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Oil and gas exploration and production activities in areas with defined benthic conservation objectives: A review of potential impacts and mitigation measures

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Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

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ABSTRACT

This paper summarizes the results of a literature review on key potential effects of routine marine oil and gas exploration, development and production activities on benthic species and habitats, and considers measures that may reduce impacts in areas with defined benthic conservation objectives. “Areas with defined benthic conservation objectives” may include benthic species (demersal fishes and invertebrates); benthic habitats (spawning, nursery and feeding grounds), and Sensitive Benthic Areas (SBAs) (corals, sponges, canyons, seamounts and hydrothermal vents). SBAs are cornerstones of deep-sea biodiversity and ecosystem functioning, forming complex habitats and providing other biota with food and nutrients, refuge from predators, nursery grounds, hard surfaces for invertebrates, and structures for sessile organisms.

Potential impacts of the following exploration and production activities are described: seismic, electromagnetic and seabed surveys; placement and presence of seabed infrastructure; exploration and development drilling discharges; and treatment and discharge of produced water. While other activities have the potential to impact areas with defined benthic conservation objectives (e.g., accidental events, decommissioning), this review focuses on routine operational activities. Mitigation measures to reduce potential impacts and associated pros and cons are identified and emerging drilling and production technologies and management strategies are highlighted. Considerations in acquiring seabed imagery and establishing setbacks in areas with defined benthic conservation objectives are also discussed.

There remain substantial uncertainties regarding the impacts of routine marine oil and gas exploration and production activities, perhaps particularly on benthic species and habitats. The implementation of mitigation measures, management protocols and technological innovations may reduce impacts of marine oil and gas exploration and production on benthic species and habitats; however, there is a dearth of literature on their effectiveness. Increasing our understanding of pathways of effects, thresholds and potential impacts should facilitate the development and implementation of management strategies and mitigation measures that are both effective and practical. This is of particular importance when contemplating oil and gas activities in areas with defined benthic conservation areas, given their inferred or established vulnerability to anthropogenic activities.

ACRONYMS AND ABBREVIATIONS

2DHR	2-Dimensional High Resolution
BACI	Before-After, Control-Impact
C-NLOPB	Canada-Newfoundland and Labrador Offshore Petroleum Board
CNSOPB	Canada-Nova Scotia Offshore Petroleum Board
CSEM	Controlled Source Electromagnetic
CTS	Cuttings Transport System
DFO	Fisheries and Oceans Canada
DNV	Det Norske Veritas
DREAM	Dose-related Risk and Effects Assessment Model
DP	Dynamic Positioning
EEM	Environmental Effects Monitoring
ESRF	Environmental Studies Research Fund
FPSO	Floating, Production, Storage, and Offloading
IUCN	International Union for Conservation of Nature
IPIECA	International Petroleum Industry Environmental Conservation Association
LAO	Linear Alpha Olefin
MARPOL	International Convention for the Prevention of Pollution from Ships
MBES	Multibeam Echosounder
MODU	Mobile Offshore Drilling Unit
MTEM	Multi-transient Electromagnetic
MV	Marine Vibroseis
NEB	National Energy Board
NOROG	Norwegian Oil and Gas Authority
OBM	Oil-based Mud
OGP	International Association of Oil and Gas Producers
OSPAR	Convention for Protection of the Marine Environment of the North-East Atlantic
PAH	Polycyclic Aromatic Hydrocarbon
ROV	Remotely Operated Vehicle
SBA	Sensitive Benthic Area
SBM	Synthetic-based Mud
SEL	Sound Exposure Level
SOEP	Sable Offshore Energy Project
SSS	Side-scan Sonar
TPH	Total Petroleum Hydrocarbon
UNEP	United Nations Environment Programme
VSP	Vertical Seismic Profiling
WBM	Water-based Mud

* A glossary of terms is provided in Appendix 2.

INTRODUCTION

The objective of this working paper is to provide (a) a literature review of potential impacts of routine oil and gas exploration and production activities on benthic species and habitats and of the effectiveness of standard mitigation measures, while (b) highlighting emerging technologies and management strategies that may be considered to further reduce impacts to areas with defined benthic conservation objectives. The focus is the Canadian regulatory and marine environmental context; however, research and experiences from other countries are also considered where applicable.

The term “areas with defined benthic conservation objectives” may include:

1) benthic species (demersal fishes and invertebrates);
2) benthic habitats such as spawning, nursery and feeding grounds; and
3) Sensitive Benthic Areas (SBAs) including corals, sponges, canyons, seamounts and hydrothermal vents.

Corals, sponges, canyons, seamounts and hydrothermal vents are cornerstones of deep-sea biodiversity and ecosystem functioning, as they form complex habitats and provide other marine biota with food and nutrients, refuge from predators, nursery grounds, hard surfaces for invertebrates, and structures for sessile organisms.[1] Avoiding impacts to habitat-forming species such as deep-sea corals and sponges is of particular importance, as these are extremely slow to recover from disturbance given their long lifespans and slow growth rates (e.g., some deep-sea colonies live for more than 4,000 years, and coral colonies with the fastest growth rates expand at more than 15 cm per year, while most colonies expand less than 2.5 cm per year[2]). Additionally, scientific understanding of cold-water coral and sponge species is very limited, including distribution, age of maturity, fecundity, reproduction and recruitment, resilience and resistance to damage, and rates of recovery (Wareham 2010).

Potential impacts to benthic species and habitats are described that may result from the following routine exploration and production activities:[3]

- Seismic surveys (particularly the sound energy emitted) and electromagnetic surveys;
- Seabed surveys (geotechnical, geohazard, environmental sampling); and
- Exploration, delineation and/or development drilling and production, including placement, retrieval and presence of structures on the seabed (e.g., anchors, drilling units, risers, platforms, pipelines); anthropogenic underwater sound; and drilling discharges (e.g., water-based muds [WBM] and synthetic-based muds [SBM], drill cuttings, cement, produced water).

Mitigation measures to reduce potential impacts to benthic species and habitats from seismic surveys, drill cuttings and fluids, anchors and chains, pipelines and flowlines, and produced water are described, and considerations for seabed imagery acquisition, setbacks from areas

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[1] WHOI

[2] Corals and Coral Reefs

[3] While impacts can also occur through decommissioning activities and accidental events (e.g., unintended discharges, spills, leaks), these are not considered in this review.

with defined benthic conservation objectives, and mitigating technologies for drilling and production are also highlighted.

CONTEXT AND LIMITATIONS

The terminology used for the meeting differed from that of the Terms of Reference and the Statement of Work provided for the literature review because terminology is not consistent across regions and there was concern from participants about the use of the term "valued benthic components" as this could be misconstrued to imply an economic value as opposed to a conservation value. There are also differences in the meanings of sensitive and significant benthic areas between sectors; therefore, the term "areas with defined benthic conservation objectives" was used to encompass all areas discussed during the meeting. For the purpose of this meeting "areas with defined benthic conservation objectives" refer to area-based management measures (such as marine protected areas (MPAs) and other effective area-based conservation measures (OEABCMs)) applied to protect benthic components defined in conservation objectives. Defined benthic conservation objectives can include the protection of: benthic species (fish and invertebrates); benthic habitats including benthic spawning, nursery or feeding grounds; and Significant Benthic Areas, which include communities dominated by corals and/or sponges and hydrothermal vents, or locations likely to contain them such as canyons, seamounts, etc.

The body of scientific literature on the environmental effects of offshore oil and gas exploration and production has developed over decades of offshore activity, from environmental effects monitoring (EEM) and laboratory and field-based research. However, studies on potential impacts to bottom-dwelling fishes and invertebrates are limited, and most research has been laboratory-based and/or at the individual species level and cannot be used to make broader conclusions regarding population-, community- or ecosystem-level impacts. Field-based research has largely been conducted in shallower water and, while most of the current exploration drilling in Atlantic Canada is occurring or proposed in deep water, most EEM programs are at producing fields along the continental shelf.

There are substantial knowledge gaps in the Arctic environment, and this review did not specifically consider operations in ice-covered environments. While estuarine and nearshore environments were not explicitly considered, many of the descriptions of activities and mitigation measures may still be applicable.

The focus of this document is on potential effects of routine oil and gas exploration activities in areas with defined benthic conservation objectives. While benthic species and habitats can also be impacted by other activities such as accidental events and decommissioning (e.g., large spills may represent a major threat to areas with defined benthic conservation objectives), this review focuses on routine operational activities. The lack of consideration of spills constitutes an important limitation to this report, which only describes impacts related to best-case scenarios (i.e., absence of spills). The following can be referenced for further information on oil spills:

- Expert panel report on the behaviour and environmental impacts of crude oil released into aqueous environments, Royal Society of Canada (Lee et al. 2015)
- Review of the Net Environmental Benefits of Dispersant Use for Responding to Oil Spills from Oil and Gas Facilities on the Newfoundland Grand Banks (2014)
- A framework to assess vulnerability of biological components to ship-source oil spills in the marine environment (2017)

- Evaluation of Pacific Region application of a National Framework to assess the vulnerability of biological components to ship-source oil spills in the marine environment (2017)
- A framework for assessing vulnerability of biological components to ship-source oil spills (2017)
- Status Report on the Knowledge of the Fate and Behaviour of Diluted Bitumen in the Aquatic Ecosystems (2018)

Given the considerable scope and breadth of this working paper (the activities, benthic species and habitats, and mitigation measures to be addressed per the scope of work) and the strong interest of Fisheries and Oceans Canada (DFO) in obtaining this information in time to share with the National Advisory Panel on Marine Protected Areas, it is not the goal to present an exhaustive, comprehensive review; rather, the most recent and directly-applicable studies related to effects and mitigation measures specific to benthic species and habitats have been prioritized. Recent literature reviews including Cordes et al. (2016), Bakke et al. (2014) and Ellis et al. (2012) have systematically reviewed and synthesized the current scientific understanding of environmental impacts of marine oil and gas exploration and production activities, and readers are directed to these for more extensive reviews.

OFFSHORE OIL AND GAS EXPLORATION AND PRODUCTION ACTIVITIES

The three main phases of oil and gas exploration and production are exploration, development and production, and decommissioning. The exploration phase may include magnetic and/or seismic surveys to identify potential oil and gas reservoirs, and drilling into formations (“exploration drilling”) to determine whether the identified reservoirs contain oil and gas. Canada-Newfoundland and Labrador Offshore Petroleum Board (C-NLOPB) licence activity statistics indicate that less than one well is drilled per Exploration Licence, with an exploration or delineation well drilled in an average of 68 days (equating to approximately 50 drilling days over a 9-year licence term). When an exploration well does not contain commercially-viable quantities of oil or gas, it is sealed with cement to prevent leaks and contamination by drilling fluids. Appraisal or delineation wells may be drilled when oil or gas is encountered to evaluate the economic feasibility of developing the field.

Following a determination that oil or gas is present in commercially-viable quantities, the development and production phase begins. Development includes infrastructure planning and drilling of development wells, and production is the period during which a field and its associated pipelines and infrastructure are used to produce oil or gas. A small reservoir may be developed from one or more appraisal wells, while a large field requires the drilling of additional production wells, typically with satellite platforms linking to the central platform via subsea flowlines. In areas with potential for subsea iceberg scouring, dredging is conducted to enable the placement of subsea equipment below the level of the seafloor. In the offshore, oil and gas are typically produced at fixed platforms or floating production storage and offloading (FPSO) facilities. When the field is exhausted, the wells are plugged and abandoned, and production infrastructure is decommissioned.

This paper assumes of the reader a basic knowledge of offshore oil and gas exploration and production history, activities and infrastructure. Technical aspects are described herein only where relevant in discussing impacts and mitigation measures. The following documents can be referenced for detailed information:

- Strategic Environmental Assessment, Sydney Basin and Orpheus Graben, Offshore Cape Breton, Nova Scotia, submitted to the Canada-Nova Scotia Offshore Petroleum Board (CNSOPB) (Amec Foster Wheeler 2016).
    - Tables 2-1 to 2-6 summarize the purpose, methodology and equipment, typical durations, geographical area, emissions and key environmental issues associated with seismic surveys, seabed surveys, offshore exploratory drilling and well abandonment, vertical seismic profiling, vessel and helicopter traffic, and onshore to offshore drilling.
- Eastern Newfoundland Strategic Environmental Assessment, submitted to the Canada-Newfoundland and Labrador Offshore Petroleum Board (C-NLOPB) (AMEC Environment & Infrastructure 2014).
    - Detailed descriptions of offshore oil and gas exploration and production activities.
- The Marine Environment and Fisheries of Georges Bank, Nova Scotia: Consideration of the Potential Interactions Associated with Offshore Petroleum Activities (DFO 2011).
    - Section 3.0: Potential Interactions Associated with Offshore Petroleum Activities (descriptions of offshore oil and gas exploration and production activities and potential environmental impacts.

POTENTIAL EFFECTS ON BENTHIC SPECIES AND HABITATS

The primary mechanisms of impact to benthic species and habitats from offshore oil and gas activities are direct seabed disturbance and discharges to the sea, and underwater sound associated with seismic exploration activities may subsequently result in sub-lethal and behavioural impacts on benthic species. Placement of infrastructure on the seabed (e.g., pipelines, anchors, pilings, footings), drill mud and cuttings piles, and dredging drill centres and seabed disposal of dredge spoils can result in destruction of habitat, burial, and direct mortality (e.g., fragmentation of corals and sponges, smothering or crushing of sessile epifauna). Direct disturbance of the seabed may resuspend settled fine-grained particles and discharging drilling mud and cuttings introduces fines into the water column and on the seabed. This increased turbidity and excessive particle loading can obstruct gas exchange and filter-feeding mechanisms of demersal fishes and sessile invertebrates (e.g., corals and sponges).

Discharged substances such as drilling mud on cuttings, cement, produced water and other potential contaminants released at the wellhead or at surface may have toxic (lethal and/or sub-lethal) effects on marine biota and/or obstruct water-filtering mechanisms. Activities and infrastructure may introduce alien invasive species through biofouling, ballast water or direct physical mechanisms (e.g., intact plant particles or sediment on anchors). Additionally, areas with defined benthic conservation objectives provide important habitat for other biota such as plankton, pelagic fish, whales and seabirds. Given the vital role of benthic-pelagic coupling in aquatic ecosystems (i.e., the exchange of energy, mass and nutrients between benthic and pelagic habitats), impacts to benthic species and habitats may result in subsequent adverse effects to non-benthic biota (Griffiths et al. 2017).[4]

Habitat-forming species such as deep-water corals and sponges may be impacted through several mechanisms and at multiple levels, and population-level impacts to these species could

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[4] Potential indirect impacts to non-benthic biota resulting from direct impacts to benthic biota are outside the scope of this paper.

result in community-level impacts to other species through habitat destabilization. A recent literature review of potential offshore oil and gas impacts on deep-sea sponges and the habitats they form identified impacts at the community level (decrease in diversity and density of benthic communities associated with deep-sea sponges from physical disturbance); individual level (interrupting filtration from increased sedimentation); and cellular level (decreasing cellular membrane stability from exposure to drilling muds) (Vad et al. 2018). While morphology-based monitoring is typically limited to macro-invertebrates, newer monitoring techniques such as metabarcoding are facilitating field-based research on potential community-level effects, as well as on potential impacts to meio- and microfauna (Lanzén et al. 2016).

