**Direct impacts of oil and gas development: Drilling and other operational impacts (WP2)**

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# Executive summary

Oil and gas development includes the construction and installation of physical infrastructure, which cause significant disturbance to the seabed and benthic habitats. Drilling and other operational activities (e.g., support vessels and oil tankers) contribute to underwater noise levels. Furthermore, waste materials such as produced water (PW), drill cuttings and drilling muds are discharged during the drilling process.

This review evaluates the evidence for impacts of a) oil and gas development and b) drilling and other operational activities on marine life, including priority species, the habitats they inhabit and the wider ecosystem. Key findings are:

**Marine Mammals**

* Marine mammals rely on sound to sense their environment.
* Noise associated with drilling and other operational activities can cause changes in physical (e.g., avoidance and temporary displacement) and acoustic (e.g., increase in rate and/or amplitude of call) behaviour.
* In extreme cases, acute and chronic high-level acoustic stimulation can cause temporary threshold shifts (TTS) or even permanent threshold shifts (PTS). The thresholds for inducing TTS and PTS are important for assessing the risk of auditory injury in marine mammals. (Tougaard, 2015). If PTS occurs, it can influence the energetic status in marine mammals, potentially impacting their mating and nursing ability, as well as their survival (Tougaard,2015).
* Noise associated with vessels causes cetaceans to divert around the source, potentially increasing their energy expenditure. This can lead to negative impacts on reproductive success, mating and social behaviour with potential population-wide implications.
* Harbour porpoises are particularly sensitive to increased underwater noise levels from oil and gas infrastructure construction, with avoidance and reduced activity observed over entire construction periods (months).

**Fish and shellfish**

* Fish demonstrate avoidance behaviour and temporary displacement when exposed to noise, which could reduce catch rates and adversely impact commercial fisheries.
* Noise can lead to changes in DNA integrity, cause body abnormalities and reduce filtration rates in invertebrates.
* Toxic contaminants found in produced water (PW), drill cuttings and drill muds such as hydrocarbons, heavy metals, barite etc. may cause severe biological and physiological impacts on fish that negatively impact individual fitness and populations and weaken ecological integrity.
* In general, the construction of oil and gas infrastructure may also facilitate the introduction of opportunistic invasive fish and/or invertebrate species by serving as corridors, connecting otherwise separate habitats, potentially threatening native biodiversity and ecosystems.

**Wider ecosystem impacts**

* The suspension and sedimentation of drill cuttings can cause negative impacts on cold water corals via smothering and toxic effects.
* Drill cuttings can cause larval and polyp mortality through burial, which can affect the wider ecosystem.
* The toxic contaminants found in produced water (PW) can cause DNA damage, decrease filtration rates, and reduce mussels' growth and survival. Damage to these valuable ecosystem engineers thus has negative implications for the wider ecosystem.

**Cumulative impact footprint**

* With the proposed expansion of oil and gas licensing in UK waters, the impacts associated with drilling and other operational activities (i.e., noise, physical infrastructure and wastes) would have a larger cumulative footprint on marine species and habitats.
* These impacts should be considered alongside the impacts associated with offshore wind farms (for which extensive research has been conducted) and climate change. Cumulative, multi-stressor impacts and interactions can seriously affect the health of marine ecosystems.

Overall, there is a lack of research into the effects of drilling and other operational activities (especially non-seismic noise and physical infrastructure) on marine life. However, this does not mean that there are no negative impacts. Instead, this only highlights the research gaps that should be filled.

Current mitigation measures are not effective enough to limit the negative impacts of drilling and other operational activities on marine species and habitats. There are gaps in the implementation of current mitigation measures, and guidance is often unclear and/or lacking. Thus, more research on the effects of drilling and operational activities on marine life is needed to inform mitigation measures to protect important species and habitats.

# Key statistics

**Noise disturbance**

* Exposure to noise associated with drilling and other operational activities led to the New Zealand scallop (*Pecten novaezelandiae*) larvae suffering significant development delays, with 46% of them developing body abnormalities. This suggests that routine noise produced associated with oil and gas activities can impact the survival of scallops (Soto *et al.,* 2013).
* The exposure to playbacks of ship noise led to a 12% reduction in oxygen consumption and an 84% decrease in the filtration of blue mussels (Wale *et al*. 2019).
* Noise can have negative economic repercussions for commercial fisheries. According to a study by Løkkeborg et al., (2012), commercial catches of haddock in the Barents Sea may experience up to 80% reductions due to noise as the fish flee the area.

**Marine pollution**

* There is a presumption that produced water from future oil and gas developments on the UK Continental Shelf (UKCS) will be reinjected and not discharged to reduce the impact on the marine environment. However, the proportion of re-injected produce water was only 24% in 2016, representing only a 2% increase since 2012 (OSPAR Commission, 2018).
* The cumulative impact of noise from whale-watching boats and commercial vessels resulted in a 20% to 23% (4.9-5.5 hours) loss of foraging time in killer whales per day (Vancouver Fraser Port Authority, 2017) which could potentially contribute to the species’ decline or lack of recovery (NFMS, 2002; Weilgart *et al.*, 2007)
* In an experiment, standard barite, which represents a 58% weight composition in water-based muds (WBM), led to 100% mortality in all four bivalve test species (including horse mussels, blue mussels and scallops) (Strachan, 2010).
* Jones *et al*., (2012) found that the physical disturbance associated with drilling caused decreased densities and richness of benthic fauna even after ten years at the Laggan deep-water hydrocarbon drilling site in the Faroe−Shetland Channel.

# Main content

## Introduction to drilling and other operational impacts

The extraction of oil and gas involves operational activities such as the drilling of production wells and the construction and installation of physical surface (e.g., floating production rigs, storage, and offloading vessels) and subsea infrastructure (e.g., manifolds, control cables, and export lines) (Cordes *et al*., 2016). This infrastructure can significantly impact the seabed with oil rig pylons, pipelines and anchors of operating vessels directly disturbing the seabed and benthic habitats (Cordes *et al*., 2016).

Noise pollution is a serious impact of offshore oil and gas operational activities, with loud and possibly disturbing sounds produced at each oil extraction stage (Hammond *et al*., 2014). Underwater sound is generated from production platforms and operational activities, including drilling, vessel traffic and pipeline laying. Where the drilling rig or production platform is reliant upon support and supply from other standby and supply vessels, these are often equipped with dynamically positioned thrusters and powerful engines and therefore contribute towards the overall noise level of drilling and production activities (Genesis Oil and Gas Consultants, 2011).

Marine pollution is a further impact of offshore oil and gas operational activities, with waste materials such as drill cuttings, drill muds and produced water (PW) leaking into the marine environment during operation (Table 1). Drill cuttings are fragments of solid material that are removed from a well during the drilling process, while drill muds are used to lubricate the well during the drilling process and can consist of either oil-based muds (OBM) or water-based mud (WBM) (Grant, 2003). PW, however, is the formation and injection of water containing production chemicals (Neff *et al*., 2011). The contaminants in these materials, Alkylphenols (AP) and polyaromatic hydrocarbons (PAH), are known to pose a threat of toxicity to marine life, which could result in sublethal effects (Bakke *et al*., 2013).

Despite the impacts associated with offshore oil and gas operational activities, an expansion of UK offshore oil and gas licensing has been proposed. Therefore, it is important to compile the scientific knowledge available on the impacts of drilling and other operational activities on marine habitats and species to safeguard them.

The following sections will introduce the uncovered impacts of infrastructure construction, drilling and other operational impacts on each class (marine mammals, fish, invertebrates) in a broad sense, followed by the specific impacts uncovered on each species. The last section will assess the effectiveness of UK guidance and mitigation measures to address the negative impacts of offshore UK oil and gas operational activities.

*Table 1. Table summarises the common contaminants in drill cuttings, drilling muds and produced water.*

|  |  |
| --- | --- |
| **Waste Product** | **Contaminant** |
| Drill cuttings | The contaminants in drill cuttings include polyaromatic hydrocarbons (PAH) and heavy metals. |
| Oil-based (OBM) and Water-based (WBM) drilling muds | OBM are based on crude oil, oil products, and other mixtures of organic substances (diesel, paraffin oils etc.). WBM are based on water (freshwater or seawater) mixed with [bentonite](https://www.sciencedirect.com/topics/earth-and-planetary-sciences/bentonite), [barite](https://www.sciencedirect.com/topics/earth-and-planetary-sciences/barite) etc. (Speight *et al*., 2015). Both drilling muds can contain PAHs. |
| Produced water | Produced water contains Alkylphenols (AP) and PAHs (Bakke et al., 2013). |

## Marine Mammals

### Introduction

UK waters are home to several marine mammal species, all of which are protected under national and international legislation (JNCC, 2021). Cetaceans, in particular, are strictly protected from injury, killing and disturbance (JNCC, 2021). Furthermore, the designation of Special Areas of Conservation (SACs) has been required for the harbour porpoise, bottlenose dolphin and grey and harbour seal (JNCC, 2021).

Marine mammals, especially cetaceans, are highly vocal and dependent on sound for almost all aspects of their lives, e.g., foraging, reproduction, communication, detection of predators/hazards (Weilgart, 2007). They are, therefore, sensitive to underwater noise (Erbe *et al*., 2002) produced during each stage of the oil extraction process, such as during hammering strikes involved with the impact pile-driving process (Kent *et al*., 2016).

Sound can disrupt marine mammal behaviour through masking, or interfering with, an animal's ability to detect, recognize, or discriminate between acoustic signals of interest (e.g., those used for intraspecific communication and social interactions, prey detection, predator avoidance and navigation) (Richardson et al., 1995). The impacts of underwater sound on marine mammals include impairment of foraging, disruption of social interactions, auditory threshold shifts, hearing loss and, in extreme cases, injury or even death (Hammond et al., 2004; NOAA, 2022). The level of effects of these impacts can range from mild to severe. In addition, there could be potential long-term effects on populations' reproductive success, growth and/or recovery following disruption to mating and social behaviour, e.g., migration routes in cetaceans. There is currently a lack of information on non-auditory tissue and organ damage or lethal effects on marine mammals from underwater noise produced by oil and gas activities (Kent *et al*., 2016). Although assessments of the cumulative effects and impacts of anthropogenic sound from multiple sources on marine mammals and their habitat are required by legislation, they have proven challenging to carry out (Moore *et al*., 2012).

