Flat oysters on offshore wind farms

Opportunities for the development of flat oyster populations on existing and planned wind farms in the Dutch section of the North Sea

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Yerseke, April 2017.

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Summary

This report is about opportunities for the development of flat oyster populations (*Ostrea edulis*) on existing and planned wind farms in the Dutch section of the North Sea. On behalf of the Ministry of Economic Affairs, the requirements that flat oysters make on their environment have been identified, with a focus on the habitat features of wind farm sites in the North Sea. The study is based on the premise that no seabed-disturbing activities are carried out on these wind farm sites that have adverse effects on flat oysters.

Crucial preconditions for the development of flat oyster beds on the wind farms in the Dutch section of the North Sea are (i) large-scale and small-scale seabed dynamics, (ii) sediment composition, (iii) concentrations of suspended particles, and (iv) the possibility of successful recruitment. The latter factor depends on the size of the parent population and the inflow of larvae through water flow. Other important factors such as food supply and oxygen content have no limiting effect in the North Sea areas concerned here. Predation and competition are also important, but it is impossible to say to what extent they limit the development of flat oyster beds on the wind farm sites concerned and to what extent those wind farm sites differ in these respects.

According to our analysis, the relative suitability of wind farm sites for flat oysters is determined by small-scale seabed dynamics expressed in sea bed shear stress, sediment composition, the concentration of suspended particles and the chance of recruitment. Large-scale seabed dynamics in the form of sand waves have limiting effects in part - but not all - of the Borssele site, and are absent from the other sites. Also historical data on the range of oyster beds, as a qualitative benchmark for the suitability of sites, has been addressed in the study.

It is concluded that **Zee-energie** combined with **Buitengaats** are the most suitable locations for the development of oyster beds, followed by **Borssele** and **Luchterduinen**. Shallower coastal sites also provide opportunities for growing oyster beds, but there the seabed is not quite as stable. Data on water motion and the duration of the larval phase have made it possible to estimate the distance over which the larvae are dispersed. In that analysis, **Zee-energie** and **Buitengaats** emerge as the most suitable sites for spat settlement, followed by **Borssele**. Other locations along the coast of Noord- and Zuid-Holland are currently less likely to become self-sufficient in terms of larvae, even though some are already capable of providing other wind farms or channels in the Wadden Sea with larvae.

In view of the assumptions and uncertainties involved, the conclusions will have to be subjected to empirical testing in pilot experiments as a necessary step in the further development of flat oyster beds on North Sea wind farms. **Luchterduinen** is particularly attractive as a pilot site as it has been in use as a wind farm since 2015, is relatively easily accessible and can be used immediately for that purpose.

1. Introduction

1.1 Aims

The project aims to identify opportunities for the development of flat oyster populations (*Ostrea edulis*) within existing and planned wind farm sites in the Dutch section of the North Sea, and to specify what is needed to realize pilots for the development of those populations.

1.2 Background

In September 2014, the Dutch government designated three areas for the development of offshore wind farms over the years to come: Borssele, Noord-Holland and Zuid-Holland (Figure 1.1). In the *Noordzee 2050 Gebiedsagenda* (North Sea 2050 Spatial Agenda) the Ministries of Economic Affairs and Infrastructure & the Environment expressed their ambition to arrive at the combined use of offshore space. More specifically, the Ministry of Economic Affairs wishes to establish whether the areas recently designated as offshore wind farm sites offer opportunities for the development of flat oyster beds. Wind farms tend to offer such opportunities as they are free from seabed-disturbing activities, which is regarded as a major precondition for the restoration of flat oyster beds, which were widespread in the North Sea in the past (Gercken & Schmidt, 2014; Smaal et al., 2015).

The study into the opportunities for developing flat oyster beds on offshore wind farm sites was prompted by the environmental regulations (including design regulations) incorporated into the Wind Farm Site Decisions for new wind farms. The framework is delineated on the one hand by national government policy on *Bouwen met Noordzeenatuur* (building with nature in the North Sea), which promotes the preservation and sustainable use of species and habitats native to the North Sea and, on the other, by the various plans for reintroducing flat oyster beds in the North Sea.

This framework was developed from an awareness of the changes that various types of human activity have brought about in the North Sea (Houziaux et al., 2011), due in part to the loss of several extensive flat oyster beds that grew in the North Sea in the nineteenth century (Olsen, 1883; Smaal et al., 2015). The plans for extending the area designated for wind farms have raised the question whether this could also offer opportunities for developing the flat oyster population in the areas concerned.

Figure 1.1 and Table 1.1 show the sites covered by this study. These are the OWEZ, Amalia en Luchterduinen sites, which are already in use, plus sites currently under construction (Buitengaats and Zee-energie), recently licensed (Borssele) or in the process of being licensed (Noord-Holland and Zuid-Holland). Sites scheduled for development in the long term have not been taken into account in this study (see Table 2.1).

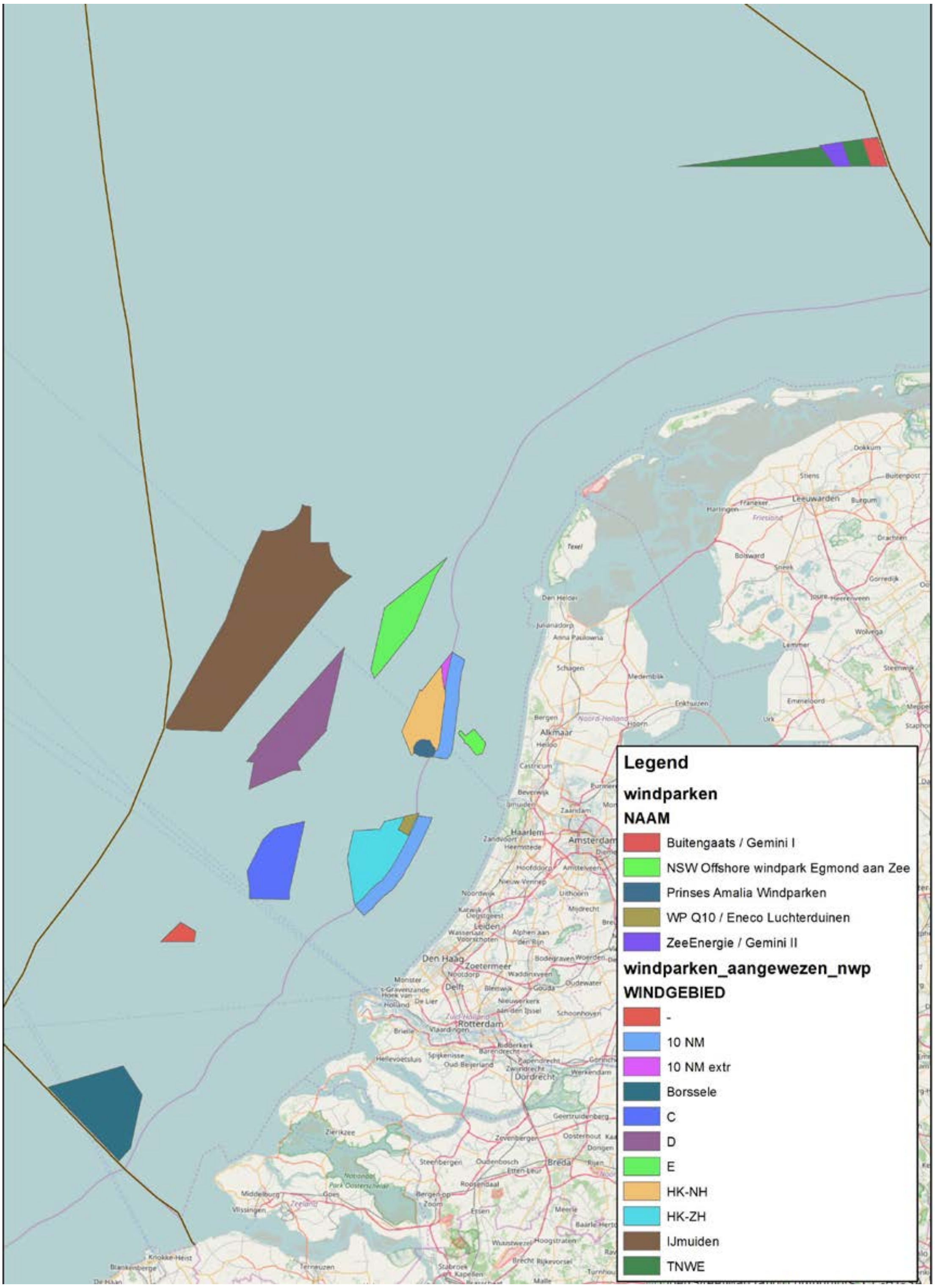


Figure 1.1 Map of the locations of existing and planned wind farms in the Dutch section of the North Sea (DSC: Dutch Continental Shelf). This study focuses on the sites listed in Table 1.1.

Table 1.1 Wind farm sites in the DCS that are analysed in this study.

No.	Name	Surface area (km2)	Depth (m)
1	Borssele total	34,501	20-40
2	Buitengaats	3428	28-36
3	OWEZ	2612	15-21
4	Holl. Kust N	17,368	20-27
5	Holl. Kust Z	23,593	20-27
6	Luchterduinen	1590	20-27
7	Pr. Amalia	2167	20-27
8	Zee-energie	3337	33-40

1.3 Habitat requirements for flat oysters (*Ostrea edulis*)

Flat oysters live on the sea bed, where they can form biogenic reefs, hence they are called eco-engineers (Smaal et al., 2015). They absorb oxygen through their gills and feed by filtering algae from the water. At excessive suspended particle concentrations in the water, the gills will get clogged and the oysters cannot absorb all the nutrients they need. Oysters start life as males and become females as they grow older. After that they can change sexes again. Following fertilisation, the larvae initially remain in the mantle cavity of the female oyster. After that, they swim in the water for about 7 to 14 days before settling on the seabed (Smyth et al., 2016). They settle only once. Oysters, and especially young ones, are susceptible to predation by crabs, starfish and predatory snails such as oyster drills.

Flat oysters occurrence depends on abiotic factors (sea bed dynamics, water depth, salinity, water temperature, water oxygen content, current velocity (also in connection with larval retention and spat settlement), concentration of suspended particles in the water column, substrate (which should also be suitable for spat settlement) and biotic factors (sufficient levels of phytoplankton, little predation, low mortality due to diseases, and sufficiently large populations for spat settlement levels that are able to sustain and expand the reef). Combining the habitat requirements of flat oysters and the habitat characteristics of the existing and planned wind farm sites in the Dutch section of the North Sea, this report examines the opportunities for developing flat oyster populations in those areas.

1.3.1 Sea bed dynamics

Potential locations for restoration projects should be selected on the suitability of their habitats not only for adult populations, but also for spat settlement. Reef-producing shellfish such as flat oysters are known as ecosystem engineers. This means that these species influence their physical environment to such an extent that they improve it as a habitat for themselves and for other species. Flat oysters need a certain amount of hard substrate for their initial settlement, but they can then extend an existing reef across a soft substrate. Reefs require a relatively stable sea bed. Whether a particular site is suitable is determined by the composition of the sea bed on that site, as well as by sea bed mobility. Reefs have a stabilising effect on the sea bed, but they are not resistant to the huge sand waves migrating across the area in many parts of the DCS (*Dutch Coastal Shelf*, the Dutch section of the North Sea). Models have been used to produce estimates of the small-scale and large-scale sea bed dynamics at each of the wind farm sites, based on simulations of sea bed shear stress and sea bed structure.

1.3.2 Other habitat characteristics

A certain level of stability is not the only relevant habitat requirement where flat oysters are concerned. In order to thrive, they need sufficient oxygen and food (phytoplankton), the right level of salinity and water within a specific temperature range, not too many predators and sufficient suitable substrate for settlement. They may have to compete for food and space with other species living on the sea bed. Chapter 4 presents the results of a study into what is known about these variables in the search areas concerned.

1.3.3 Larval dispersal

When flat oysters reproduce, the eggs are fertilised inside the shell of what is then a female, and released after some time. They then float around in the water column in the form of plankton during a free-swimming period of approximately ten days (depending on the water temperature), are dispersed by the current and then settle on suitable substrate. Larvae that are about to settle are known as 'competent' larvae. Populations need a sufficient supply of such competent larvae to remain viable. Chapter 4 shows how larvae disperse across the North Sea from a variety of sources (in this case, from several wind farms). The data originates from a dispersal model based on a validated current model of the North Sea. The model results have made it possible to estimate the dispersal range of the larvae produced on a specific wind farm, and of the extent of larval retention in a specific area. On the one hand, a high level of retention is important for the success of a restoration project. If all larvae have disappeared from a wind farm after ten days, that particular site will never become self-sufficient because it lacks the required supply of larvae. On the other hand, a certain degree of dispersal is desirable if a restoration project is also to serve as a source for populating other suitable habitats in the future.

1.3.4 Critical mass of flat oysters

One crucial question in the development of oyster populations concerns the minimum size that is required to ensure sufficient recruitment for a viable population. The minimum size depends on the age structure, density, the number of larvae produced and water motion. In this connection, it should be noted that oysters start life as males and do not undergo the metamorphosis into females until they are three to four years old (after which they can still change sexes). This means that the population not only needs to have a specific minimum size, but should also have the right structure in terms of age classes. Estimates in the literature as to the required critical mass are quite diverse. According to Berghahn & Ruth (2005), a very large oyster population in the North Sea is required – many tens of millions of individual oysters – if successful recruitment is to be achieved in the North Sea and the Wadden Sea. This is linked to the openness of these systems and the origin of the larvae, which, according to these authors, originate principally from the English Channel. However, Smyth et al. (2016) have demonstrated that following a period of over-exploitation, a flat oyster population in Strangford Lough could be restored on the basis of a limited critical mass of flat oysters. Model calculations of the dispersal of oyster larvae generated by wind farms in the North Sea have yielded estimates of the size of parent populations required to maintain sufficient numbers of larvae for new recruitment.

1.4 Problem definition

The request as formulated by the client concerns preliminary research into the habitat factors for flat oysters presented by specific sites in the North Sea. The study focuses on sites within existing and planned wind farms in the EEZ of the Dutch section of the North Sea, on a scale relevant to the development of flat oyster reefs, where pilot experiments can be conducted. Analysis of the results of this study should make it possible to identify the sites that offer the best potential for flat oyster introduction and reintroduction experiments.

1.5 Acknowledgements

The authors would like to thank Dr E. Knegtering of the Ministry of Economic Affairs for commissioning this report and for his valuable comments on the draft version, and Dr J. Wijsman (WMR) for reviewing the report. For the translation into English Metamorfose Vertalingen is acknowledged.

2.Knowledge requirement

The central knowledge requirement in this study is the following:

Which offshore wind farm sites (and any locations within those sites) present suitable habitat factors for the introduction or reintroduction of flat oysters, and where are these habitats situated?

The study focuses on areas within the wind farm sites in the Dutch section of the North Sea (DCS , Figure 1.1). For each wind farm site, Table 2.1 shows the period within which it is to be realised. This realisation period serves as the basis for prioritising the sites in this study, which focuses on the sites with either two or three stars.

