Do wind farms affect turbidity? What are the effects on benthos?

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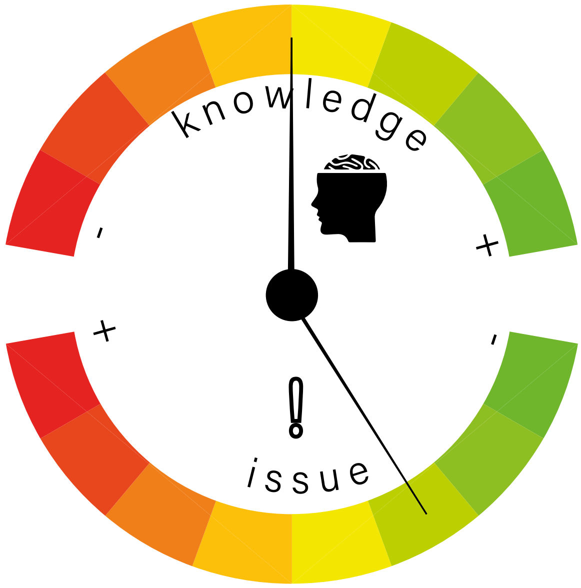

Question deemed by the experts to be "a low-level issue given that offshore wind farms, as such, are not a source of turbidity and that there is moderate knowledge of this issue (good knowledge of the effects of turbidity on certain habitats but knowledge of the effects during the operational phase remains limited)"

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Introduction

Among the many activities carried out at sea, some affect the turbidity conditions: marine aggregate extraction, dredging and dumping, trawling, maritime works, etc. Offshore wind farm development is also an activity that is liable to affect turbidity conditions off the coastline.

The concept and the origins of turbidity in the marine environment will be outlined in the first section of this bulletin. The second section will focus on the potential effects of offshore wind farm development on turbidity, in particular during the construction phase. The potential effects of these turbidity variations on benthos and the different types of monitoring that exist will be addressed in the third section.

Given the fields of expertise of the contributors to this bulletin, only the effect on benthos will be addressed here. This does not imply that this is the only ecological compartment affected by turbidity variations. All ecological compartments (pelagic fish, marine mammals, birds, etc.) can show different levels of sensitivity to these variations. Benthos is, however, the most affected compartment. Mobile species can avoid temporary turbidity plumes and are therefore less affected.

In short

Turbidity is often perceived as harmful to the health of marine ecosystems. However, many ecosystems, particularly estuaries, are naturally turbid. They support a rich biodiversity and enable certain species to perform ecological functions that are essential to their survival (e.g. the role of estuaries as nurseries or the importance of suspended solids for filter feeders and suspension feeders). Turbidity as such is therefore not detrimental to the marine environment. However, sudden variations in natural turbidity conditions are anomalies and can have an impact on marine ecosystems. Benthic communities, due to their characteristics (attached or relatively sessile organisms), are particularly exposed to such impacts. Many offshore human activities lead to variations in natural turbidity conditions. **In the case of offshore wind farms, the likelihood of a farm having a significant impact on turbidity conditions appears low.**

Definitions

Anoxic

Relating to a depletion of dissolved or bioavailable oxygen (i.e. oxygen that can be assimilated by living organisms) in the environment (water, soil, air, etc.) (1).

Benthos

From the Greek word "benthos", meaning "depth", benthos refers to all living organisms (animals or plants), whether sessile or mobile, that develop in close relationship with or in the seabed (1).

Biofouling

The result of a biological process known as biocolonisation which occurs whenever a medium (of natural or anthropogenic origin) is introduced into an aquatic environment, or a surface already present in the environment becomes bare (28).

Sediment availability

Relates to the ability of undissolved matter to be resuspended in the water column. In the case of sediment availability, undissolved matter may become resuspended due to a change in local hydrodynamic conditions (whether caused by human activity or not). Sediment availability does not necessarily result in suspended solids; undissolved matter may be available without necessarily being able to be mobilised (1).

Suspended solids

All solid particles (mineral or organic) present in water without being dissolved and which can be removed by filtration or centrifugation (1, 18).

