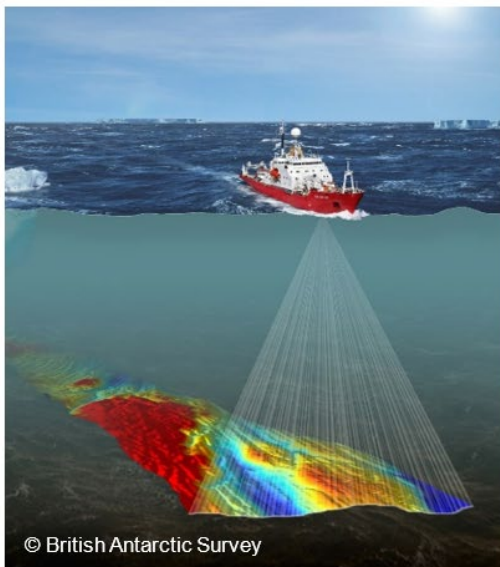


Underwater acoustic surveys: Review of source characteristics, impacts on marine species, current regulatory framework and recommendations for potential management options



Kongsberg GeoPulse



Klein Marine Systems 3000
side scan sonar



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Report No: 448

Author Name: A.M. Brown, F. Marubini, D.M. Borthwick, J.P. Hartley

Author Affiliation: Hartley Anderson Limited

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4. Glossary of acronyms and terms

Acronym	Definition
ADCP	Acoustic Doppler Current Profiler. Uses the Doppler effect to measure the speed and direction of currents in the water column.
AEP	Auditory evoked potentials
AMAPPS	Atlantic marine assessment program for protected species
Amplitude	The magnitude of an oscillating quantity, for example sound pressure or vibration level.
AUV	Autonomous underwater vehicle
BEIS	Department for Business, Energy and Industrial Strategy
BOEM	Bureau of Ocean Energy Management
Boomer	A type of sub-bottom profiler which generates an impulsive signal through the rapid downward movement of one or more plates (accelerated water mass). See Section 5.2.1.
CAS	Continuous active sonar
Chirper	A Chirper (Compressed High Intensity Radar Pulse) is a type of sub-bottom profiler that uses one or more transducers to generate a frequency-modulated signal. See Section 5.2.1.
Cumulative sound exposure level	The total sound exposure level determined for an extended period or sequence of pulses/events.
DAERA	Department of Agriculture, Environment and Rural Affairs
dB	Decibel, a logarithmic unit to measure sound level
Defra	Department for Environment, Food and Rural Affairs
Doppler effect	The change in frequency of a wave in relation to an observer who is moving relative to the wave source.
DOSITS	Discovery of sound in the sea, a website focused on ocean acoustics
DTI	Department of Trade and Industry (superseded)
EC	European Commission
Echo-location	The determination of the time interval between the sound emitted and the arrival of its reflection/ refraction at detectors.
Echo-sounders	Diverse group of commercial and civilian sonar sources used to collect information on bathymetry, seabed features and objects in the water column. Single-beam echo-sounders emit a pulse of sound in a single narrow cone, whereas multi-beam echo-sounders (MBES) use multiple beams elongated in the across-track direction to cover a fan-shaped sector (or swath).
ECJ	European Court of Justice
EDR	Effective deterrence radius
EEZ	Exclusive economic zone
EIA	Environmental impact assessment