Table 2.1: List of wind farm sites in the DCS , estimated period to completion and the priority level adopted in this study for a detailed realisation of the potential flat oyster habitats (*** and **); (Ministry of Infrastructure and the Environment, Ministry of Economic Affairs, 2014, 2016)

Code	**Location**	**Operational status**	**Priority**
C	OWEZ (Egmond aan Zee),	In operation	**
C	Prinses Amalia	In operation	**
C	Luchterduinen	In operation	**
A	IJmuiden-Ver	No decision to be expected soon	*
B	Borssele Wind Farm Zone		
	Site I	Operator known	***
	Site II	Operator known	***
	Site III	Operator known	***
	Site IV	Operator known	***
	Site V (Innovation Site)	Wind farm Site Decision	**
C	"Hollandse kust" Wind Energy		**
	Zuid-Holland Site I	Draft Wind Farm Site Decision, tender opens mid-2017	**
	Zuid-Holland Site I	Draft Wind Farm Site Decision, tender opens mid-2017	**
	Zuid-Holland Site I	Tender opens approx. 2018	**
	Zuid-Holland Site I	Tender opens approx. 2018	**
	Noord-Holland Site I	Tender opens approx. 2019	**
	Noord-Holland Site I	Tender opens approx. 2019	**
	Zuid (Sites III + IV)	Decision being prepared	**
	Remaning site (1)	No decision to be expected soon	*
	Remaining site (2)	No decision to be expected soon	*
	Remaining site (3)	No decision to be expected soon	*
	Remaining site (4)	Not included for the time being	
D	"Ten noorden van de Waddeneilanden" Wind Energy Zone		
	Gemini: Buitengaats	Under construction	**
	Gemini: Zee-energie	Under construction	**
	Remaining site (1)	No decision to be expected soon	*
	Remaining site (2)	No decision to be expected soon	*

3. Methodology

This desk study comprises a literature and source study, supplemented by model simulations. The literature and source study was performed using open literature, databases and a range of recent reports, more specifically by Capelle, 2008, Smaal et al., 2015, Kamermans et al., 2015, van der Have & van der Zee, 2016, Sas et al., 2016 and van Duren et al., 2016. In addition, the authors consulted information about historical and recent flat oyster ranges in and around the North Sea. This field data has made it possible to identify the sites that are evidently the most promising for oysters.

3.1 Habitat requirements

The demands made by flat oysters on their environment have been analysed in terms of the limit values for abiotic and biotic factors. Information on these values was obtained from the literature (including sources such as de WUR Library, Scopus and Google Scholar), via the authors' existing contacts and using data on the range of flat oysters.

The conditions for the long-term development of a flat oyster bed are largely determined by four life-history processes: survival, growth, reproduction and recruitment. Reproduction refers to the capacity to produce offspring; recruitment denotes the successful settlement of larvae in a specific site.

These four processes are influenced by a range of abiotic and biotic factors, which are listed in Table 3.1.1. *Survival* depends on environmental factors such as large-scale and small-scale sea bed dynamics, oxygen content, salinity and predation. *Growth* is mainly determined by phytoplankton and the concentration of suspended particles. *Reproduction* requires a parent population in suitable age classes, and the right water temperature for spawning. *Recruitment* depends on water temperature, the quantity of larvae in a specific area and the presence of suitable substrate for settlement. Recruitment is determined by the size of the parent population that produces the larvae and serves as substrate, and by the water motion that determines larval retention in a specific area (see also Vera et al., 2016; Smyth et al., 2016).

Structure of the document

This reports discusses the habitat requirements of flat oysters on the one hand, and aims to identify the values for the various environmental factors on the wind farms on the other. These factors are listed in Table 3.1.1. and, where possible, presented in further detail in Table 4.1.1. The results for sea bed shear stress, sea bed structure and suspended particles (silt) are derived from model calculations which are explained in detail in Section 3.2. The results for the other factors are based on information from the literature. Data on larval dispersal and critical mass estimates are also derived from model calculations, which are explained in Section 3.4. The models and calculation results are also discussed separately in Chapter 4.

Table 3.1.1. Environmental factors relevant to the various life-history processes

	survival	growth	reproduction	recruitment
Sea bed shear stress	x			
Sea bed motion	x			
Concentration of suspended particles		x		
Water temperature			x	
Sediment composition / substrate				x
Water depth	x			
Salinity	x			
Concentration of nutrients		x		
Oxygen content	x			
Current velocity				x
Predation	x			
Competition		x		
Composition of parent stock			x	
Size of parent stock				x

3.2 Sea bed motion and bed shear stress

Sea bed dynamics can be described on different levels of scale. For this reason, a distinction is made between bed motion (geomorphology), which concerns bed dynamics on a larger scale, and bed shear stress, as a measure for local bed dynamics.

Sea bed motion

Figure 3.2.1 presents the sea bed structure and sea bed motion features of the North Sea as derived from the North Sea Atlas (Icona, 1992). The Atlas describes the sea bed structure as follows: 'The seabed along the Dutch coast presents various morphological features, such as sand banks, sand waves and ebb deltas. Overall, we can make a distinction between the flat seabed and the underwater shoreline. The flat seabed has a maximum gradient of 1:1000. The southern part is characterised by sand waves of declining height, from over six metres in the south to two metres near Den Helder. Further north, sand waves are practically absent, with the exception of an area off the islands of Texel and Vlieland. The sand banks are a few kilometres to several dozens of kilometres in length, and one or a few kilometres wide. The sand banks in the southern complex (the Zeeland Banks) are deeper under water (20-30 metres below sea level) than those in the northern complex (14-20 metres below sea level). The southern sand banks are 4 to 20 metres high, compared with 3 to 6 metres for those in the north. Coastward, the flat seabed transitions into the more steeply sloping underwater shoreline. The transition zone is generally around 20 metres below sea level (15 metres below sea level at the central part of the Noord- and Zuid-Holland coastline). The underwater shoreline near the tidal inlets in the Delta Area and Wadden Area is dominated by outer deltas with the associated channels and shallows. The gradient of the underwater shoreline increases coastward off Zuid- and Noord-Holland and the central parts of the Wadden Islands.'

As for the wind farms, Borssele in particular is characterised by a relatively dynamic seabed in part of its area. For this reason, the sand waves have been analysed in further detail in this area (Section 4.2.2) based on 14 sea bed surveys conducted between 1988 and 2014. The data concerned was gathered by the Royal Netherlands Navy and generated by Deltares for the Borssele wind farm. For more details about methodology, see Riezebos et al. (2014). The sea bed structure in the other farms is more stable (Figure 3.2.1).

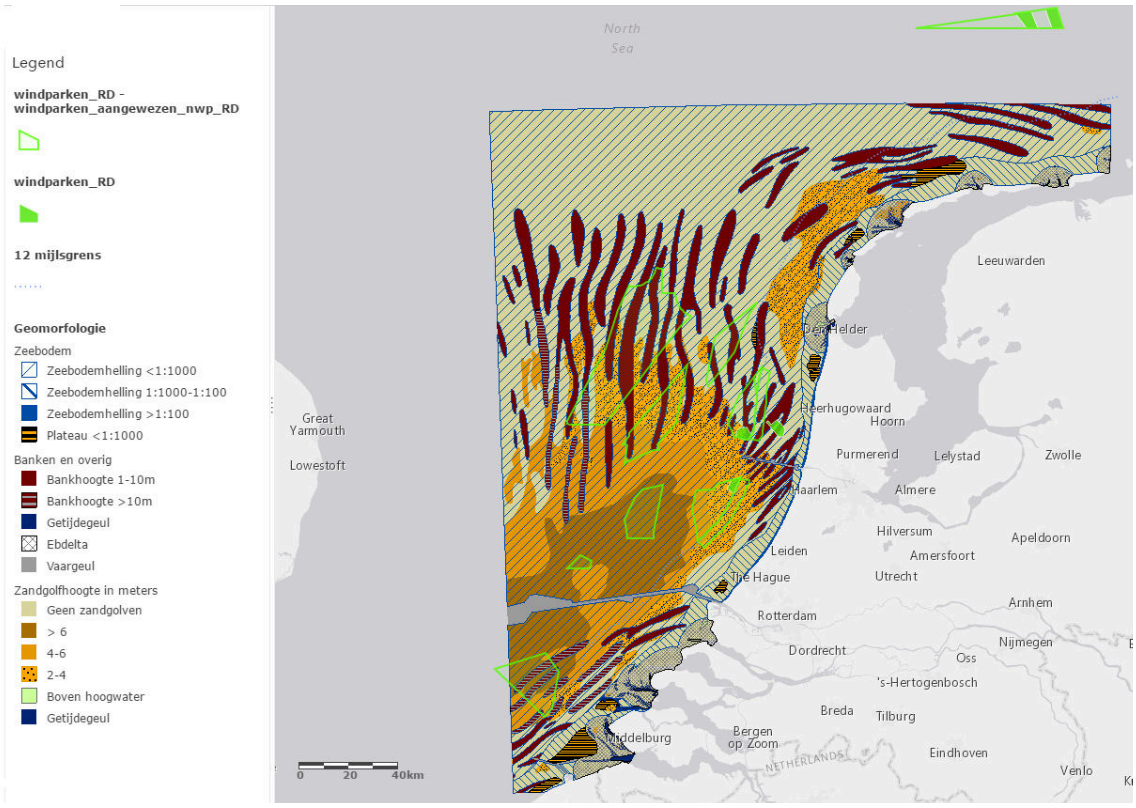


Figure 3.2.1 Sea bed structure / motion (source: North Sea Atlas, Icona, 1992) and wind farm sites in the Dutch section of the North Sea.

Sea bed shear stress and silt model

Sea bed shear stress is the force exerted on the seabed by water motion, resulting both from currents and waves. The effect of waves tends to be the most powerful in shallow waters. In deep waters, waves do not reach the seabed. Sea bed shear stress determines whether particles (such as silt, sand or oyster larvae) are swirled up or settle.

Sea bed shear stress levels have not been measured in practice, and can only be obtained from model calculations. Silt-modelling data from the sand extraction EIR has been used to gain an impression of average and maximum sea bed shear stress in the North Sea. Rijkswaterstaat and Stichting LaMER will jointly commission an environmental impact report (EIR) for the envisaged sand extraction activities in 2018-2027. Deltares and Wageningen Marine Research have conducted a preliminary study into the effects of sand extraction on silt management (van der Kaaij et al., 2017). This study involved the use of a detailed silt model, which is based in turn on a validated hydrodynamic model of water motion in the southern part of the North Sea (Figure

3.2.2). This state-of-the-art model is based on earlier model studies and is the best tool currently available. The effects of currents and silt are based on validation data series covering the yeas from 2003 through 2011. This long-term data series has been used to validate the model and also provides insight into year-on-year variability.

In addition, the hydrodynamic model has provided input for modelling the dispersal of oyster larvae as described in Section 4.4.

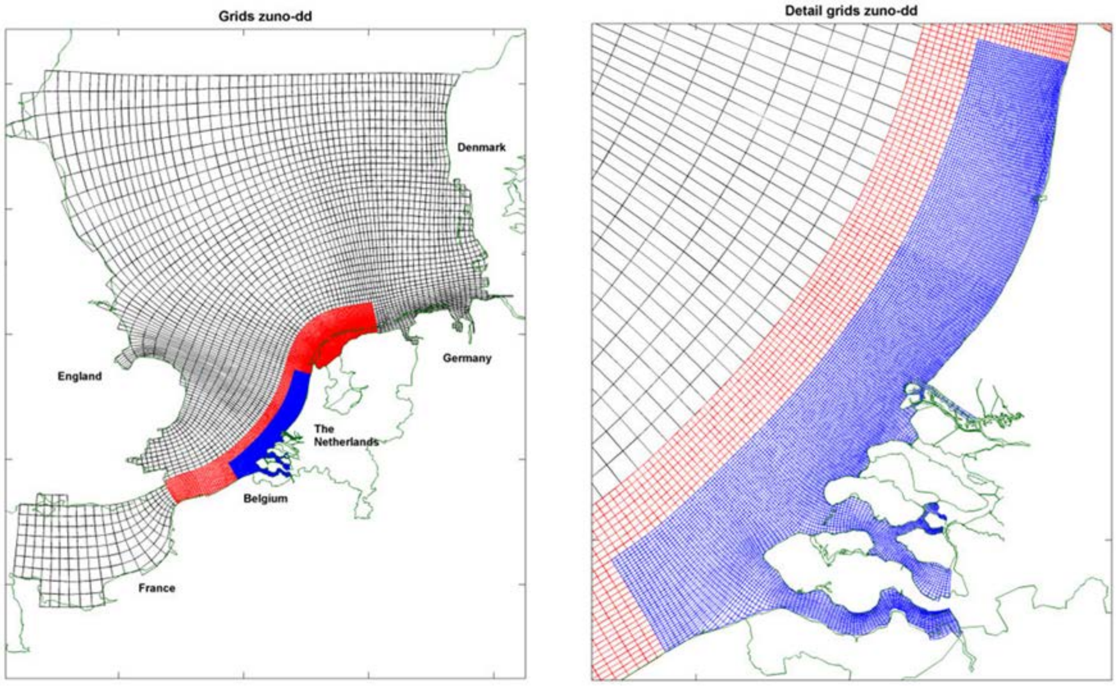


Figure 3.2.2: The grid size used for the hydrodynamic model, represented at two different scale levels.

In addition to current modelling, silt modelling also involved the use of a wave model developed by Delft University of Technology (SWAN, F. Kleissen pers.comm.). The combined results of the hydrodynamic model and the wave model made it possible to produce an estimate of the sea bed shear stress. In turn, this information served as the basis for an estimate of sediment swirl, which gives an indication of suspended matter concentration levels in the various layers of the model. The model approach is essentially the same as he approach adopted in the previous EIR (Keetels et al., 2012) and MOS-II (Cronin et al., 2013). However, for this particular study the approach was adapted in a number of respects:

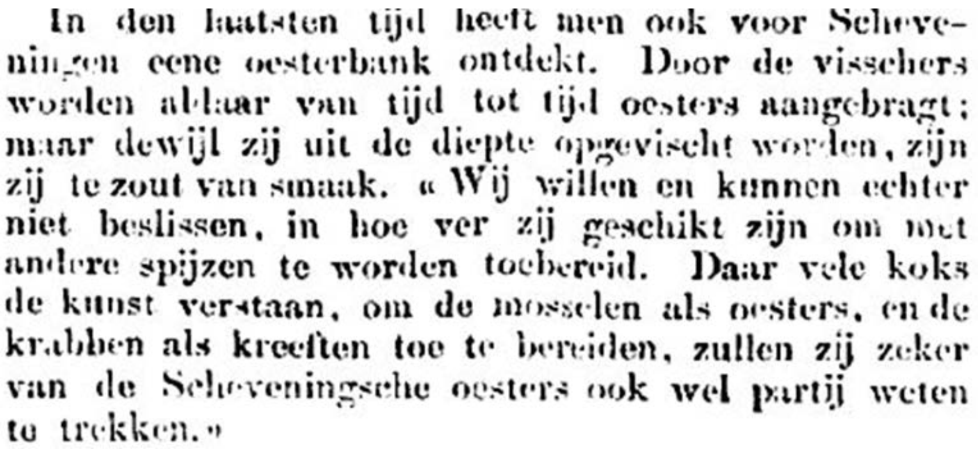
- The model was updated using the most recent parameter settings as applied in MOS II and the Loswal Noord dump site studies, which were conducted after the previous sand extraction EIR (Keetels et al., 2012). The parameter settings were validated on the basis of additional and more recent silt concentration measurement data. Also note that for the dump site study the effect of harbour silting on the one hand and maintenance dredging spoil dispersal on the other were added to the model.
- The model was converted to a new grid and a new seabed.
- The wave model was run again over the 2003–2011 period to account for the new grid and seabed, using the same wave assimilation technique as that used in the previous sand extraction EIR and the Maasvlakte-2 EIR.