Pelagic

From the Greek word "pelagos", meaning "sea", pelagic qualifies all living organisms found in the open sea, whether active and capable of propelling themselves against the currents (nekton) or passive and carried along by the currents (plankton) (1).

Turbidity

The decrease in water transparency due to the presence of undissolved matter (19). Solids present in water may be particles of clay, organic or inorganic compounds, plankton, micro-organisms, etc. Turbidity is an indication of the concentration of suspended solids in the environment and depends on the optical and geometric characteristics of the particles (shape, size, composition, quantity, etc.). Turbidity is measured by drawing on the optical properties of water and the ability of suspended solids to scatter or absorb light. Depending on the measurement tools used, turbidity may be expressed in NTU (Nephelometric Turbidity Units, based on the measurement of diffuse radiation, i.e. indirect radiation induced by light scattering by suspended solids) or in FNU (Formazin Nephelometric Units, based on the measurement of the decrease in transmitted light due to suspended solids) (14).

Key concepts

Turbidity is often perceived in common thinking as harmful to biodiversity and ecosystem quality. However, this is not always the case, with many naturally turbid ecosystems such as estuaries and mangroves supporting a rich biodiversity. These environments are indeed not conducive to algal growth and the proliferation of certain primary producers, whose development is heavily dependent on access to light. Nevertheless, they are highly favourable for other organisms, including filter feeders such as bivalves (oysters, mussels, sponges, anthozoans, ascidians, etc.), for which the abundance of dissolved and particulate organic matter is beneficial to their growth and development (1, 14). These naturally turbid environments are home to rich and specific communities of species, such as the honeycomb worm reefs in the Mont-Saint-Michel Bay, which thrive in turbid environments and yet are highly sensitive to environmental variations (1).

A **turbidity "anomaly"** (Fig. 1) refers to deviation between a reference situation (i.e. established over time) which takes into account natural forcings (tides, waves, terrigenous inputs, topography, exposure, etc.) and an anomaly situation generally induced by an extreme event (100-year storm, phytoplankton bloom, etc.) or anthropogenic activity: maritime works (installation of maritime structures, dredging, dumping, etc.), aggregate extraction, eutrophication, fishing with dragged gear, etc.

