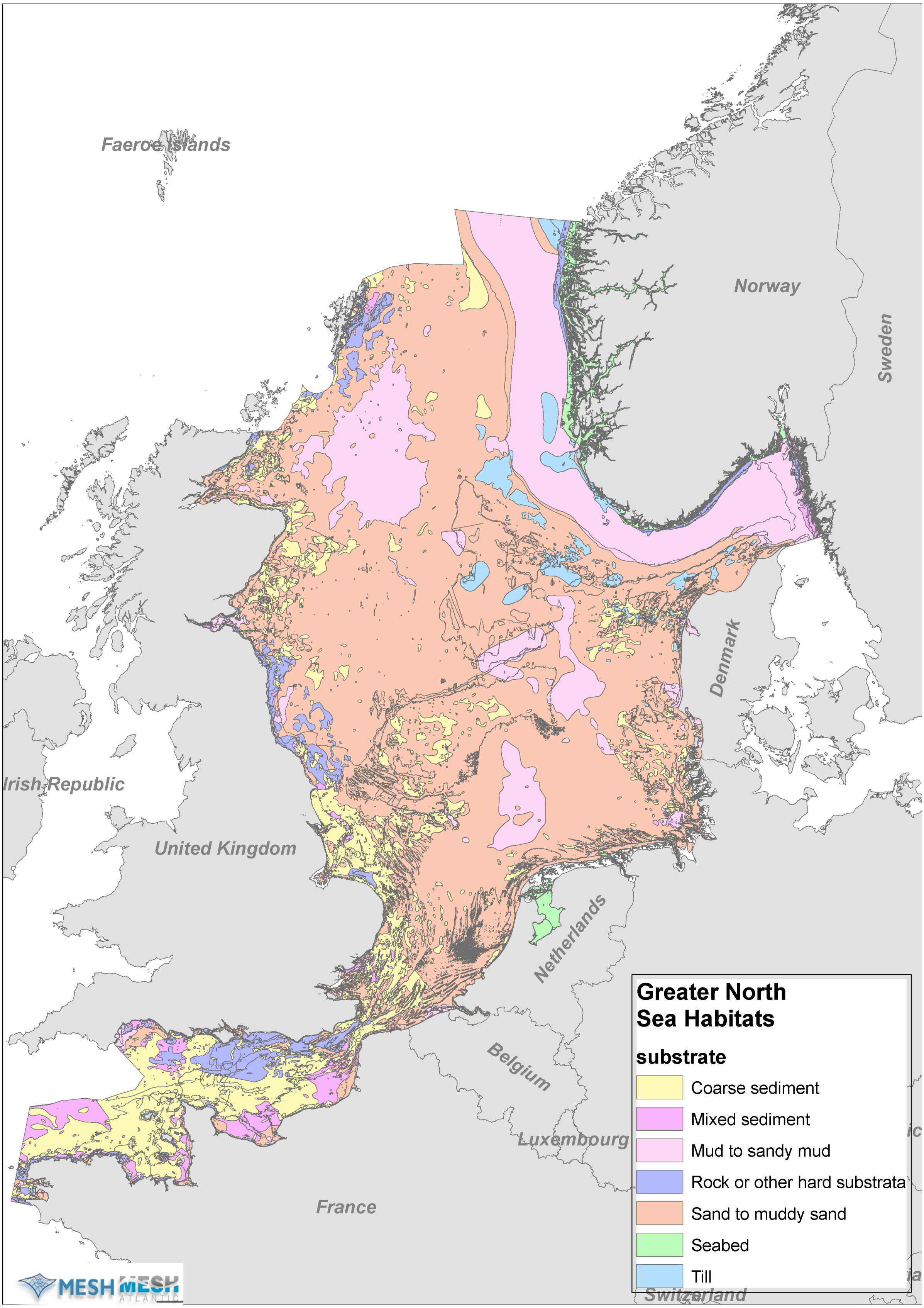
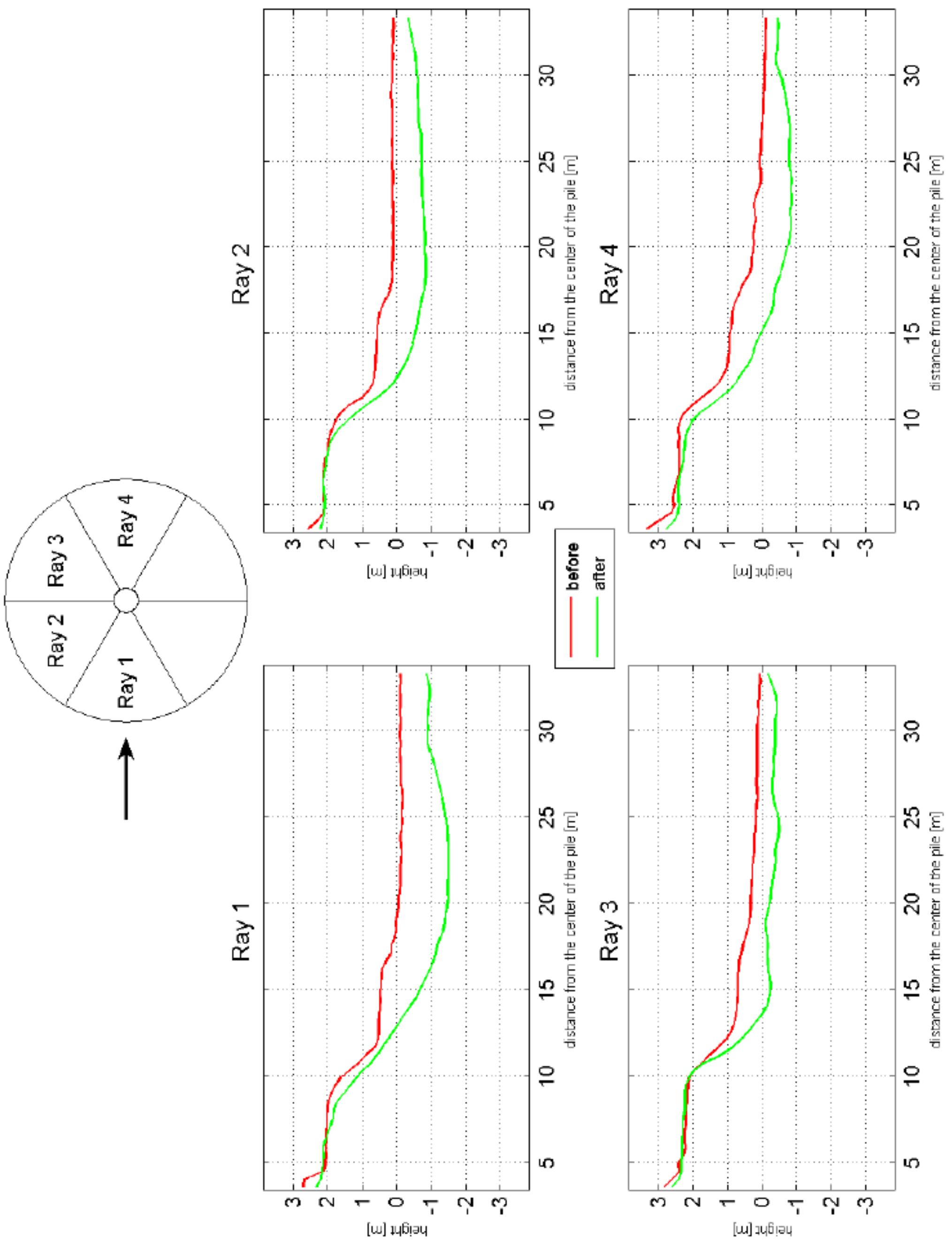


Figure D.1: Substrates in the North Sea
Source: Mesh

Figure D.2: Names of areas in the North Sea
Source: commons.wikimedia.org, author: Halava



Layer thickness of armour layer before and after the test and the net difference	Pile 4	Tidal Current
	40/200kg, 1-3"	
Deltares	Test A01	App. F.1.5.4

Figure D.3: Deformation of the 40/200 kg armour layer in test conditions
Source: Deltares