There is currently no research to suggest that physical infrastructure or waste materials (PW, drill cuttings, drilling muds) have a direct negative impact on marine mammals. However, this is not to say that there are no adverse impacts; instead, there is a lack of research focused on exploring the impact of physical infrastructure and waste materials on marine mammals. The following section will, therefore, focus on the impacts of noise pollution associated with oil and gas operational activities on marine mammals.

### Bottlenose dolphin (*Tursiops truncatus*)

Limited research was uncovered that investigated the impact of non-seismic noise associated with oil and gas development on bottlenose dolphins. However, noise from oil and gas development, drilling and other operational activities contributes to increased ambient noise in the ocean (Harland *et al*., 2005). Studies have found that dolphins adjust their calls when noise levels are elevated at a range of frequencies, including below the frequencies of their whistle calls. Increased low-frequency ambient noise could drive dolphins to change their vocalisation behaviour to avoid or compensate for masking, which could be detrimental to conspecific communication (Fouda *et al*., 2018; Morisaka *et al*., 2005). For instance, dolphins produce whistles at varying frequencies with greater modulations with less ambient noise. However, when ambient noise is greater, dolphins produce whistles of lower frequencies with fewer frequency modulations. As seen in terrestrial species, changing to dolphin vocalisation could potentially diminish group cohesion (Barber *et al*., 2010; Fouda *et al.*, 2018).

Other studies have been conducted on the effect of noise associated with offshore renewable energy developments on bottlenose dolphins. These studies help consider similar potential impacts of oil and gas development.

The installation of foundation piles for offshore wind farms are known to cause high levels of impulsive underwater noise (Fernandez-Betelu *et al*., 2021). There is evidence of potential short-term modifications in vocalisations with monitoring the far-field responses of dolphins, which has been reported for other marine mammal species ([Gomez *et al*., 2016](https://www.frontiersin.org/articles/10.3389/fmars.2021.664230/full#B28)). Changes in vocalisation rate ([Blackwell *et al*., 2015](https://www.frontiersin.org/articles/10.3389/fmars.2021.664230/full#B7)) or the amplitude of their calls ([Holt *et al.*, 2009](https://www.frontiersin.org/articles/10.3389/fmars.2021.664230/full#B35); [Parks *et al*., 2011](https://www.frontiersin.org/articles/10.3389/fmars.2021.664230/full#B43)) in response to the impulsive noise generated by offshore activities have been suggested. In an experiment with captive bottlenose dolphins, the playback of pile-driving noise increased the number of clicks ([Branstetter](https://www.frontiersin.org/articles/10.3389/fmars.2021.664230/full" \l "B11) [*et a*l., 2018](https://www.frontiersin.org/articles/10.3389/fmars.2021.664230/full#B11)).

Bottlenose dolphins might also change their behaviour in response to noise. One study found that at a fine temporal scale, there was a significant change in dolphin occurrence dependent upon the presence or absence of impulsive noise associated with offshore activity on different days (Fernandez-Betelu *et al.*, 2021).

### Harbour Porpoise (*Phocoena phocoena*)

Limited research was uncovered that investigated the impact of non-seismic noise associated with oil and gas development on the Harbour porpoise. However, research has been conducted on the response of harbour porpoises to pile driving associated with wind farm installation in the North Sea (Brandt *et al*., 2018). Noise pollution during the construction phase (e.g., when steel foundations are driven into the sea floor) can cause temporary avoidance of the area by marine mammals like harbour porpoises. Displacement in the range of 20km, for example, has been observed in areas commonly abundant with harbour porpoises following construction noise (Merchant & Robinson, 2019; Dähne *et al*., 2013).

Construction noise can inflict physical damage to the auditory system of harbour porpoise (Madsen *et al*. 2006; Thomsen *et al*., 2006; Southall *et al.* 2007) and can reduce echolocation activity within several km of the construction site for the entire construction period. A recent study, for example, observed reduced harbour porpoise activity and abundance out to a mean distance of 17.8km over a 5-month construction period (Brandt *et al*., 2011). The behavioural response of harbour porpoises to noise emitted by pile driving can, therefore, have far-reaching adverse disturbance effects and potential risk for hearing damage, thus, highlighting the importance of implementing suitable mitigation measures.

### Humpback Whale (*Megaptera novaeangliae*)

Limited research was uncovered that investigated the impact of non-seismic noise disturbance associated with oil and gas extraction (i.e., drilling) on the humpback whale. However, in general, extensive research has been conducted on the response of humpback whales to vessel noise (e.g., whale-watching boats). In the short term, humpback whales have been seen to respond to loud anthropogenic noise, such as whale-watching boats, with increased respiration rate and movements. These responses are expected to increase maternal energy expenditure, especially if the noise exposure is cumulative (e.g., repeated throughout the day, from many sources, or prolonged exposure) (Sprogis *et al*., 2020). These noise-induced disturbances can lead to a negative offset in the energy available for nursing, fending off males/predators and migrating back to their polar feeding ground ([Braithwaite *et al*., 2015](https://elifesciences.org/articles/56760#bib10); Sprogis *et al*., 2020).

Blair *et al*., (2016) observed statistically significant alterations in humpback whale foraging behaviour from high levels of ship noise exposure. A correlation was found between ship passages and humpback dives without bottom side rolls, which implied either a cessation of feeding or a switch from bottom side-roll feeding to another method. Short and chronic cessations of feeding can result in biologically relevant decreases in balaenopterid foraging efficiency, which could ultimately reduce individual fitness (Blair *et al*., 2016). Therefore, small reductions in foraging efficiency could affect individual fitness and potentially translate to population-level effects on humpback whales exposed to ship noise in critical foraging areas (Blair *et al*., 2016).

Studies on other whale species provide a valuable reference to understand better the impacts of oil and gas exploration-related noise on humpback whales. Grey whales (*Eschrichtius robustus)* and bowhead whales*(Balaena mysticetus),* for example, have been observed diverting around continuous industrial noise at levels of 114 dB (Richardson *et al*., 1985; National Research Council, 2013). Beluga whales (*Delphinapterus leucas)* have also shown increasing avoidance (i.e., increased dive duration and swim speed) in response to vessels, as well as other changes in both physical and acoustic behaviour ([Blane & Jaakson, 1994](https://www.frontiersin.org/articles/10.3389/fmars.2019.00606/full#B23); [Lesage *et al*., 1999](https://www.frontiersin.org/articles/10.3389/fmars.2019.00606/full#B138); Erbe *et al*., 2019). For instance, the Lombard response, defined as the increased intensity of vocalisations in increased noise, has been observed in response to elevated levels of shipping noise (Scheifele *et al*., 2005; Erbe *et al*., 2019). The consequences of acoustic masking could be particularly dire in the case of crucial vocalisations that maintain contact between mothers and their dependent calves (Vergara *et al.*, 2021). Despite these documented changes in physical and vocal behaviour, there is still a lack of understanding of the potential long-term and population-level impacts of underwater noise associated with oil and gas operations and the corresponding biological significance (Erbe *et al.*, 2019).

### Northern Minke whale (*Balaenoptera acutorostrata*)

Limited research was uncovered that investigated the impact of non-seismic noise associated with oil and gas development on the northern minke whale. However, Helble *et al*., (2020) documented that minke whales in Hawaii demonstrated the Lombard effect by increasing their boing call intensity in increased background noise. Although they partially compensated for the increasing background noise, they were unable or unwilling to increase their source levels (SLs) by the same amount as the background noise. In a relatively low-noise environment, minke whales can be heard by others from distances up to 114 km away. However, as noise levels increased, the minke whales’ range decreased to just 19 km (Helble *et al.*, 2015). As oceans get noisier with oil and gas development, drilling and other operational activities, this compression in communication space could adversely impact minke whale populations’ health (Helble *et al*., 2020).

### Killer whale (*Orcinus orca*)

Research uncovered on the impact of non-seismic noise associated with oil and gas development on the Killer whale was limited. However, research investigating the impact of vessel traffic and associated noise on killer whale vocalisation was widely available (Williams *et al*., 2021).

In general, vocalisations can vary in multiple parameters, such as call rate, frequency, amplitude, or duration, and many factors can contribute to the change in these parameters (Wieland *et al*., 2009). In some cases, killer whales have been shown to alter either learnt or more innate vocalisation to overcome the masking effects of background noise, e.g., vessel noise (Erbe, 2002). In one study, for example, killer whales were observed to increase the duration of their calls as vessel traffic intensified (Foote *et al.,* 2004). This indicates that killer whales adjust their vocal behaviour to compensate for anthropogenic noise once it reaches a threshold level (Foote *et al.*, 2004).

Studies have shown that killer whales increase the amplitude of their most common call types in the presence of vessel noise (Holt *et al*. 2009), increasing their call amplitude by 1 dB for every 1 dB increase in background noise levels (Holt *et al*., 2009). There are, however, potential costs of this vocal compensation. Increasing vocal output to compensate for noise may have negative implications for killer whales, including energetic costs (Oberweger & Goller, 1991), elevated stress levels, or degraded communication among individuals, thus affecting their activity budget (Holt *et al*., 2009).

At certain levels, background noise can also entirely hinder the use of calls by killer whales for communicative functions and potentially impact their efficiency in using acoustics to forage and navigate (Wieland *et al*., 2009). For example, the cumulative impacts of noise pollution from whale-watching boats and commercial vessels in an area were found to reduce killer whale foraging time by roughly 20% a day (~5.5 hours) (Vancouver Fraser Port Authority, 2017). These short-term behavioural changes can lead to biologically significant consequences and long-term impacts that could contribute to killer whales becoming endangered. (Lusseau *et al*., 2009). The International Union for Conservation of Nature (IUCN) currently classes killer whales as data deficient on the IUCN Red List of Threatened species (IUCN, 2017) . Therefore, noise impact on killer whales can potentially contribute to the species’ decline or lack of recovery (NFMS, 2002; Weilgart *et al.*, 2007).