- For validation purposes, the model was run for the 2003-2011 period with the new grid and seabed and the new wave modelling system. This was done using the post-processing and validation scripts as developed in the MOS II project (Cronin et al., 2013) and the previous sand extraction EIR (Keetels et al., 2012).

Further details on this model can be found in the validation report for the sand extraction EIR (van der Kaaij et al., 2017).

3.3 Other habitat characteristics

In addition to seabed and silt dynamics, data has been collected (from the literature and elsewhere) on other variables that are relevant to flat oysters, such as sediment composition, water temperature, phytoplankton, oxygen content and salinity (see also Section 3.1). This data was derived from the North Sea Atlas (Icona, 1992) and other databases. Data known about fauna (including potential predators) at the wind farm sites was also gathered, drawing on sources such as studies into the vegetation growing on shipwrecks at the wind farm sites (Lengkeek et al., 2013). Additionally, use was made of historical maps on oyster ranges and the habitat characteristics of those areas. In the section of the North Sea that is part of the Netherlands today, flat oysters are found only in the Voordelta and, incidentally, on hard substrates. This means that field knowledge about the relevant abiotic and biotic factors mainly originates from other parts of the flat oyster range. Additional information on the historical range of flat oysters in the North Sea is also available (e.g., Olsen, 1883; Gercken & Schmidt, 2014; Smaal et al., 2015). This historical range information has therefore been used as an extra 'habitat factor' in evaluating the suitability of areas in the North Sea for flat oysters. In this connection, the following quote from the *Dagblad van Zuid-Holland en 's-Gravenhage* newspaper dated 29 February 1856 is of interest:



In den laatsten tijd heeft men ook voor Scheveningen eene oesterbank ontdekt. Door de visschers worden aldaar van tijd tot tijd oesters aangebragt; maar dewijl zij uit de diepte opgevischt worden, zijn zij te zout van smaak. « Wij willen en kunnen echter niet beslissen, in hoe ver zij geschikt zijn om met andere spijzen te worden toebereid. Daar vele koks de kunst verstaan, om de mosselen als oesters, en de krabben als kreeften toe te bereiden, zullen zij zeker van de Scheveningsche oesters ook wel partij weten te trekken.»

This message of 1856 says that fishermen had discovered an oyster bed in deeper waters offshore Scheveningen / The Hague area. The taste was not much appreciated due to high salinity.

The selected wind farm sites were assessed on the basis of the maps composed for the most relevant habitat requirements. The resulting values were evaluated with reference to the tolerance limits for flat oysters presented in the literature.

3.4 Larval dispersal

3.4.1 General

For an estimate of potential oyster larvae dispersal from various locations and the chance of recruitment, a particle dispersal model has been used (with the particles representing the larvae) that is driven by water motion data from the Delft3D-FLOW model. Delft3D-FLOW, which is part of the Delft3D suite of models, generates the water motion that drives the transport of substances. Other Delft3D modules such as those for water quality, primary and secondary production and particle transport are linked directly to this model. The three-dimensional water motion is derived from the ZUNO-DD model that was created for Rijkswaterstaat within the context of the sand extraction EIR (van der Kaaij, 2017). ZUNO-DD is a hydrodynamic model of the southern part of the North Sea (see Figure 3.4.1.1.). In view of the fact that it is used mainly to simulate the effects of sand extraction on biota near the coast and in the Wadden Sea, the model has a much higher resolution for those areas than for areas further out in the North Sea. The result of that within the context of this study is that some wind farms which have been studied as source locations are covered in the model in more detail than other sites. The curvilinear grid means that the cells are not all of the same size. The cells in the fine-meshed part of the grid are several hundreds of metres across, compared with several kilometres per cell further out in the North Sea. While this means that the fine-meshed part offers some scope for differentiation as to the release site for larvae within a wind farm, overall the model is not sufficiently refined to make firm statements regarding the successful recruitment of oysters at the level of individual turbines.

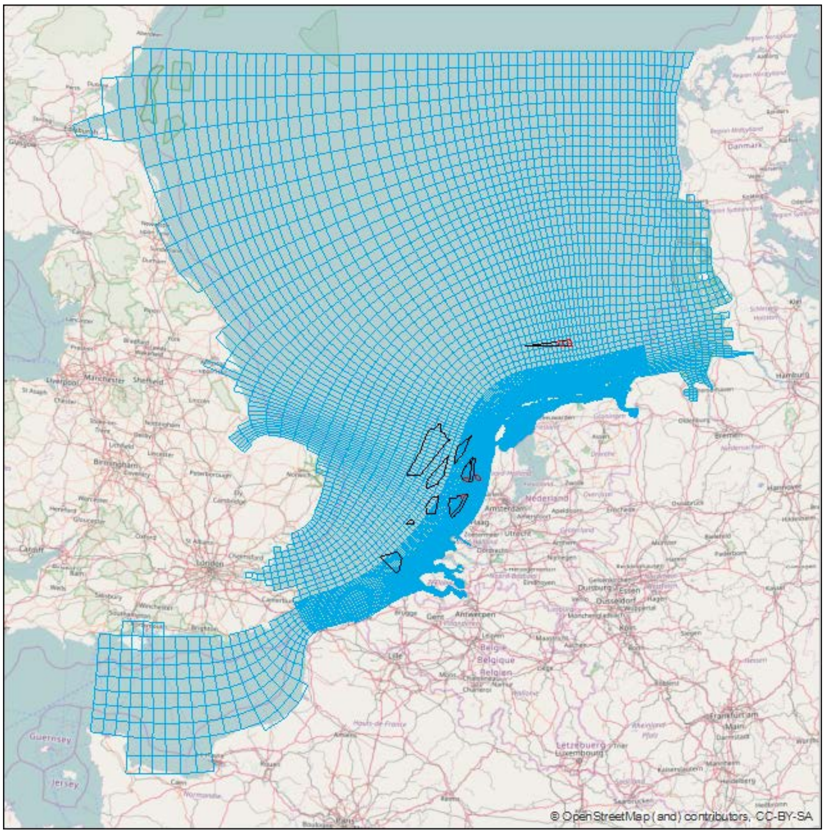


Figure 3.4.1.1: ZUNO-DD grid in the southern part of the North Sea and the English Channel, indicating the wind farm locations.

Hydrodynamic data is available for the years 2003 through 2011 on the following features: water levels, current velocity, water temperature and salinity. The forcing functions for simulations using the hydrodynamic model are based on actual data such as river outflows, water temperature and wind data. Since this data covers a period of nine years, it offers a useful picture of the annual fluctuations in sea currents.

The particle model (D-PART) driven by current data also forms part of the Delft3D model suite. In a particle model, large numbers of particles are used to simulate the larvae. The transport of these particles is driven by water motion and by dispersal and diffusion processes. During the simulation, each particle in the model is monitored in three dimensions to obtain a good picture of the dispersal pattern. In this study, the larvae were modelled as passive particles.

3.4.2 Assumptions for the particle model

The assumptions used in the model are boundary conditions in the interpretation of its results. The dispersal of larvae from specific source sites is meant to:

1) produce an estimate of the extent to which a certain source site is potentially self-sufficient in terms of the supply of larvae and population recruitment, and
2) estimate the likelihood of success of that site serving as a source for other potentially favourable habitats, and other wind farms in particular.

One important aspect in this context is the approximate age at which the larvae begin to settle. The maximum age assumed in this study is ten days from the moment the larvae leave the mother oyster. This means that particles are removed from the model as soon as they are more than ten days old, and they play no further role in the simulation. This means that this age limit restricts the potential settlement range. A further assumption is that larvae that are less than ten days old are unable to settle. This has been taken into account in the post-processing of the model results.

For the purposes of this study, the model disregarded any type of larval behaviour, such as active vertical migration. The simulation only allowed for vertical transport driven by advection (current) and dispersal.

Where possible, the particles were entered into the model in a way that reflects data from actual larval counts during the season (Kamermans data). This has yielded the model values for the relative contribution of larval production in the North Sea over time as represented in Figure 3.4.2.1.

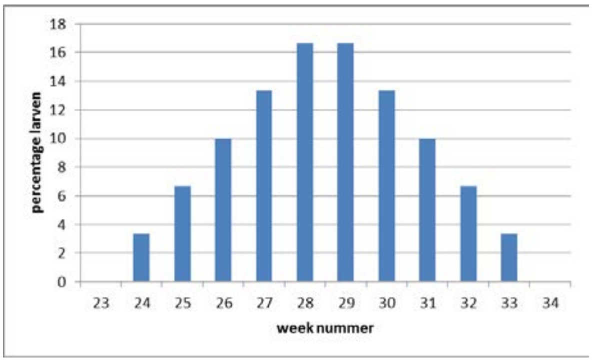


Figure 3.4.2.1: Model values for relative larval production in the North Sea during the summer period as used in this study.

This relative distribution was then transposed to the release of larvae from the parent oysters in the model. As standard, in the model 1.26 x 10^8 particles are introduced near the seabed. This is an arbitrary figure. The concentrations in the bottom water layer at the site concerned are related to this number of particles. To link these numbers to the actual number of released larvae (nlarv), a proportional calculation (nlarv/1.26 x 10^8) will have to be made. As described in Section 1.3.3, flat oyster larvae grow up within the mantle cavity of the female oyster for the first few days, and are released once they have grown sufficiently.

The model does not present absolute concentration figures, but offers proportional figures of larval concentration relative to the total number of larvae generated in a specific period. In addition, the model does not take the survival rate into account. All particles released in the model are assumed to survive for a full ten days. The model also assumes that the larvae are able to settle as soon as they are ten days old, but not before that time. This is why the average dispersal of larvae that are ten days old is taken as the model result for the purpose of estimating the chance of recruitment.

In the model, the particles are released near the seabed in every source location. This is a realistic choice, because in reality the source (mature flat oysters) is also located on the seabed. This is why the results that provide a measure for the presence of larvae in a certain area are limited to the bottom layer. The results are formally expressed in units per cubic metre, but since the analysis only concerns the bottom layer of the water column they can also bee seen to express the number of larvae that are able to settle on the seabed. In that case, units per cubic metre is converted to units per square metre.

3.4.3 The source terms

The sources of the larvae are based on the wind farms listed in Figure 1. The areas that have been assigned the highest analysis priority, were selected from that list (see Chapter 2). The following areas were included in this study as a source:

1. Borssele
2. Buitengaats
3. Egmond aan Zee
4. Hollandse Kust Noord
5. Hollandse Kust Zuid
6. Luchterduinen
7. Prinses Amalia
8. Zee-energie

One release site has been created in the centre of each of these areas, as indicated by the dots in the figure below.

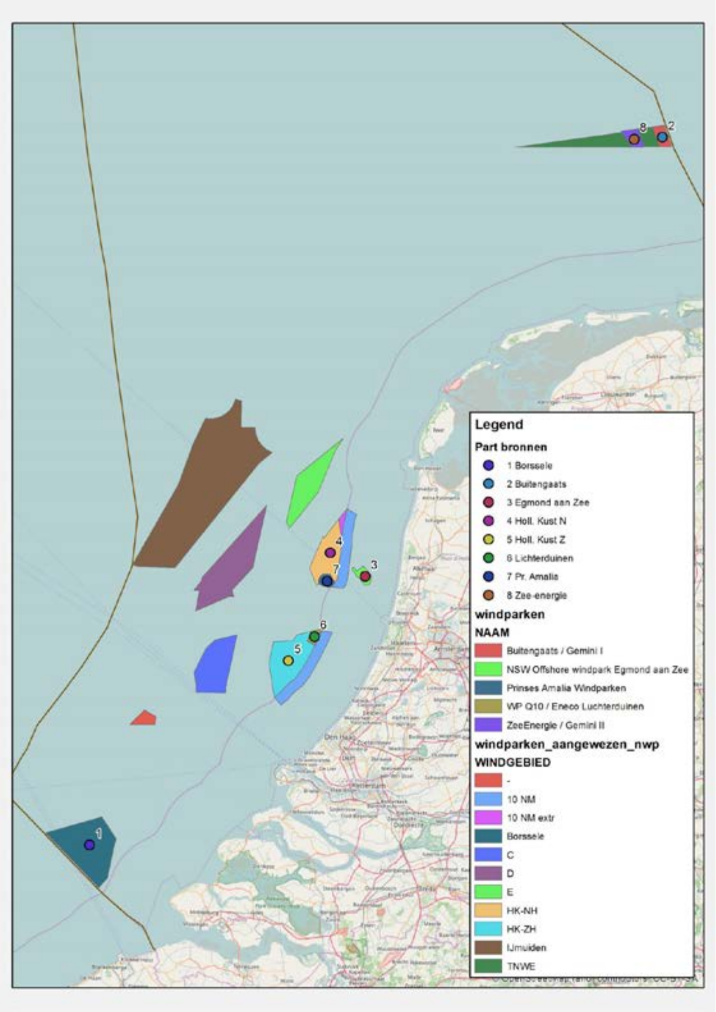


Figure 3.4.3.1: Release sites at wind farm locations for the simulation of larval transport in the North Sea and North Sea coastal zone.

The simulations were run for a period of about three months for each of the nine available years. After that, the average dispersal of 10-day-old larvae in the bottom water layer (near the seabed) was established. A specific total number of larvae were released at each release site, which number is derived from the percentage flux per week (Figure 3.4.2.1). While the result is formally expressed in units per cubic metre, wherever the larvae can be assumed to have been able to settle in the bottom water layer this can be translated to the number of larvae per square metre, which can serve as a measure for the likelihood of larval settlement. For example, if 1 x 10^{10} larvae are released during the three-month period, the actual output rate is 1 x 10^{10}/1.26 x 10^{8} = 79.2, as indicated in Section 3.4.2. In that case, the result is expressed as the number of larvae that have settled per square metre of seabed. Hence, if an estimate is available of the number of (surviving) larvae produced, this can be scaled up to the number of larvae that are able to settle (in suitable habitats) per square metre. Note that since this figure is an average over the three-month period concerned, it should be seen rather as a measure for the likelihood of settlement. The effect of the potential variation over time in the concentration of 10-day-old larvae has not been taken into account.

3.5 Critical mass

'Critical mass' is defined as the quantity of oysters required to ensure a larval count that is sufficient for potentially successful spat settlement and survival in the bed of origin. Using the larval model, this was determined by calculating the quantity of - or area for - oysters required in a certain source area to ensure successful larval settlement in that area or in another area close by (the settlement area), based on the following assumptions:

- oyster density per m^2: 50 (Smyth et al., 2016)
- number of larvae per female oyster: $2x10^6$ (Helm et al., 2004)
- larval survival rate during the first ten days: 30% (Helm et al., 2004)
- minimum larval concentration required: 50 per cubic metre in the settlement area (Kamermans et al., 2003)

The present model does not provide for the calculation of absolute critical mass values, as it involves too many assumptions to arrive at outcomes that allow reliable interpretation. In addition to the assumptions listed above, it also involves assumptions regarding oyster larvae behaviour (among others, see Fuchs et al., 2013; Smyth et al., 2016). The larvae are currently modelled as inert particles while in reality larvae behaviour is far more complex. This is why it was decided to calculate the relative size of the oyster population required for successful recruitment in the various areas, rather than absolute numbers.