A summary of the main potential impacts (within the scope of this literature review) of offshore oil and gas activities and infrastructure on benthic species and habitats is provided in Table 1.

Table 1: Potential impacts to benthic species and habitats from offshore oil and gas activities and infrastructure (expanded from Cordes et al. 2016; DNV 2013).

Activity / infrastructure	Mechanism	Estimated area(s) of influence	Potential impacts to benthic species and habitats
Seismic surveys	Physical (components of sound energy – hydrostatic pressure and particle motion)	• Unknown (and highly variable)	Direct mortality; tissue and/or physiological damage (indirect mortality); hearing impairment; masking; changes in behavioural response (displacement from preferred habitats, changes in movement patterns, delay or prevention of migration to spawning or feeding grounds; prevention of recruitment or settlement in preferred habitats); habitat changes from altered sediment reworking
Electromagnetic surveys	Physical (magnetic disruption; direct impact from receiver sand anchors)	• Unknown (and likely highly variable)	Interference with marine animals' use of electromagnetic waves; crushing/burial within receiver sand anchor footprint
Seabed surveys **(2DHR geohazard, geotechnical, environmental sampling)**	Physical (sound energy; direct impact; sedimentation)	• Unknown for 2DHR survey (assume lower compared to typical 2D seismic)	Similar (assume lower) impacts as typical 2D seismic surveys (physical, physiological and behavioural); direct mortality in physical footprint; clogging of feeding and gas exchange structures from excessive particle loads

Activity / infrastructure	**Mechanism**	**Estimated area(s) of influence**	**Potential impacts to benthic species and habitats**
Underwater sound / vibrations (high-impact seabed activities, vessel traffic, dynamic positioning thrusters)	Physical (components of sound energy – hydrostatic pressure and particle motion)	• Unknown (and highly variable)	Potential impacts as described above for seismic surveys, amplified for species living close to or within the substrate (interface waves and particle motion) and/or through chronic exposure
Anchors and chains, grappling hooks, pennant wires	Physical (direct impact; sedimentation; hard substrate)	• ~50 m (pennant / grappling corridor) ±15 m (position inaccuracies during pre-laying)	Crushing / burial / fragmentation and clogging of feeding and gas exchange structures from sediment resuspension at emplacement and retrieval; possible continued particle loading through tidally-induced motions; provision of hard substrate for colonization by sessile epifauna and associates
Drilling infrastructure (e.g., drilling units, risers, wellhead systems, dredging & dredge spoils disposal)	Physical (direct impact; sedimentation; hardscape in water column)	• ~100-500 m radius from infrastructure	Crushing / burial / fragmentation and clogging of feeding and gas exchange structures from sediment resuspension at emplacement/retrieval; provision of hardscape in the water column for colonization by sessile epifauna and associates; altered species distributions through increased habitat connectivity; introduction of alien invasive species; chemical toxicity (direct and/or sublethal); anoxic/hypoxic conditions (enrichment effects); physical effects on tissues; habitat destabilization

Activity / infrastructure	Mechanism	Estimated area(s) of influence	Potential impacts to benthic species and habitats
Drilling discharges (cuttings, drilling fluids, cement, chemicals)	Physical (direct impact; sedimentation) Chemical (toxicity; enrichment effects)	• Solids on seabed: 100-500 m radius from wellhead (exploration wells at lower end, production wells at higher end) • Suspension of fine particulates in water column: possible far-field deposition • WBM (elevated sediment barium concentration) zone of influence: 2-20 km • SBM (elevated sediment barium concentration) zone of influence: 200-2,000 m • Possible WBM and SBM impacts on benthic community diversity and abundance: 100-1,000 m	Crushing / burial / fragmentation; smothering; clogging of feeding and gas exchange structures from excessive particle loads; chemical toxicity (direct and/or sublethal); anoxic/hypoxic conditions (enrichment effects); physical effects on tissues; habitat destabilization
Pipelines and flowlines	Physical (direct impact; sedimentation; hard substrate)	• 50 to 100-m wide corridor of influence for length of flowlines • 100-m wide corridor of influence for length of pipelines	Crushing / burial / fragmentation and clogging of feeding and gas exchange structures from sediment resuspension at emplacement and/or embedding (sediment jetting, gravel dumping); provision of hard substrate for colonization by sessile epifauna and associates; altered species distributions through habitat connectivity (for indigenous and invasive species)
Produced water and dissolved components	Chemical (toxicity)	• Possibly 1-2 km from discharge source (based on DREAM modelling)	Direct toxicity; possible sub-lethal effects from chronic exposure; food-chain and trophic amplification

ENVIRONMENTAL EFFECTS MONITORING PROGRAMS

The prevalence of offshore oil and gas exploration and production activities provides a valuable opportunity to acquire field data and increase understanding of impacts through robust and standardized Environmental Effects Monitoring (EEM) programs. However, long-term environmental monitoring of deepwater oil and gas developments is extremely limited, with producing fields primarily located in shallower water and along the continental shelf.

Cordes et al. (2016) indicate that most jurisdictions have only minimal requirements for follow-up and monitoring, and they found considerable uncertainty associated with operator estimates of the spatial extent (area of influence) of biological impacts reported from some EEM programs. They suggest that monitoring programs may not be detecting more subtle effects, be limited in sampling spatial coverage, or include only a small number of reference sites (Cordes et al. 2016). For example, a recent study intending to use the UK Benthos industry database to measure the scale and persistence of drill cuttings at sites across UK installations in the North Sea determined that the ecological data provided by the UK industry's basic compliance monitoring was not sufficiently robust to conduct effective analyses, and data from only 19 of the 351 installations in the database was standardized such that it could be used in the study (Henry et al. 2017).

In contrast, several producing fields offshore Atlantic Canada provide robust, long-term EEM data, with mandatory EEM programs conducted on a regular (project-specific) schedule for the life of the producing field and reports publicly available. The original EEM program design was developed with involvement of DFO, ECCC, academia, consultants, industry and the offshore petroleum boards. All EEM programs start with a baseline survey for BACI (Before-After, Control-Impact) design prior to commencement of activities. EEM parameters are defined on a project-specific basis, with components including sediment (e.g., particle size, infauna, physical and chemical characteristics), water (physical and chemical characteristics) and biota (e.g., toxicity, benthos, fish, body burden, histopathology). Current EEM programs do not explicitly monitor benthic conservation objectives, and while there is no formal EEM structure for exploratory wells, monitoring and follow-up of exploration drilling may be conducted to assess the effectiveness of mitigation measures and verify the accuracy of predictions (e.g., drill mud and cuttings dispersion modeling).

The offshore petroleum boards in Atlantic Canada recognize the role of EEM in improving the methods and processes employed in offshore petroleum activities. The C-NLOPB and CNSOPB are actively involved in progressive improvement of EEM techniques and protocols, evaluating the results and challenges of each monitoring program and incorporating these learnings to improve subsequent EEM programs (CNSOPB 2018).

SEISMIC SURVEYS

Seismic surveys use an artificially-generated energy source (airguns) to reveal subsurface geology and identify potential oil and gas reservoirs, hugely increasing success rates in locating commercially-viable reservoirs. Airguns are towed behind a survey vessel and fire compressed air into the water at regular intervals, generating high-energy, low-frequency sound waves (with most sound produced between 10 and 300 Hz) (Carroll et al. 2017) that travel through the water and seabed. The sound energy reflects off the layers of rock and is recorded by sensitive hydrophones (streamers) also towed behind the survey vessel. Computer processing then converts the sound signals into seismic data, creating two- or three-dimensional images of the subsurface geologic features.

Depending on the information required, seismic data may be acquired through 2D (greater area), 3D (greater resolution) or wide-azimuth (wider offset data) surveys (Amec Foster Wheeler 2016). Seismic sound energy is also emitted during vertical seismic profiling (VSP), which is conducted once the targeted well depth has been achieved. Receivers, placed at intervals in the well, record reflected energy from a seismic source at surface to confirm and provide greater accuracy of the surface seismic data (referred to as 'check-shots') (Amec Foster Wheeler 2016).

The document *Sound Exposure Guidelines for Fishes and Sea Turtles: A Technical Report prepared by ANSI-Accredited Standards Committee S3/SC1 and registered with ANSI (Popper* *et al. 2014)* is the culmination of a working group's multi-year consensus efforts to establish broadly-applicable sound exposure guidelines for a wide range of taxa, grouped by the way they detect sound. Where possible, numerical exposure guidelines were defined and, where data was insufficient to support quantitative values, the relative likelihood of effects occurring was evaluated. While based on the best available scientific knowledge at the time of writing, the Working Group stated that the sound exposure guidelines should be treated as interim and identified high-priority research areas (Popper et al. 2014).

Impacts to benthic species and habitats from exposure to anthropogenic underwater sound can include death; physical and/or physiological effects; hearing impairment; masking; and/or adverse behavioural responses. Table 2 summarizes potential impacts of underwater sound on fish.[5]

Table 2: Potential impacts of anthropogenic underwater sound on benthic species and habitats (modified from Hawkins and Popper 2017).

Impact	Description of potential sound-related impacts on fish
Death	• Immediate mortality or tissue and/or physiological damage that is sufficiently severe that death occurs some time later due to decreased fitness. • Mortality can have a direct impact on animal populations.
Physical and/or Physiology Effects	• Tissue and other physical damage or physiological effects that are recoverable but that may place animals at lower levels of fitness, render them more open to predation, or impair feeding, growth or breeding success until recovery takes place.
Impaired Hearing	• Short- or long-term changes in hearing sensitivity (temporary or permanent threshold shift) may reduce fitness and survival. • May affect the ability of animals to capture prey and avoid predators and cause deterioration in communication between individuals, affecting growth, survival and reproductive success.
Masking	• Anthropogenic sounds may make it difficult to detect biologically-significant sounds against the noise background. • Masking of sounds made by prey organisms may result in reduced feeding with effects on growth. • Masking of sounds from predators may result in reduced survival. • Masking of spawning signals may reduce spawning success and affect recruitment. • Masking of sounds used for orientation and navigation may affect the ability to find preferred habitats including spawning areas, affecting recruitment, growth, survival and reproduction.
Behavioural Responses	• Adverse behavioural responses may occur at relatively low sound levels. • Displacement from preferred habitats may affect feeding, growth, predation, survival and reproductive success.

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[5] Refer to DOSITS for further information on underwater sound propagation.

Impact	Description of potential sound-related impacts on fish
	• Changes in movement patterns may affect energy budgets, diverting energy away from egg production and other vital functions. • Migrations to spawning or feeding grounds may be delayed or prevented, with detrimental effects upon growth, survival and reproductive success. • Prevention of recruitment and settlement in preferred habitats may affect colonization and population sizes in areas exposed to high levels of anthropogenic sound.

DFO (2004) conducted a literature review on potential impacts of seismic sound on marine animals and concluded that “seismic sounds in the marine environment are neither completely without consequences nor are they certain to result in serious and irreversible harm to the environment”; however, they also indicated that the available scientific information was “incomplete to varying degrees in essentially all areas related to impacts of seismic sound on marine ecosystems” (DFO 2004). Recent literature does not appear to have added substantially to our understanding. As Carroll et al. (2017) indicate, there remains a vast gap in the scientific literature, particularly related to sound thresholds and recovery from impact for most fishes and almost all invertebrates, with few data on physical impacts such as barotrauma (damage to internal organs); no data on masking of natural sound cues; and substantial gaps in understanding potential impacts on metabolic rate, reproduction, larval development, foraging and intraspecific communication.

Marine invertebrates are particularly underrepresented in the literature. There are almost no data on sound detection in invertebrates, only a few studies on behavioural effects on aquatic invertebrates from anthropogenic sounds, and no data on whether masking occurs in aquatic invertebrates (Hawkins et al. 2014). Virtually all research to date on impacts of anthropogenic underwater sound has focused on (and only reported values for) the pressure component of sound (Carroll et al. 2017), yet invertebrates and many fishes (especially those lacking a gas-filled bladder such as all elasmobranchs and marine invertebrates) are sensitive only to the particle motion component of sound (Edmonds et al. 2016; Solan et al. 2016).

Popper and Hawkins (2018) state that it is “very possible that the particle motion component of the sound field is the major cause of any effects,” as species with gas-filled organs (e.g., swim bladders) appear to transform sound pressure into particle motion. To facilitate understanding, an animal being moved back and forth could be referred to as being “squeezed” or “shaken”; in the context of sound components, pressure equates to squeezing (i.e., of gas-filled organs) and particle motion to shaking (i.e., direct stimulation of the inner ear) (pers. comm. Carlson 2017 *in* Popper and Hawkins 2018).

Seismic surveys result in large vertical and horizontal particle motion components (in addition to pressure components) when the acoustic energy encounters the seabed; therefore, particle motion is a priority research area in understanding impacts of seismic sound on benthic species (Hawkins et al. 2017). A current research project is recording the natural soundscape and studying seismic sound propagation on Canada’s East Coast, with support from the Environmental Studies Research Fund (ESRF), to “create new knowledge on the natural soundscape in the region, generate accurate models of the effects of seismic surveys, and validate particle motion models for seismic airguns.”[6]

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[6] ESRF

Most studies on fishes and invertebrates exposed to seismic airguns are conducted in experimental cages or tanks, with sound exposure scenarios that may not accurately simulate conditions encountered by marine organisms during actual seismic operations (Carroll et al. 2017). For example, exposure timeframes may not be realistic, or the sound source may only include the pressure component of sound and not the particle motion component. Significant developmental delays and body abnormalities were observed in 46% of scallop larvae exposed in laboratory to lengthy periods of seismic pulses (de Soto et al. 2013). Conversely, a series of laboratory-based studies on lobster found no evidence of mortality or overt gross pathology[7] from eight hours of recorded seismic survey soundtrack, and no mortality or altered general pathology or protein, glucose or triglyceride serum concentrations over a 6-month period following seismic exposure[8] (Payne et al. 2015).