### Pinnipeds (Seals)

Limited research was uncovered that investigated the impact of non-seismic noise associated with oil and gas development on seals. However, an understanding can be drawn from the known effects of construction and operation noise associated with offshore wind farms on seals.

The mammalian auditory system is likely vulnerable to damage from intensive sounds like pile driving associated with offshore wind farm construction (Hastie *et al*., 2015; Kastelein *et al*., 2018). Studies have shown that exposure to intensive pulsed sounds can cause elevated hearing thresholds (Henderson & Hamernik, 1986; Finneran *et al*., 2002; Yost, 2000). These threshold shifts can be described as either temporary (TTS) or permanent (PTS), depending on the capacity for post-exposure recovery (Hastie *et al*., 2015). A 2015 study, for example, found that 50% of tagged seals received sound levels from pile driving that exceeded auditory damage thresholds for pinnipeds (Hastie *et al*., 2015). A previous study had similar findings, predicting that half of the seals exposed to pulsed sounds exceeded the PTS threshold (Southhall *et al*., 2007). The loss of hearing in pinnipeds is expected to have profound implications; however, the biological consequences of a permanent reduction in auditory sensitivity are uncertain (Hastie *et al*., 2015). One implication, for example, could be reduced reproduction success. For example, low-frequency vocalisations play an essential role in reproduction; males use acoustic signals to defend established underwater territories as well as “roar” to attract females (Matthews & Parks, 2016). Impairment to auditory sensitivity may, therefore, affect female seals’ detection of vocalisations with implications for reproductive success (Hastie *et al*., 2015). In addition, seals listen for auditory cues to help them detect and avoid predators (Sills et al., 2015). Therefore, auditory impairment can potentially impact prey avoidance ability.

Another study investigated the effects of the construction and operation of a large Danish offshore wind farm on harbour seal (*Phoca vitulina*) and grey seal (*Halichoerus grypus)* behaviour within a nearby seal sanctuary. A significant short-term decrease was observed in the number of seals on land during sheet pile driving in or near the wind farm (Edr[é](https://onlinelibrary.wiley.com/action/doSearch?ContribAuthorRaw=Edr%C3%A9n%2C+Susi+M+C)n *et al*., 2010). Displacement has been found to result in reduced foraging opportunities and increased energetic costs (Russel *et al*., 2016). However, further research needs to be conducted to understand the population-level impacts of oil and gas development, drilling and other operational activities to quantify the long-term impacts on individual fitness, fecundity and survival of pinniped species. 

*Table 2. Table shows the varying impacts of oil and gas development, drilling and other operational activities on priority marine mammal species at distance from the source.*

|  |  |
| --- | --- |
|  |  |
|  |  | **Distance from source** | | | | |
|  |  | **Impact** | **At source** | **10's m** | **10's km** | **100s 'km** |
| **Species** | *Humpback whale* | Increase in respiration rate and movements. | [Sprogis et al., 2020](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7324156/) | [Sprogis et al., 2020](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7324156/) | [Sprogis et al., 2020](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7324156/) |  |
| Increased maternal expenditure. | [Sprogis et al., 2020](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7324156/) | [Sprogis et al., 2020](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7324156/) | [Sprogis et al., 2020](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7324156/) |  |
| *Northern minke whale* | Increased boing call intensity | [Helble et al., 2020](https://doi.org/10.1121/10.0000596) | [Helble et al., 2020](https://doi.org/10.1121/10.0000596) | [Helble et al., 2020](https://doi.org/10.1121/10.0000596) | [Helble et al., 2020](https://doi.org/10.1121/10.0000596) |
| *Bottlenose dolphin* | Changes in the rate and amplitude of their call to avoid or compensate for masking | [Fouda et al., 2018](https://doi.org/10.1098/rsbl.2018.0484)  [Morisaka et al., 2005](https://academic.oup.com/jmammal/article/86/3/541/839193#38051268)  [Branstetter et al., 2018](https://pubmed.ncbi.nlm.nih.gov/29390736/) | [Fouda et al., 2018](https://doi.org/10.1098/rsbl.2018.0484)  [Morisaka et al., 2005](https://academic.oup.com/jmammal/article/86/3/541/839193#38051268)  [Branstetter et al., 2018](https://pubmed.ncbi.nlm.nih.gov/29390736/) |  |  |
| *Killer whale* | Increased duration of calls | [Foote et al., 2004](https://www.nature.com/articles/428910a) | [Foote et al., 2004](https://www.nature.com/articles/428910a) | [Foote et al., 2004](https://www.nature.com/articles/428910a) |  |
| Elevated stress levels or degraded communication among individuals which could affect their activity budget | [Holt et al., 2009](https://pubmed.ncbi.nlm.nih.gov/19173379/) | [Holt et al., 2009](https://pubmed.ncbi.nlm.nih.gov/19173379/) |  |  |
| Reduced foraging activity | [Vancouver Fraser Port Authority, 2017](https://www.portvancouver.com/wp-content/uploads/2017/01/2017-07-ECHO-Program-Estimating-the-effects-of-noise-from-commercial-vessels-and-whale-watch-boats-on-SRKW.pdf) | [Vancouver Fraser Port Authority, 2017](https://www.portvancouver.com/wp-content/uploads/2017/01/2017-07-ECHO-Program-Estimating-the-effects-of-noise-from-commercial-vessels-and-whale-watch-boats-on-SRKW.pdf) |  |  |
| *Seals* | Potential to cause elevated hearing thresholds. | [Hastie et al., 2015](https://besjournals.onlinelibrary.wiley.com/doi/10.1111/1365-2664.12403) | [Hastie et al., 2015](https://besjournals.onlinelibrary.wiley.com/doi/10.1111/1365-2664.12403) |  |  |
| Reduced foraging opportunities and increased energetic costs | [Russel et al., 2016](https://besjournals.onlinelibrary.wiley.com/doi/10.1111/1365-2664.12678) | [Russel et al., 2016](https://besjournals.onlinelibrary.wiley.com/doi/10.1111/1365-2664.12678) | [Russel et al., 2016](https://besjournals.onlinelibrary.wiley.com/doi/10.1111/1365-2664.12678) |  |
| *Harbour Porpoise* | Potential risk of hearing damage | [Thomsen *et al*., 2006](https://tethys.pnnl.gov/sites/default/files/publications/Effects_of_offshore_wind_farm_noise_on_marine-mammals_and_fish-1-.pdf)  [Southall *et al*. 2007](https://infrastructure.planninginspectorate.gov.uk/wp-content/ipc/uploads/projects/EN010053/EN010053-001080-DONG%20-Aquatic%20Mammals%20Noise%20Exposure%20Criteria%20Southall%20et%20al%20(2007)%20Appendix%20O%20.pdf) |  |  |  |

## Fish

### Introduction

The physical infrastructure of oil and gas exploration (e.g., oil rigs, pipelines etc.) often occurs in the vicinity of fish habitats. Fish are, therefore, exposed to impacts associated with that infrastructure and its construction.

Drilling and other operational activities associated with oil and gas extraction, therefore, also occur close to fish habitats. Fish are, consequently, exposed to noise pollution associated with these activities (e.g., pile driving and motorised vehicle activity). However, the potential impacts of noise pollution associated with these activities have only recently gained interest (Masud *et al*., 2020).

Furthermore, fish are exposed to the cumulative wastes discharged by drilling and other operational activities. Fish are known to suffer the short and long-term impacts of drill spoil-produced water and other pollution associated with drilling and extraction activities.

The majority of fish species appear to be similarly impacted by oil and gas-related drilling and operational activities. Therefore, to reduce repetition in this section, the broader impacts on fish will be discussed first, followed by sections on key commercial species that go into more detail. In particular, Atlantic cod and Haddock have been highlighted due to heightened research interest in the response of these fish to pollution (associated with drilling).

### Fish Overview

Fish are vulnerable to many impacts from drilling and other operational activities associated with oil and gas development.

The discharge of toxic wastes (e.g., drilling muds, drill cuttings and produced water) associated with drilling activities into the marine environment may cause adverse impacts on aquatic biological systems (Sil *et al*., 2012). Drill cuttings, for example, may cause disease and physiological impacts such as the repression of the immune system in adult fish and the malformation and mortality of fish eggs and larvae (Gerrald *et al*., 1999).

Hydrocarbons, especially polyaromatic hydrocarbons (PAHs) found in drill-cutting piles, are known to cause teratogenicity (defects in developing foetus), mutagenicity (permanent and transmissible changes in genetic material) and carcinogenicity by bonding to cellular proteins (Neff, 1979; Tuvikene, 1995). PAHs have been observed to cause physiological effects in benthic fish, such as neoplasias (abnormal tissue masses), haemorrhages, and liver and epithelial lesions (Stein *et al.*, 1994; Gerrald *et al.*, 1999). High DNA adduct values, used as a proxy to assess genotoxicity, have also been measured in fish, indicating DNA damage from PAHs associated with oil toxicity.

The contaminants in produced water (PW) have profound effects on the individual, such as loss of membrane integrity, genotoxicity, cytotoxicity, changes in gene expression, hepatic lid composition, and disrupt reproductive functions (shifts in spawning time, larval survival) (Bakke *et al*., 2013; Igtisamova *et al.*, 2020). Exposure to genotoxic contaminants and the increased risk of effects on individuals and populations may weaken fish's ecological integrity (Stein *et al*., Karr, 1993). However, the severity of the effects depends on the type, dosage and exposure duration (Ezemonye *et al*., 2008; Sil *et al*., 2012).