4.Results

4.1 Habitat requirements of flat oysters in the North Sea

The conditions for the long-term development of a flat oyster bed are largely determined by four life-history processes: survival, growth, reproduction and recruitment. The presence of flat oysters depends on the manner in which the abiotic and biotic environmental factors influence these four processes, as indicated in Table 3.1.1. As discussed in the previous chapter, variables such as current velocity and local sea bed dynamics operate interactively. The same applies to other variables. The tolerance limits of oysters with respect to these factors should provide a window within which a habitat can be deemed to be suitable for oysters. In addition, biotic factors such as predation and competition will affect oyster beds, but for those factors no tolerance limit can be specified. In the table (Table 4.1.1) tolerance limits are given for the most important quantifiable factors. This is explained in further detail in the text, and linked to the conditions found in the North Sea.

Table 4.1.1. Relative suitability of environmental factors for flat oysters in the North Sea given the tolerance of oysters with respect to the variables mentioned; 0 = unsuitable, 1 = moderately suitable, 2 = suitable. The first five environmental factors (green) have been used to evaluate the suitability of the wind farm sites (Section 4.3).

	environmental factor	**suitability**		
		0	**1**	**2**
1	sea bed shear stress (N/m^2)	>1	> 0.6	0.25 - 0.6
2	sea bed motion (cm/day)	?	?> - >0.8	< 0.8
3	suspended particulate matter (mg/l)	> 180	60 – 180	< 60
4	water temperature (°C)	< 3, >30	3– 7 25-30	7 – 25
5	sediment composition	coarse sand > 210 µm	fine sand > 63 µm	gravel and silt with shell fragments
6	water depth (m below MSL)	< -80	79	< -1
7	salinity (‰)	< 20	20 - 25	25 – 35
8	food conc (chl µg/l)	?	< 1.68	> 1.68
9	oxygen con (mg/l)	<0.5	>1.5	> 3,5
10	current velocity (m/s)	> 0,8	< 0.25	0.25 - 0,8
11	Predation			
12	competition			

4.1.1 Sea bed shear stress

In this study, sea bed shear stress is used as a measure for local sea bed dynamics. Low sea bed shear stress is a prerequisite for oyster settlement. Sea bed shear stress is a function of sea bed surface roughness and current velocity. The presence of structures such as epifauna, biogenic reefs or empty shells potentially affects sea bed surface roughness. Water motion caused by tidal movements and waves is the process that determines substrate dynamics. Substrate can be more or less movable, depending on sediment, current velocity and wave energy supplied. Wave energy is often expressed as orbital velocity: the velocity of water just above the seabed caused by waves. The extent to which wave energy reaches the seabed depends on the height of the waves and the depth of the water. Waves are lower in coastal waters, but because these waters are shallow the orbital velocity is high. Offshore waves are higher, but under normal conditions their effect only reaches the seabed in shallower areas (such as the Dogger Bank). Orbital velocity has been factored into the model for sea bed shear stress with wave action (see Figure 4.2.1.1).

There are no direct measurement data for the tolerance limits of flat oysters with regard to sea bed shear stress. To fill this gap, the historical oyster distribution in Olsen (1883) were compared with recent sea bed shear stress maps, as current patterns are unlikely to have seen much change over the past 150 years. An area of the North Sea north of the Wadden Islands featured a large and uninterrupted population that was fairly sharply delineated on its southern and eastern edges by the 0.6 N/m^2 contour for average sea bed shear stress. Likewise, the Dogger Bank population was found in areas with relatively low levels of sea bed shear stress. The more southerly populations near the mouth of the English Channel and in the English Channel itself presented a different situation. There, extensive flat oyster populations were found historically along the coast and further out at sea in areas currently characterised by relatively high average and maximum sea bed shear stress levels. Note however that the maximum sea bed shear stress in several offshore areas is relatively low, and comparable with levels found in the Central Oystergrounds, for example.

The mouth of the English Channel and the English Channel itself feature extensive areas with hard substrate in the form of gravel. Perhaps this type of substrate offers sufficient compensation for flat oysters under relatively high sea bed shear stress levels, but no research data is available to verify this.

The above information allows us to assume that areas where sea bed shear stress is less than 0.6 N/m^2 must be deemed suitable for the development of flat oyster beds. Areas where sea bed shear stress levels are higher are only moderately suitable for that purpose, although individual oysters are probably quite capable of surviving there. It is difficult to identify the limit in excess of which sea bed shear stress levels make an area unsuitable for both the development of oyster banks and the survival of individual oysters. However, this is not particularly relevant to the central question of this study as regards the suitability of the wind farm sites, because the sea bed shear stress at all those sites is less than 1 N/m^2; see Section 4.2 for further details.

4.1.2 Sea bed motion

The sea bed structure may change under the influence of sand waves. This type of sediment transport is important for spat settlement and survival, and depends on the critical sea bed shear stress, i.e. the threshold in excess of which spat will begin to move and/or swirl up. The threshold is determined by sediment grain size, sediment density and the influence of biota on sediment strength. In a laboratory experiment, Grant et al. (1990) demonstrated that low concentrations of suspended sediment, when swirled up 0.1 cm/day, can contribute to nutrient intake and, as such, have a positive effect on the growth speed of *Ostrea edulis*, but that sediment churned up to 0.8 cm per day reduces growth. Tolerance of sea bed motion of up to 0.8 cm/day is therefore assumed. See Section 4.2.3 for a discussion of the model calculations performed for sea bed motion.

4.1.3 Concentration of suspended particles

The concentration of suspended particles is an important factor in oyster growth. Oysters filter suspended matter from the water; this includes phytoplankton, detritus and inorganic matter. The oysters use the phytoplankton to fuel their growth, but they have no use for the inorganic material in their metabolism. Higher concentrations of inorganic material will reduce the oysters' capacity for growth. This applies to most filter feeders, including flat oysters (e.g., Laing et al., 2005). Experiments have confirmed that suspended particle concentration levels in excess of 90 mg/l strongly inhibit growth in Japanese oysters (*Crassostrea gigas*) (Barillé et al., 1997). Measurements in a field set-up by Sawusdee et al. (2015) have shown that the total concentration of suspended matter just above the seabed (60 mg/l) is significantly higher than 80 cm above the seabed (40 mg/l). This resulted in significantly lower filtration rates for *Ostrea edulis,* although no significant effect was found on the condition of the oysters after 15 months. See Section 4.2.3 for a discussion of the model calculations performed for average and maximum suspended particle concentration levels.

4.1.4 Water temperature

Water temperature mainly impacts reproduction. Gonads develop at temperatures between 7 and 14 ^{0}C (Lubet, 1976). Larval survival and growth have been observed at temperatures between 10 and 31 °C with an optimum range of 25-27 ^{0}C (Davis & Calabrese, 1969). Spat settlement is found from 18.5 °C (Hoek, 1902). Spat survival requires a temperature higher than 3 °C (Child & Laing, 1998). Adult survival decreases at water temperatures in excess of 30 °C (Haure et al., 1998). Note however that populations are able to adapt to local water temperature ranges. In addition, more larvae are produced in water temperatures above the minimum of 18.5 °C. Figure 4.1.1. presents the modelled water temperature ranges in the North Sea. It shows that, in principle, water temperature is not a limiting factor for survival, although it may limit reproduction.

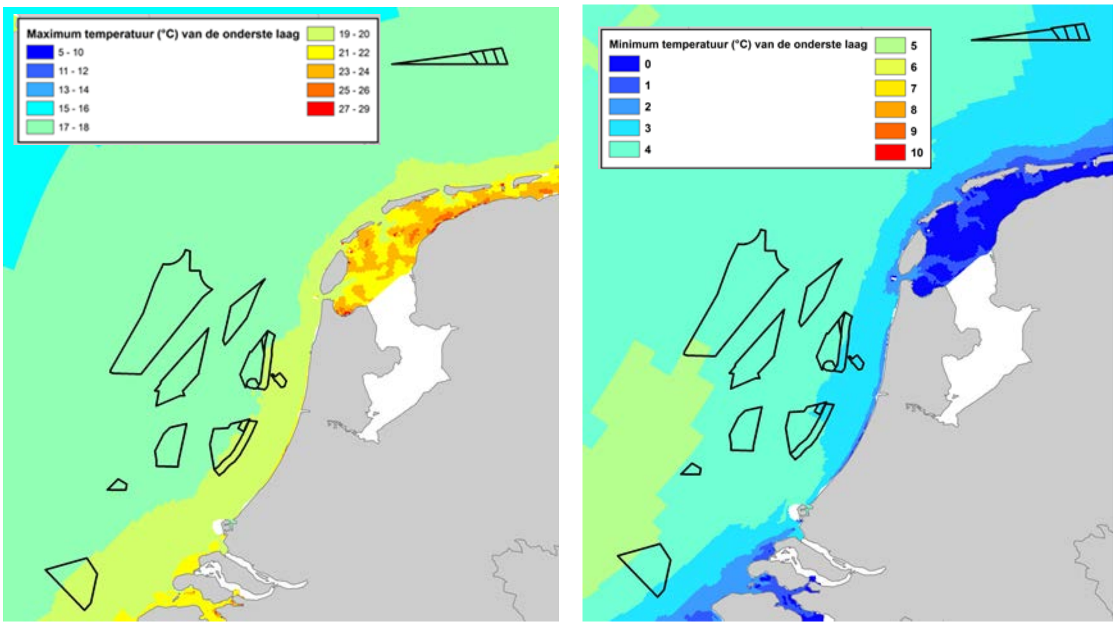


Figure 4.1.1. Maximum (left) and minimum (right) annual water temperatures in ºC near the seabed

4.1.5 Sediment composition

Sediment composition is important as it determines substrate suitability for recruitment. First of all, shells and existing oyster beds will promote recruitment. In the absence of shells and oyster beds, sediment grain size is the most commonly used parameter. Sediment grain size is easy to measure. Spatial patterns in the range of shellfish often correlate with sediment grain size, but there is little evidence that this is the primary factor; other factors that covary with grain size are probably far more important (Snelgrove & Butman, 1994). Water motion can have an impact on sediment composition because heavy particles settle sooner than light ones. This is why silt tends to accumulate in sheltered spots, while coarser sediment particles are found in exposed areas. As a rule, grain size varies according to the average local current. Houziaux et al. (2011) made a reconstruction of sediment composition along the Belgian coast as it was a hundred years ago. In their reconstruction, the seabed that accommodated extensive oyster beds before 1860 is described as follows: a heterogeneous gravel field partially covered by a thin layer (<15 cm) of sand through which bits of stone protruded. Wasson (2010) studied factors that could explain the dispersal of Olympia oysters (*Ostrea lurida*) in an estuary in California. Burial under a layer of fine sediment impeded the oysters' survival on small hard substrates. In areas with large amounts of silt, the oysters could only be found on large rocks. In the north-western part of the Mediterranean, oyster growth on shipwrecks is dominated by *Ostrea edulis* (Peirano, 2013).

Based on this dispersal data, coarse sand (grain size >210 µm) is classified as unsuitable, fine sand (>63 µm) as moderately suitable and firm silty sand or silty gravel with shells and stones (not defined in terms of grain size) as suitable for oyster growth. Figure 4.1.2 shows that sand with a large amount of silt only occurs in the northern wind farm sites. The sea bed in the other sites mainly consists of fine sand.

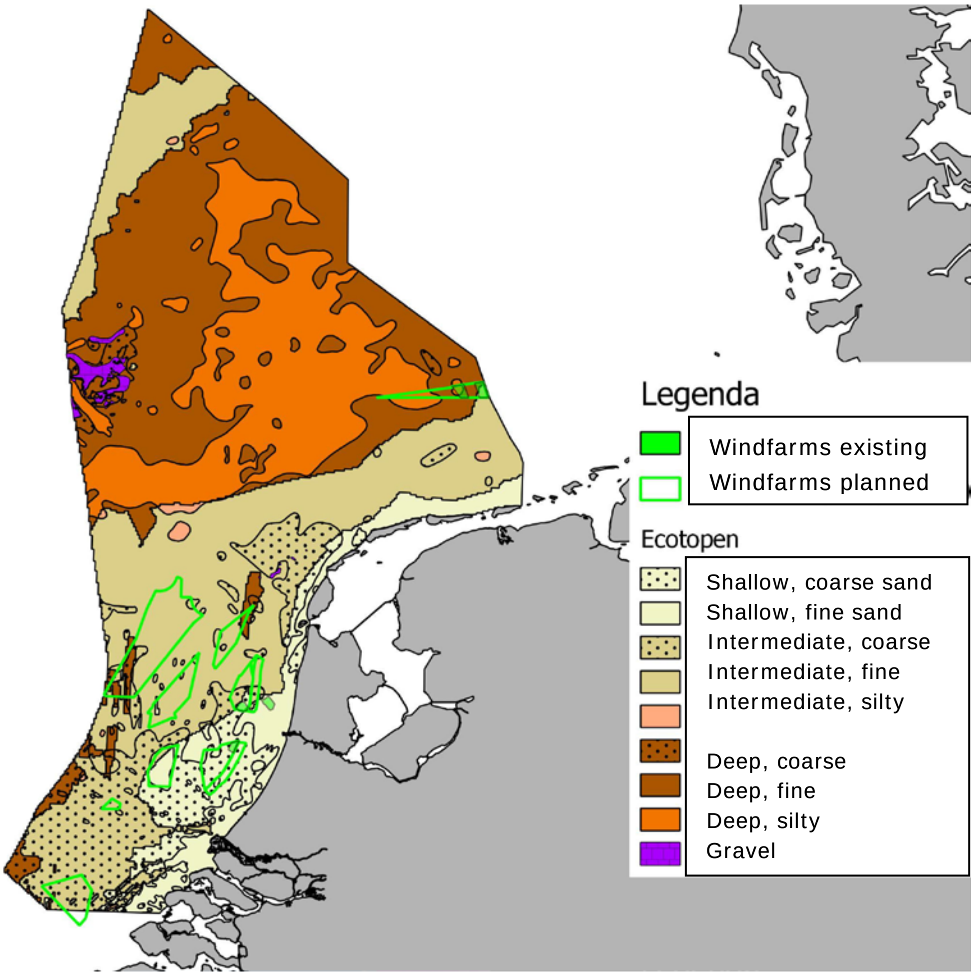


Figure 4.1.2 Sediment composition in the Dutch Continental Shelf (Icona, 1992).

4.1.6 Water depth

Water depth is an important factor in survival rates. In the intertidal zone, the time in between inundations is a limiting factor due to the unavailability of nutrients; in deeper water food and oxygen may be limiting factors. Flat oysters occur in estuaries (inshore tidal areas) up until the low low-tide zone (up to one metre below sea level) (Montes et al., 1991). In offshore and near-shore areas, flat oysters may occur down to depths of 80 metres (Hayward & Ryland, 1998). This means that, in principle, most areas within the DCS are suitable for flat oysters as regards depth (see Figure 4.1.3).