While field studies may be more ecologically realistic, these can be complicated by environmental unpredictability, spatiotemporal variability and the difficulty of finding and tracking individual organisms (Przeslawski et al. 2018). For example, field-based seismic exposure studies on scallops found no mortality attributable to seismic exposure in one study (Przeslawski et al. 2018), yet significantly increased mortality rates, disrupted behavioral patterns (during and following exposure) and physiological changes in another (Day et al. 2017).[9]

Studies suggest that seismic airgun exposure can result in physical, physiological and/or behavioural impacts on individuals or groups of marine animals; however, debate remains about potential impacts at the population, community and ecosystem levels (Lee et al. 2011a). Based on the current scientific literature, there is no evidence of reduced catch or abundance of invertebrates following seismic activities, and the evidence for fish is conflicting, with studies showing increased, decreased or unchanged catches (Carroll et al. 2017). Recent research on the effects of seismic surveys on snow crab catch rates along the Grand Banks of Newfoundland found no measurable change in catch rates (Morris et al. 2018).

There is concern that disrupted behavioural patterns could delay and/or displace migration, spawning and feeding, potentially resulting in population-level impacts, should this coincide with ecologically-important life history events such as spawning (Worcester 2006; Boudreau et al. 2001). While startle responses are commonly reported in the literature, Hawkins and Popper (2017) note that “short-lasting startle responses to sounds that rapidly diminish with repeated presentation or that do not change the overall behaviour of the animals are unlikely to affect key life functions or result in changes to vital rates.”

Evidence from recent research suggests that exposure to seismic sound could cause substantial mortality in zooplankton populations (McCauley et al. 2017), which may impact benthic species given the integral role of zooplankton communities in supporting higher trophic

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[7] With respect to histopathology, some differences were observed between the control and experimental groups (such as higher degree of epithelial vacuolation and tubular dilation) and no effects were noted in ovarian tissues (an organ to which attention is often drawn) (Payne et al. 2015).

[8] Two slight differences were noted: the experimental group had a slightly lower yet statistically significant concentration of serum calcium when standardized to serum protein (possibly due to an elevated, statistically-insignificant level of serum protein in the exposed lobsters) and the control group had a higher occurrence of shell disease (Payne et al. 2015).

[9] The scallops were transplanted in Day et al. (2017) and in-situ in Przeslawski et al. (2018); the studies were not compared to determine other variables (e.g., water depth, seismic intensity, exposure periods).

levels by transferring energy and materials up the food chain.[10] Experimental airgun signal exposure decreased zooplankton abundance and caused a two- to three-fold increase in dead adult and larval zooplankton. While the previously-assumed impact range was 10 m, impacts were observed out to 1.2 km (the maximum range sampled), and while no adult krill were present in the samples, all larval krill were dead after airgun passage. McCauley et al. (2017) concluded that there is a “significant and unacknowledged potential for ocean ecosystem function and productivity to be negatively impacted by present seismic technology.” It should be noted that this research has been widely and heavily criticized based on the study design (Richardson et al. 2017), approach to statistical analysis and basis for its conclusions (Martin and Radford 2018).

ELECTROMAGNETIC SURVEYS

Airgun seismic methods detect contrasts in acoustic impedance, whereas controlled source electromagnetic (CSEM) and multi-transient electromagnetic (MTEM) methods detect contrasts in electrical conductivity to identify layers that are conducive and resistive (as hydrocarbon-bearing rock shows greater resistivity than water-bearing rock) (Buchanan et al. 2011). Following deployment of an array of receivers on the seabed (typically a grid of up to 200 receivers spaced 1-3 km apart), a survey vessel tows an electromagnetic source that transmits an electromagnetic field, alterations in which are detected by the receivers. CSEM methods employed for more than 30 years have required that the source be towed 30-50 m above the seabed and, due to surface interference, have been mostly limited to depths >300 m. Conversely, the recently-developed MTEM systems can be towed near-surface and used in both deeper and shallower water.

Technological advancements are anticipated to enable CSEM and MTEM systems to tow both sources and receivers near-surface as in seismic surveys (Buchanan et al. 2011); however, these methods currently require the deployment of several hundred receivers, typically weighted by compacted sand anchors. These descend through the water column and settle on the seabed, potentially impacting benthic species and habitats through direct mortality (crushing) or local sedimentation. The receivers are retrieved following the grid survey while the sand anchors remain in place, degrading within one year (LGL Limited 2014).

CSEM and MTEM both generate modulating electromagnetic waves that may affect marine biota. While it is known that many animals can detect electromagnetic fields and may react or use these in a variety of ways, almost nothing is known of the actual operating mechanisms used to acquire, process and use magnetic data, and without this understanding it is not possible to predict potential impacts of magnetic disruption (Claisse et al. 2015a). However, based on a review of the (albeit limited) scientific literature related to potential effects on marine organisms of electromagnetic fields emitted from subsea cables, Baruah (2016) concludes that “there does not appear to be enough empirical evidence to suggest a significantly detrimental biological effect upon marine organisms from electromagnetic fields.”

SEABED SURVEYS

Prior to drilling a well, surveys are conducted to identify seabed features and subsurface conditions that may interfere with well-drilling operations (i.e., geohazards), and to characterize

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[10] Food chains transfer energy and organic materials through various trophic levels of marine organisms. Herbivorous zooplankton species (primary consumers) feed directly on marine algae, carnivorous zooplankton species (secondary consumers) feed on herbivorous species, and carnivores (tertiary consumers, including many fish) feed on smaller carnivores (Lalli and Parsons 1997).

the seabed and benthic habitat. Surveys are typically conducted using 2-dimensional high resolution (2DHR) digital seismic, which is similar to a standard 2D seismic program but likely with reduced impacts compared to standard 2D seismic as it uses a small-volume compressed air source or device. Additional data collection techniques may include sidescan sonar, sub-bottom profiling, multibeam echo sounder and/or camera imagery.

Seabed surveys may also involve physical collection of seabed samples through geotechnical surveys (e.g., core sampling, vibrocores, cone penetrator technology) and environmental sampling to characterize benthic habitat (e.g., grab samples). Surveys that contact the seabed may impact benthic species and habitats through direct mortality, smothering or clogging of filter-feeding mechanisms and gills from local sedimentation (Järnegren et al. 2017; Lee et al. 2011a).

EXPLORATION AND DELINEATION DRILLING

The main potential impacts to benthic species and habitats from exploration and delineation drilling are associated with placing infrastructure on the seabed, and depositing drill muds and cuttings at the seafloor and/or in the water column, as described below.

Placement and presence of infrastructure

Placing infrastructure on the seabed (e.g., drill rig anchors and chains, jack-up rigs, drill heads, gravity-based structures, wellhead systems) can result in burial and physical disruption and direct mortality (crushing) within the footprint, and adjacent species and habitat can also be affected by increased particle exposure from local sedimentation (DNV [Det Norske Veritas] 2013). The placement of structures on the seafloor can crush organisms directly beneath supporting legs or mats. Increased turbidity (concentration of suspended particles in the water column) in the water column, anticipated during removal/recovery of infrastructure, burial and disruption of the benthos and through sediment resuspension, can obstruct the gills and filter-feeding mechanisms of fishes and sessile invertebrates.

Semi-submersible drill rigs are typically moored with 8-12 anchors, with associated chains and grappling hooks. These can crush, injure and/or fragment benthic organisms, communities and habitats as they drag along the seabed as they set (DNV 2013). Anchor pick-up is typically conducted either by grappling or remotely operated vehicle (ROV). Grappling involves dragging a grappling anchor along the seabed for typically 100-150 m (DNV 2013), therefore direct retrieval by ROV is preferred in SBAs. Physically-fragile habitats such as those formed by corals and sponges are particularly vulnerable to direct impact from anchor placement and retrieval. Benthic species and habitats can also be impacted by the increase in local sedimentation associated with anchor deployment and retrieval, resulting in an estimated 50-m wide corridor of influence (DNV 2013).

The International Petroleum Industry Environmental Conservation Association (IPIECA) guidance on preventing and managing alien invasive species in the oil and gas industry (IPIECA 2010) describes how indigenous species can be impacted by biofouling (biological growth on artificial structures in the aquatic environment) when communities include alien invasive species. Examples of infrastructure and equipment in or on which biofouling may occur include (IPIECA 2010):

- Vessel hulls and niche areas (e.g., bilges, internal seawater systems);
- Exploration and production rig/platform legs, seabed pipelines and umbilicals, and sub-sea development systems and wellheads; and

- Ancillary equipment that has previously been in seawater (e.g., monitoring or sampling gear, anchors, marine emergency rescue equipment, fenders and buoys).

Underwater sound

The potential impacts of anthropogenic underwater sound described in the above section on seismic surveys may also result from drilling activities such as wellhead/conductor installation, pile driving and well drilling (DFO 2011). These high-impact seabed activities produce substrate vibrations that travel as compressional (longitudinal), transverse (shear) and/or surface ("ground-roll" or interface) soundwaves. The latter may be of substantial concern to benthic species, as interface waves are trapped within the substrate/water interface where they can travel considerable (undetermined) distances, potentially affecting epifaunal and infaunal species and communities far from the source (Roberts et al. 2016).

Interface waves generate large vertical and horizontal particle motion components within the substrate (Hawkins et al. 2014). Given that marine animals living close to or within the substrate are primarily sensitive to the particle motion component of sound (Edmonds et al. 2016), interface waves may be of major significance to benthic species and habitats. Some infaunal species play a significant role in sediment structuring, resorting and inorganic nutrient exchange and organic material flow; therefore, direct impacts to infaunal species from substrate sound propagation may also subsequently affect other biota, by altering the habitat and disrupting benthic-pelagic coupling (Popper and Hawkins 2018; Griffiths et al. 2017).

Drilling discharges

Offshore exploration drilling typically results in the discharge of drilling wastes in the water column or at the seafloor (e.g., drilling fluids/muds, drill cuttings, excess cement, hydraulic fluid). These wastes can affect water quality and impact individual organisms through physical and/or chemical mechanisms such as smothering, oxygen reduction, organic enrichment and increased metal concentration, and can result in altered density, biomass and diversity of seabed communities (Cordes et al. 2016). Drilling mud is a liquid product with an oil, synthetic or water base to which fine, dry clay microparticles (bentonite) are added to form a stable colloidal suspension. Various components are added to the mud to achieve the properties required at a given site, such as barite (for extra density); tannins and lignosulfonates (for thinning); caustic soda (pH control); biocides (corrosion control); and carboxymethyl cellulose or starch (for gelling and filter cake properties) (West Coast Offshore Exploration Environmental Assessment Panel 1986 *in* Haggarty et al. 2003).

The Norwegian Oil and Gas Authority (NOROG) suggests that visible dispersion of particles at the seafloor generated from top-hole drilling is normally limited to 150 m downstream of the discharge point, but that fine particles in suspension may travel much further and are occasionally visible up to 600 m from the wellhead (DNV 2013). Ellis et al. (2012) assessed the zone of influence of sediment contamination and biological effects of drilling muds on benthic communities by synthesizing results from 26 papers and technical reports that surveyed sediment samples from 72 production or exploration platform sites. Ellis et al. (2012) determined the WBM and SBM zones of influence (based on sediment barium concentrations) to be 2-20 km and 200-2,000 m, respectively, while biological impact on benthic community diversity and abundance ranged from 100-1,000 m for both WBM and SBM (Ellis et al. 2012). Based on their synthesis of available scientific information, Cordes et al. (2016) determined that ecological changes from drilling both exploration and production wells have typically been observed within 200-300 m of the wellhead, with elevated concentrations of barium (common in drilling muds) at distances of at least 1 km.

Drilling fluids and cuttings

Impacts to benthic species and habitats from drill cuttings and fluids occur primarily through the following mechanisms (Lee et al. 2011a; Hutchison et al. 2016):

- Chemical toxicity from pollutants and/or products of biodegradation;
- Anoxic/hypoxic conditions resulting from organic enrichment;
- Smothering; and
- Physical effects on tissues from chronic exposure (even at low concentrations).

Offshore Atlantic Canada, cuttings produced with WBM can be discharged to sea, as can SBM cuttings following treatment with the best available technology (e.g., shakers, centrifuges, dryers and blowers), with a performance target of 6.9 g/100 g retained synthetic-on-cuttings pursuant to the *Offshore Waste Treatment Guidelines* (NEB, C-NLOPB and CNSOPB 2010). The use and disposal of oil-based mud (OBM) is restricted in most jurisdictions worldwide, and its use would only be approved in Canada under exceptional circumstances. UK and Norway only permit offshore discharge of WBM cuttings and used WBM (Bakke et al. 2013).

WBM is generally considered non-toxic; however, exposure to barite (a primary component of WBM) has been shown to result in toxicity in deep-water sponges (Edge et al. 2016). Metals and organic compounds in WBM may accumulate in tissues, reducing growth and reproduction, tainting exposed organisms (for human consumption) and/or bioaccumulating (passing up the food chain and impacting predator species), even at relatively low concentrations (Lee et al. 2011a).

SBM is readily biodegradable in Atlantic marine sediments under ambient environmental conditions (Li et al. 2009). However, it is not clear whether impacts to benthic organisms are greater from rapid or slow biodegradation rates. While rapid degradation reduces exposure time to potentially-toxic and bioaccumulating substances, bottom-dwelling aerobic organisms can suffocate from rapid degradation’s higher oxygen demands (Lee et al. 2011a). A 6-year field study of benthic macrofauna found that microbial degeneration of SBM (linear alpha olefin [LAO] nonaqueous drilling fluid) resulted in hypoxia, with chemical and biological recoveries evident ≥ 200 m from an exploration well site 33 months following completion of drilling (Tait et al. 2016).

The bulk of drilling mud settles quickly and accumulates on the seabed; however, resuspension and deposition tend to concentrate fines and particulates in suspension near the seabed before they are dispersed by currents, resulting in increased sedimentation rates, depletion of oxygen in sediments, alterations in sediment grain size and increased turbidity in the water column (Muschenheim and Milligan, 1996). Smothering of slow-moving and sessile benthic organisms is more likely in low energy areas, as discharged muds and cuttings tend to accumulate near the point of discharge, whereas in high-energy environments these drill wastes generally disperse quickly over a larger area (Lee et al. 2011a).

Haggarty et al. (2003) note that studies of biological effects of drilling muds have focused on the scallop, given its “commercial value on the Atlantic Coast (Georges Bank), and its susceptibility due to its benthic habitat, limited juvenile mobility, and its filter-feeding in the benthic boundary layer where drill waste concentrations are the largest.” As barite and bentonite are not considered highly toxic to scallops, studies have focused on sub-lethal effects (e.g., impaired growth) apparently caused by fine inorganic particles adversely affecting feeding mechanisms (Crawford et al. 2002). Compared to bentonite, barite impacts to scallop growth are observed at much lower concentrations (for reasons that are not understood) and barite seems to affect marine organisms beyond what would be expected based on its theoretical toxicity (Crawford et al. 2002).