The construction of oil and gas infrastructure may also directly impact marine habitats (Hjorth *et al*., 2017). As oil and gas production often occurs in areas with a homogeneous substrate, introducing artificial reefs in these areas will increase the substrate's complexity and change the seabed's characteristics. International studies have shown that the expansion rate of invasive fish species increases quickly in areas with artificial reefs, threatening native biodiversity and ecosystems (Hjorth *et al.*, 2017) (No UK-focused evidence was uncovered on invasive species occurring/dominating oil and gas infrastructure). Movable structures can also be vectors for the introduction of non-native and invasive fish species into new areas (McLean, 2022). For example, non-native damselfish (*Chromis limbate)* performed a transoceanic crossing from Africa to Brazil by “rafting” on towed rigs (Anderson et al., 2017). In the North Sea, elevated abundances of commercially important cod, haddock and saithe (*Pollachius virens* ) have been found around artificial structures (Fujii, 2015). Oil and gas infrastructure may thus facilitate the propagation of both native and invasive species by connecting habitat mosaics (Bohnsack, 1989; Schramm *et al.,* 2021).

Limited research was uncovered that investigated the impact of noise pollution (non-seismic) associated with oil and gas drilling and operational activities on fish. However, it has been suggested that marine noise associated with drilling may cause behavioural reactions (e.g., avoidance) and the temporary displacement of fish (Hiscock *et al.*, 2002). Noise from anthropogenic sources can also impede the female fish’s detection of sounds produced by male fish, hindering female fish’s ability to locate mates (Popper & Hawkins, 2019). In more extreme examples, organ damage in Chinook salmon (*Oncorhynchus tshawytscha)* has been observed following exposure to repeated pile driving signals (Halvorsen *et al.*, 2012). This demonstrates that noise pollution can damage organs (André et al. 2011), causing the loss of buoyancy control, disorientation and stranding (Weilgart, 2018). Possible hearing damage could also decrease the distance individuals can communicate and hinder the detection of predators and prey, which likely affects their survival and reproduction (Amoser & Ladich 2003; Weilgart, 2018).

Overall, noise has been found to have negative economic implications for commercial fisheries. Commercial catches of haddock in the Barents Sea, for example, have experienced up to 80% reductions due to noise as bigger fish flee the area (Løkkeborg et al., (2012). Note, however, that this evidence relates to seismic noise disturbances, as limited studies have been conducted on the response of fish to noise pollution associated with oil and gas operational activities (e.g. drilling, vessel noise etc). The avoidance response of fish to seismic sound, however, is a good indication of how fish may react to other loud underwater noises.

### Atlantic Haddock (*Melanogrammus aeglefinus*)

Atlantic haddock is known to be exposed to a number of impacts simultaneously, including PW, drill cuttings, muds, and accidental spills from offshore oil production. Thus, highlighting the potential severe cumulative impacts of drilling and other operational activities on the species. There is evidence that the haddock caught near North Sea oil and gas installations have elevated levels of PAHs associated with discharge by oil and gas activities (Grøsvik *et al*., 2010). Balk *et al* (2011), for example, found a general relationship between the intensity of oil production in the investigated North Sea areas and adverse biological effects in Atlantic haddock and Atlantic cod. The effects include oxidative stress, altered fatty acid composition, and genotoxicity (Balk *et al*., 2011).

During laboratory experiments, haddock larvae collected from the Austevoll Research Station at the Institute of Marine Research (IMR) experienced craniofacial deformities when exposed to produced water collected at an offshore platform in the Norwegian Sea (Hansen *et al*., 2019). This could ultimately lead to premature death either as a direct consequence or as an indirect effect of jaw malfunction and starvation (Meier *et al.*, 2010).

Elevated DNA adducts have been observed in the liver of Atlantic haddock when exposed to PAHs found in PW or drilling muds (Meier *et al*., 2020). [DNA adducts](https://www.sciencedirect.com/topics/medicine-and-dentistry/dna-adduct) are segments of DNA bound to cancer-causing chemicals. They are, therefore a biomarker for exposure to marine pollutants such as PAHs (Balk *et al*., 2011). High levels of DNA adducts were still found in the liver following a two-month recovery period, indicating genotoxicity and adverse intracellular toxic effects in the body (Meier *et al.,* 2020).

Skeletal malformations, such as vertebral deformities, have been observed in haddock exposed to PAHS (Meier *et al.,* 2020). Powell *et al*., (2009) found that skeletal deformities in haddock can result in higher routine and maximum oxygen consumption in deformed fish compared to standard fish. Altered oxygen consumption indicates increased routine metabolic scope in fish with vertebral fusion, suggesting that fish can be rendered incapable of prolonged anaerobic activity (Powell *et al.*, 2009). Skeletal deformities can, therefore, have differential effects on swimming performance and result in high metabolic costs for the affected fish (Powell *et al*., 2009). These performance and metabolic costs can subsequently have impacts on reproduction, growth, susceptibility to diseases, predation risk and even death (Eissa *et al.*, 2021).

The skeletal deformities in haddock arising from PAHs found in wastes (produced by drilling and other operational activities) make the fish “unsightly”, which can hinder their attractiveness to customers and their ability to be sold. Reductions in sales of the fish can result in significant economic damage (Eissa *et al*., 2021), given that Atlantic haddock was valued at £35,534,000 in 2021 (Uberoi *et al*., 2022). This is concerning, considering that deformed wild haddock have been caught in the North Sea in recent years (Jawad *et al*., 2018). Therefore, the increasing number of oil and gas installations in the UK EEZ has the potential to negatively financially impact the fishing industry by increasing the risk of aforementioned damages to haddock.

Finally, no uncovered literature investigated the impact of physical infrastructure and/or noise associated with drilling and other operational activities on haddock. However, this does not point to a lack of adverse impacts that physical infrastructure and/or noise associated with drilling has on haddock, just a lack of research being conducted.

### Atlantic Cod (*Gadus morhua*)

PW, a product of drilling and other operational activities, has led to genotoxic effects in Atlantic Cod. Similar to Atlantic haddock, embryonic exposure to PW can cause cardiac toxicity and deformations in Atlantic cod larvae (Hansen *et al*., 2019). During laboratory experiments, larvae that were subjected to embryonic exposure of PW extracts were smaller, displayed signs of cardiotoxicity and had jaw and craniofacial deformities after hatching (Hansen *et al*., 2019).

A shift in hatching time of cod has been observed following a four-day exposure to PW. Reduced oestrogen levels and a delay in spawning time of 17-28 days were observed in first-time spawning female fish exposure to PW and AP (Meier *et al*., 2007). Impaired testicular development has also been observed in first-time spawning males exposed to AP (Meier *et al*., 2007). Survival during the first year of life is critical to determining how much cod will grow to a size commercial fisheries can harvest later (NOAA Fisheries, 2021). Earlier or delayed hatching may, therefore, increase the risk of prey mismatch. Thus, the shift in spawning phenology can potentially cause starvation, impeded survival and eventual mortality (NOAA Fisheries, 2021). This suggests that PW discharge is highly likely to negatively influence the early life stages and overall reproductive fitness and health of cod populations (Sundt & Björkblom, 2011).

In response to ship noise, horizontal and vertical movements away from vessels have been reported for Atlantic cod (Handegard *et al*., 2003; Slabbekoorn *et al*., 2010). Atlantic cod larvae exposed to regular playback recordings of ship noise also had lower body width–length ratios (Nedelec *et al.*, 2015). In a predator-avoidance experiment, larvae with lower body width–length ratios were easier to catch (Nedelec *et al.,* 2015). Therefore, noise associated with the operational impacts of oil and gas activities can impact survival during fish development (Nedelec *et al.*, 2015).

OSPAR lists Atlantic cod as a threatened and declining species. Over the last century, Atlantic cod has been overexploited in the marine areas around the British Isles, with stocks struggling to recover. Warming waters as a result of climate change further add pressure to declining stocks (Copernicus, 2019). Overexploitation is reflected in the rocketing prices of the species as seen in March 2022, where the price for a kilo of fresh Atlantic cod was selling at an average of £3.78, a 56% increase from the year before (Nilson *et al.*, 2022). Cod stocks in the North Sea are predicted to decrease in the next decade and not recover, even with the implementation of management measures (Koul *et al*.,2021). Thus, the further advancement of oil and gas licensing in the UK EEZ places further pressure on the already fragile status of Atlantic cod stocks and impairs their recovery.

No literature was uncovered that suggested an impact of physical infrastructure on Atlantic cod. However, this does not necessarily point to a lack of adverse impacts that physical infrastructure has on Atlantic cod, just a lack of research being conducted.

### Other commercial fish species

Both acute and sublethal effects of PW have been observed to reduce overall fish fitness. PW can cause abnormalities in the gill morphology in juvenile turbot, (*Cophthalmus maximus)* through exposure to various concentrations of crude oil (Stephens *et al*., 2000). For example, the fusion of the gill lamellar can progress into an almost continuous barrier leading to impaired oxygen uptake that can cause reduced swimming activity (Stephens *et al*., 2000). Significant adverse effects on herring (*Clupea harengus*) and saithe liver tissue integrity were also observed in the inner German Bight due to PAH (Hylland *et al*., 2002).