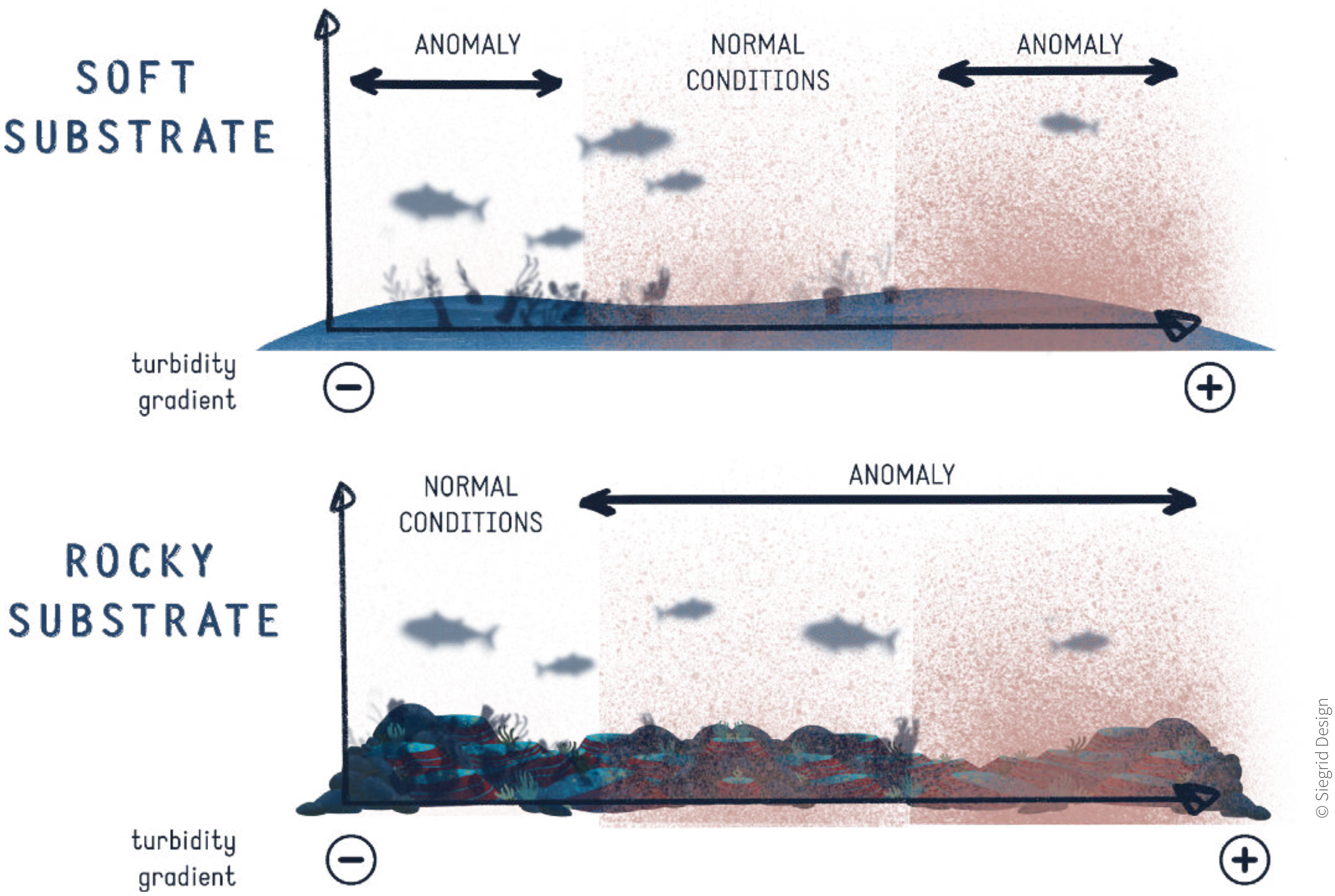

Fig. 1 *Concept of a turbidity "anomaly" for two types of substrates: soft and rocky.*

This notion of anomaly is useful in order to understand, analyse and study the effects of turbidity variations on different species and their preferred turbidity conditions. For instance, in certain naturally turbid environments, the danger thresholds set for certain filter feeders are naturally exceeded. The creation of a turbidity plume in an already turbid environment (such as an estuary, for instance) will have little effect on benthic communities. On the other hand, a small quantity of sediment deposited on a rocky substrate and that cannot be resuspended by natural currents (tides, waves, etc.) could reduce the attachment, filtration, respiration or growth capacities of certain benthic organisms, or even create anoxic conditions and have non-negligible effects on the communities. Turbidity measurements and the definition of maximum limits to ensure species preservation should therefore be carried out on a case-by-case basis, taking into account the natural turbidity and its variability due to environmental forcings (natural increase through resuspension with each tide, season, variation in river flow rates, etc.) (1).

Particles placed in suspension after the passing of a wave, leading to the formation of sediment vortices.

It is important to note that benthic communities are particularly sensitive to variations in turbidity conditions. Outside of turbidity anomalies, the development of these communities is influenced by environmental forcings, which have potentially been strengthened over recent decades due to the effects of climate change (changes in prevailing wind and wave patterns, rising water temperatures, variations in telluric inputs and salinity, etc.). Each community can therefore be characterised by a gradient of sensitivity to turbidity and turbidity anomalies in the environment (duration and frequency of extreme events – storms, etc.), which will determine the community's response to variations in the environment.

To what extent can offshore wind farms affect turbidity?