Significant mortality occurred in cold-water coral (*Lophelia pertusa*) larvae exposed for 24 hours to an increased drill cuttings sediment load (Järnegren et al. 2017). The larval cilia became clogged and prevented the larvae from swimming actively, which could have wider implications given that larvae of many species use cilia for swimming and feeding. The study concluded that while adult *L. pertusa* can survive (at least temporarily) under extreme sediment load, all or part of the cohort may be lost should cuttings release occur during larval development (Järnegren et al. 2017).

Tolerance to burial cannot be generalized across species, as responses have been shown to be highly species-specific (Hendrick et al. 2016; Hutchison et al. 2016). Following discharge of WBM and cuttings during exploration drilling at the Minerva gas field, Currie and Isaacs (2005) reported decreases in population densities evident up to 200 m from the wellhead, and densities of the most abundant phyla (crustaceans and polychaetes) declined by 45–73 percent at all sites within a 100-m radius of the wellhead. Significant community changes in sediment microbiota may not extend beyond the visible cuttings pile. Nguyen et al. (2018) identified three bacterial groups that were confined almost exclusively to the upper two centimeters at an exploratory well WBM cuttings pile in the Barents Sea, suggesting that these may serve as valuable bioindicators for the spatial extent and persistence of drilling waste discharges.

Deposition of drill muds and cuttings may also affect ecosystem processes, such as infaunal burrowing and feeding, which are key in mediating sediment oxygen levels, and redistributing and decomposing organic matter. Recent research on sediment reworking activity in water-based drill cuttings found a significant reduction in downward transportation of sediment particles and in maximum mixing depth (Trannum 2017).

Recovery following deposition of drill fluids and cuttings depends on the magnitude of the impact and is highly dependent on individual species' biological factors such as sensitivity and resilience to disturbance, recruitment rates and longevity. Some benthic species may recover relatively quickly from drilling activity impacts, for example Trannum et al. (2011) observed recolonization of macrofaunal communities on sediments capped with water-based mud (WBM) cuttings within 6 months post-drill. Conversely, in species with slow growth, long lifespans and variable recruitment such as deep-water corals and cold-seep communities, recovery could be extremely prolonged (Fisher et al. 2014 estimated centuries to millennia for recovery of deep-water corals from the Deepwater Horizon blowout). Recovery can also be affected by persistence of the discharge in the environment, as demonstrated at well sites on a deep-sea sponge ground (Jones et al. 2012). There was evidence of partial megafaunal recovery between 3 and 10 years post-disturbance in areas where drill cuttings had eroded, yet few megafauna (e.g., sponges, echinoderms, cnidarians) were observed even 10-years post-drill in an area that had remained covered by drill cuttings[11] (Jones et al. 2012).

DEVELOPMENT DRILLING AND PRODUCTION

Compared to exploration drilling, development drilling and production are generally considered to have increased risks of impacts to benthic species and habitats, with additional activities, greater seabed footprints and longer timeframes. Development drilling requires additional infrastructure such as different and/or more platforms, pipelines and flowlines. It also generally involves drilling several wells, with increased quantities of drill muds and cuttings and resulting discharges. Production also results in the marine discharge of large quantities of treated produced water, potentially increasing the risk of acute toxicity and impacts to benthic species

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[11] Likely attributable to the presence of cement (Jones et al. 2012).

and habitats from chronic exposure to lower concentrations of contaminants (Boudreau et al. 2001). Production infrastructure may alter available habitat by introducing habitat connectivity and introducing complex vertical hardscape (e.g., platform legs) and hard substrate (e.g., pipelines and flowlines); however, this may be of limited magnitude in the context of this discussion, given that areas with defined benthic conservation objectives are often areas with high structural complexity. While this habitat alteration may have positive effects for indigenous species (Claisse et al. 2015b), it may also benefit invasive species (Sheehy and Vik 2010).

Placement and presence of infrastructure

Potential impacts to benthic species and habitats from the placement of infrastructure during the production phase are similar to those described in exploration drilling; however, impacts may be amplified through the substantially-increased infrastructure requirements and seabed footprint (from more and/or different platforms, greater number of wells, larger diameter boreholes, pipelines and flowlines, rock dumping to secure or level-off platforms or pipelines, etc.). Additionally, in regions at risk of iceberg scour (e.g., Grand Banks, Newfoundland), subsea equipment is protected by placing it in excavated drill centres, recessed below the seafloor. An area[12] is dredged to 9-11 m below the existing level of the seabed, and the dredged material is discharged on the seafloor at an approved dredge spoils disposal area. Pipeline deployment may include embedding by sediment jetting and/or gravel dumping, with benthic species and habitats in the footprint directly impacted through crushing and those in the vicinity impacted through sediment loading from resuspension of fine particulates in the water column. NOROG estimates the pipeline installation corridor of influence at 100-m wide for coral and sponge structures and other species sensitive to particle loading (DNV 2013).

The presence of production infrastructure (particularly platforms) introduces hard substrate and hardscape in the water column, which may provide structure for reef-forming species (Claisse et al. 2015b). In an assessment of secondary production per unit area of seafloor at oil and gas platforms off the coast of California, Claisse et al. (2014) found the highest secondary production of fish communities of any marine ecosystem for which similar estimates exist, with high levels of larval and pelagic juvenile settlement. The platforms provide hardscape habitat in the water column, with a high ratio of structural surface area to seafloor surface area, which provides juvenile and adult demersal fishes with substantial complex hardscape habitat with a “relatively small footprint” of seafloor (Claisse et al. 2014).

Placing flowlines and pipelines on the seabed similarly adds hard substrate, which can support sessile epifauna, attract motile benthic organisms and/or increase habitat connectivity (Atchison et al. 2008); while this may have positive effects for indigenous species, it can also introduce and/or support the propagation of invasive species (Sheehy and Vik 2010). Results from a study of fish diversity and abundance at two Australian underwater pipelines (60-80 m and 120-130 m depth) indicate that pipelines may not only attract but may enhance fish stocks (McLean et al. 2017). Thousands of unidentified larval fishes were observed in addition to 92 species of juvenile, sub-adult and adult fishes, and there was a strong positive correlation of fish abundance with the prevalence and high complexity of sponges (60-80 m depth) and deep-water corals (120-130 m depth), suggesting these habitats may provide a significant source of food and refuge, both for fishes and the invertebrates upon which they feed (McLean et al. 2017).

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[12] Variable dimensions, for example ~45 m wide X 80 m long (maximum base dimension) with one vertical and three horizontal graded sloped sides (Husky Energy 2012).

McLean et al. (2017) observed that many species appeared to be using unsupported pipeline sections (spans) as refuges, as these were associated with greater fish abundance (both pipelines) and diversity (60-80 m pipeline). Similarly, in a study on sediment transport-induced changes to embedment of spans of a subsea pipeline, Leckie et al. (2016) observed span openings at several points along the pipeline that appear to have been opened up by marine fauna, most likely fish, and speculate that these may be attributable to bioturbation (direct and deliberate digging or burrowing), swimming action and/or progressive tunneling while feeding on invertebrates adjacent to and underneath the pipeline. McLean et al. (2017) note that while results suggest that pipeline spans may offer significant habitat, further studies (including off-pipeline surveys) are needed to conclusively determine their ecological value.

It is important to note that the above-noted studies primarily compare highly-complex habitats along pipelines to much less complex, primarily soft-bottom, adjacent seafloor; given that areas with defined benthic conservation objectives are largely comprised of complex habitat, in the context of this discussion these potential positive effects may be non-existent, minimal and/or outweighed by the associated adverse effects.

Underwater sound

Potential impacts to benthic species from anthropogenic underwater sound during development drilling and production may be as described for seismic surveys and exploration drilling; however, there may be a greater risk of impacts from chronic exposure to underwater sound, given the substantially longer timeframes. While acute anthropogenic underwater noise (e.g., seismic surveys and pile driving) can impact benthic species, Solan et al. (2016) state that the more significant risk to populations and ecosystems may be from chronic exposures such as to vessel traffic noise. Dynamic positioning (DP) vessels and rigs maintain position through the operation of thrusters (powered propellers). While a transiting vessel represents a temporary sound source to an individual receptor, DP thrusters comprise a constant source of underwater sound at a given location, as the thrusters are designed for continuous operation (ABS 2013).

Tank-based studies on exposure to boat-noise playback observed a reduction in successful development of sea hare (a marine invertebrate) embryos by 21 percent and increased mortality of recently-hatched larvae by 21 percent (Nedelec et al. 2014), and increased metabolism (a potentially growth-reducing sign of stress) in shore crabs (Wale et al. 2013). In addition, there is evidence that chronic underwater noise from offshore shipping and construction activity can alter sediment-dwelling invertebrate contributions to fluid and particle transport, which are key processes in mediating benthic nutrient cycling (Solan et al. 2016).

Drilling discharges

Development drilling results in greater quantities of drilling discharges (e.g., drill muds and cuttings, produced water) than does exploration drilling, and treatment of produced water generally requires additional chemicals not used in exploration drilling. The areal extent of drilling mud and cuttings dispersion is similar for a single exploration or development well; however, development drilling is associated with a greater number of well sites and deposition areas, increased volumes of drilling mud and longer timeframes.

Drilling fluids and cuttings

Body burdens of metals and hydrocarbons were analyzed in Iceland scallop and American plaice and taste tests conducted for taint over a 10-year span as part of the EEM program at the Terra Nova oil development offshore Newfoundland, Canada (DeBlois et al. 2014a). DeBlois et al. (2014a) concluded that, based on the analysis in combination with a parallel study on fish bioindicators (Mathieu et al. 2011), the results indicate little to no detectable biological effects from Terra Nova activities on Iceland scallop and American plaice.

Laboratory toxicity tests of the SBM drilling fluid used at Terra Nova (low-toxicity synthetic iso-alkane mixture) (DeBlois et al. 2014b) indicated that acute toxicity should not occur below hydrocarbon concentrations of 1,900 mg/kg (Payne et al. 2001); however, benthic invertebrate data from Terra Nova suggest thresholds at lower hydrocarbon levels. These field results (including lagged responses in Phyllodocidae and Tellinidae) may be reflecting chronic sublethal effects or indirect effects such as organic enrichment on benthic communities (Paine et al. 2014).

Annual EEM programs of natural gas production activities offshore Nova Scotia at Deep Panuke and the Sable Offshore Energy Project (SOEP) have consistently observed less adverse effects than had been predicted. A plume of drilling waste was detected on only one occasion and appeared to be lighter and of shorter duration than anticipated from the modelling, and of the 24 metal chemical test parameters monitored in sediment at SOEP, elevated concentrations were only detected for total petroleum hydrocarbon (TPH) and barium (from the drill muds and cuttings piles deposited on the seafloor), and these only extended out to 500 m and returned to baseline concentrations within four years post-drill (CNSOPB 2018).

Ecological changes from exposure to WBM were detected at Terra Nova up to 1-2 km from the discharge source, including enrichment effects on some tolerant taxa (e.g., polychaete family Phyllodocidae and bivalve family Tellinidae) and decreased abundance of sensitive taxa (e.g., polychaete families Orbiniidae and Paraonidae) (Paine et al. 2014). Zones of influence from WBM and SBM drilling discharges as assessed by Cordes et al. (2016) and Ellis et al. (2012) are described in the above section on exploration drilling discharges.

Produced water

Produced water typically comprises the largest volume waste stream from offshore oil and gas production, with tens of millions of barrels discharged daily to the sea (Lee et al. 2011a). In Canada, produced water must be treated prior to discharge, in order to reduce hydrocarbon content to acceptable levels pursuant to the *Offshore Waste Treatment Guidelines* (NEB, C-NLOPB and CNSOPB 2010). Oil/water separation processes remove a substantial amount of the dispersed oil as free oil and larger oil droplets; however, dissolved oil is more difficult to remove, and small droplets, or emulsified oil, are discharged with the water (Zheng et al. 2016). The composition of produced water varies by reservoir type, age and management. In addition to organic and inorganic substances from geologic formations, produced water contains various additives and treatment chemicals introduced during extraction and production processes. Constituents can include seawater, dissolved organic salts, dissolved and dispersed hydrocarbons, dissolved minerals, trace metals, naturally occurring radioactive substances, production chemicals and dissolved gases (Bakke et al. 2013).

Conducting research on the potential impacts of produced water is challenging. The constituents and characteristics of produced water are entirely site-specific; sampling in the water column is difficult due to the turbulent nature of plumes (typically discharged from pipes 10 to 60 m below the water's surface); and the constituents undergo complex chemical kinetic reactions following discharge that alter the behavior and toxicity of the component chemicals (Lee et al. 2011a). However, for offshore developments in Atlantic Canada, acute toxicity is considered unlikely beyond the immediate discharge source given the typical discharge volumes and the rapid dispersion and degradation of the plume (Lee et al. 2011a; Neff et al. 2011).

Produced water discharges to shallow estuarine and marine waters may result in accumulation in the sediment of some metals and higher molecular weight aromatic and saturated hydrocarbons, and elevated polycyclic aromatic hydrocarbon (PAH) concentrations can be observed in surficial sediments out to a few hundred meters from high-volume produced water discharges in offshore and well-mixed estuarine waters (Neff et al. 2011). Resulting metal and hydrocarbon sediment concentrations depend on the volume and density of produced water discharged, the water depth and the local mixing regime, with offshore EEM programs generally finding concentrations of toxic metals in the water column and sediments just slightly above natural background concentrations (Neff et al. 2011).

To assess fish health before and after the discharge of produced water at the Terra Nova Offshore Oil Development site, bioindicators were evaluated in the bottom-dwelling American plaice (*Hippoglossoides platessoides*); these were found to be generally absent or similar between the reference and development sites suggesting no significant project-related effects on American plaice (Mathieu et al. 2011). Research on the effects of treated produced water on blue mussel (*Mytilus edulis*) resulted in significant sublethal responses following five weeks of exposure to produced water diluted with seawater (concentrations of 0.01–0.5%), even though individual chemical compounds were at extremely low concentrations both in the water and in the mussel tissues (Brooks et al. 2011).

Crawford et al. (2002) describe a joint study from Norway and Sweden that examined sublethal effects of alkylphenols (a natural constituent of produced water) by dosing cod (*Gadus morhua*) with body burdens of 1-10 mg/g (based on a simulation of theoretical accumulation near platforms). Reproductive impairment was observed in males (e.g., reduced testosterone levels, decreased sperm production) and females (e.g., smaller egg size, 3-week delay in spawning).