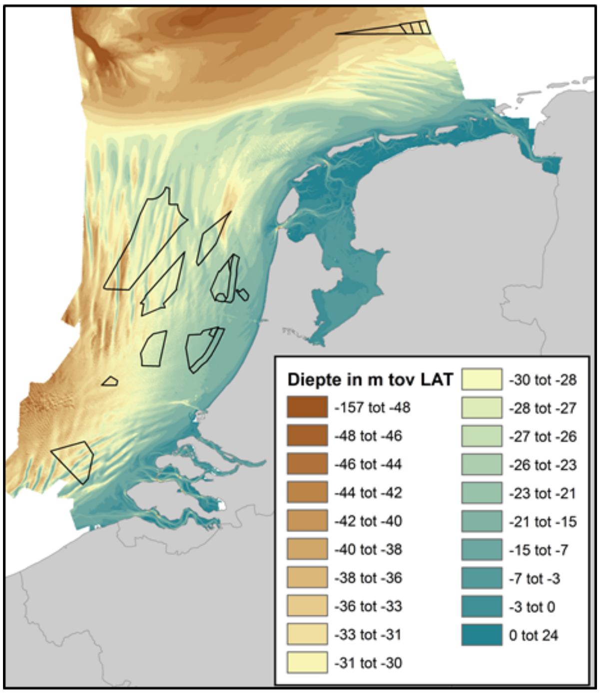


Figure 4.1.3. Wind farm sites in relation to depth (in metres) within the DCS .

4.1.7 Salinity

A salinity of 25–30 ‰ is optimal for spat survival and growth. A level between 20 and 25 ‰ is sub-optimal and salinity levels below 20 ‰ are unsuitable (Davies & Ansell, 1962). The salinity levels at all the wind farm sites in the Dutch section of the North Sea are suitable for oyster growth: see Figure 4.1.4.

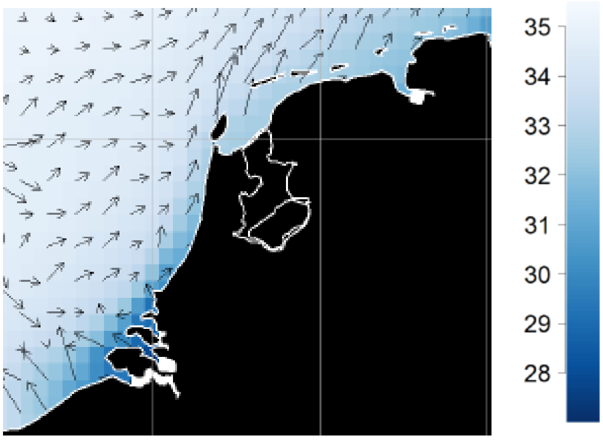


Figure 4.1.4. Salinity and water currents (Herman et al., 2014)

4.1.8 Supply of nutrients

The availability of nutrients is important to sustain growth and is expressed as the amount of chlorophyll per litre. Hatchery studies have shown that 1.68 µg/l is the optimal concentration for reproduction (Millican & Helm, 1994). Effective growth is achieved as soon as the available concentration exceeds 0.5 µg/l (Yildiz et al., 2011). As shown in Figure 4.1.5, shallow waters contain more nutrients than deeper offshore waters, but enough food can be found even there. It is safe to assume that in all wind farm sites, the supply of phytoplankton during most of the year is sufficient to sustain the growth and reproduction of flat oysters (Figure 4.1.4).

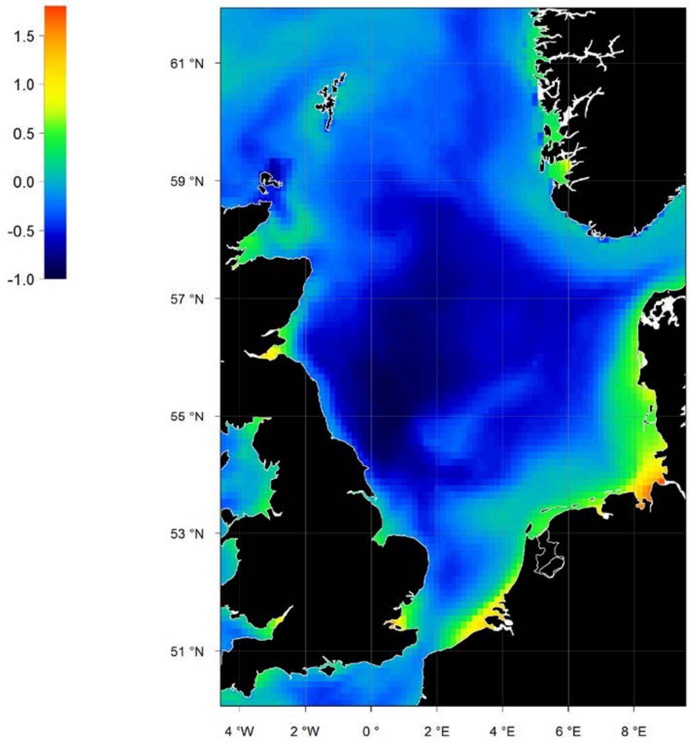


Figure 4.1.5. Long-term average chlorophyll concentration in the upper ten metres of the water column (µg/l). The figure is based on a logarithmic scale, 0 = 1 µg/l and n 1 = 10 µg/l. (Source: Herman et al., 2014).

4.1.9 Oxygen content

Oxygen content is another important factor in survival rates. Bivalve shellfish can survive without oxygen for a time, because they are adapted to temporary exposure to the air at low tide when they close their shells and switch to breathing without requiring oxygen. At low temperatures they can survive like that for several days, which explains why they do not have to be stored under water. In the North Sea there are no areas that fall dry, so there are no triggers either for shellfish to close their shells. Under such conditions, the minimum oxygen content for short-term survival is 0.5 mg/l (Davis, 1975). The review by Vaquer-Sunyer & Duarte (2008) has shown that the 412-hour LC 50, the concentration that allows 50% of bivalve shellfish to survive for 412 hours, is 1.5 mg/l. The LC 90, with 90% surviving, is 3.5 mg/l. The water at the wind farm sites is strongly mixed, which prevents stratification and eliminates the risk of low oxygen levels.

4.1.10 Current velocity

Current velocity is an important factor in recruitment and in the supply of nutrients and oxygen. Flat oysters show high growth and survival rates even in strong currents, as has been demonstrated in experiments in the North Sea (Pogoda et al., 2011). However, this does depend on the type of substrate available. Tolerance levels on hard substrate are much higher than on soft substrate. In 1961, Drinkwaard showed that flat oysters on soft substrate in the

Oosterschelde required current velocities of less than 0.25 m/s, with an optimum speed at around 0.03 m/s. This preference had to do mainly with the limited dispersal of flat oyster larvae, which tend to settle preferably on or near existing oyster beds. A low current velocity is an important condition that allows them to do so. However, historical data shows that flat oysters also thrived along the edges of gulleys, where currents are much stronger (Gercken & Schmidt, 2014). In addition, a relatively high current velocity prevents oysters from being buried by silt sediments. Based on this data and flat oyster ranges found on historical maps, the estimated optimum current velocity is between 0.25 and 0.6 m/sl; higher speeds are deemed to make a site unsuitable (for spat settlement) and lower speeds to make it sub-optimal (due to the higher sedimentation rate).

4.1.11 Predation

The absence of predation is an important factor in survival rates. Young flat oysters are vulnerable to predation until they are about 3 cm in size, mainly because of their thin shell (Gercken & Schmidt, 2014). Important generalist predators in this stage are starfish (*Asterias rubens*), whelk (*Buccinum undatum*), dogwhelk (*Nucella lapillus*) and large mobile crustaceans such as shore crab (*Carcinus maenas*) and edible crab (*Cancer pagurus*). In addition, there are several species of predatory snails that specialise in oysters (especially young specimens), such as the European sting winkle (*Ocenebra erinacea*), a native species, and the Atlantic oyster drill (*Urosalpinx cinerea*) and Japanese oyster drill (*Ocinebrellus inornatus*). The latter two oyster drills are invasive exotic species that have only recently been found in the Delta area (Oosterschelde; the Japanese oyster drill is also found in Lake Grevelingen). All these predatory snails depend on hard substrate to deposit their eggs, and do not produce pelagic larvae. Since they probably spread very little, if at all, across soft sediment (Didderen & Gittenberger, 2013), the chance that they are able to colonise offshore flat oyster beds is very slim. Most generalist predators, including starfish and crabs, can be found everywhere in the North Sea, and there are no indications that this does not include the wind farm sites.

4.1.12 Competition

Competition is an important factor in estimates of flat oyster survival and growth. A number of invertebrates compete with flat oysters for food (throughout their life cycle) and space. Most shellfish species which, like flat oysters, live on the seabed (epifauna) and filter phytoplankton (filter feeders) compete with flat oysters for food. In the deeper parts of the North Sea those species used to be more numerous, such as the northern horse mussel (*Modiolus modiolus*), but today they have all but disappeared. Flat oysters may also have to compete with Echinodermata such as the brittlestar (*Amphiura filiformis)* (Duineveld et al., 1987). This is a common species in the Central Oystergrounds and elsewhere in the deeper parts of the North Sea, up to the Gemini sites (Duineveld et al., 1987). Like flat oysters, brittlestars prefer deeper waters with large amounts of silt. However, the extent of competition is unknown because flat oysters disappeared from this area a long time ago.

4.2 Model simulations: sea bed dynamics and suspended particles on the wind farm sites

4.2.1 Sea bed shear stress

Permanently high levels of sea bed shear stress are found in the English Channel and around the eastern part of England (Norfolk). These are the areas with the strongest currents. In addition, sea bed shear stress levels are also relatively high in areas where wave energy can reach the seabed. Under normal conditions, this mainly occurs in very shallow coastal waters (Figure 4.2.1.1). In stormy weather sea bed shear values may well be in the next higher category. Under such conditions, the distribution of maximum levels for sea bed shear stress is largely determined by waves. This becomes evident when Figure 4.2.1.2 is compared with Figure 4.2.1.3. In fact, the only areas where these figures are different are the English Channel and the coastal waters off eastern England, where high average current velocities are found and where the sea bed shear stress is determined in part by water currents. On all other sites the pattern in the two figures is quite similar, confirming the notion that it is the waves that are responsible for the forces exerted on the seabed.

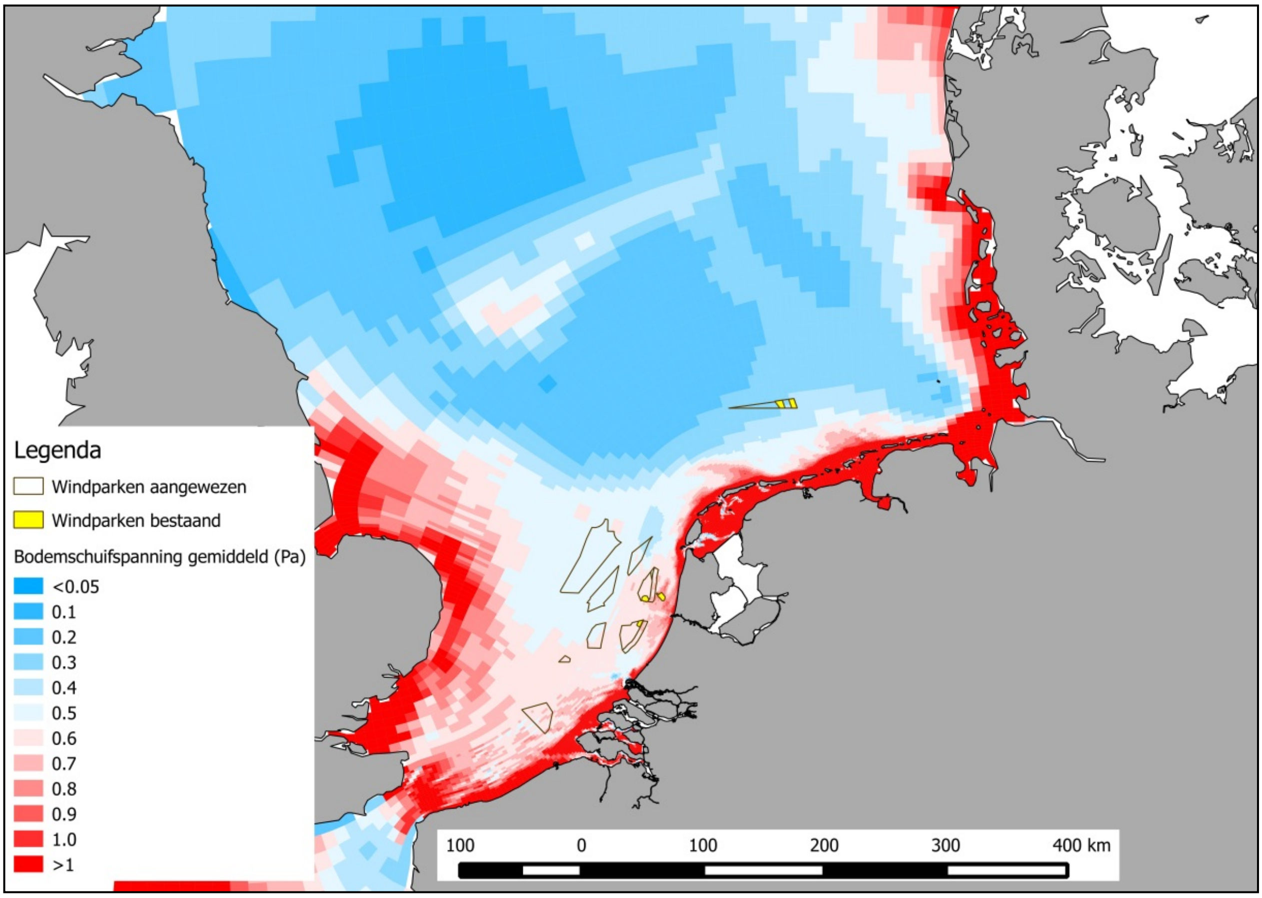


Figure 4.2.1.1. Average sea bed shear stress (in Pascal) in the North Sea, with combined effects of current and waves.

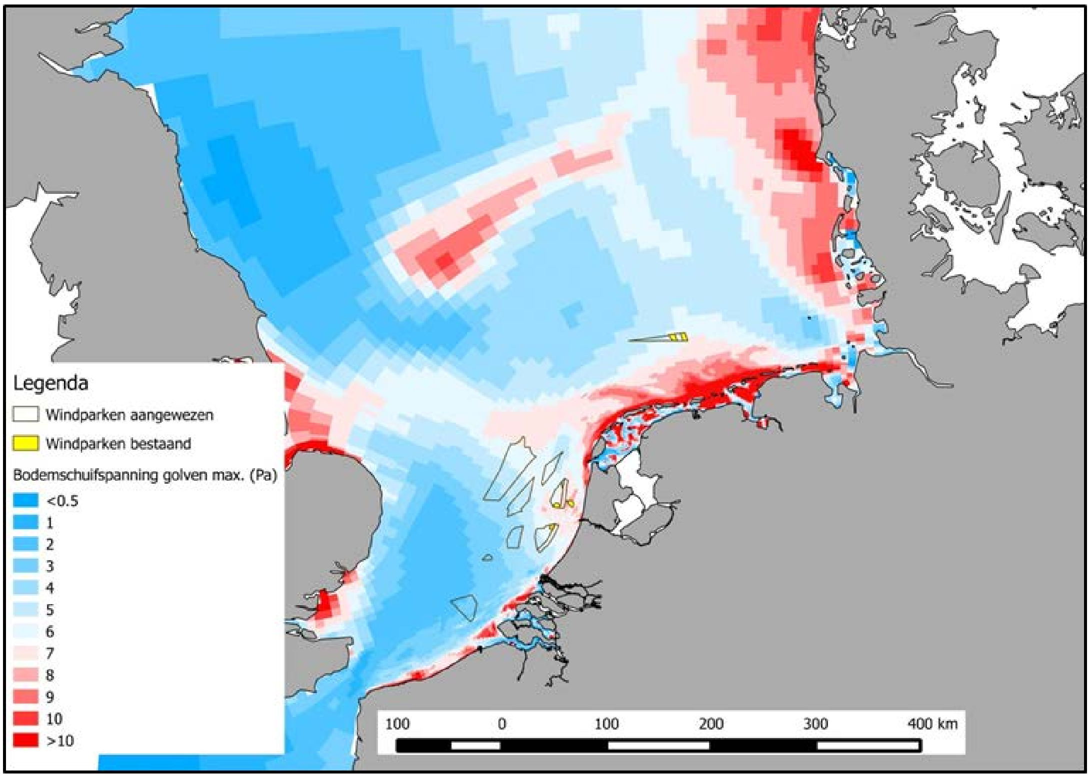


Figure 4.2.1.2. Wind farm sites in the DCS in relation to maximum sea bed shear stress (Pa) in the North Sea, presenting the combined effects of waves and current. NB.: The colour scale is one level higher than in Figure 4.2.1.1.