To identify and assess the effects of turbidity, it is essential to take into account the local context. To take an example, the London Array offshore wind farm, located in the Outer Thames Estuary (an environment with relatively low hydrodynamics and good sediment availability), has specific environmental, seasonal and technical characteristics and its presence induces specific effects on the environment (and in particular on sediment resuspension) (29). The observations and conclusions made for this site cannot therefore be directly extrapolated and considered valid for all offshore wind farms, even although the London Array is located off an estuary as is the case for the Saint-Nazaire offshore wind farm, for example, which is located on a wave-cut platform in an area with relatively strong hydrodynamics and low sediment availability. **To identify, understand, and assess the environmental effects of offshore wind farms, it is essential to have knowledge of all the local specificities and characteristics.**

The effects of an offshore wind farm on turbidity will depend on the duration of exposure and the distance from the source of emission. Over and above these spatiotemporal characteristics, several important factors must be considered when assessing the effects **(Table 1)**:

Site-specific characteristics relating to the local hydro-sedimentary context	Characteristic of the offshore wind farm
• Natural turbidity; • Sediment stock availability; • Type of bottom and sediments; • Particle size and % of fine-grain sediment in substrate; • Local hydrodynamics: waves/swell, tide, water depth, river flow rate, etc.; • Presence/absence of anthropogenic activities liable to affect ambient turbidity conditions: dredge fishing and bottom trawling, dredging, dumping, maritime works, etc.; • Topography; • Bottom slope; • Etc.	• Cable laying/foundation installation technique; • Type of wind farm (bottom-fixed/floating); • Type of foundation (gravity, monopile, jacket) or mooring system (TLP, anchor); • Cable protection technique (burial, protection by riprap/concrete mattress, etc.); • Extent of riprap protection of structures; • Presence/absence of scour protection; • Etc.

Table 1 *Overview of the environmental and technical characteristics to be considered to study the effects of an offshore wind farm on turbidity.*

Given the multitude of parameters to be considered, it is not insightful to attempt to assess the overall effects of offshore wind farms on turbidity conditions. The importance of a case-by-case approach has already been stated. However, by putting forward an approach involving a **risk-based non-quantitative assessment** focusing on key parameters that define the sediment dynamics in a given area, we can contextualise the effects assessed and thereby provide certain insights. To do so, several scenarios, taking into account the main parameters that contribute to turbidity variations, were studied:

- **Type of bottom:** rocky environment, cohesive habitats, non-cohesive habitats;
- **Sediment availability:** high, low;
- **Local hydrodynamic conditions:** low, strong.

Two matrices for assessing the potential effects of offshore wind farms on turbidity during the construction phase and the operational phase have been developed, based on elements from the literature and expert input.

Construction phase

Cable laying and foundation installation will cause sediment to be resuspended due to the mechanical action of the machinery on the seabed (rock fragmenting, burial, drilling, etc.). These operations are considered to be **temporary** (limited to the construction period) and are **monitored in real time** with established maximum turbidity levels.

The main effects (increase and change in turbidity) occur within the boundaries of the wind farm itself (immediate vicinity) and are considered "nil" further from the wind farm (wider area) based on available knowledge **(Table 2)**. The effects on benthic communities will depend on their sensitivity to turbidity variations (1). The purpose of the monitoring measures put in place during the construction phase is to manage the risk of increased turbidity and to identify the benthic communities present to determine their resilience and define appropriate thresholds.

	Bottom-fixed offshore wind farm		Floating offshore wind farm	
	Immediate vicinity	Wider area	Immediate vicinity	Wider area
Rocky environment with low sediment availability and strong hydrodynamic conditions	I	N	I	N
Rocky environment with low sediment availability and low hydrodynamic conditions	I	N	I	N
Cohesive habitats with high sediment availability and strong hydrodynamic conditions	I [ref.25]	N [ref.25]	C	N
Cohesive habitats with high sediment availability and low hydrodynamic conditions	I [ref.25]	N [ref.25]	C	N
Non-cohesive habitats with low sediment availability and strong hydrodynamic conditions	I [ref.15,26]	N [ref.15]	C	N
Non-cohesive habitats with low sediment availability and low hydrodynamic conditions	I [ref.15,26]	N [ref.15]	C	N
Non-cohesive habitats with high sediment availability and strong hydrodynamic conditions	I [ref.15,26]	I	C	N
Non-cohesive habitats with high sediment availability and low hydrodynamic conditions	I [ref.15,26]	N	C	N