Fertilization and hatching success in Atlantic cod (*Gadus morhua*) were affected from 24 hours of exposure to produced water from two East Coast offshore gas production operations (Venture and Thebaud), while early life stages (larvae and juveniles) were not affected by short-term exposure to environmentally-relevant concentrations of produced water (Courtenay et al. 2013). Courtenay et al. (2013) conclude: “Discharge of produced water to the waters of the Scotian Shelf and edge of the Grand Banks, two highly productive areas that have some of the highest abundance of cod in Canadian waters, could pose a risk to juvenile cod. The effects of chronic, low level exposures of produced water on important marine species such as cod may become evident only after monitoring several life stages. Earlier life stages (egg, larval and juvenile) of cod are vulnerable as they have little control over their movement in the ocean currents and may be unable to avoid being caught in a plume of produced water in the near-field or a patch or pocket in the far-field.”

Documenting the effects of produced water on populations or communities has not yet been feasible, and there is virtually no information on potential long-term impacts from produced water on population and community functions such as production, reproduction and trophic interaction (Bakke et al. 2013). Therefore, potential impacts and ecological risks are predicted using complex fate and effects models such as DREAM (Dose-related Risk and Effects Assessment Model). Modelling results suggest that the potential area of influence of treated produced water on benthic organisms is limited to 1-2 km from the discharge location (Cordes et al. 2016), and that there is a negligible risk of widespread, long-term population, community or ecosystem impacts.[13] However, accurate modelling of contaminant risk depends on identifying and quantifying toxic effect-inducing chemicals; the causative agents of the most toxic produced

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[13] However, Bakke et al. (2013) state that this risk rating cannot be verified in the published literature, as modelling results have not yet been validated with confidence.

waters are unknown, but “may be linked to the extremely high total dissolved solids (salinity) concentrations, altered ratios of major seawater ions, and elevated concentrations of ammonia” (Lee et al. 2011a).

Neff et al. (2011) state that sub-lethal effects to populations and communities from continual chronic exposure may result in “decreased community and genetic diversity, lower reproductive success, decreased growth and fecundity, respiratory problems, behavioral and physiological disorders, decreased developmental success and endocrine disruption.” Such impacts may only become apparent by monitoring several life stages, generations of keystone species or long-term ecological effects (Lee et al. 2011a; Neff et al. 2011).

CUMULATIVE EFFECTS

Cumulative effects are “changes to the environment that are caused by an action in combination with other past, present and future human actions” (Hegmann et al. 1999). Cumulative impacts may result from a single human activity producing multiple stressors, multiple activities producing a common stressor, or multiple activities producing multiple stressors on a suite of ecological components (Clarke Murray et al. 2014). Key types of cumulative effects include additive (the sum of effects of two or more physical activities); synergistic (the resultant combination of two or more effects is greater or different than the simple sum of effects); compensatory (effects from two or more physical activities offset each other such that they may not be measurable); or masking (the effects of a project mask the effects of another project) (Canadian Environmental Assessment Agency 2018).

Assessing cumulative effects is critical in understanding how activities and associated stressors may impact ecosystems across space (local, regional, global) and time (past, present and predicted future activities). Types of cumulative effects analyses include project-based and regional or strategic-based assessments. Project-based is the most common type of cumulative effects assessment, typically conducted as part of a project’s environmental impact assessment. The reader is directed to recent Environmental Impact Statements of exploration drilling programs proposed for the Newfoundland and Labrador Offshore Area for examples of comprehensive project-based cumulative effects assessments.[14] This type of assessment tends to consider impacts from activities occurring within the scope of a single project without addressing the potential cumulative impact of all activities on all ecological components in a given area.

Regional assessments consider cumulative effects from all projects in an area of interest, while strategic assessment focuses on strategic decision-making to support sustainable development or planning. Doelle and Sinclair (2018) describe the difference between regional and strategic assessments as follows: “It is our view that a regional assessment is an assessment whose primary defining features are its regional scope and its focus on understanding the interactions between all past, present and future human activities and the natural world within a given study area... a strategic assessment (is distinguished) from a regional assessment largely based on its focus on a particular set of human activities, either a particular policy, plan or program, a particular issue, or a particular industry or sector of the economy. A regional assessment, on the other hand, would include all human activities within a given study area.” The C-NLOPB and CNSOPB have conducted several strategic assessments for offshore areas in Atlantic Canada, and a regional assessment is anticipated to be completed in 2019.

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[14] Canadian Impact Assessment Registry

Research in the marine environment has largely focused on the impact of single stressors on ecological components, and research on the overall cumulative effects of human activities on marine ecosystems is limited (Clarke Murray et al. 2014). Scientific literature focusing on cumulative effects of human activities on benthic habitat tends to incorporate multiple sectors (e.g., oil and gas, trawling, dredging, pipelines, renewable energy) and assesses the spatial extent associated with component "pressures" from various activities (e.g., smothering, abrasion, obstruction and sediment removal) (Kenny et al. 2018; Foden et al. 2011; Eastwood et al. 2007). As described in Eastwood et al. (2007): "Our assessment of pressure is distinct from an assessment of impact, which would require information on ecosystem components and attributes and how they respond to varying pressures and their intensities. Instead, we focused attention on estimating pressure, and not impact."

MITIGATION MEASURES

Prior to conducting offshore exploration and development activities, a suite of mitigation measures is proposed by the operator and/or required by the regulator as a condition of authorization. Such measures are ideally identified and implemented in accordance with the widely-accepted mitigation hierarchy of avoid, minimize/reduce, rehabilitate/restore and offset/compensate (World Bank 2012). The DFO document *Fisheries Protection Policy Statement* (DFO 2013) refers to the mitigation hierarchy fundamentals of "avoid, mitigate and offset" as best practice in reducing impacts to biodiversity. DFO emphasizes that efforts should first be made to prevent (avoid) impacts, then to minimize (mitigate) impacts that cannot be avoided. Offsetting measures are implemented to counterbalance residual impacts, which are those remaining after efforts have been made to avoid and mitigate impacts.

Avoidance is the most effective mitigation measure available, as it removes all potential pathways of effects by eliminating the possibility of interaction. Management strategies can include spatial (changing locations), temporal (changing the time at which an activity is conducted), and activity (e.g., restricting or banning certain activities, altering practices). Where avoidance is not feasible, mitigation measures may be effective. In areas with defined benthic conservation objectives, lower impact thresholds and higher avoidance and mitigation expectations in accordance with the precautionary principle[15] may be appropriate, given that a higher vulnerability to anthropogenic activities is either inferred or has been explicitly identified in these areas. In accordance with the mitigation hierarchy, key steps in offshore oil and gas exploration and production include identifying and mapping SBAs through high-resolution seabed surveys, then avoiding and minimizing impacts by implementing corresponding risk management strategies and mitigation measures.

The NOROG guideline *Monitoring of Drilling Activities in Areas with Presence of Cold Water Corals* details numerous management methods and technologies for mitigating the risks of drilling activities to cold-water corals (almost all of which would also apply to other areas with defined benthic conservation objectives) (DNV 2013). The comprehensive document culminates with a simple concluding statement synthesizing NOROG's recommendations to operators, which can be summarized as follows:

1) Consider the available risk reducing technologies for mitigating the impacts of drilling and incorporate these as applicable during planning and design.

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[15] "Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation" *Canadian Environmental Protection Act*, SC 1999, c. 33.

2) Position the wellhead where it will have the least impact on the sensitive fauna of concern (while maintaining well objectives and in recognition of shallow geological hazards).
3) Consider the impact of anchors and mooring chain activity in positioning the wellhead (if using a moored drilling rig) and implement additional mitigations if necessary.

Many currently-implemented standard mitigation measures, emerging technologies and management strategies can reasonably be expected to reduce impacts to benthic species and habitats. However, the body of scientific literature specifically focused on the effectiveness of mitigation measures to avoid and/or minimize environmental impacts of offshore oil and gas activities is negligible. While some implemented mitigation measures have resulted in well-documented, quantifiable impact reductions,[16] measures that may reduce impacts only incrementally (such as pre-laying anchors or using the smallest seismic source necessary to accomplish the exploratory goal) have not been studied or documented to the same extent.

This section and the summary table in Appendix 1 describe the following key mitigation measures that may be considered to minimize potential impacts of exploration and production activities in areas with defined benthic conservation objectives:

- Seismic survey mitigations
- Pile driving mitigations
- Considerations in acquiring seabed imagery
- Infrastructure planning and setbacks from areas with defined benthic conservation objectives
- Drill cuttings and fluids mitigations
- Anchors and chains mitigations
- Pipelines and flowlines mitigations
- Produced water mitigations
- Drilling and production mitigation technologies

SEISMIC SURVEY MITIGATIONS

The use of seismic surveys to locate commercially-viable oil and gas reservoirs presents a tradeoff: while seismic surveys have been shown to impact marine species, their use reduces the number of exploration wells that must be drilled, thereby reducing drilling-related impacts (Amec Foster Wheeler Environment & Infrastructure UK Ltd. 2016).

It is possible that mitigation measures may reduce impacts to benthic species from seismic surveys, such as factoring biological information into the planning (e.g., timing surveys to avoid important spawning periods for sensitive species), changing the sound source, or decreasing the intensity of emissions (Carroll et al. 2017). However, the effectiveness of these measures cannot be adequately determined without a thorough understanding of sound exposure

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[16] Such as the major shift away from oil-based muds (OBM) with impacts to benthic components beyond 5 km from the discharge point (Olsgard and Gray, 1995), to SBM and WBM drilling muds with their smaller areas of influence (100-500 m), reduced biological impacts and decreased persistence (Cordes et al. 2016).

thresholds (including sound pressure and particle motion components, and in consideration of sub-surface signals) in fishes and invertebrates. In fact, this knowledge is a prerequisite to determining whether an activity is likely to result in impacts (therefore, whether mitigation is even necessary and, if so, the form and extent of mitigation measures that would avoid or reduce the impacts). Knowing the responses of animals to the potential stimulus may facilitate the design of appropriate types and levels of mitigation; however, given the absence of data that could enable a more targeted approach, the below broad-brush mitigation measures may be considered.

Mitigation measures that apply to all air source array seismic activities in non-ice-covered Canadian marine waters are formalized and standardized in DFO's *Statement of Canadian Practice with respect to the Mitigation of Seismic Sound in the Marine Environment* (DFO 2008). While most of the described measures are aimed primarily at reducing potential impacts on marine mammals and sea turtles (such as establishing and monitoring a safety zone, passive acoustic monitoring, ramp-up and prescribed shut-down), the following strategies may also minimize impacts to areas with defined benthic conservation objectives (DFO 2008):

- Each seismic survey must be planned to:
    - Use the minimum amount of energy necessary to achieve operational objectives.
    - Avoid dispersing aggregations of spawning fish from a known spawning area.
    - Avoid diverting aggregations of fish from known migration routes or corridors if it is known there are no alternate migration routes or corridors, or that if by using those alternate migration routes or corridors, the aggregations of fish would incur significant adverse effects.

The International Union for Conservation of Nature (IUCN) developed a similar planning tool to guide industry, regulators and scientists in best practices to reduce impacts of seismic surveys on marine life (Nowacek and Southall 2016). While also focused on marine mammals, the guide presents the following mitigations that may also reduce impacts to areas with defined benthic conservation objectives:

- Having a systematic, risk assessment-based means of conducting effective monitoring and mitigation;
- Using the smallest source necessary (e.g., smallest number/size of airguns) to accomplish the exploratory goal (source power scaled appropriately for required substrate penetration);
- Modifying the survey area, timing and/or duration to avoid or reduce impacts within SBAs or during periods of sensitive life-history events (e.g., spawning) of habitat-forming species;
- Avoiding redundant surveys in the same area (e.g., consideration of multi-operator surveys – reduced impacts without compromising desired data types and quality);
- Pursuing alternative, lower energy sources (consideration of existing and new geophysical survey technologies that may have reduced acoustic output levels); and
- Ensuring open access of environmental data in a reasonable time frame (Nowacek and Southall 2016).

Advances in seismic technology are focused on providing highly-accurate seismic data while increasing the efficiency of seismic programs. Alternative marine seismic sources are being developed that may reduce impacts of seismic sound on sensitive biota. In contrast to the high-pressure firing of an airgun, marine vibroseis (MV) can produce a constant amplitude signal, with real-time modification of the frequency, duration and amplitude (Duncan et al. 2017). A modelling study comparing received sound levels from MV and airgun arrays showed that MV produces lower broadband sound exposure levels (SELs) and lower peak pressure (Duncan et al. 2017). While this suggests reduced impacts to marine receptors, Duncan et al. (2017) note that laboratory and field testing should be conducted on a wide range of sensitive taxa and propagation conditions (ideally in tandem with design and testing of MV units), and receptor behavioural responses should be studied both at low levels and levels where injury is likely.

Better planning and implementation of coordinated exploration seismic efforts can also be an important mitigative strategy. In Newfoundland and Labrador, Nalcor Energy Oil and Gas manages exploration efforts of the province’s frontier and deep-water basins through direct investments in new geoscience data acquisition. Having this crown corporation directing seismic collection and distribution of data to the oil and gas industry reduces the need for repeated seismic operations in the same location conducted by multiple companies seeking their own data, and as such reduces overall seismic operations.

PILE DRIVING MITIGATIONS

Impact pile driving is one of the main sources of underwater noise from marine industrial activities, generating high energy impulsive sounds that are of particular concern to animals living near or in the substrate (as described in the above sections on seismic surveys and underwater sound). The Subsidiary Body on Scientific, Technical and Technological Advice for the United Nations Environment Programme’s Convention on Biological Diversity proposes the following mitigation measures for pile driving that may reduce impacts to benthic species (UNEP 2012):

- Enclosing the ramming pile with mantling (acoustically-isolated material) can decrease the source level by 5–25 dB (higher frequencies are more affected than lower ones).
- Precautionary spatial and temporal mitigation measures (e.g., not conducting pile driving near areas with sensitive species and habitats, avoiding periods of sensitive life-history events such as spawning).
- Consideration of hydraulic pile driving as it results in lower noise emissions which are close to the background sound levels at sea (<100 dB re 1µPa).

SEABED IMAGERY ACQUISITION

Surveys are generally conducted where exploration and production infrastructure may contact or impact the seabed (e.g., well sites, anchor mooring locations, footings, pipelines) to identify, map and quantify benthic species, communities and habitat (e.g., species present, abundance, size, condition/health). Survey patterns and areal extents/corridors should be determined in consideration of several factors such as cuttings dispersion modelling results, biological effects thresholds and the activity or infrastructure (Iversen et al. 2015). Although the areal extent of seabed surveys (geotechnical and environmental sampling) is very small, presence/absence of sensitive benthic species and habitats should be confirmed via drop camera/video system transects prior to undertaking seabed sampling in protected areas and/or where there is a high probability of occurrence of corals or sponges (Amec Foster Wheeler Environment & Infrastructure 2015).