*Table 3. Table shows the varying impacts of oil and gas development, drilling and other operations on priority commercial and non-commercial fish species at distance from the source.*

|  |  |
| --- | --- |
|  |  |
|  |  |
|  |  | **Distance from source** | |
|  |  | **Impact** | **At source** |
| **Species** | *Atlantic cod* | Shift in time of hatching leading to prey mismatch. | [Meier et al., 2017](https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0240307)  [NOAA, 2022](https://www.fisheries.noaa.gov/feature-story/climate-change-raises-risk-prey-mismatch-young-cod-alaska) |
| Spinal deformations. | [Hansen et al., 2019](https://www.sciencedirect.com/science/article/pii/S0141113618308936) |
| Changes in craniofacial and jaw development. | [Hansen et al., 2019](https://www.sciencedirect.com/science/article/pii/S0141113618308936) |
| Starvation leading to mortality if changes in jaw development are severe. | [Hansen et al., 2019](https://www.sciencedirect.com/science/article/pii/S0141113618308936) |
| Susceptibility to infection, cancer and other diseases. | [Eissa et al., 2021](https://onlinelibrary.wiley.com/doi/abs/10.1111/are.15125) |
| Decreased size of larvae after hatch. | [Hansen et al., 2019](https://www.sciencedirect.com/science/article/pii/S0141113618308936) |
| Biotransformation enzymes, oxidative stress, altered fatty acid composition, and genotoxicity. | [Balk et al., 2011](https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0019735) |
| Reduced reproductive fitness. | [Meier et al., 2017](https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0240307)  [Sundt & Björkblom, 2011](https://pubmed.ncbi.nlm.nih.gov/21391097/) |
| *Atlantic haddock* | Changes in craniofacial and jaw development. | [Hansen et al., 2019](https://www.sciencedirect.com/science/article/pii/S0141113618308936) |
| Starvation leading to mortality if changes in jaw development are severe. | [Hansen et al., 2019](https://www.sciencedirect.com/science/article/pii/S0141113618308936) |
| Biotransformation enzymes, oxidative stress, altered fatty acid composition, and genotoxicity. | [Balk et al., 2011](https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0019735) |
| *Turbot* | Abnormalities to the gill morphology. | [Stephens et al., 2000](https://www.sciencedirect.com/science/article/abs/pii/S0025326X0000031X) |
| Decreased oxygen uptake leading to reduced swimming activity. | [Stephens et al., 2000](https://www.sciencedirect.com/science/article/abs/pii/S0025326X0000031X) |
| *Herring* | Adverse effects on liver integrity | [Hylland et al., 2002](https://imr.brage.unit.no/imr-xmlui/bitstream/handle/11250/106363/CM_2002_X_13.PDF?sequence=1&isAllowed=y) |
| *Saithe* | Adverse effects on liver integrity. | [Hylland et al., 2002](https://imr.brage.unit.no/imr-xmlui/bitstream/handle/11250/106363/CM_2002_X_13.PDF?sequence=1&isAllowed=y) |

## Invertebrates

### Introduction

Benthic invertebrates are a crucial part of marine ecosystems as they play a key role in ecosystem processes and functions and food webs dynamics and provide valuable ecosystem services (Culhane *et al*., 2019).

Although research on the impact of noise associated with oil and gas development on invertebrates is scarce, some studies have investigated the impact of vessel noise on invertebrates which is comparable. Exposure to noise associated with drilling and other operational activities can negatively impact invertebrates by increasing the risk of sensory damage (Solé *et al*., 2016).

Furthermore, exposure to the waste materials (e.g., produced water, drill cuttings, drilling muds) produced during oil and gas activities can severely impact invertebrates and cause mortality (Larsson & Purser, 2011).

The construction of physical infrastructure can also function as corridors ([Glasby & Connell 1999](https://besjournals.onlinelibrary.wiley.com/doi/10.1111/j.1365-2664.2009.01751.x#b44)), connecting otherwise separate invertebrate populations.

### Cold water communities

The cold water coral (CWC) is widely distributed and thrives in UK waters, where many reefs are located in the vicinity of oil platforms or exploration areas ([Järnegren](https://www.sciencedirect.com/science/article/abs/pii/S0967064516301758" \l "!) *et al.*, 2017). The conservation importance of *L. pertusa* reefs, the most common CWC in UK waters, has been increasingly recognised due to their longevity, high biodiversity, biomass-rich ecosystems, and benefit to commercial fisheries (Maddock, 2008; Purser & Thomsen, 2012). Concern over the impacts on CWC reefs from oil and gas activities has encouraged several field studies to investigate the impacts of oil and gas activities on CWC ([Lepland & Mortensen, 2008](https://www.sciencedirect.com/science/article/pii/S0141113619307913" \l "bib24); [Purser & Thomsen, 2012](https://www.sciencedirect.com/science/article/pii/S0141113619307913#bib28); [Larsson *et al.*, 2013](https://www.sciencedirect.com/science/article/pii/S0141113619307913#bib22); [Godø *et al*., 2014](https://www.sciencedirect.com/science/article/pii/S0141113619307913#bib14); [Buhl-Mortensen *et al*., 2015](https://www.sciencedirect.com/science/article/pii/S0141113619307913#bib8); [Purser, 2015](https://www.sciencedirect.com/science/article/pii/S0141113619307913#bib29)).

Discharge of drill cuttings and drilling muds from oil and gas drilling and operational activities impact CWC communities in deep waters via smothering and toxic effects (Lepland & Mortensen, 2008; Purser &Thomsen, 2012; Larsson *et al*., 2013). Discharged water-based mud (WBM) cuttings containing barite can cause biological effects on CWC communities during its suspension in the water column and after sedimentation. For example, when discharged, WBM cuttings can cause a local reduction in hard bottom fauna species in areas close to discharge sites. The burial of CWC by drill cuttings has resulted in damaged *L. pertusa* colonies and polyp mortality (Larsson & Purser, 2011). Suspended cuttings may also cause the cilia of *L. pertusa* to become clogged, hindering larvae from swimming actively, which causes larvae to sink and ultimately cause mortality ([Järnegren](https://www.sciencedirect.com/science/article/abs/pii/S0967064516301758" \l "!) *et al*., 2010).

The construction of oil and gas infrastructures can provide a hard substratum for colonising benthic invertebrates, including corals (Cordes *et al*., 2016). *L. pertusa* has been found on many oil field structures in the North Sea. Such structures may enhance population connectivity and allow native and invasive species to exploit the area (Cordes *et al*., 2016). Uncovered research, however, does not specify which invasive species would be expected to occur around oil and gas structures in UK waters. In Brazil, however, the invasive sun polyp *(Tubastrea)* has been found to colonise rigs-to-reef structures in the Gulf of Mexico (Sammarco *et al.*, 2010). The net impact of the connectivity provided by artificial structures is thus complex to determine, making it hard to predict the benefits or harm of the increased availability of deep-sea hard substrate.

The impact of noise on CWC reefs appears to remain unstudied (de Clippele & Risch, 2021). However, there are useful studies that demonstrate the impact of anthropogenic noise (produced by motorboats, maritime shipping etc.) on tropical coral reef organisms that can give us context. For example, noise is known to affect the behaviour, physiology and ecology of tropical coral reef organisms (Ferrier-pages et al., 2021). Boat noise, in particular, has been found to adversely impact the risk assessment in damselfish belonging to coral reef communities, reducing fitness and survival (McCormick et al., 2018).

### Lobsters and Crabs

In the presence of boat noise, Spiny lobsters (*Palinurus elephas*), which are classified as a Priority Species under the UK Post-2010 Biodiversity Framework (NatureScot, 2020), have demonstrated behavioural and physiological changes such as increased locomotor behaviour andbiochemical stress responses (Filiciotto *et al*., 2015). The former may be especially ecologically detrimental as the lobsters may increasingly reveal themselves to predators under noisy conditions (Filiciotto *et al*., 2015). In another study, the joint exposure of lobster (*H. Gammarus)* young to constant low-frequency noise and predator presence reduced hiding behaviour and increased exploration behaviour (Leiva *et al*., 2021). Noise, therefore, adversely interferes with early-life stage lobsters’ decision-making processes which could lead to increased predation risk (Leiva *et al.*, 2021).

Contaminants found in waste material associated with drilling and other operational activities can adversely impact lobsters. Capuzzo (1984) has documented adverse effects on the growth, development, respiration and feeding rates of lobster (*Homarus americanus*) larvae at drilling fluid concentrations as low as 10 mg L-1. Thus, certain drilling muds can severely damage lobster populations in the exposed area (Atema et al., 1979). Chronic toxicity studies investigating lobsters have demonstrated that relatively low concentrations of petroleum hydrocarbons in water (0.04-0.05 ppm range) can still affect animal health (Boudreau et al., 2001).

Landings of European lobster (*Homarus gammarus*) into English ports alone were worth £17.7 million in 2014, which made it the third most valuable species landed in England (DEFRA, 2016). Due to its substantial economic importance, the species is subject to considerable fishing pressure. Further pressure stemming from noise and wastes produced by drilling and other operational activities may thus lead to the collapse of lobster stocks, as seen in Scandinavia and throughout the Mediterranean (Steinhoff, n.d).

It is of interest to understand if noise from drilling and other operational activities harms commercially important crabs in the UK like the Brown Crab (*C. pagurus*). However, it is unknown if the brown crab suffers direct harm as a result of exposure to high-amplitude anthropogenic noise (Edmonds *et al*., 2016). Some useful studies on related species of crabs have shown that crabs can suffer detrimental physical and behavioural impacts as a result of high-amplitude anthropogenic noise (Edmonds *et al*., 2016). In an experiment by Wale *et al*., (2013b), shore crabs that were exposed to playbacks of ship noise consumed more oxygen than those who were not exposed to the playbacks, indicating a higher metabolic rate and higher stress levels. They also found that the crabs were slower to retreat back to shelter in response to simulated predatory attacks (Wale et al., 2013a). This could mean increased predatory risk for crabs which could affect their survival.

Very sparse literature was uncovered that suggested impacts of physical infrastructure associated with oil and gas development on lobster and crabs specifically. However, it has been suggested pipelines with large diameters might introduce a physical barrier to mobile invertebrates, impeding range extensions (McLean *et al*., 2022). Useful research has been conducted on the impacts of physical infrastructure associated with wind farm development on the population structures of European lobsters and brown crabs. A smaller population of lobsters, with larger average sizes, were found within the demonstration wind farm site compared to the inshore “control” (Skerritt *et al*., 2012). A larger population of brown crabs, with a larger average size, was also reported at the wind farm site (Skerritt *et al.*, 2012).

### Mussels

Mussels play an essential part in a healthy functioning marine ecosystem, having a role in coastal sediment dynamics. Adverse impacts of WBM on horse mussels (*Modiolus modiolus*) are a cause for concern as horse mussel beds are a Priority Marine Feature, a UK BAP habitat, and an OSPAR-threatened and declining habitat (Nature Scot, 2017). Horse mussel beds also provide valuable ecosystem services, such as serving as feeding and nursery grounds for commercially important whelks (*Buccinum undatum*) (Kent *et al*., 2016).