Table 2 *Matrix for assessing the potential effects of the construction phase of offshore wind farms on turbidity, developed based on similar characteristics presented in the literature (blue) and expert input (green). Given that the results are identical for both the summer and winter periods, seasonal variations are not presented here. With the exception of certain specific cases, rocky environments have low sediment availability while cohesive environments have high sediment availability. The potential effect of offshore wind farms on turbidity is classified into three probabilities: N, nil; I, probable increase in turbidity and C, probable change in turbidity.*

Operational phase

In most cases, the effects of operational offshore wind farms, whether bottom-fixed or floating, on turbidity are considered "nil". The main effects (increase and change in turbidity) occur within the boundaries of the wind farm itself (immediate vicinity) and are considered "nil" further from the wind farm (wider area) based on available knowledge **(Table 3)**.

	Bottom-fixed offshore wind farm		Floating offshore wind farm	
	Immediate vicinity	Wider area	Immediate vicinity	Wider area
Rocky environment with low sediment availability and strong hydrodynamic conditions	N[ref.12]	N[ref.12]	N	N
Rocky environment with low sediment availability and low hydrodynamic conditions	N[ref.12]	N[ref.12]	N	N
Cohesive habitats with high sediment availability and strong hydrodynamic conditions	N[ref.7]	N[ref.7]	C	N
Cohesive habitats with high sediment availability and low hydrodynamic conditions	C	N[ref.7]	N	N
Non-cohesive habitats with low sediment availability and strong hydrodynamic conditions	C[ref.5,6,7,8,12,19]	N[ref.5,6,12,22]	C	N
Non-cohesive habitats with low sediment availability and low hydrodynamic conditions	C[ref.5,6,7,8,12,19]	N[ref.5,6,12,22]	N	N
Non-cohesive habitats with high sediment availability and strong hydrodynamic conditions	C[ref.5,6,7,8,12,19]	N[ref.5,6,12,22]	C	N
Non-cohesive habitats with high sediment availability and low hydrodynamic conditions	C[ref.5,6,7,8,12,22]	N[ref.5,6,12,22]	N	N

Table 3 *Matrix for assessing the potential effects of the operational phase of offshore wind farms on turbidity developed based on similar characteristics presented in the literature (blue) and expert input (green) under the same assessment conditions as for the construction phase (see Table 2). The potential effect of offshore wind farms on turbidity is classified into three probabilities: N, nil; I, probable increase in turbidity and C, probable change in turbidity.*

During the operational phase, **discharges from biofouling on structures** are the only potential sediment source identified within offshore wind farms. As with the sediment deposits generated by filter feeders (oysters, mussels) in shellfish farms or ports, the presence of these organisms attached to foundations could lead to sediment deposits at the foot of structures. These deposits could locally affect the particle size and increase the sediment stock that could potentially be mobilised. Depending on local hydrodynamic conditions, this sediment may be trapped at the foot of the structures (reduced hydrodynamic conditions due to the presence of the foundations) or resuspended (increased hydrodynamic conditions due to the presence of the foundations) and deposited at a certain distance from the structure, possibly in an area where sediment deposits do not generally occur (e.g. rocky habitats). These same filter feeders will also help to reduce turbidity by capturing suspended organic matter to feed and grow. The extent of change (increase/decrease) in ambient turbidity caused by filter feeders will therefore be dependent on the species, but also on natural turbidity conditions, the season, etc.

The presence of foundations may alter the hydrodynamics by inducing faster currents on either side of the structure, but will lead to a different sediment distribution locally (11, 24). Sediment resuspension caused by these changes in local hydrodynamics is minimal and will cause a local and temporary redistribution of turbidity, before it rapidly becomes stabilised.

It therefore appears unlikely that offshore wind farms, whether bottom-fixed or floating, in their operational phase will cause a long-term increase in turbidity (1).