Seabed imagery may be acquired through acoustic technologies (e.g., side-scan sonar [SSS], multibeam echosounder [MBES]) and/or visual technologies (e.g., ROV camera or drop camera); however, at present the available acoustic technologies cannot necessarily be considered substitutes for visual methods when identifying and mapping areas with sensitive benthic species and habitats. Operators in the Canada-Newfoundland and Labrador Offshore Area recently proposed to conduct pre-drill seabed surveys using MBES and SSS at 0.5 m X 0.5 m resolution based on the NOROG guidelines (DNV 2013). DFO responded that, while certain seabed features can be detected by MBES and SSS (e.g., ice scouring plough marks, potential coral features), this resolution is not adequate to detect all known coral and sponge community types in the region (e.g., important habitats generated by species <30 cm in height and coral structures down to 1 m^2) (DFO 2018). The operators were advised to review and adjust the proposed criteria for identifying and avoiding corals and sponges, and DFO indicated that seabed contact and impact locations should be surveyed with an ROV (DFO 2018). While imaging technologies with greater resolution are emerging (e.g., Synthetic Aperture Sonar is currently being tested on *L. pertusa* reefs in the NE Atlantic down to a 3-cm scale), DFO (2018) noted that these technologies would need to be tested on regionally-representative communities.

SETBACKS AND INFRASTRUCTURE PLANNING

When sensitive benthic species and habitats are identified in the potential area of influence, various measures may be considered to avoid or minimize impacts, such as risk-reduction technologies and management strategies (e.g., horizontal drilling to access the reservoir subsea); methods to generate less drilling wastes; relocating the well and/or infrastructure; or redirecting drill cuttings through a subsea cuttings transport system. The locations of SBAs can be factored into planning by including their locations and applicable setbacks in constraints analyses.

Establishing setbacks is a key mitigative measure for minimizing impacts to areas with defined benthic conservation objectives; however, determining effective setback distances relies on having sufficient knowledge of the species and habitats of concern. For example, transition zones surrounding high-biomass sensitive habitats such as deep-sea coral and cold-seep ecosystems can extend at least 100 m beyond the visually-apparent site border. Cordes et al. (2016) state the following: “Considering the inherent sources of uncertainty associated with the management of deep-sea habitats, from the imprecise placement of seafloor infrastructure, to the variability in discharge impact distances, to the uncertainty in seafloor navigation and the locations of the sensitive deep-sea habitats and species, we strongly recommend that buffer zones be incorporated into spatial management plans.”

The United States is one of the only countries to specify legally-mandated setbacks (based mostly on *L. pertusa* reefs in the Gulf of Mexico): currently 610 m for drilling mud and cuttings discharges on the seafloor and 150 m (or down to 75 m with a waiver) for anchors and other seafloor infrastructure (Cordes et al. 2016). While operators in most jurisdictions are required to avoid impacts to sensitive species and habitats, scientists are generally reluctant to specify setback distances, given the number of variables (e.g., variability of species’ thresholds, geophysical processes, biophysical dynamics, infrastructure and activities) and the complex and changing nature of ecosystems (Blanchard et al. 2014). Gaps in basic knowledge result in a high degree of uncertainty regarding potential impacts on benthic species and habitats and, therefore, appropriate setback distances. For example, many qualities of deep-sea corals remain unknown and there are currently no means with which to measure the environmental factors and biological processes that regulate their lives and distribution (Freiwald et al. 2004).

The typical approach to mitigating and avoiding effects of oil and gas activities on sensitive habitat-forming species is to implement setbacks from visually-identified SBA locations, as described above. Recent DFO advice and guidance related to avoiding serious or irreversible harm to SBAs from fishing activities provides an alternate approach that may be considered for oil and gas activities, emphasizing protection of the ecological integrity and functionality of the habitat, rather than just of the visible, physical location of an individual outcrop location (DFO 2017a; DFO 2017b). Cordes et al. (2016) recommend the following for the spatial management of deep-sea ecosystems in the vicinity of oil and gas industrial activity:

1) Establish robust baseline ecological survey data within planning area and in appropriate reference areas.
2) Determine the locations, size and type of Ecological and Biological Significant Areas through comprehensive surveys including visual imagery.
3) Establish protected areas around significant areas of representative communities.
4) Establish borders of protected areas to be set-back distances based on typical distances[17] of impacts from installations:
    - 200 m from seafloor infrastructure with no expected discharges
    - 2 km from any discharge points and/or surface (i.e., floating) infrastructure
5) Consider activity and temporal management to restrict impacts.
6) Implement a comprehensive and robust monitoring programme that can reliably detect significant environmental changes in areas of exploration activity, areas inside the established (protected) areas, and reference sites outside of (protected areas) and activity zones.

DRILL CUTTINGS AND FLUIDS MITIGATIONS

Potential impacts to areas with defined benthic conservation objectives can be minimized by reducing the volume of drilling fluids used, the quantity of drilling waste generated, and the amount of muds and cuttings discharged at the wellbore and/or water surface. Should drilling be considered in an area with defined benthic conservation objectives and/or sensitive benthic habitat, a subsea cuttings transport system (CTS) may be used to transport cuttings from the wellhead to a more appropriate disposal area. Alternatively, a riserless mud recover system could be employed during top-hole drilling to return drill muds and cuttings to the rig for separation, reuse (drilling fluids) and alternate disposal (cuttings).

Reduction of generated drilling waste

Drill muds and cuttings are typically disposed of offshore, either directly on the seabed during riserless drilling or at surface following treatment of cuttings, or reinjected during development drilling (e.g., Hibernia and Hebron). Therefore, strategies and technologies that reduce the volume of generated drilling wastes and/or the discharge of fines also minimize the associated potential impact to areas with defined benthic conservation objectives.

In accordance with the *Offshore Waste Treatment Guidelines* (NEB, C-NLOPB and CNSOPB 2010), operators offshore Atlantic Canada are expected to take all reasonable measures to:

- Reduce amounts of waste material generated and discharged offshore;
- Reduce effluent volumes to the minimum required;

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[17] A synthesis of studies and activities (e.g., varying water depths and hydrodynamic environments, wells drilled using various drilling fluids).

- Reduce the concentrations of substances of potential environmental concern in effluents through process management and effective treatment; and
- Reduce toxicity of effluent streams by practicing effective source control at the chemical selection phase, following the process described in the Offshore Chemical Selection Guidelines for Drilling and Production Activities on Frontier Lands (NEB, C-NLOPB and CNSOPB 2009).

While the Guidelines state that operators are expected to minimize concentrations and volumes of wastes to be discharged to the environment by adopting best practices in waste management and treatment, they are not prescriptive as to methods (NEB, C-NLOPB and CNSOPB 2009).

Table 3 summarizes NOROG's evaluation of technologies to reduce the quantity of generated solids when drilling in areas with sensitive benthic species and habitats (DNV 2013).

Table 3: Options for reducing generated solids from drilling (modified from DNV 2013).

Technique	Description	Pros (to benthic species and habitats)	Cons (to benthic species and habitats)
Piling the conductor	Conductor (36"-section) is forced/piled approx. 80 m into seafloor, then drilled with 26" bit.	Reduced generation and discharge of drill cuttings. Reduced sedimentation risk for sensitive benthic species and habitats.	Marginal gains. Limited to specific soil or formation characteristics. Considerable risk of failure.
Slimhole well design	Top-hole cross section diameter and corresponding volume of generated cuttings is reduced. Technique often used in exploration wells.	Reduced discharge of fines. Reduced generation and discharge of drill cuttings. Reduced particle distribution. Reduced sedimentation risk for sensitive benthic species and habitats.	No cons for benthic species and habitats. Operational risks (possible limitation in equipment availability, limitations in flexibility to mitigate against drilling problems in the well, restriction in maximum possible completion size).
Reduced number of sections	Replacing 26"-section with a longer 17 ½" (or 12 ½") -section. Installation of riser prior to drilling 17 ½"-section eliminates discharge of drill cuttings and fluids from drilling a 26"-section.	Reduced discharge of fines. Reduced generation and discharge of drill cuttings. Reduced particle distribution. Reduced sedimentation risk for sensitive benthic species and habitats. Increased flexibility in location of well or template.	Increased use and discharge of drilling fluids with special specifications (17 ½" or 12 ½"). Use and discharge (if permitted) of "yellow"[18] chemicals. Operational risks (limitations in flexibility to mitigate against drilling problems in the well).

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[18] Chemicals classified as "yellow" in Norway mean non-PLONOR with "environmentally acceptable" possible effects.

Technique	Description	Pros (to benthic species and habitats)	Cons (to benthic species and habitats)
Drilling without barite / bentonite by using heavy brine and cellulose	Cellulose is used in viscous pills to replace bentonite and heavy brine is used as drilling fluid to avoid use of barite.	Reduced discharge of fines. Reduced risk of exposure to suspended matter. Barite exposure eliminated.	No cons for benthic species and habitats.

Additional developments in drilling technology are facilitating drilling of micro borehole wells (Kamyab and Rasouli 2016). Where typical drill bits for conventional wells have diameters as large as 12.25”, slimhole and micro borehole wells use drill bits (by definition) with <6” and <3” diameters, respectively, for at least 90 percent of the well (Kamyab and Rasouli 2016; Natgas 2013). Purported to reduce a well’s environmental footprint by as much as 75 percent (Natgas 2013), a narrower borehole requires less drilling fluids and generates less waste, minimizing potential impact to areas with defined benthic conservation objectives by reducing the volume of cuttings and resulting cuttings pile footprint, and minimizing discharge of fines, particle distribution and risk of sedimentation in SBAs (DNV 2013).

Combining slimhole or micro-borehole drilling with coiled tubing technology can further reduce impact and the amount of required drilling fluids by using a long, flexible coiled pipe string instead of the rigid, jointed drill pipe used in conventional drilling (Natgas 2013). Generated cuttings may also be reduced through directional drilling, as several separate reservoirs could be accessed horizontally from the primary vertical well, eliminating the need to drill a number of conventional vertical wells (Ma et al. 2016).

Subsea cuttings transport system

When drilling in areas with defined benthic conservation objectives, impacts to sensitive species and habitats may be avoided or minimized by using a CTS to collect and transport drill cuttings and fluids up to 500 m[19] away from the wellhead to a suitable discharge area (DNV 2013; Enhanced Drilling 2018). CTS is a proven technology and is currently employed offshore Newfoundland to transport cuttings away from the drill centre during riserless drilling. The ability to transport cuttings may increase flexibility in selecting well sites. NOROG states that when drilling activities may impact sensitive benthic species and habitats, use of CTS “generally reduces the impact to an acceptable level” (DNV 2013). A key factor in the effectiveness of subsea CTS as a mitigation method is the ability to identify and access a disposal area with sufficient setback from SBAs.

Return to rig for alternative disposal/use

Riserless mud recover systems enable drilling fluids and cuttings to be returned to the rig during top-hole (riserless) drilling. The technology was primarily developed to optimize use of engineered drilling fluid systems and reducing the volume of drilling fluids required during top-hole drilling, as drilling fluids can be separated from cuttings on the rig and reused in the

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[19] Theoretically a range of >3,000 m could be possible, but experience of discharge transfer >1,000 m is limited (DNV 2013).

wellbore (DNV 2013). However, it also significantly reduces impacts to areas with defined benthic conservation objectives from discharge of drilling fluids and cuttings at the wellhead.

NOROG assessed several options for disposing of the drilling fluids and cuttings returned to the rig (summarized in Table 4). However, following their evaluation of reliability, complexity, environment and cost-benefit of the technologies, they concluded that the preferred option in SBAs is to transfer cuttings and fluids via subsea CTS to a suitable disposal location (DNV 2013).

Table 4: Options for disposal/use[20] of drill cuttings and fluids returned to rig via riserless mud recover system (modified from DNV 2013).

Technique	Description	Pros to benthic species and habitats	Cons to benthic species and habitats
Discharge untreated from rig	Discharge of cuttings from rig after passing shaker (separation).	Significant dilution of fines reduces risk to benthic species and habitats (compared to discharge at the wellbore).	Cuttings discharge at surface is less controllable and may pose a higher risk to SBAs than using subsea CTS to discharge to a suitable disposal location.
Coarse slurrification and discharge from rig	Cuttings are processed through grinding to finer particles, mixed with water and discharged to sea.	Significantly reduced risk of cuttings sedimentation or particle exposure at the seafloor near the wellbore.	Increased operational risks and bottleneck in the waste management system that could result in reduced performance.
Slurrification and reuse as spud mud	Cuttings are ground to finer particles and mixed with (significant volumes of) water and “yellow” chemicals to obtain drilling fluid specifications. Slurrified fluid may be reused in next well section and/or (in some cases) at a different rig. No existing system for transport, treatment and reuse of slurrified cuttings and recovered drilling fluids from top-hole drilling.	Significantly reduced risk of cuttings sedimentation or particle exposure at the seafloor near the wellbore. Reduced generation of cuttings and use of drilling fluid equal to the volume of one section.	Reduction in discharge of cuttings and drilling fluid is limited to the volume equal to one section. No established system for reuse within industry. Increased “yellow” chemical use.

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[20] Reinjecting cuttings into a dedicated disposal well is an additional option for production platforms, not presently feasible for exploration wells (Buchanan et al. 2003).

Technique	Description	Pros to benthic species and habitats	Cons to benthic species and habitats
"Skip and ship" of separated drill cuttings	Collection of separated drill cuttings and transportation to shore for disposal (typically for OBM-generated cuttings). Can be significantly impacted by weather (increased risk for suspension in drilling operations from restricted crane operations).	Avoids associated impacts to benthic species and habitats, as no drill fluids or cuttings are discharged to sea.	Increased vessel traffic (and associated underwater sound). System has not been extensively used for the collection and transportation of WBM-generated cuttings and performance has been lower than expected. Significant increase in operational and safety risks, resource requirements and air emissions (increased vessel traffic).
Bulk handling of cuttings to a supply vessel whilst drilling, for transport and disposal onshore	Bulk storage tanks allow continuous, unrestricted drilling. Comparable to skip and ship with all cuttings collected and transported to shore for disposal, but less impacted by weather (significantly reduced number of crane-lifting operations).	Avoids associated impacts to benthic species and habitats, as no drill fluids or cuttings are discharged to sea.	Increased vessel traffic (and associated underwater sound). Limited successful experience. Increased operational risks, resource requirements and air emissions (increased vessel traffic). Not suitable for recovery of top-hole cuttings without additional equipment. Limited to inhibited (glycol) fluids.
"Blowing" cuttings to vessel while drilling, for transport and disposal onshore	Drill cuttings transferred directly to a vessel from the shakers by temporary lining and pressurized air. Continuous, unrestricted drilling if bulk transfer hose can be connected. Comparable to skip and ship with all cuttings collected and transported to shore for disposal, but less impacted by weather (significantly reduced number of crane-lifting operations).	Avoids associated impacts to benthic species and habitats, as no drill fluids or cuttings are discharged to sea.	Increased vessel traffic (and associated underwater sound). Increased operational risks, resource requirements and air emissions (increased vessel traffic and requires dedicated supply vessel). Not suitable for recovery of top-hole cuttings without additional equipment.