Studies of the impacts of waste materials (e.g., PW, WBM, drill cuttings) on mussels have focused on two common UK species, blue mussels (*Mytilus sp.*) and horse mussels. Research has found that the suspensions of barite-based WBM cause histopathological gill changes, reduced lysosome membrane stability, oxidative stress, DNA damage, decreased filtration rates, growth, survival and modified haemolymph protein pattern in blue mussels (Bakke *et al.,* 2013). For example, barite-based WBM has been found responsible for damaging the gill structure of four bivalve species in an experimental study, including horse mussels and blue mussels (Strachan, 2010). The suspension of WBM ultimately altered the filtration rates leading to 100% mortality (Strachan, 2010).

PW has resulted in biological effects such as higher stress levels (biomarker parameters) in mussels, with some measurements being higher than environment assessment criteria levels from ICES. In a laboratory study, PAH bioaccumulation increased in soft mussel tissue even at the lowest exposure dose, highlighting the potential impact of PW stemming from North Sea oil and gas development (Sundt *et al*., 2011).

Noise associated with drilling and other operational activities can cause changes in DNA integrity, indicating an underlying source of stress (Wale *et al*., 2019). The exposure to playbacks of ship noise led to a 12% reduction in oxygen consumption and an 84% decrease in the filtration of blue mussels (Wale *et al*. 2019). The exposure to playbacks of pile driving noise also negatively affected byssal thread production and the mechanical performances of the thick shell mussel (*M. coruscus* ) which could potentially impede essential functions and pose a threat to both mussel aquaculture and mussel-bed ecosystems. (Zhao *et al*., 2021). In another study, blue mussels demonstrated reduced responsiveness (habituation) to repeated sound exposures, which may result in reduced responsiveness to other sensory stimuli (Hubert et al., 2022).

No uncovered literature was found that suggested the impact of physical infrastructure associated with oil and gas development on mussels. However, there is useful research available on the impact of the physical infrastructure associated with wind farm development. Blue mussel is the most predominant colonising species on offshore wind farms (Degraer *et al*., 2020). The high biomass of blue mussels on wind farms may have bioengineering and reef-building effects (Degraer *et al.,* 2020). Feedback caused by mussels ingesting their prey and egesting faecal wastes on the surrounding sediments can also result in the creation of local hotspots of biological activity and altered ecosystem dynamics (Maar et al., 2009). This is evidenced in Belgian and USA waters, where blue mussel aggregations with distinct macrofaunal communities found in areas near turbines (Degraer *et al*., 2020)

### Scallops

Scallops are commercially important, with the King scallop (*Pecten maximus*) being one of two species of scallop harvested in the UK. In 2019, around 29.2 thousand tonnes of scallops were landed in total, with a value of £62 million (Marine Management Organisation, 2020).

Scallops experience similar impacts to WBM as mussels, such as histopathological gill changes, reduced lysosome membrane stability, oxidative stress, DNA damage, decreased filtration rates, growth, and survival and modified haemolymph protein pattern. For example, the suspension of barite-based WBM altered the filtration rates of four bivalves in an experimental study, which led to 100% mortality in scallops (Strachan, 2010). The variegated scallop (*Chlamys varia*)*,* was the least tolerant to standard barite out of the four bivalves tested (Strachan, 2010).

Exposure to noise associated with drilling and other operational activities led to the New Zealand scallop larvae suffering significant development delays, with 46% of them developing body abnormalities. Therefore, routine noise associated with oil and gas activities can potentially impact the survival of scallops (Soto *et al.,* 2013).

No uncovered literature suggested any impact of physical infrastructure on scallops. However, this does not necessarily point to a lack of adverse impacts that physical infrastructure has on scallops, just a lack of research being conducted.

### Benthic fauna

Benthic fauna, such as deep-sea sponges, play an important role in supporting the provision of ecosystem services in our oceans (Henry and Murray, 2014). Aggregations of deep-sea sponges are listed on the OSPAR list of Threatened and/or Declining species and habitats (OSPAR Commission, 2022).

Drilled cuttings discharged on the seabed can smother benthic fauna that requires particular sediments to feed and spawn on. Contamination by drill cuttings can result in significant effects recorded in diversity indices. Major reductions in diversity have been found within a 200-metre radius of production platforms in the Faroe-Shetland channel (Jones *et al*., 2012). Vad *et al*. (2018) also found that on an individual level, increased sedimentation due to drill cuttings can hinder filtration (Vad *et al*., 2018). A study by Tjensvoll et al., (2013) also revealed that large amounts of sedimentation results in 86% reduced respiration rate in the deep-water sponge (*Geodia barretti*) (Tjensvoll et al., 2013)

Even if the physical smothering of benthic organisms does not occur, the toxicity or physical interference from materials discharged may still lead to mortality (Cranford & Gordon, 1991). For example, drilling muds can result in a reduction in cellular membrane stability in deep sea sponges (Vad *et al.,* 2018). The physical disturbance associated with drilling also caused decreased densities and richness of benthic fauna even after ten years (Jones *et al*., 2012).

*Table 4. Table shows the varying impacts of oil and gas development, drilling and other operations at distance from the source.*

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  |  | **Distance from source** | | | | |
|  |  | **Impact** | **At source** | **10s’ m** | **100s’ m** | **100s’km** |
| **Species** | *Deep-water coral colonies* | Larval mortality. | [Järnegren et al., 2010](https://www.researchgate.net/publication/304909040_Effects_of_drill_cuttings_on_larvae_of_the_cold-water_coral_Lophelia_pertusa) |  |  |  |
| Mortality. | [Larsson & Purser, 2011](https://www.researchgate.net/publication/51086176_Sedimentation_on_the_cold-water_coral_Lophelia_pertusa_Cleaning_efficiency_from_natural_sediments_and_drill_cuttings) |  |  |  |
| Increased connectivity. | [Henry et al., 2018](https://www.nature.com/articles/s41598-018-29575-4#Sec8) | [Henry et al., 2018](https://www.nature.com/articles/s41598-018-29575-4#Sec8) | [Henry et al., 2018](https://www.nature.com/articles/s41598-018-29575-4#Sec8) | [Henry et al., 2018](https://www.nature.com/articles/s41598-018-29575-4#Sec8) |
| *Lobster* | Reduced growth. | [Capuzzo (1984)](https://www.sciencedirect.com/science/article/abs/pii/0141113684900795) |  |  |  |
| Impeded development. | [Capuzzo (1984)](https://www.sciencedirect.com/science/article/abs/pii/0141113684900795) |  |  |  |
| Adverse impacts on respiration. | [Capuzzo (1984)](https://www.sciencedirect.com/science/article/abs/pii/0141113684900795) |  |  |  |
| Decreased feeding rates. | [Capuzzo (1984)](https://www.sciencedirect.com/science/article/abs/pii/0141113684900795) |  |  |  |
| *Crab* | Higher oxygen consumption, indicating higher metabolic rate and higher stress levels. | [Wale et al., 2013](https://royalsocietypublishing.org/doi/10.1098/rsbl.2012.1194) |  |  |  |
| Slower retreat back to shelter in response to simulated predatory attacks, with potential impacts on survival. | [Wale et al., 2013](https://www.sciencedirect.com/science/article/abs/pii/S0003347213001991) |  |  |  |
| *Horse mussels* | Mortality. | [Strachan, 2010](https://www.semanticscholar.org/paper/Studies-on-the-impact-of-a-water-based-drilling-mud-Strachan/cbdb57c7dafadcd23eca3bed181cb575cc2cfe0b) |  |  |  |
| *Blue mussels* | Histopathological gill changes. | [Bakke et al., 2013](https://pubmed.ncbi.nlm.nih.gov/24119441/) | [Bakke et al., 2013](https://pubmed.ncbi.nlm.nih.gov/24119441/) | [Bakke et al., 2013](https://pubmed.ncbi.nlm.nih.gov/24119441/) |  |
| Reduced lysosome membrane stability. | [Bakke et al., 2013](https://pubmed.ncbi.nlm.nih.gov/24119441/) | [Bakke et al., 2013](https://pubmed.ncbi.nlm.nih.gov/24119441/) | [Bakke et al., 2013](https://pubmed.ncbi.nlm.nih.gov/24119441/) |  |
| Oxidative stress. | [Bakke et al., 2013](https://pubmed.ncbi.nlm.nih.gov/24119441/) | [Bakke et al., 2013](https://pubmed.ncbi.nlm.nih.gov/24119441/) | [Bakke et al., 2013](https://pubmed.ncbi.nlm.nih.gov/24119441/) |  |
| DNA damage. | [Bakke et al., 2013](https://pubmed.ncbi.nlm.nih.gov/24119441/) | [Bakke et al., 2013](https://pubmed.ncbi.nlm.nih.gov/24119441/) | [Bakke et al., 2013](https://pubmed.ncbi.nlm.nih.gov/24119441/) |  |
| Reduced growth and survival. | [Bakke et al., 2013](https://pubmed.ncbi.nlm.nih.gov/24119441/) | [Bakke et al., 2013](https://pubmed.ncbi.nlm.nih.gov/24119441/) | [Bakke et al., 2013](https://pubmed.ncbi.nlm.nih.gov/24119441/) |  |
| Modified haemolymph protein pattern. | [Bakke et al., 2013](https://pubmed.ncbi.nlm.nih.gov/24119441/) | [Bakke et al., 2013](https://pubmed.ncbi.nlm.nih.gov/24119441/) | [Bakke et al., 2013](https://pubmed.ncbi.nlm.nih.gov/24119441/) |  |
| Decreased filtration Rates. | [Bakke et al., 2013](https://pubmed.ncbi.nlm.nih.gov/24119441/) | [Bakke et al., 2013](https://pubmed.ncbi.nlm.nih.gov/24119441/) | [Bakke et al., 2013](https://pubmed.ncbi.nlm.nih.gov/24119441/) |  |
| PAH bioaccumulation. | [Sundt & Björkblom, 2011](https://pubmed.ncbi.nlm.nih.gov/21391097/) | [Bakke et al., 2013](https://pubmed.ncbi.nlm.nih.gov/24119441/) | [Bakke et al., 2013](https://pubmed.ncbi.nlm.nih.gov/24119441/) |  |
| *Scallops* | Histopathological gill changes. | [Bakke et al., 2013](https://pubmed.ncbi.nlm.nih.gov/24119441/) | [Bakke et al., 2013](https://pubmed.ncbi.nlm.nih.gov/24119441/) | [Bakke et al., 2013](https://pubmed.ncbi.nlm.nih.gov/24119441/) |  |
| Reduced lysosome membrane stability. | [Bakke et al., 2013](https://pubmed.ncbi.nlm.nih.gov/24119441/) | [Bakke et al., 2013](https://pubmed.ncbi.nlm.nih.gov/24119441/) | [Bakke et al., 2013](https://pubmed.ncbi.nlm.nih.gov/24119441/) |  |
| Oxidative stress. | [Bakke et al., 2013](https://pubmed.ncbi.nlm.nih.gov/24119441/) | [Bakke et al., 2013](https://pubmed.ncbi.nlm.nih.gov/24119441/) | [Bakke et al., 2013](https://pubmed.ncbi.nlm.nih.gov/24119441/) |  |
| DNA damage. | [Bakke et al., 2013](https://pubmed.ncbi.nlm.nih.gov/24119441/) | [Bakke et al., 2013](https://pubmed.ncbi.nlm.nih.gov/24119441/) | [Bakke et al., 2013](https://pubmed.ncbi.nlm.nih.gov/24119441/) |  |
| Reduced growth and survival. | [Bakke et al., 2013](https://pubmed.ncbi.nlm.nih.gov/24119441/) | [Bakke et al., 2013](https://pubmed.ncbi.nlm.nih.gov/24119441/) | [Bakke et al., 2013](https://pubmed.ncbi.nlm.nih.gov/24119441/) |  |
| Modified haemolymph protein pattern. | [Bakke et al., 2013](https://pubmed.ncbi.nlm.nih.gov/24119441/) | [Bakke et al., 2013](https://pubmed.ncbi.nlm.nih.gov/24119441/) | [Bakke et al., 2013](https://pubmed.ncbi.nlm.nih.gov/24119441/) |  |
| Decreased filtration rates. | [Bakke et al., 2013](https://pubmed.ncbi.nlm.nih.gov/24119441/) | [Bakke et al., 2013](https://pubmed.ncbi.nlm.nih.gov/24119441/) | [Bakke et al., 2013](https://pubmed.ncbi.nlm.nih.gov/24119441/) |  |
| *Benthic Fauna* | Decreased densities and richness. | [Jones et al., 2012](https://www.int-res.com/articles/meps_oa/m461p071.pdf) | [Jones et al., 2012](https://www.int-res.com/articles/meps_oa/m461p071.pdf) | [Jones et al., 2012](https://www.int-res.com/articles/meps_oa/m461p071.pdf) |  |
| Reduced cellular membrane stability | [Vad et al., 2018](https://researchportal.hw.ac.uk/en/publications/potential-impacts-of-offshore-oil-and-gas-activities-on-deep-sea-) |  |  |  |
| Reduced respiration and filtration rates | [Vad et al., 2018](https://researchportal.hw.ac.uk/en/publications/potential-impacts-of-offshore-oil-and-gas-activities-on-deep-sea-)  [Tjensvoll et al., 2013](https://www.researchgate.net/publication/257938058_Rapid_respiratory_responses_of_the_deep-water_sponge_Geodia_barretti_exposed_to_suspended_sediments) |  |  |  |