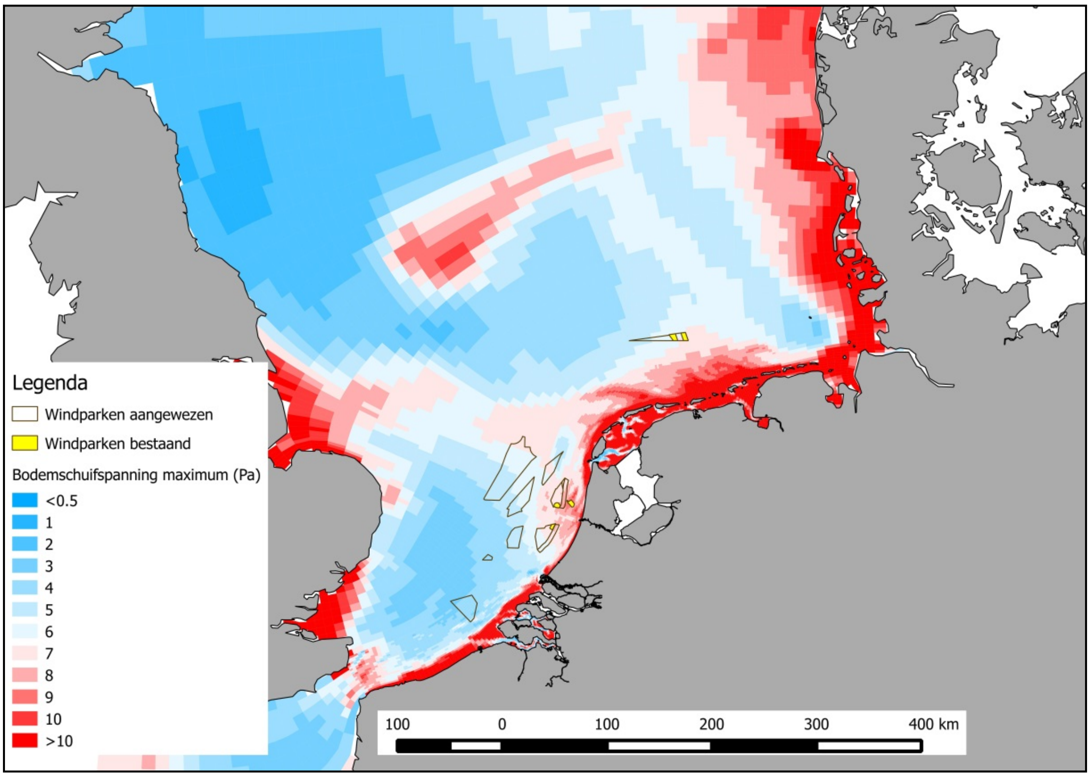


Figure 4.2.1.3. Wind farm sites in the DCS in relation to maximum sea bed shear stress (Pa) in the North Sea, presenting the effect of waves only. NB.: The colour scale is the same as in Figure 4.2.1.2.

The location of the Dogger Bank immediately stands out in both these figures. The seabed in this shallow area in the North Sea is more exposed to the impact of waves than surrounding areas.

A comparison of the spatial distribution of sea bed shear stress and the historical range of oysters provides an indication of the significance of water motion for the availability of suitable habitats. In Figure 4.2.1.4, the old oyster range map from Olsen's *Piscatorial Atlas* (1883) has been superimposed on model data of maximum sea bed shear stress and the distribution of wave-induced sea bed shear stress. The figure appears somewhat distorted, due to the slightly different projection of the old map compared with the model data. For completeness' sake, Olsen's original map is also presented separately in Figure 4.2.1.5.

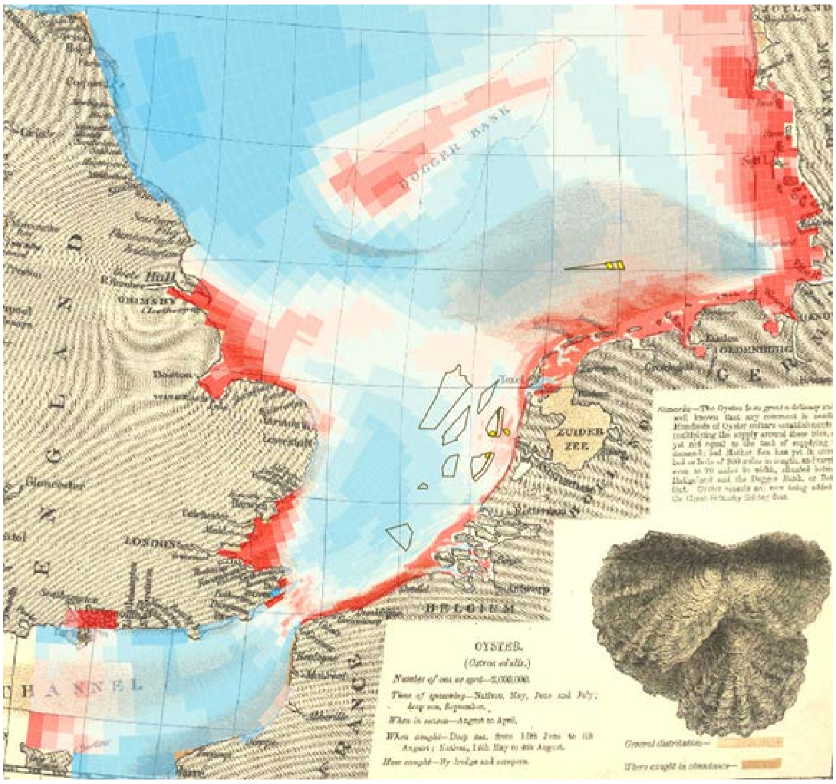


Figure 4.2.1.4. Wind farm sites in the DCS in relation to maximum sea bed shear stress in the North Sea and the historical oyster range (outlined) (Olsen, 1883). The legend is the same as for Figure 4.2.1.2.

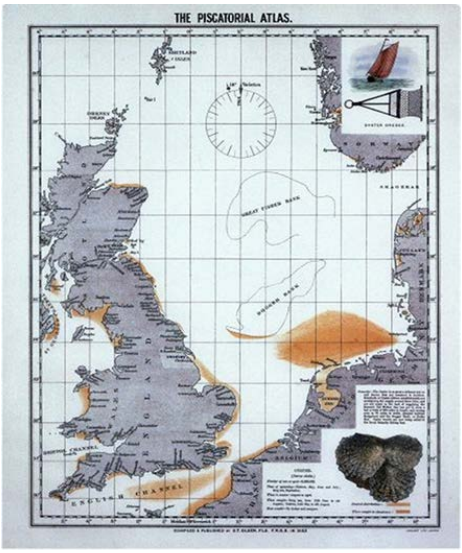


Figure 4.2.1.5. Map from Olsen's *Piscatorial Atlas* (1883) with the oyster range represented in brown.

This comparison shows in particular that flat oysters used to be fairly common in areas characterised by high current velocities near the seabed. Flat oysters could be found in relative abundance in the English Channel south of England up to the Straits of Dover. These are areas where current velocities (and the associated sea bed shear stress levels) are high, although the sea bed is relatively unaffected by waves (see Figure 4.2.1.5). There are no known figures from the literature on critical values that trigger oyster movement. This will also depend strongly on the type of substrate (whether the oysters are attached to hard substrate or other oysters, or are lying unattached on top of the sediment).

4.2.2 Sea bed structure / motion

The diagrams below present the height and migration speed of sand waves on the Borssele wind farm. The sand waves on this site vary in terms of length, height and 'propagation speed'. A sand wave with an average wave length (from crest to crest) and height of one metre has an average gradient of 2 cm per metre (the 1-metre difference in height is covered twice over a distance of 100 metres, from crest to trough and vice versa). A propagation speed of two metres per year for this wave results in an average change in sea bed height of around 4 cm per year, which works out at 0.011 cm/day. Wave lengths at the Borssele site vary from 114 to 513 metres (median length 234 metres), wave heights vary from 1.4 to 7 metres (median 3.7 metres) and propagation speeds vary from 0.6 to 3.2 metres per year (median 1.7 metres per year).

The average change in sea bed height (sedimentation or erosion) is 0.015 cm per day (or 5 cm per year), with a maximum of 0.108 cm/day (± 40 cm per year) and a minimum of 0.001 cm/day. This is well below the estimated tolerance limit for oysters of 0.8 cm/day. If only these net annual averages were taken into account, the entire Borssele wind farm would, in principle, qualify as suitable as far as sea bed motion is concerned. However, we should remember that sea bed motion is not usually a gradual process, but tends to occur mainly during brief episodes of stormy weather. The more dynamic areas in particular, with annual sea bed change averages of 0.1 cm per day, are very likely to see the oyster tolerance levels being exceeded several times a year. The existing level of knowledge offers little scope for predicting exactly where the tolerance limits will *not* be exceeded. However, as far as the selection of sites within the Borssele wind farm is concerned, it would definitely make sense to opt for locations where wave migration speeds are low. These are the white areas in the bottom diagram. There is no data on sea bed motion for the other wind farms. Since Borssele is probably the most dynamic site, all the other wind farms are likely to be suitable for flat oysters where sea bed motion is concerned.

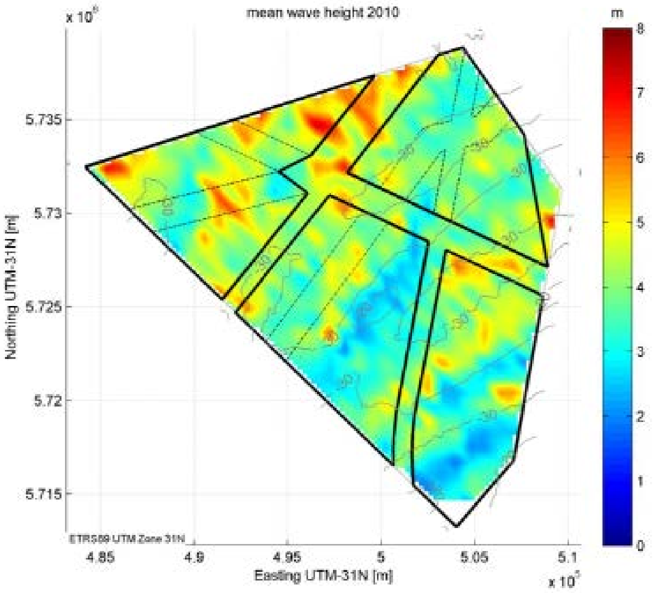


Figure 4.13 Map plots of wave lengths (top plot) and wave heights (bottom plot) estimated using the automatic selection of crest and trough points of 665 transects from the 2010 survey

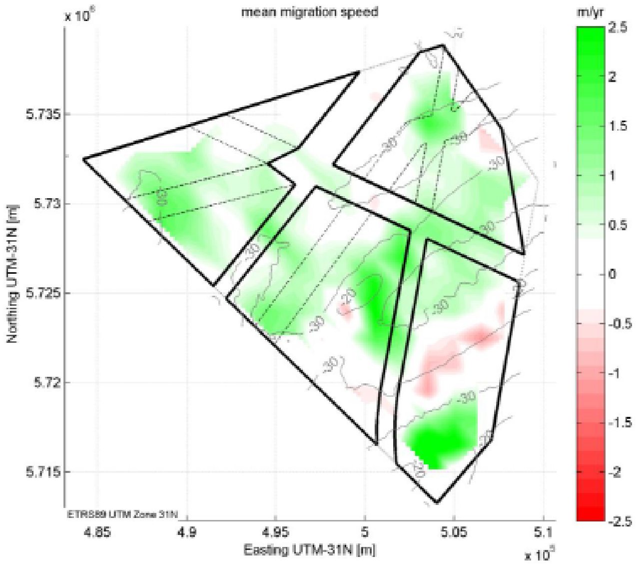


Figure 4.11 Map plots of migration distances (top plot) and migration speeds (bottom plot) estimated using the manual selection of crest and trough points of 153 transects in BWFZ (red = NE, green = SW).

Figure 4.2.2.1. Sand wave height (top) and migration speed in a north-easterly and south-easterly direction (bottom) on the Borssele wind farm. Source: Riezebos et al., 2014. Top right: site I; bottom right: site II; centre: site III; top left: site IV.

4.2.3 Concentration of suspended particles

The data for silt levels - both annual averages and peak values of suspended particles - in the bottom layer of the water is derived from model calculations; see Figure 4.2.3. The two maps employ the same colour scale. This model also presents high silt levels (> 50 mg/l, even under 'normal' conditions) for sites where flat oysters are currently found in the Grevelingen estuary. However, the model resolution is not sufficiently high to identify extremely local conditions (such as shelter provided by a breakwater or a dam, which results in lower levels of suspended particles).

Year-average data always locate the highest concentrations of suspended particles in shallow coastal waters, due to wave-induced turbulence. Note that the model also identifies fairly high silt levels, even in the bottom layers over oyster beds, under peak conditions. These sites are likely to see settlement of material churned up elsewhere during a storm, resulting in relatively high concentrations on these sites.

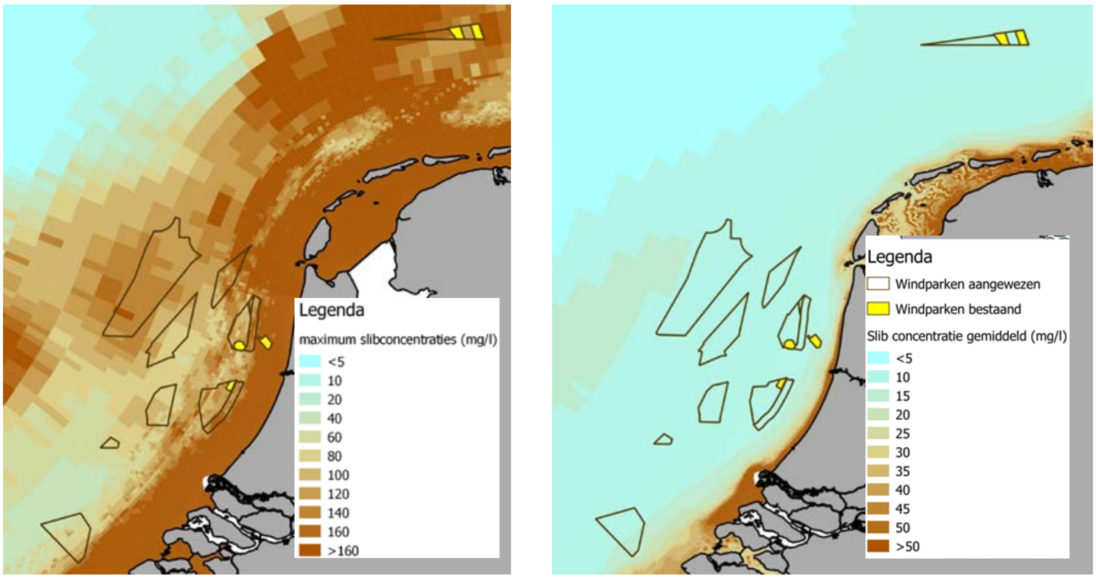


Figure 4.2.3. Maximum and average concentrations of inorganic suspended particles (mg/l) near the seabed in Dutch coastal waters, based on model simulation data.