Effects of biofouling on particle size distribution: feedback from Belgian offshore wind farms (12)

Most species developing on artificial structures are suspension feeders, which filter organic matter from the water column to feed (10). These organisms thus help to remove organic suspended particulate matter from the water column, resulting in lower turbidity **(Fig. 2)**. However, monitoring carried out at Belgian offshore wind farms (17, 23) on samples obtained from the seafloor less than 50 metres from the foundations three to six years after installation showed evidence of finer sediments and increased organic matter. The sediment around the foundations could therefore be enriched by the faecal pellets excreted by all the filter feeders attached to the structure. Although this variation in sediment particle size is less evident for monopile foundations than for jacket foundations, the benthic communities located near the foundations all showed increased densities and species richness and/or diversity than the communities studied further away (9, 17, 23).

Fig. 2 *Diagram of biofouling on an offshore wind turbine foundation, comprising suspension feeders that filter organic matter from the water column and enrich the surrounding seabed with organic matter (faeces). Adapted from Degraer, 2020 (12).*

Focus on a French offshore wind farm

Turbidity monitoring during the construction phase

As is the case for all offshore wind farms, turbidity monitoring was carried out during the construction phase of the Saint-Brieuc offshore wind farm. An official monitoring and alert programme was established in light of the advice issued by the wind farm's consultative bodies (expert assessment by specialised organisations, in this case Cerema, the farm's management and monitoring committee, etc.) and of the need to limit the potential impacts of high levels of sediment resuspension.

A network of several instrumented buoys was set up during the construction phase for real time turbidity monitoring. Three "stationary" buoys were positioned at three "strategic" points to monitor turbidity around the wind farm boundaries and within the area immediately surrounding the wind farm: to the north, to the south-east near the Natura 2000 protected area, and to the west near a scallop bed. Additionally, the monitoring network included "mobile" buoys positioned next to the foundations.

All these buoys were able to take turbidity measurements at different depths: at the surface, 1.5 metres below the surface and 3 metres above the seabed. Different alert levels were defined according to the measured concentrations of total suspended solids (TSS):

- Level 1, Vigilance threshold. TSS concentration between 20 and 50 mg/L, triggering additional measurements (TSS, pH, chlorophyll a, etc.).
- Level 2, Alert threshold with construction work adaptation. TSS concentration between 50 and 85 mg/L, triggering a reduction in the pace of the construction work and additional measures as for level 1.
- Level 3, Alert threshold with suspension of construction work. TSS concentration above 85 mg/L, triggering the temporary suspension of construction work (4).

The measures specified for the different alert levels remain applicable until the TSS concentrations have returned to below 20 mg/L (4). These thresholds were defined for the Saint-Brieuc offshore wind farm, taking into account its specific environmental characteristics. They were established based on reference data acquired on site in order to detect any exceeded thresholds which, for the area studied, would constitute a turbidity anomaly compared to a reference situation (1). Throughout the two-year construction phase (2021, 2022), these thresholds were never exceeded (2, 3). **No turbidity anomalies occurred during the construction work** and the work did not affect the turbidity conditions.

Turbidity monitoring during the operational phase

Unlike the construction phase, the operational phase is not liable to trigger a sudden, sharp change in turbidity conditions and to create an anomaly. During the operational phase, organic matter discharged due to biofouling on structures is the only potential source of sediment. Changes in turbidity conditions due to biofouling, as well as the potential remobilisation of sediment from the construction phase, can therefore only occur gradually over the long term (1).

Of all the monitoring measures carried out at the Saint-Brieuc offshore wind farm during its operational phase, water quality and water mass measurements are the only data that can be used to assess turbidity conditions. This monitoring programme, first implemented in 2024, will be continued annually until 2026, then conducted every five years thereafter.

In the event of an anomaly, what are the potential effects on benthic communities?

In the event of an anomaly, the effects induced by a change in turbidity conditions will depend on the frequency, duration of exposure and intensity of the disturbance. Two types of effects may occur:

- **Reduced water transparency** due to an increase in the quantity of suspended solids;
- **Deposition of resuspended solids** in initially clear areas (27).