# The effectiveness of guidance and mitigation measures around drilling and other operational impacts associated with oil and gas development

## Guidance and mitigating measures on drilling and other operational impacts in UK waters

The key requirements and guidance for the preparation and mitigation of noise and the discharge of wastes associated with drilling and other operational activities in UK waters include;

1. The establishment of a Marine Noise Registry (MNR) as a commitment made in the [UK Marine Strategy](https://www.gov.uk/government/publications/marine-strategy-part-one-uk-initial-assessment-and-good-environmental-status) requires the mandatory or voluntary provision of data (including location, dates, frequency, maximum airgun volume, maximum hammer energy, sound pressure level and sound exposure level) depending on the type of activity and whether there are any relevant consenting procedures.
2. All ‘Responsible Persons’ (Installation Operators, Well Operators and Owners of Non-Production Installations) must prepare a legally required Oil Pollution Emergency Plan (OPEP). An OPEP sets out a robust and effective response to an oil pollution incident that minimises the impact of a spill on the marine environment. The OPEP must be prepared and implemented in accordance with the OPRC Regulations and the Department’s [Guidance Notes for Preparing Oil Pollution Emergency Plans.](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1082788/OPEP_Guidance_-_Rev_7_-_June_2022.pdf)
3. Under the [Offshore Chemicals Regulations 2002](https://www.legislation.gov.uk/uksi/2002/1355/contents/made) offshore operators are required to apply for permits for the use and/or discharge of chemicals in all relevant offshore energy activities. This includes well operations, production operations, pipeline operations, and decommissioning operations. The [2011 Amendment Regulations](https://www.legislation.gov.uk/uksi/2011/982/contents/made) extended the provisions to take enforcement action in the event of any unintentional offshore chemical release.
4. [Offshore Installations (Emergency Pollution Control) Regulations 2002](https://www.legislation.gov.uk/uksi/2002/1861/contents/made) provide powers to the Secretary of State to prevent and reduce pollution, and the risk of pollution, following an accident involving an offshore installation where there may be significant pollution and/or when an operator is failing or has failed to implement effective control and preventative operations.
5. [The Offshore Oil and Gas Exploration, Production, Unloading and Storage (Environmental Impact Assessment) Regulations 2020](https://www.legislation.gov.uk/uksi/2020/1497/contents/made) informs the Secretary of State’s decision of whether to agree to the grant of consent for proposed offshore projects when considering the environmental impacts of such projects.
6. The Statutory Nature Conservation Bodies (SNCB’s) [SAC Noise Guidance 2020](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/889842/SACNoiseGuidanceJune2020.pdf) outlines guidance that should be considered by competent authorities when undertaking Habitat Risk Assessments (HBAs). The approach applies to all plans and projects within or affecting a site that could cause significant noise disturbance to harbour porpoise, alone or in combination with other plans or projects.
7. Under the [Offshore Petroleum Licensing (Offshore Safety Directive) Regulations 2015](https://www.legislation.gov.uk/uksi/2015/385/pdfs/uksi_20150385_en.pdf), declarations or demonstrations of financial liability provisions must be made in accordance with these Guidelines.
8. [Offshore Petroleum Activities (Oil Pollution Prevention and Control) Regulations 2005](https://www.legislation.gov.uk/uksi/2005/2055/contents/made) aims to prevent and eliminate pollution by oil and other substances caused by discharges of produced water into the sea. Before oil discharges are made, permit applicants must undertake an assessment to identify oil discharges to be made from the installation to the relevant area and submit a permit application to the Department. Permit holders must comply with the conditions attached to the permit.

## Are the guidance and mitigating measures effective?

This section will discuss the effectiveness of the above guidance and mitigating measures on drilling impacts and other operational impacts in UK waters.

### Guides and commitments alone are not enough to minimise the impact of noise from drilling activities and other operational impacts on marine species.

Guidance such as the [SAC Noise Guidance](about:blank) and the Marine Noise Registry (MNR) made as a commitment under the UK Marine Strategy can only serve as guidelines, as there is often little meaningful enforcement associated with them. Within and outside SACs, projects with the potential to result in injury or disturbance can only go move forward if mitigation measures to mitigate the risks are employed (JNCC, 2020). However, whether the mitigation methods, such as marine mammal officers (MMO) enforcing mitigation zones, are the most effective is questionable. For example, the effectiveness of MMO as a mitigation strategy decreases with poor weather conditions or low visibility (Barton, 2019). If there no alternative methods that can reduce the risk of injury of disturbance, licences can then be issued (JNCC, 2020).

Although required by legislation, assessments of the cumulative effects and impacts of anthropogenic sound from multiple sources on marine mammals and their habitat have proven difficult to carry out. As such, more research into this area as well as more meaningful strategies, need to be implemented to strongly deter operators from generating noise from drilling activity that adversely impacts marine species.

### Fines do not work/ are not effective as a measure to mitigate the impacts associated with drilling and operational activities on marine species/habitats.

The mitigating measures around pollution focus on fines (as outlined in the [Merchant Shipping (Oil Pollution Preparedness, Response and Co-operation) Regulations 2015 (Amended)).](https://www.legislation.gov.uk/uksi/2015/386/contents/made) However, these fines are insignificant compared to a typical oil and gas company's annual profit, making them unlikely to be a solid incentive to mitigate oil spills.

For example, BP has made £5bn in profits in the first quarter of 2022 alone due to a global surge in oil and gas prices (Carrell, 2022). However, BP was fined £7000 when 95 tonnes of crude oil spilt into seas west of the Shetland islands in Scotland (Watts, 2020) in 2020. Fines of this amount are, therefore, unlikely to be an effective incentive to reduce pollution associated with drilling activities from taking place. This lack of incentive is evidenced by BP’s continued engagement in activities leading to marine pollution, in some cases even consciously. For example, the company recently sought approval to dump 14 pipes and control cables 120 miles west of Shetland, a designated MPA home to rare giant deep-sea sponges, gravel ecosystem and ocean quahog, a very slow-growing mollusc (Carrell, 2022).