4.3 Suitability of wind farm sites for flat oysters

A selection of habitat criteria was used to assess the suitability for flat oysters of the wind farm sites studied. The criteria concerned are sea bed shear stress, concentration of inorganic suspended particles, water temperature, sea bed structure and motion, and sediment composition. Historical range data based on Olsen (1883) and Houziaux (2011) was incorporated into this assessment, as were recent finds of unattached flat oysters on, for example, stone embankments and foundation piles on the OWEZ and Prinses Amalia wind farms (Bouma & Lengkeek, 2013; Smaal et al., 2015). The maps in Sections 4.1 and 4.2 were used to arrive at the values for the various habitat factors. The assessment of each of the wind farm sites is based on these values combined with the tolerance limits of flat oysters found in the literature (Table 4.1.1).

The most extensive range of flat oysters in the North Sea is known from publications from the second part of the nineteenth (Olsen, 1883) and the early twentieth century (cited in Gercken & Schmidt, 2014; Houziaux 2011). More recently, flat oysters in the Dutch section of the North Sea were found particularly in the Voordelta (in a mixed population of flat oysters and Japanese oysters) and in Grevelingen and the Oosterschelde. The historical range of flat oysters in the

Dutch section of the North Sea covered the area from the mouth of the English Channel to the Vlakte van de Raan (nearshore; Houziaux 2011), the Central Oystergrounds and the southern edge of the Dogger Bank (offshore, Olsen, 1883). The species was also found in the sublittoral zones (inshore) of the northern North Sea (today the Wadden Sea) and the former southern Zuiderzee (today IJsselmeer, Markermeer and IJmeer). In the Central Oystergrounds (the northern part of the DCS), the flat oyster range covers a large and uninterrupted area far away from the coastal waters. In the English Channel up to the Vlakte van de Raan (the southern part of the DCS), the areas where flat oysters are found are smaller, fragmented and at a relatively constant distance from the coast.

These three ranges (inshore, nearshore and offshore) are quite different in terms of several abiotic factors (sediment composition, current velocity, sea bed shear stress, suspended particles and water temperature). This makes it difficult to extract an unambiguous profile of the flat oyster range. Perhaps conditions that are unfavourable in a particular stage of the flat oyster life cycle can be compensated by other, favourable factors. For this reason, the historical range will be used as a separate factor in evaluating the potential suitability of an area: Table 4.3.1.

Table 4.3.1. Suitability of wind farm habitats for flat oysters based on sea bed shear stress, suspended particles, water temperature (winter minimum and summer maximum), sea bed structure and motion, sediment composition and historical range: white = less suitable, red = moderately suitable, green = suitable.

wind farm	sea bed shear stress (N/m2)			suspended matter (mg/l)		water temperature oC		sea bed motion	sediment composition	historical occurence
	max	max wave action	avg	max	avg	min	max	cm/dag		
Borssele	2	2	0,6	25	10	4	20	0 (local)	coarse to fuine sand	yes
HK-Zuid	4	5	0,6	35	10	4	18	?	fine sand	no
OWEZ	8	8	0,8	50	20	3	20	?	fine sand	no
HK-noord	5	6	0,6	35	10	4	18	?	fine sand	no
Luchterduinen	5	6	0,6	35	10	3	20	?	fine sand	no
Prinses Amalia	5	7	0,6	35	10	3	18	?	fine sand	no
Buitengaats	4	7	0,4	40	10	3	18	?	fine sand	yes
Zee-energie	4	6	0,3	40	10	3	18	?	silty sand	yes

The average sea bed shear stress (τ_{gem}) in the Gemini sites of Buitengaats and Zee-energie is suitable; elsewhere it is moderately suitable (see 4.2.1). Total maximum sea bed shear stress levels and maximum levels for wave action alone are lowest in Borssele and slightly higher on the other sites. On the criterion of suspended particles (average and minimum concentration levels), all sites are suitable with the exception of OWEZ (see Section 4.2.3). As expected, minimum and maximum water temperature levels near the seabed are slightly higher on the southern sites (Borssele up to Luchterduinen) and slightly lower on the more northerly sites (Gemini Buitengaats and Zee-energie). However, water temperature levels are suitable for flat oysters on all sites. Borssele is the only site for which detailed sea bed motion data is available in terms of sand wave height and migration speed (see Section 4.2.2). The wind farm sites offer sufficient areas with zero or extremely low sea bed motion. Sea bed shear stress in the troughs of the sand waves may be lower than the overall area averages. Sand with large quantities of silt that qualifies as suitable for flat oysters is only found on the northern wind farm sites, particularly Gemini Buitengaats. On the other wind farms the seabed is composed mainly of fine sand, which is only moderately suitable for flat oysters. As pointed out in Section 4.1, the potential of a site for spat settlement is determined mainly by the quantity of shell material on the seabed, but no data is available for that feature. In the nineteenth century, flat oyster beds were common in the North Sea north of the Wadden Islands, including the Gemini sites (Olsen, 1883). The Borssele site is also known to have supported oyster beds in the past (Houziaux, 2011).

This habitat suitability analysis has revealed that all wind farm sites are at least 'moderately suitable' for flat oysters, and that Borssele, Gemini Buitengaats and Gemini Zee-energie are 'suitable'. The latter is due in particular to the low levels of average (Gemini) and maximum (Borssele) sea bed shear stress, low sea bed dynamics (Borssele), and suitable sediment, i.e. sand with a large amount of silt (Gemini Zee-energie). Recent finds of unattached flat oysters near Borssele and at OWEZ and Amalia (Smaal et al., 2015) have confirmed that most wind farm sites are suitable for the survival, growth and reproduction of flat oysters. Historical observations of the range of flat oyster beds at Borssele and Gemini show that these sites offer promising habitat for the development of flat oyster beds, provided that there is a source of larvae and a sufficient supply of suitable substrate for settlement (shells): Table 4.3.2.

Table 4.3.2. Suitability of habitats offered by the wind farm sites. The table shows the relative suitability of each site (0 = unsuitable; 1 = moderately suitable; 2 = suitable; - = cannot be assessed), based on the tolerance limits set out in Table 4.1.1.

wind farm	sea bed shear stress	suspended matter		water temperature		sediment	historical occurence
	avg	max	avg	min	max		
Borssele	1	2	2	2	2	1	2
HK-Zuid	1	2	2	2	2	1	1
OWEZ	1	1	2	2	2	1	1
HK-noord	1	2	2	2	2	1	1
Luchterduinen	1	2	2	2	2	1	1
Prinses Amalia	1	2	2	2	2	1	1
Buitengaats	2	2	2	2	2	1	2
Zee-energie	2	2	2	2	2	2	2

4.4 Larval transport

The figures below present the simulated larval dispersal from the various sources (wind farms). They show the average concentrations per square metre near the seabed for 10-day-old particles, based on a total released quantity of 1.26×10^8 (arbitrary units). In other words, the dispersal maps present a picture of larval dispersal in relative terms. In colours ranging from dark green to yellow to represent decreasing larval concentration levels, the maps show that larval retention in Borssele (Figure 4.4.1a) and the two northerly wind farms Buitengaats and Zee-energie (Figures 4.4.1 g and h) is much higher than on the other wind farms along the Zuid- and Noord-Holland coast, which are subject to the outflow of the Rhine and the northward current. While the Borssele and Gemini sites do experience tidal currents, the net current is relatively weak. This means that most 10-day-old larvae on the wind farms along the Zuid- and Noord-Holland coast leave the site. They can however reach neighbouring wind farms with relative ease. Populations located within these wind farms are likely to depend on other areas for a considerable part of their larval supply. Needless to add, this model simulation and the conclusions drawn from it are susceptible to the assumptions made with regard to the duration of the larval phase (a 10-day planktonic phase) and the way in which the larvae move (passive transport). Given the temperatures during the spawning season, it may well be the case that the actual planktonic period is slightly longer; moreover active settlement behaviour of the larvae is likely to occur as well. While this would not affect the overall pattern, the average larval population density would rise, thereby increasing the chances of settlement. The maximum distance covered by the larvae would also increase.

Figure 4.4.1a Simulated larval dispersal from the Borssele wind farm over a 10-day period. The legend presents relative concentration values. This means that the figure presents dispersal rather than absolute concentration figures.

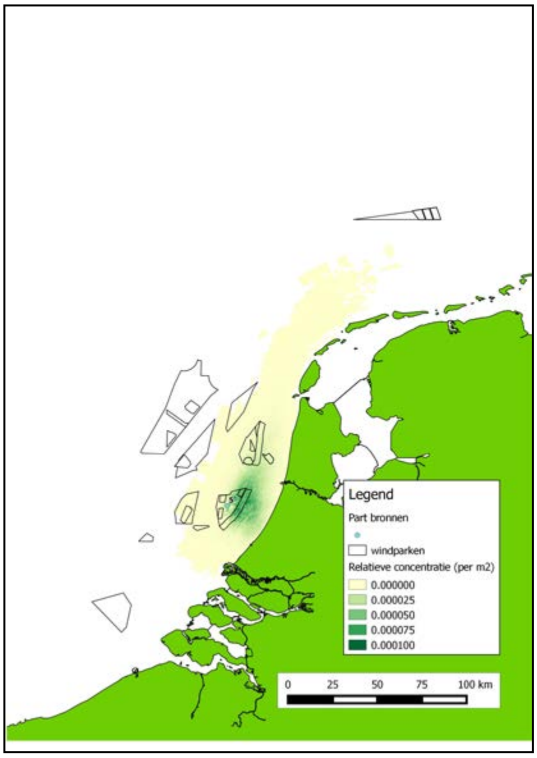


Figure 4.4.1b Same for HK-zuid.

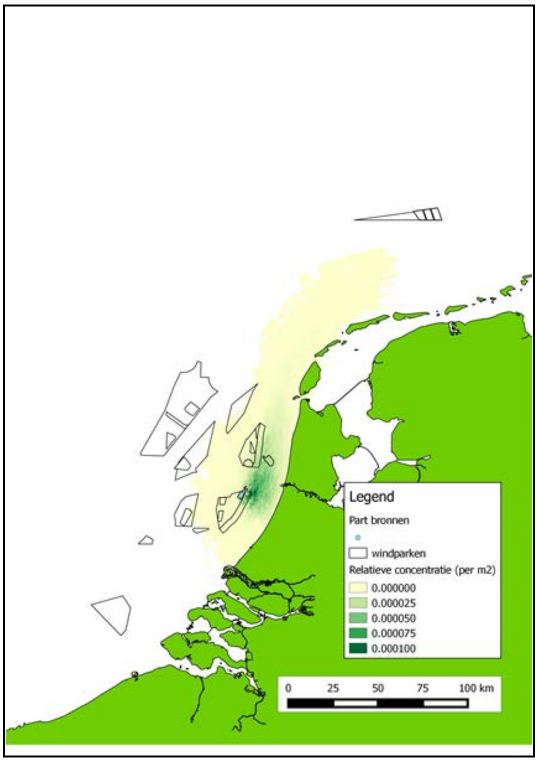


Figure 4.4.1c Same for Luchterduinen.

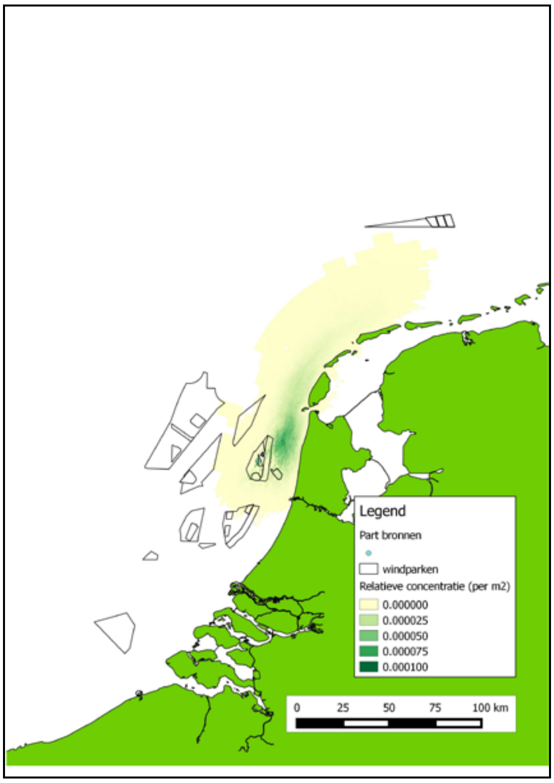


Figure 4.4.1d Same for HK-noord.

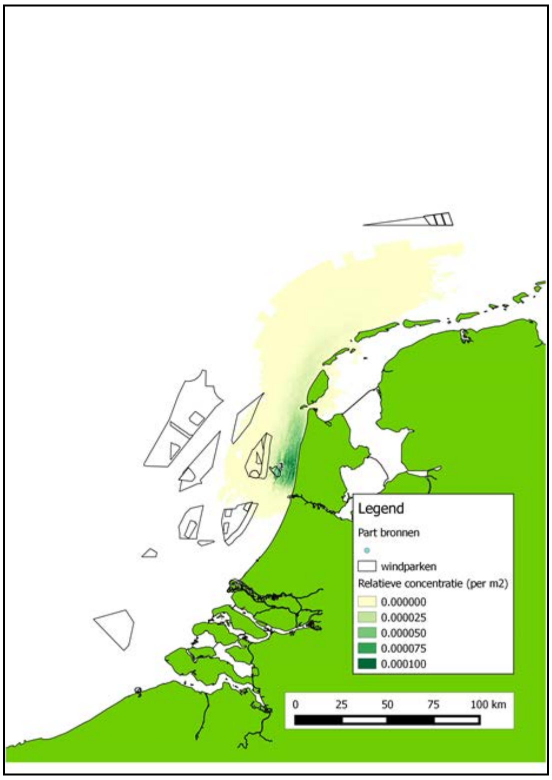


Figure 4.4.1e Same for OWEZ.