Technique	Description	Pros to benthic species and habitats	Cons to benthic species and habitats
Coarse slurrification of separated cuttings for disposal at seafloor	Combines CTS and mud recovery techniques. Coarse slurrifying at the rig enables transport of cuttings and drilling fluids (with reduced risk for obstructions) to a more optimal deposit site away from the well.	Significantly reduced risk of cuttings sedimentation or particle exposure at the seafloor near the wellbore. Suitable for all well sections (not just top-hole). Perceived lower overall environmental impact than skip and ship.	High complexity over alternative solutions – very limited experience and unproven technology. Increased operational risks and resource requirements.

ANCHORS AND CHAINS MITIGATIONS

Avoiding and/or reducing the potential impact of anchors and chains is particularly important in areas that may support fragile habitat-forming coral and sponge species. Prior to arrival of a mobile offshore drilling unit (MODU) on location, a site anchor-spread and mooring analysis is conducted to ensure stable and safe positioning and to avoid conflicts with existing seabed infrastructure. Potential impacts may be avoided or reduced by factoring in (as constraints in the mooring analysis) the location of sensitive species and habitats, with applicable setbacks based on ecological thresholds (DNV 2013).

Anchoring characteristics that may affect the magnitude of potential impacts include anchor size, method of deployment and retrieval and types of mooring lines and attachments (Seibert, M.G. 2011). The following measures may reduce potential anchor and chain impacts to areas with defined benthic conservation objectives (Seibert, M.G., n.d.):

- Selecting properly-sized anchors based on detailed site surveys;
- Increasing anchor bottom roughness (to decrease dragging and seabed scouring);
- Adding sinkers to drag embedment anchors to reduce mooring scope; and
- Using line floats to raise anchor connection points or portions of chain off the seafloor.

NOROG identifies the following strategies for mitigating potential impacts to cold-water corals from anchors and chains (DNV 2013):

- Dynamic positioning rig
- Pre-laid anchors and chains
- Pick-up buoys
- Fiber wire and subsurface buoyancy
- Larger anchor and/or chain dimension

Dynamic positioning (DP) rigs and vessels

Drill rigs and vessels that employ DP for station-keeping avoid potential mooring-related impacts on benthic species and habitats; however, impacts to benthic species and habitats may not be entirely avoided, as DP rigs require deployment of an array of transponder beacons on the seabed and the operation of DP thrusters may result in impacts from chronic exposure to underwater noise. Additionally, compared to moored rigs, DP rigs consume more fuel and have greater air emissions (CO2, SO2, NOx, HC and CO) (Aalbers et al. 2006), a trade-off that may factor into rig selection, particularly in areas without sensitive benthic species. Efforts to increase efficiency and decrease emissions are ongoing; however, given the comparatively higher cost, fuel consumption and downtime associated with DP rigs, Shinn (2018) anticipates a return to moored rigs (even in Norway); this further emphasizes the need for effective risk-based management and measures to mitigate mooring-associated impacts to areas with defined benthic conservation objectives.

Pre-laid anchors and chains with pick-up buoys

Pre-laying anchors and chains prior to rig arrival can minimize risk of impact to sensitive benthic components by increasing accuracy of positioning in accordance with the anchor-spread and mooring analysis, as optimal placement is ensured by monitoring anchor handling operations by ROV (DNV 2013). Installing pick-up buoys on the pre-laid anchors can further reduce potential impacts, as this enables an ROV to retrieve them directly instead of grappling at anchor chains (DNV 2013).

Fiber wire and sub-surface buoyancy

To minimize impacts to sensitive benthic components from anchor chain touchdown, anchor chains can be given buoyancy by partly replacing chains with fiber (nylon) wire and attaching buoys. This reduces the risk of damage to fragile species by extending the point of anchor chain touchdown and reducing the potential horizontal footprint (as sideways movement decreases further from the rig) (DNV 2013).

Larger anchor and/or chain dimension

Using heavier anchors and chains (e.g., larger anchor sizes, larger chain dimensions) can reduce the footprint of anchors and chains by enabling anchors to be positioned closer to the rig, and increases flexibility in positioning anchors and chains, which may be utilized to avoid impact to sensitive benthic features (DNV 2013).

PIPELINES AND FLOWLINES MITIGATIONS

The primary mitigation measure to reduce potential benthic impacts from pipelines, flowlines, control lines and umbilicals is to identify the locations of sensitive benthic species and habitats (via ROV survey of the proposed route) and include the locations and applicable setbacks in constraints analyses. NOROG (DNV 2013) recommends that a 200 m-wide corridor (i.e., 100 m to each side) be surveyed of the planned pipeline route via ROV in areas where sensitive species or habitats may be present, with the survey corridor extended to 500 m in areas with known sensitive species and/or habitats. NOROG recommends that pipelines be located no closer than 50 m from corals and other SBAs (DNV 2013); however, this guidance was developed specifically for Norway's *L. pertusa* reefs. In addition, impacts during pipeline deployment can be minimized by using DP laydown vessels, as these avoid anchoring-associated effects on benthic species and habitats (DNV 2013).

PRODUCED WATER MITIGATIONS

Lee et al. (2011a) state the following with regards to monitoring and minimizing effects of produced water: "For a comprehensive protection plan, there is a need to support the development of improved monitoring protocols to provide early warning of any potential problems related to sediment and water quality (e.g. primary productivity), fish quality and fish health. Development of real-time monitoring systems (i.e. contaminant specific sensors and data-transfer technologies) may enhance our capacity to manage the ocean and its living resources. In consideration of natural perturbations currently occurring in the ocean (e.g. climate change) and the impacts potentially associated with other marine users (e.g. marine transport, fisheries, etc.), an ecosystem based integrated management approach must be taken to fully evaluate the risks of produced water discharge into the ocean. In addition, alternative approaches to produced water management may also be considered."

The following management strategies are intended to be considered and implemented consecutively, per the mitigation hierarchy (Igwe et al. 2013):

1. Water minimization: generate less water from the well by modifying processes, adapting technologies or substituting products.
2. Water recycle/reuse: following implementation of water minimization strategies, water recycle/reuse is employed (e.g., offshore reinjection to enhance oil production and/or maximize oil recovery).
3. Water treatment/disposal: following implementation of water minimization and recycle/reuse strategies, produced water is treated for discharge or disposal.

Techniques to minimize produced water include mechanically blocking water from entering the well, using chemicals in the formation to block water-bearing channels or fractures, and employing down-hole oil/water separation (Zheng et al. 2016). Minimizing the volume of produced water also reduces the amount requiring treatment and the quantity of chemicals used in oil/water separation, and results in less marine discharge of produced water and associated contaminants. While treated produced water can be reused onshore for industrial activities and irrigation (Zheng et al. 2016), the only viable option for reuse offshore is for enhancing production through reinjection (Judd et al. 2014).

Produced water treatment removes solids and dispersed non-aqueous liquids (oil, suspended solids, scales, bacterial particles) and most volatile hydrocarbons and corrosive gases (e.g., carbon dioxide, hydrogen sulphide) (Neff et al. 2011). Experience by the offshore oil industry with produced water treatment for ocean disposal has shown that removing dispersed oil also reduces concentrations of volatile and dissolved hydrocarbons to acceptable levels (Ayers and Parker 2001 as cited in Neff et al. 2011), therefore regulations stipulating discharge parameters generally only reference total oil and grease or TPH concentration (Neff et al. 2011):

- Oslo-Paris Commission Convention for the Protection of Marine Environments of the North-East Atlantic (OSPAR Convention) requires a performance standard of 30 mg/L and recommend that new and substantially modified installations consider discharge minimization and "zero discharge" practices.
- U.S. Environmental Protection Agency stipulates an average amount of oil in water per month of 29 mg/L, with a maximum daily discharge of 42 mg/L.
- Atlantic Canada *Offshore Waste Treatment Guidelines* set a performance target of 30-day volume weighted average oil-in-water concentration not exceeding 30 mg/L, and 24-hour average oil-in-water concentration in discharged produced water not exceeding 44 mg/L.
- Norwegian Authorities and Operators on the Norwegian Continental Shelf have agreed to aim for Zero Harmful Discharges to the North Sea.

Produced water is most commonly treated offshore through gravity separation; however, the resulting water does not generally meet discharge limits. As a result, secondary treatment techniques (such as chemical treatment followed by sedimentation or dissolved air flotation) are employed to decrease the levels of dissolved, emulsified and dispersed oil (Igwe et al 2013). Innovative technologies for treating produced water are in various stages of development, testing and application. While detailing these and assessing their effectiveness is beyond the scope of this paper, the best options for treating produced water at offshore platforms, such as membrane technology, evaporation, packed bed adsorption and ion exchange, are described in detail in Igwe et al. (2013).

Jiménez et al. (2018) also describe the following state-of-the-art produced water polishing (tertiary) treatment methods in considerable detail (although all may not be practicable in the offshore):

- Physical treatment (adsorption, cyclones, enhanced flotation)
- Biological treatment (microbial biodegradation)
- Membrane treatment (polymetric membranes, inorganic membranes, microfiltration/ultrafiltration, reverse osmosis and nanofiltration)
- Thermal technologies (evaporation, multistage flash, multieffect distillation, vapour compression distillation, freeze-thaw/evaporation, hybrid multieffect distillation–vapour compression)
- Chemical treatment (chemical precipitation, electrochemical processes, room temperature ionic liquids, demulsifiers, ion exchange, macro-porous polymer extraction technology, advanced oxidation processes)
- Various commercial treatments

Treatment technologies and substitutes for toxic chemicals have resulted in substantial reductions in toxicity. Elevated micronuclei frequencies (i.e., evidence of chromosomal damage) were detected in caged blue mussels up to 1.6 km away from the produced water discharge point at the Ekofisk field in 2008 (Sundt et al. 2008). Following installation and implementation of new produced water treatment technology (C-Tour) at the platform, total discharge of oil reduced by 38 percent and elevated micronuclei frequencies were only detected in cages 500 m from the source (Brooks et al. 2009). As described above, there are almost no means with which to assess potential long-term impacts to marine life of produced water at low concentrations (Meier et al. 2008 as cited in Blanchard et al. 2014); therefore there is a lack of agreement as to whether marine discharge of treated produced water adheres to the precautionary principle and, if so, at what concentrations (Blanchard et al. 2014).

ADDITIONAL TECHNOLOGICAL MITIGATIONS

Directional and cluster drilling

Horizontal drilling is enabling rigs to drill directionally, either from land or from a conventional vertical well offshore, into reservoirs located several kilometers away. Cluster drilling is a similar concept in that several reservoirs may be accessed by wells drilled diagonally from a central platform. These drilling methods can reduce impacts in areas with defined benthic conservation objectives by eliminating the need for satellite platforms, which minimizes the infrastructure footprint on the seabed and concentrates operational drilling and production discharges at one location (e.g., drill muds and cuttings, produced water). Directional drilling could also be employed to access reservoirs located underneath areas with protected or sensitive benthic species and habitat.

Subsea production systems

The need for satellite platforms (and their associated footprints and discharges) is also being reduced by the development of remotely-operated subsea production systems. The complexity of subsea production systems can range from a single satellite well with a flowline linked to a central fixed platform or floating facility, to several wells clustered around a manifold and transferring to a fixed or floating facility or directly to an onshore installation.

Floating LNG facilities

Combining onshore and offshore LNG facilities into a single floating LNG installation that could capture and store the produced gas would eliminate the need for a pipeline to shore, avoiding potential impacts in areas with defined benthic conservation objectives from pipeline-associated dredging, jetting/burial and laydown (Amec Foster Wheeler Environment & Infrastructure UK Ltd. 2016).

CONCLUSION

Current Canadian standards for oil and gas exploration and development activities meet or exceed global environmental standards; however, these practices were not developed for areas with defined benthic conservation objectives. Regardless, many currently-implemented standard mitigation measures, emerging technologies and management strategies can reasonably be expected to reduce impacts to benthic species and habitats. Areas with defined benthic conservation objectives are areas where higher vulnerability to anthropogenic activities is either inferred or has been explicitly identified. Therefore, greater expectation of impact avoidance and more conservative impact thresholds and mitigation measures may be considered for oil and gas exploration and production activities proposed or occurring in these areas. There remain substantial uncertainties regarding potential impacts of routine marine oil and gas exploration and production activities, perhaps particularly on benthic species and habitats. Increasing our understanding of pathways of effects, thresholds and potential impacts should facilitate the development and implementation of management strategies and mitigation measures that are both effective and practical.

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APPENDIX 1: MITIGATION MEASURES TO REDUCE POTENTIAL IMPACTS OF OFFSHORE OIL AND GAS ACTIVITIES IN AREAS WITH DEFINED BENTHIC CONSERVATION OBJECTIVES

Potential impacts	Mitigation measures
Seismic survey underwater sound (2D, 3D, wide-azimuth, 2DHR): • Direct mortality • Tissue and/or physiological damage (indirect mortality) • Hearing impairment • Masking • Changes in behavioural response • Habitat changes from altered sediment reworking	• Use the smallest source (number and size of airguns) and minimum amount of energy necessary to achieve operational objectives. • Reduce the survey boundaries to only include areas where data are essential. • Modify the survey area, timing and/or duration to avoid or reduce potential impacts for key protected and sensitive species habitat during sensitive periods (e.g., avoid main spawning periods of coral and other ecologically important species). • Avoid dispersing aggregations of spawning fish from a known spawning area or diverting aggregations of fish from known migration routes or corridors. • Consider alternative, lower-energy sources and technologies that may have reduced acoustic output levels (e.g., marine vibroseis). • Avoid redundant surveys in the same area and/or consider multi-operator surveys. • Implement better planning and coordinated efforts (e.g., central management of collection and distribution of exploration efforts). • Some of the above measures may also reduce the likelihood and magnitude of impacts to sensitive benthic species from electromagnetic surveys (potential impacts are unknown).
Noise/vibrations from high-impact seabed activities (e.g., wellhead/conductor installation, pile driving): • Direct mortality • Tissue and/or physiological damage (indirect mortality) • Hearing impairment • Masking • Changes in behavioural response	• Enclose the ramming pile with acoustically-isolated material (mantling). • Avoid conducting high-impact seabed activities near[21] areas with sensitive benthic species and habitats and during periods of sensitive life-history events (e.g., spawning, migration). • Consider hydraulic pile driving which results in lower noise emissions that are near the background sound levels at sea.