Depending on the biogeographical areas concerned (nature of the bottom, species present, life history of individuals, etc.), changes in turbidity conditions can affect benthic communities by modifying: (i) the respiration and/or filtration capabilities of certain filter-feeding species (20, 27); (ii) predator-prey relationships (reduced hunting capabilities for predators that detect their prey visually or protection of certain prey that are less readily visible and therefore less vulnerable) (11, 20).

The effects can be assessed according to a distance gradient from the pressure source whereby the further a point is from the source of emission, the lower the physical impacts on the substrate and the resuspension capacity will be, and the lower the effects on associated benthic communities. However, identifying the source of the disturbance that triggered a change in the community structure is a complex task, as the balance of these communities depends on a multitude of parameters that are already affected by climate change and numerous maritime activities. In this respect, it can be beneficial to introduce monitoring of certain trophic groups, in order to assess the extent of the changes in an environment using various indices, such as the biotic index. This index, based on the analysis of benthic communities, can be used to assess the level of ecosystem disturbance according to the species or groups of species present (16). These monitoring measures, when combined with environmental parameter measurements, can be used to detect anomalies and to distinguish between environmental changes due to natural forcings and those resulting from human activity (1).

When assessing the effects on these communities, it is important not to only consider the new source of pressure studied (in this case, the installation of an offshore wind farm) but also the health status of the environment and the potential cumulative effects with other natural sources and/or anthropogenic activities that generate turbidity. It is therefore important to have knowledge of the condition of benthic communities prior to the installation of an offshore wind farm. It is also crucial to monitor the cumulative effects of the different pressures exerted on these communities to consider the ecosystem's resilience capacity. In this way, it may be possible to avoid reaching a threshold effect that could cause the health of the entire community to deteriorate, sometimes irreversibly.

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Recommendations

In the case of offshore wind farms, **measures to mitigate the effects of the construction phase on turbidity should be encouraged**. When such measures prove possible and necessary based on the results of the impact assessment, they may involve the use of drilling techniques that cause less seabed disturbance, the installation of silt curtains to reduce the formation of turbidity plumes, or the use of materials with a low particulate fraction for riprap (as implemented for the Courseulles-sur-Mer offshore wind farm for example).

When defining maximum turbidity limits for the construction phase, it is important to have good knowledge of the specific characteristics of the marine ecosystem prior to the construction work. In this regard, the reinforcement of existing multiannual monitoring programmes would help to better characterise the environment and natural variations at different time scales and thereby to define relevant maximum turbidity limits.

The standardisation of monitoring within offshore wind farms should also be encouraged through the introduction of shared protocols (including environmental parameter measurements) and the integration of standards already implemented at national level (for instance regulatory monitoring, monitoring of estuarine plumes using satellite imagery, etc.) to guarantee interoperability and data access (21). By examining all biotic and abiotic parameters, these monitoring efforts provide insight into the effects of offshore wind farms on marine ecosystems, as well as contributing to better knowledge and monitoring of coastal communities. With over ten offshore wind farm projects off the French coastline, all of the monitoring efforts carried out within the farms constitutes an opportunity to improve and pool knowledge, and to track changes in ecosystem health.

Conclusion

Turbidity is not necessarily detrimental to biodiversity, it can even be conducive to the development of certain species (mussel and oyster growing areas are generally located off estuaries). Certain turbid environments such as gulfs, rias, estuaries and bays (for instance the Mont-Saint-Michel Bay) are home to a rich and specific biodiversity due to their high turbidity conditions. **Sudden changes in natural turbidity, however, constitute "anomalies"** and pose a risk to biodiversity, particularly for certain sensitive and less mobile species. In the case of the construction and operation of offshore wind farms, **the likelihood of an offshore wind farm having a major, lasting effect on turbidity conditions appears low**. Outside of the construction phase, during which mechanical action on the seabed will cause sediment to be resuspended, the effects on turbidity conditions are deemed negligible. However, it is essential to implement appropriate monitoring initiatives to track changes in turbidity conditions and detect potential anomalies in order to prevent potential effects on benthic communities that are already heavily exposed to anthropogenic pressure and the effects of climate change.

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