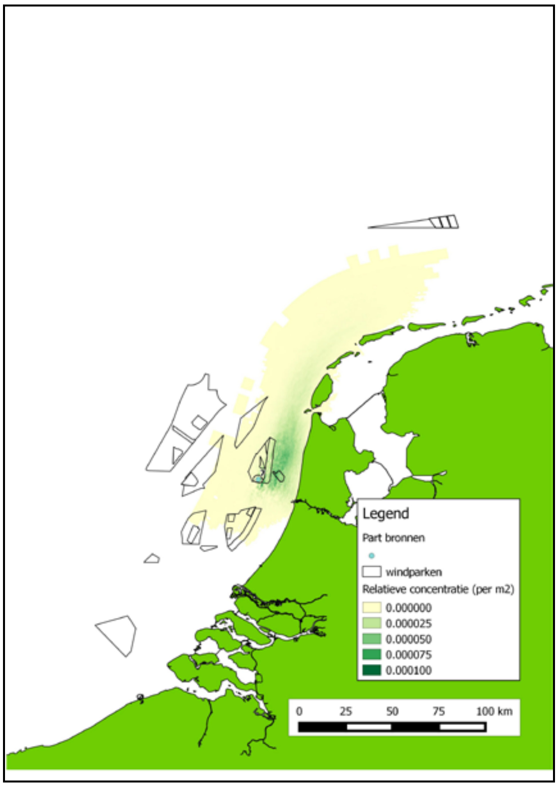


Figure 4.4.1f Same for Prinses Amalia.

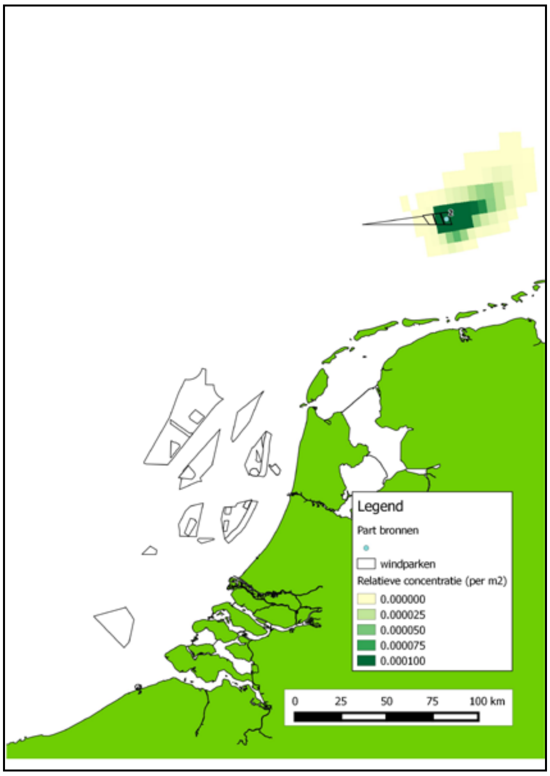


Figure 4.4.1g Same for Buitengaats.

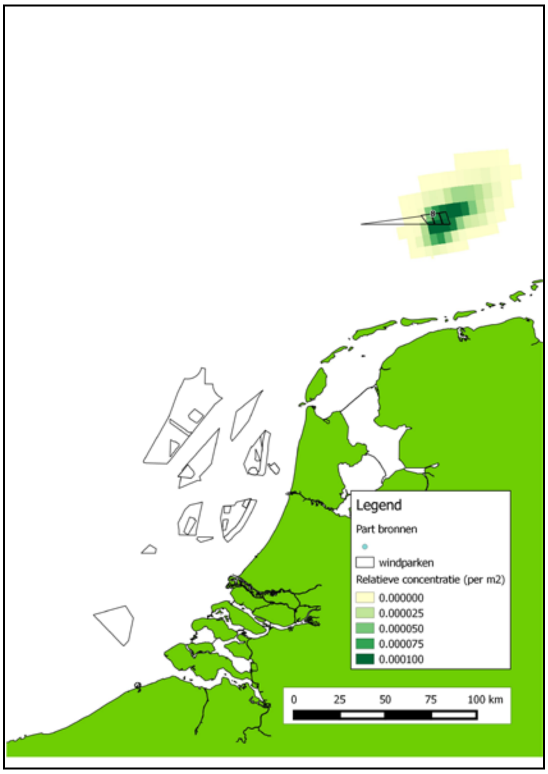


Figure 4.4.1h Same for Zee-energie.

Table 4.4.1 shows the extent to which larvae from a specific wind farm end up on the same wind farm (green) or also manage to reach other wind farms (blue). In the current simulation, larvae from Borssele appear to be unable to reach the other sites, but only by a narrow margin. It is conceivable that with a slightly longer planktonic phase, Borssele too can serve as a source location. Larvae from Kust-zuid also reach Luchterduinen, OWEZ and Amalia. Luchterduinen is a source of larvae for OWEZ and Amalia. The larvae from the Amalia wind farm move towards OWEZ and do not result in spat settlement within Amalia itself. Larvae from Zee-energie also reach Buitengaats, while larvae from Buitengaats flow out in an easterly direction.

Table 4.4.1. Indication of larval transport within (green) and among (blue) wind farm sites in the DCS
.

	Source							
Station	Borssele	Kust Z	Luchterduinen	Owez	Amalia	Kust N	Zee-energie	Buitengaats
Borssele	🟩	-	-	-	-	-	-	-
Kust-Z	-	🟩	-	-	-	-	-	-
Luchterduinen	-	🟦	🟩	-	-	-	-	-
Owez	-	🟦	🟦	🟩	🟦	🟦	-	-
Amalia	-	🟦	🟦	-	-	🟦	-	-
Kust-N	-	-	-	-	-	🟩	-	-
Zee-energie	-	-	-	-	-	-	🟩	-
Buitengaats	-	-	-	-	-	-	🟦	🟩

4.5 Critical mass

The model was used to calculate the quantity of oysters required in a given area to ensure sufficient production of larvae for a concentration of 50 per square metre, which is regarded as the minimum level to achieve recruitment. The calculation not only covered the source area itself, but also aimed to establish the number of oysters in the source area required to produce larvae in sufficient quantities to also 'fertilise' other wind farm sites. In a number of cases this was indeed shown to be possible, meaning that recruitment may be achieved with larvae from a different wind farm.

The model simulation offers qualitative indications only; quantification requires a more solid substantiation of the model assumptions. For that reason, five categories have been distinguished, A through E, with categories A and E representing situations in which the fewest and the most oysters are required, respectively, to retain sufficient larvae for recruitment. The qualitative indications in Table 4.5.1 show that relatively few oysters are required on the northerly Zee-energie site, especially for recruitment in the Buitengaats area (categories A and B). Table 4.5.1 also shows that Hollandse Kust Zuid and Amalia generate recruitment in Luchterduinen and OWEZ, respectively, on the basis of a relatively small oyster population. These wind farm sites are presented in blue, because they fail to ensure effective recruitment in the source area itself. Recruitment in Luchterduinen requires a larger number of oysters; the same applies to Borssele (category C). Recruitment from Hollandse Kust Noord requires a relatively large oyster population, because the majority of larvae will flow out up into the Wadden Sea.

Table 4.5.1. Relative size of oyster populations required for on-site recruitment or recruitment in neighbouring areas. Cat A = minimum, Cat E = maximum stock required. Green indicates on-site recruitment, while blue represents the absence of on-site recruitment. Red denotes less recruitment within the wind farm sites.

	Source							
Station	Borssele	Kust Z	Luchter duinen	Owez	Amalia	Kust N	Zee-energie	Buiten gaats
Borssele	C	-	-	-	-	-	-	-
Kust-Z	-	D	-	-	-	-	-	-
Luchterduinen	-	B	C	-	-	-	-	-
Owez	-	E	D	C	B	E	-	-
Amalia	-	E	E	-	-	E	-	-
Kust-N	-	-	-	-	-	E	-	-
Zee-energie	-	-	-	-	-	-	B	-
Buitengaats	-	-	-	-	-	-	A	D

4.6 Integration

Oyster beds in the North Sea can only develop under conditions that are favourable for the entire life cycle: survival, growth, reproduction and successful recruitment. Survival is determined mainly by large-scale and local sea bed dynamics, or sea bed motion and sea bed shear stress respectively. As regard sea bed motion, the situation was examined at Borssele, a location known to have relatively many sand waves compared with the other sites. It was found that sea bed motion does not inhibit oyster development at all sites within Borssele, which means that large-scale sea bed dynamics as such is not a limiting factor. The various sites do however experience different levels of sea bed shear stress, with the lowest values found in the Gemini area and on the Zee-energie and Buitengaats wind farms. At most wind farms, sea bed shear stress corresponds with sea bed sediment composition; the seabed at Zee-energie contains slightly larger amounts of silt. As regards survival, the highest scores are for Zee-energie, Buitengaats and Borssele – which are all relatively close to sites where flat oysters occurred in the past. The coastal sites attract lower scores in terms of sea bed shear stress, sediment composition and historical range. Factors such as oxygen content and salinity have no limiting effect on oyster survival on the wind farms. Growth and reproduction mainly depend on the availability of food, which is determined by the presence of phytoplankton and suspended particles. While phytoplankton is not seen as a limiting factor, suspended particles do qualify as an inhibitor. For that reason, it was determined to what extent the levels of suspended particles near the seabed differ among the various wind farm sites and have limiting effects. Such an effect was found only at OWEZ, the site which is closest to the coast. Water temperature does not inhibit reproduction, as is confirmed by data on the historical range of flat oysters in the North Sea. As regards the chance of settlement, model simulations show that Buitengaats qualifies for potentially successful recruitment, especially from a relatively small parent population at Zee-energie, aided by proximity and the net eastward current. The simulations also show that the Prinses Amalia site should be able to serve as a source for spat settlement in OWEZ. With a moderate population, the Borssele wind farm could see successful recruitment within its boundaries; the same applies to Luchterduinen.

From a whole life-cycle perspective, therefore, Zee-energie combined with Buitengaats appear to be relatively suitable for the development of flat oyster beds, followed by Borssele and Luchterduinen. The shallower coastal sites also offer opportunities for developing oyster beds, but the seabed in these locations is slightly less stable and they experience more larval outflow without immediately benefiting neighbouring sites.

Table 4.6.1. Overview of relative suitability of wind farm sites for the development of flat oyster beds.

wind farm	sea bed shear stress	suspended matter		water temperature		sediment	historical occurence	larval supply	sum
	gem	max	gem	min	max				
Borssele	1	2	2	2	2	1	2	2	14
HK-Zuid	1	2	2	2	2	1	1	1	12
OWEZ	1	1	2	2	2	1	1	2	12
HK-noord	1	2	2	2	2	1	1	1	12
Luchterduinen	1	2	2	2	2	1	1	2	13
Prinses Amalia	1	2	2	2	2	1	1	1	12
Buitengaats	2	2	2	2	2	1	2	1	14
Zee-energie	2	2	2	2	2	2	2	2	16

5. Conclusions

The following conclusions can be drawn from this study into the opportunities for survival, growth, reproduction and recruitment of flat oyster populations (*Ostrea edulis*) within existing and planned wind farms in the Dutch section of the North Sea:

1. Crucial habitat factors for the development of flat oyster beds on the wind farms in the Dutch section of the North Sea are (i) large-scale and small-scale seabed dynamics, (ii) sediment composition, (iii) suspended particle levels in the water column, and (iv) the possibility of successful recruitment. The latter factor depends on the size of the parent population and water motion.
2. Other important factors such as phytoplankton, salinity and oxygen content have no limiting effect. Predation and competition are also important, but it is impossible to say to what extent they limit the development of flat oyster beds on the wind farm sites concerned.
3. In this analysis, the relative suitability of wind farm sites for flat oysters is determined by sea bed shear stress (small-scale sea bed dynamics) and by the related factors of sediment composition, suspended particle concentrations and the chance of recruitment. Sand wave migration (large-scale sea bed dynamics) has limiting effects in part - but not all - of the Borssele site, and is absent from the other wind farms. Historical data on the range of oyster beds can be considered as a qualitative benchmark for the suitability of habitats.
4. That analysis shows that **Zee-energie** combined with **Buitengaats** are relatively suitable for the development of oyster beds; **Borssele** is also deemed suitable, followed by **Luchterduinen**. Luchterduinen also qualifies as a pilot site because it is already in use and is favourably situated from a logistics point of view. The shallower coastal sites also offer opportunities for developing flat oyster beds, but the seabed in these locations is slightly less stable and they experience more larval outflow without immediately benefiting neighbouring sites.
5. In view of the assumptions and uncertainties involved, the conclusions will have to be subjected to empirical testing in pilot studies and experiments as a necessary step in the further development of flat oyster beds on North Sea wind farms.

6. Recommendations for a pilot

Given the habitat characteristics of several wind farms in the Dutch section of the North Sea, some of those sites in principle provide opportunities for the development of flat oyster beds. However, the habitat analysis has identified uncertainties regarding the combination of environmental factors and the role of predators. In addition, several assumptions have been made in calculations of the critical mass required for a self-sustaining oyster population. Those uncertainties can be reduced by conducting pilots in the field to identify the most relevant factors. The pilots will also yield the empirical data required to test the model calculations. Experiences gained in the pilots conducted at Voordelta (Sas et al., 2016) and experiments carried out elsewhere (zu Ermgassen et al., 2016) provide a basis for the development of a pilot for wind farms in the North Sea.

The objective of such a pilot could be formulated as follows: conducting practical tests to establish (1) the extent to which flat oysters are able to survive, grow and reproduce on the chosen site, (2) whether the oyster bed is able to sustain itself through recruitment (larval production and sufficient substrate for settlement), and (3) the extent to which the oyster bed can serve as a habitat for other species.

In outline, the following approach could be pursued: (1) create a source of larvae and (2) provide suitable substrate. To generate a source of larvae it is necessary to establish a minimum flat oyster population with different age (= size) classes, of which a part is protected against predators. Oyster development will have to be monitored during the growth and spawning seasons for survival, growth and gonad development. During the spawning season, water samples can be taken to establish the larval count. Spat collectors can be used to monitor larval settlement. Clean shell materials (mussels, oysters) can be deposited at the pilot site to serve as substrate to promote the settlement of flat oyster larvae.

Given the fact that Luchterduinen emerged from the analysis as a comparatively promising location for the development of oyster beds, has been in operation for several years already and is relatively easy to reach, it qualifies as a suitable pilot site. However, alternatives are conceivable provided that they remain free from seabed disturbance.

A plan of action could be drafted for the pilot; to that end, the following questions should preferably be answered first:

1 - Choice of location

= what are the specific habitat characteristics of the site?
= will it be possible to obtain a permit for the pilot?
= what are the preconditions and synergies in terms of logistics?

= to what extent will it be possible to incorporate existing research, monitoring and environmental regeneration programmes (if applicable)?
= are there any other operators in the area whose activities potentially affect the pilot?

2 – Preconditions for implementation

= is there any suitable substrate available on site or will it have to be transported there?
= what is the time scale for the pilot, and what are the spatial requirements?
= is there any risk of significant predation, and if so, can this risk be averted?

3 – Starting material

= what is the size of the initial population?
= to what extent should the initial population be Bonamia-free?
= what sources are available to obtain the initial population?

It is recommended to conduct the pilot in a structure that incorporates the client (or clients), researchers, support, financing, scientific guidance and stakeholder involvement.

Quality assurance

Wageningen Marine Research utilises an ISO 9001:2008 certified quality management system (certificate number: 187378-2015-AQ-NLD-RvA). This certificate is valid until 15 September 2018. The organisation has been certified since 27 February 2001. The certification was issued by DNV Certification B.V.

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Justification

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This report has been prepared with the utmost care. Its scientific quality has been tested by fellow researchers and by the relevant MT member from Wageningen Marine Research.

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Wageningen Marine Research is the Netherlands research institute established to provide the scientific support that is essential for developing policies and innovation in respect of the marine environment, fishery activities, aquaculture and the maritime sector.

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