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[21] There is insufficient science to determine distances of sound propagation or potential impacts and species' thresholds.

Potential impacts	Mitigation measures
• Habitat changes from altered sediment reworking	
Deposition of drill muds and cuttings and placement of infrastructure: • Direct impacts (crushing, burial, fragmentation) • Sedimentation (smothering, clogging of feeding and gas exchange structures) • Chemical toxicity (enrichment effects, physical effects on tissues, habitat destabilization)	• Acquire seabed imagery to identify, map and quantify sensitive benthic species, communities and habitats where activities and/or infrastructure may contact or impact the seabed (e.g., geotechnical surveys, environmental sampling, well sites, anchor mooring locations, footings, well sites, flowlines). o Ensure acoustic imaging technologies have adequate resolution to detect sensitive benthic species and habitats known to occur in the region. o Determine survey patterns and areal extents/corridors in consideration of cuttings dispersion modelling results, biological effects thresholds and the activity or infrastructure. o Confirm presence/absence of sensitive benthic organisms and habitats via drop camera/video system transects in protected areas and/or where there is a high probability of occurrence of sensitive benthic species and habitats. • Adjust planned well and infrastructure locations to avoid sensitive benthic species and habitats by including their locations and applicable setbacks in constraints analyses. o Determine sufficient setbacks in consideration of biological factors of sensitive benthic organisms and habitats. o Minimum proposed setbacks for sensitive benthic species and habitats (Cordes et al. 2016): ▪ 200 m from seafloor infrastructure with no expected discharges ▪ 2 km from any discharge points and/or surface (i.e., floating) infrastructure o A cuttings transport system (CTS) may be employed to transfer drill muds and cuttings to a discharge location with sufficient setback from SBAs. • Reduce the volume drilling fluids required and the generated drill cuttings by considering alternate methods and technologies (considering associated pros and cons)[22]: o Piling the conductor o Slimhole or micro borehole wells o Reducing the number of well sections o Drilling without barite/bentonite by using heavy brine and cellulose o Coiled tubing

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[22] For example, piling the conductor may generate (marginally) less cuttings but increase impacts to benthic species by generating interface soundwaves.

Potential impacts	Mitigation measures
	○ Directional drilling ○ Combining methods to increase effectiveness (e.g., slimhole drilling with coiled tubing technology) • Consider using a mud recovery system during riserless (top-hole) drilling to return drill muds and cuttings to the rig for alternate use or disposal (considering associated pros and cons): ○ Discharge (of WBM drill cuttings) untreated from rig ○ Coarse slurrification and discharge from rig ○ Slurrification and reuse as spud mud ○ "Skip and ship" for onshore disposal of separated drill cuttings ○ Bulk handling of cuttings to a supply vessel whilst drilling for transport and disposal onshore ○ "Blowing" cuttings to vessel while drilling ○ Coarse slurrification of separated cuttings for disposal at sea floor • Cuttings reinjection may be considered from production platforms. • Cluster and/or direction drilling may be considered to minimize the need for satellite platforms, concentrate discharges in one location and/or access reservoirs under areas with protected or sensitive benthic species and habitat. • Subsea production systems may be used to minimize the need for satellite platforms.
Placement and retrieval of anchors: • Direct impacts (crushing, burial, fragmentation) • Sedimentation (smothering, clogging of feeding and gas exchange structures)	• Avoid anchoring by using a dynamic positioning (DP) rig. • Select anchors and chains with impact-reducing characteristics: ○ Properly-sized anchors based on detailed site surveys ○ Rougher anchor bottom to decrease dragging and seabed scouring ○ Added sinkers to drag embedment anchors to reduce mooring scope ○ Line floats to raise anchor connection points or portions of chain off the seafloor ○ Installed pick-up buoys to enable retrieval by ROV • Pre-lay anchors and chains by ROV to increase positioning accuracy. • Retrieve anchors by ROV to avoiding grappling. • Use fiber wire and buoys to give chains buoyancy. • Increase anchor and chain weights to reduce anchor spread, enabling placement closer to rig and flexibility in positioning.
Placement and embedding of pipelines: • Direct impacts (crushing, burial, fragmentation)	• Conduct an ROV survey of the proposed pipeline route: ○ 200-m wide corridor where sensitive species and/or habitat may be present ○ 500-m wide corridor in areas with known sensitive species and/or habitat

Potential impacts	**Mitigation measures**
- Sedimentation (smothering, clogging of feeding and gas exchange structures)	- Adjust planned pipeline route to avoid sensitive benthic species and habitats by including their locations and applicable setbacks in the constraints analysis. o Determine sufficient setbacks in consideration of biological factors of sensitive benthic organisms and habitats. o NOROG (DNV 2013) recommends pipelines be located no closer than 50 m from corals and other sensitive benthic species and habitats. o Cordes et al. (2016) propose setbacks for sensitive benthic species and habitats of 200 m from seafloor infrastructure with no expected discharges (i.e., pipelines). - Use dynamic positioning (DP) laydown vessels for pipeline deployment. - Floating LNG facility technology (in development) can eliminate need for pipeline to shore.
Treatment and discharge of produced water and dissolved components: - Direct toxicity - Sub-lethal effects from chronic exposure - Food-chain and trophic amplification	- Generate less produced water by modifying drilling processes, adapting technologies or substituting products (while factoring in associated pros and cons): o Mechanically block water from entering the well o Use chemicals in the formation to block water-bearing channels or fractures o Employ down-hole oil/water separation - Recycle/reuse produced water by reinjecting to enhance oil production and/or maximize oil recovery. - Employ innovative treatment methods (e.g., membrane technology, evaporation, packed bed adsorption and ion exchange).

APPENDIX 2: GLOSSSARY OF TERMS

Abandoned well

A drilled well that has been converted to a condition that can be left indefinitely without further attention.

Alien Invasive Species

A species that is not native to an area and has been introduced intentionally or unintentionally by humans.

Anthropogenic

Created by humans.

Biofouling

The accumulation of microorganisms, plants, algae or animals on wetted surface.

Benthic

Defining a habitat or organism found on a freshwater or marine bottom (compare with Pelagic).

Benthos

The collection of organisms (plants and animals) living on or closely associated with the bottom of a body of water, especially the ocean.

Bioaccumulation

The concentration of long-lived compounds in the flesh and organs of organisms that ingest prey that have ingested those compounds themselves.

Biodiversity

The variety of organisms considered at all levels, from genetic variants belonging to the same species through arrays of species to arrays of genera; families, and still higher taxonomic levels; includes the variety of ecosystems, which comprise both communities of organisms within particular habitats and the physical conditions under which they live.

Bioindicator

An organism whose status in an ecosystem is analyzed as an indication of the ecosystem's heath.

Corals

Corals are marine invertebrates that may exist as individual coral polyps, as diversely-shaped colonies containing many polyps of the same species, and as reefs with many colonies made up of one or more species. “Cold-water” or “deep-sea” corals obtain the energy and nutrients they need to survive by trapping tiny organisms in passing currents. Due to the continuous regeneration of new polyps, some deep-sea coral reefs have been actively growing for as long as 40,000 years.

Conservation

The sustainable use as well as protection, maintenance, rehabilitation, restoration, recovery and enhancement of ecosystems, natural habitats and viable populations of species in their natural surroundings.

Cuttings

Chips and small fragments of rock produced by drilling that are circulated up from the drill bit to the surface by drilling mud.

Delineation well

Well drilled after a discovery well to determine the areal extent of a reservoir.

Development well

A well drilled within a proven field or area of hydrocarbons for the purpose of completing the desired pattern of production.

Demersal

Part of the ocean or lake that comprises the water column that is near to (and is significantly affected by) the seabed and the benthos. The demersal zone is just above the benthic zone. The term can also refer to all species that live on or near the seabed.

Directional drilling

Drilling non-vertical wells. Several wells may be grouped together (e.g., 40 or more wells), fanning out from one platform. Reservoirs that are not readily accessible from available surface locations may be accessed through directional drilling.

Drill pipe

Steel pipe sections, approximately 9 metres long, that are screwed together to form a continuous pipe extending from the drilling rig to the drilling bit at the bottom of the hole. Rotation of the drill pipe and bit causes the bit to bore through the rock.

Drill string

A string of individual joints of drill pipe that extend from the bit to the kelly pipe (used to transmit rotary motion from the rotary table to the drillstring). The drill string carries the mud down to, and rotates, the drill bit.

Drilling fluid

Fluids continuously circulated down the wellbore, to cool and lubricate the drill bit, lubricate the drill pipe, carry rock cuttings to the surface and control down hole pressure.

Drilling mud

A common term for drilling fluids.

Ecosystem

A dynamic complex of organisms (including humans), and the physical environment (soils/bottom type, water, geology etc.) interacting as a functional unit. They may vary greatly in size and composition and display functional relationships within and between systems; be relatively pristine through to extensively altered by human activities/uses; be aquatic or terrestrial; and be barren or highly productive.

Epifauna

Organism that spend most of their feeding activity on top of the benthic surface.

Exploratory well

A well in an area where petroleum has not been previously found or one targeted for formations above or below known reservoirs.

Flow line

Subsea pipeline connecting satellite wells and/or platforms to a central production platform.

Formation

The term for the primary unit in stratigraphy consisting of a succession of strata useful for mapping or description which possesses certain distinctive lithologic and other features.

Geophysical survey

Searching and mapping the subsurface structure of the earth's crust using geophysical methods (e.g., seismic) to locate probable reservoir structures capable of producing commercial quantities of hydrocarbons.

Habitat

A functional area used by organism(s) as a life supporting system. Habitat can vary greatly in size and composition. A habitat consists of biotic and abiotic features. At times, it can be closely linked to ecosystems.

Hard substrate/hardscape

Sessile organisms and seaweeds need to attach themselves to a secure, hard base material. Sedentary organisms use hard substrate as a temporary or permanent site of residence. Hard substrate refers to hard material along the seabed, while hardscape refers to hard material within the water column.

Horizontal drilling

A subset of the more general term "directional drilling," used where the departure of the wellbore from vertical exceeds about 80 degrees.

Hydrocarbon

An organic compound containing only carbon and hydrogen.

Indigenous

Native to an area but can be found elsewhere as well.

Infauna

Benthic species living in the seabed.

Injecting

Injecting water or gas into a producing reservoir to maintain reservoir pressure, maximize recovery and conserve resources.

Injection

The process of pumping gas or water into a producing reservoir to provide a driving mechanism for increased production.

Keystone species

Species which are critically important for maintaining ecological processes or the diversity of their ecosystems.

Masking

Masking occurs when noise interferes with an animal’s ability to perceive (detect, interpret, and/or discriminate) a sound. Both natural (e.g., snapping shrimp) and anthropogenic (e.g., shipping noise) sound sources can increase the noise in the environment. The degree of masking is influenced by the level, frequency band and the duration of the noise in comparison to the sound of interest.

Nursery ground

An area in which the density of sub-adult organisms is greater than in other habitats, and in which the habitat confers advantages that result in greater survival of such organisms into the next larger size class.

Offshore area

The area offshore Nova Scotia or Newfoundland and Labrador under the Boards' jurisdictions as defined in Schedule 1 of the Accord Implementation Acts.

Oil-based mud

Drilling mud in which mineral oil is the continuous phase.

Operator

The holder of an authorization to conduct petroleum activities in the offshore area.

Pelagic

Defining a habitat of or an organism that inhabits/frequents the open ocean/water column, away from the sea bottom (compare with Benthic).

Plankton

A collective term for the small plants and animals which float and drift in currents. Phytoplankton is the plant component and zooplankton the animal component.

Phytoplankton

Suspended microscopic plant organisms.

Pipeline

A submarine pipeline (also known as marine, subsea or offshore pipeline) is a pipeline that is laid on the seabed or below it inside a trench, primarily used to carry oil or gas. A flowline is an intrafield pipeline (i.e., used to connect subsea wellheads, manifolds and the platform within a given development field), while a pipeline (sometimes referred to as an export pipeline), is used to transport the resource to shore.

Population

A group of interbreeding organisms occupying a given space; the number of living creatures in a designated area.

Produced water

Water produced from a wellbore along with the oil and gas, composed of organic and inorganic substances from geologic formations, and various additives and treatment chemicals introduced during extraction and production processes. Characteristics of produced water vary and constituents can include seawater, dissolved organic salts, dissolved and dispersed hydrocarbons, dissolved minerals, trace metals, naturally occurring radioactive substances, production chemicals and dissolved gases.

Producing/production

Flowing oil or gas from a well to the production systems.

Production platform

An offshore structure equipped to produce and process oil or gas.

Production well

A well drilled and completed to produce crude oil or natural gas.

Reservoir

A porous, permeable rock formation that forms a trap for the accumulation of hydrocarbons.

Resistivity

The electrical resistance of a formation.

Satellite wells

Subsea wells located remote from the production facility and connected to the facility by flowlines.

Sessile organisms

Fixed (not mobile) organisms (e.g., corals). To maintain growth and reproduction, these organisms evolved special techniques to guarantee their survival; the most common method is to extend tentacles into passing water currents to capture organisms.

Siltation

The deposition of fine-grained sediments (mud and sand). The finer the sediment, the longer it takes to settle or strand and the more readily it is disturbed.

Species

1. A reproductively isolated aggregate of interbreeding organisms having common attributes and usually designated by a common name. 2. An organism belonging to such a category.

Sponges

Aquatic animal of the phylum Porifera, with pores in its body wall and a rigid skeleton. Sponges are very primitive animals, colonies of individuals, that evolved early in the history of the earth. They are attached to the substrate and filter the water for phytoplankton.

Sustainable development

Development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

Synthetic-based mud
A drilling mud in which the continuous phase is a synthetic fluid.

Toxicity

The degree to which a toxin is harmful.

Toxin

Any substance, which in sufficient quantity is harmful to biota.

Viscosity

The resistance to flow, or "stickiness," of a fluid.

Water-based mud

A drilling mud in which the continuous phase is water.

Wellbore

The hole drilled by the drill bit.

Wellhead

Steel equipment installed at the surface of the well containing an assembly of heavy duty hangars and seals (the wellhead is used to support the weight of casing strings hung from it and to contain well pressure).

Zooplankton

Small (sometimes microscopic) animals that drift in the ocean, including protozoa, crustaceans, jellyfish and other invertebrates that drift at various depths in the water column.