### Limited effectiveness of Offshore Chemicals Regulations 2002 (as amended)

OSPAR encourages companies to seek the use of less hazardous chemicals wherever possible to achieve the objective of minimal risk to the marine environment. However, it does not dictate that the least hazardous chemicals must be used, as operational requirements may well state otherwise. Therefore, companies can still use hazardous chemicals if they fall in line with “operational requirements, " presumably set by the companies themselves. The current procedure following the increase in the rate of use and/or discharge of a chemical does not deter companies from minimising the discharge of chemicals as regulations only require a request for a variation of the chemical permit to cover future increases in the chemical use and/or discharge in some cases or submit a Regulatory Non-Compliance notification to the Department’s Offshore Environmental Inspectorate in others. Following the request for a variation of the chemical permit, the Department’s Offshore Environmental Inspectorate then establishes whether a change in the standard operating procedure led to the increase. How the Department’s Offshore Environmental Inspectorate establishes this is not clear, and the process almost seeks to justify and exonerate the increase in the use and/or discharge of a chemical.

Furthermore, there is evidence of lapses in the enforcement of regulations, as seen in 2016 when there was a 3- 4kg discharge of lead‐based pipe dope, which was erroneously permitted during drilling operations with water‐based mud. (OSPAR Commission, 2018). OSPAR’s Recommendation 2005/2 aimed to phase out the discharge of chemicals on the OSPAR List of Chemicals for Priority Action (LCPA) by 1 January 2010. However, this incident highlights the failure to prevent the discharge of LCPAs and the need to strengthen the regulation.

### The OESEA4 severely lacks acknowledgement of the impacts of drilling and other operational impacts on marine species and habitats in UK waters.

The Strategic Environmental Assessment (SEA) carried out to evaluate the implications of expanded oil and gas licencing in the UK offshore waters (OESEA4) does not sufficiently acknowledge the comprehensive scientific understanding of direct drilling impacts on UK mammals, fish, invertebrates and benthic habitats. The literature referenced in the OESEA4 is mostly downplayed, demonstrated in a more favourable light or cherry-picked to exclude the specific impacts mentioned (Table 5).

Additionally, the report states a general presumption that produced water from future oil and gas developments on the UKCS will be reinjected and not discharged to reduce the impact on the marine environment. However, the proportion of re-injected produce water was only 24% in 2016, representing only a 2% increase since 2012 (OSPAR Commission, 2018). The OSPAR Quality Status Report (QSR 2010) also notes that water column monitoring to determine possible effects from PAHs and other chemicals, such as alkyl phenols discharged with produced water, has been limited in the OSPAR area. The literature outlined in the report downplayed the adverse effects of PAHs on commercially important species such as cod. The QSR 2010 further noted that results from water column monitoring are complex to understand, especially for wild fish, for which it is not possible to link observed biological responses to a specific exposure source. While several papers have highlighted the cumulative impacts, others have clearly shown the relationship between the impacts on fish and noise/ pollutant impacts.

*Table 5. The table shows whether the proven impacts of drilling and operational activities on offshore UK habitats and species are included in the Strategic Environment Assessment (SEA) for the expansion of UK oil and gas licencing (OESEA4). The left column details the proven impact presented in scientific papers, the middle column states if that impact has been acknowledged in the OESEA4, and the right column provides a reason (if known) or note.*

|  |  |  |  |
| --- | --- | --- | --- |
|  | Scientific understanding of the impacts of oil spills on offshore habitats and species | Are these impacts included in the Environment Impact Assessment for the expansion of UK oil and gas licencing? (OESEA4) | Notes/reason |
| Marine mammals | Noise associated with oil and gas development alters behaviour in marine mammals, which might reduce reproductive fitness, increase energy expenditure etc. | The OESEA4 does not mention that oil and gas development noise can affect marine mammals. | Studies have documented that noise can cause the impairment of foraging, disruption of social interactions, auditory threshold shifts, hearing loss and, in extreme cases, injury or even death. |
| Fish | Widespread sublethal effects of pollutants (e.g., produced water, drill cuttings etc.) on fish have been observed through a large volume of studies. | The OESEA4 claims that “WBM drilling discharges generally disperse widely, and significant accumulations do not occur. It is, therefore, possible that discharge footprints will overlap, although the ecological effects will be undetectable. | PAHs found in drill-cutting piles cause physiological effects which can manifest in benthic fish, such as neoplasias, haemorrhages, and liver and epithelial lesions. |
| The impact of pollutants (e.g., produced water, drill cuttings etc.) could hinder the recovery of key commercial fish stocks such as Atlantic cod. | The OESEA4 does not mention the impact of pollutants on commercial fish and downplays the pressure on fish stocks. | Water Based Muds (WBM) and the contaminants found in them (e.g., barite) have significant impacts on fish |
| The impact of marine noise on fish (e.g., behavioural impact, temporary displacement, potential hearing damage) has been recorded in several studies. | The impact of marine noise on fish is not mentioned. | Marine noise associated with drilling may cause behavioural reactions (e.g., avoidance) and the temporary displacement of fish |
| Invertebrates | Drilling cuttings have been shown to severely impact deep-water ecosystems, including coral and benthic communities over a few km. | OESEA4 only states that “Similar effects may be possible in the cold water corals found in deeper water of the UKCS such as *Lophelia pertusa*”. | Multiple studies have shown significant impacts on *L. pertusa,* causing larval mortality and mortality. Given that coral reefs are a key part of ecosystems and play an essential role in supporting ecosystem processes and functionality, this impact must be discussed. |

# Conclusion

Research has shown that drilling and other operational activities impact species, from marine mammals to commercially important fish to vulnerable CWC. These impacts reverberate across spatial scales and are observed in the long term, sometimes up to a decade later. At local scales, these impacts are particularly acute, with potential for organ damage and/or widespread mortality.

In general, there is limited research on the impact of non-seismic noise associated with drilling and other operational activities on marine species. However, many studies have focused on the impact of noise associated with offshore windfarms (e.g., pile driving) or shipping vessels (e.g., whale-watching boats etc.) on marine life. These studies are useful to help us understand the potential impacts of noise associated with drilling and other operational activities on marine species, including priority species, key UK commercial fish and invertebrate species.

In marine mammals, the impact of noise associated with drilling and other operational activities can lead to changes in physical behaviour, such as diversion in migratory routes, avoidance and reduced foraging activity. Hearing threshold shifts and changes in acoustic behaviour, such as the increased rate, duration and/or amplitude in call to compensate for masking, have also been observed. When combined, these impacts have serious implications on both individual fitness and the populations of marine mammals with a K-selected life history (i.e., large body size, late maturity, long gestation period, few offspring, long life expectancy). This K-selected life history makes them more vulnerable to anthropogenic threats.

In fish, noise can damage organs and cause possible hearing damage, hindering the detection of predators, mates and prey, thus affecting their survival and reproduction. The impact of noise associated with drilling and other operational activities may also cause avoidance behaviour and the temporary displacement of fish which can have negative economic repercussions for commercial fisheries.

In invertebrates, noise can lead to changes in DNA integrity, and cause body abnormalities and behavioural changes, leading to increased predatory risk.

The impact of waste materials (e.g., PW, drill cuttings and drill muds) produced during oil and gas activities on fish have been extensively studied. In particular, numerous studies have focused on the commercially important Atlantic cod and Atlantic haddock. Sub-lethal effects (e.g., DNA damage, genotoxicity, skeletal deformities) have been observed in fish. In 2021, landings of Atlantic cod and Atlantic haddock had a combined estimated value of 75 million (Marine Management Organisation, 2021). Such adverse effects stemming from waste materials produced during drilling and other operational activities can, therefore, have huge impacts on the larger economy.

In invertebrates, the suspension and sedimentation of drill cuttings can cause mortality in cold-water corals. In shellfish like mussels, contaminants found in PW and drill muds can cause biological effects such as higher stress levels, DNA damage, decreased filtration rates and mortality.

The construction of physical infrastructure on the seafloor can cause major disturbances to benthic habitats. Oil and gas infrastructure may also facilitate the introduction of both native and opportunistic invasive fish and/or invertebrate species by serving as corridors, connecting otherwise separate habitats. In a relevant example, a study recorded 33 non-native species in UK marinas which serve as artificial habitats (Foster *et al.,* 2016). This can potentially threaten native biodiversity and ecosystems.

This report only discusses scientific evidence available in the literature uncovered. However, gaps in research remain, and the specific impacts of drilling and other operational activities on marine species are few and far between (especially for non-seismic noise and physical infrastructure impacts). Literature has also presented the difficulties in discussing the long-term, cumulative impacts of oil and gas operations on marine species. It is often hard to separate the primary cause of impact (e.g., DNA damage in fish, for example) because marine species are often exposed to the impacts simultaneously (e.g., noise, PW, drill cuttings and drill muds, accidental spills). Therefore, this highlights the opportunity for future research to effectively discuss the impacts of drilling and operational activities on marine life.

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## Key challenges

* Literature on the adverse impacts of oil and gas infrastructure on marine mammals was sparse.
* Literature generally accepts that there are adverse impacts of oil and gas infrastructure on fish and invertebrates, e.g., creating a stepping stone for invasive species to exploit the area. However, detailed case studies demonstrating the adverse impacts were hard to come by.
* Literature focusing on the noise produced during oil and gas development primarily concerns seismic noise (as covered in Work Package 1). However, studies on the adverse impact of oil and gas drilling and other operational activities on marine mammals, fish and invertebrates are limited. Consequently, comparisons have had to be made by focusing on the impacts of offshore wind farm operations.
* Most studies on the impacts of PAHs and vessel noise on fish and invertebrates have been carried out in laboratory experiments. Therefore, it is difficult to extrapolate the results to wild populations due to the small sample size and the nature of a controlled environment.
* Long-term evidence for adverse impacts on all taxa groups is sparse due to the difficulty in conducting long-term research (e.g., due to funding etc.). Consequently, most studies uncovered focused on the short-term impacts (i.e., over days, months or a few years).

## Follow-up research ideas

* Expand on the mitigating measures section. E.g., compare and contrast case studies from other areas (e.g., offshore wind farms) to see where gaps and opportunities lie for UK policy.
* How can we integrate scientific findings into actual policy/measures?