Acronym	Definition
EPS	European protected species
FM	Frequency-modulated
Four dimensional (4D) seismic survey	For reservoir management, a 3D survey may be planned to be repeated and compared over time. Time being the 4 th dimension.
Fourier analysis	The study of how general functions can be decomposed into trigonometric or exponential functions with definite frequencies.
Frequency	The number of sound waves per unit of time, measured in Hertz.
Geometrical spreading	As sound moves away from the source, the area that the sound energy covers becomes larger and thus sound intensity decreases.
GR	Ground roll, a surface-wave energy that travels along or near the surface of the ground/seabed.
HDZ	Human dive zone
HRGS	High-resolution geophysical survey
Hydrophone	Underwater acoustic transducer which converts acoustic pressure in the sound wave to electrical voltage.
iPCoD	Interim population consequences of disturbance
JNCC	Joint Nature Conservation Committee
LFAS	Low-frequency active sonar
Licensing block	An administrative unit for oil and gas licensing on the UK Continental Shelf: a rectangular area of approximately 200-250 km ² . Licensing blocks are also used as the spatial unit of recording in the UK Marine Noise Registry.
Longitudinal (sound) wave	Wave of alternating pressure deviations from the equilibrium pressure, causing local regions of compression and rarefaction.
MAT	Master application template
MBES	Multi-beam echo-sounder
MCA	Maritime and Coastguard Agency
MEDIN	Marine environmental data and information network
MFAS	Mid-frequency active sonar (military)
MMO	Marine Management Organisation
MNR	Marine Noise Registry
MoD	Ministry of Defence
MPA	Marine Protected Area
MS-LOT	Marine Scotland Licensing and Operations Team
OAWRS	Ocean acoustic waveguide remote sensing
OBC	Ocean bottom cable
OBS	Ocean bottom seismometer
OPRED	Offshore Petroleum Regulator for Environment and Decommissioning
OESEA	Offshore energy strategic environmental assessment
Pa	Pascal unit of sound pressure
PAM	Passive acoustic monitoring

Acronym	Definition
Parametric SBP	A type of sub-bottom profiler which uses a piezoelectric transducer to emit two different higher frequency signals ('primary') which undergo a non-linear interaction during sound propagation through the water column to generate a resultant lower frequency signal ('secondary'). See Section 5.2.1.
PAS	Pulsed active sonar
PBD	Pulse block day
Peak sound pressure (or zero-to-peak sound pressure)	The maximum sound pressure during a stated time interval.
Peak to peak sound pressure	The sum of the peak compressional pressure and the peak rarefactional pressure during a stated time interval.
PELTIC	Pelagic ecosystem survey in the Western Channel and Celtic Sea
PETS	Portal environmental tracking system
PEXA	MoD practice and exercise areas
Piezoelectric transducer	Piezoelectric transducers generate an acoustic waveform by converting electrical energy into mechanical movement i.e. vibrations. Through the reverse of this process, the transducers can also detect sound.
Pinger	A type of sub-bottom profiler which uses a piezoelectric transducer to transmit a controlled waveform centred on a single frequency. See Section 5.2.1.
PON	Petroleum operations notice
PTS	Permanent threshold shift
Rise time	The time between the onset and the peak pressure in a signal. Units are ms.
RL	Received level, the level of an acoustic quantity at a specific spatial position within an acoustic field, usually the position of a marine receptor (which could be a hydrophone or an animal).
Root mean square (rms) sound pressure	The square root of the average of the square of the pressure of the sound signal over a given duration.
SAT	Subsidiary application template
SBP	Sub-bottom profiler
SEM	Scanning electron microscopy
Side-scan sonar	Seabed imaging technique which uses two small piezoelectric transducers orientated such that the acoustic signal covers a wide angle perpendicular to the path of the device through the water.
Signal duration	Time interval between the arrival of 5 % and 95 % of the total energy in the signal. Units are seconds or milliseconds.
SNCB	Statutory nature conservation body

Acronym	Definition
SEL	Sound exposure level, a measure of the exposure of a receptor to a sound field, a frequency weighting is commonly applied.
Sound pressure (or “instantaneous sound pressure”)	The difference between instantaneous total pressure and pressure that would exist in the absence of sound.
Sparker	A type of sub-bottom profiler which generates an impulsive signal through electrostatic discharge. See Section 5.2.1.
SPL	Sound pressure level
Statocyst	Invertebrate receptor system based on two structural elements - the statolith, a calcareous mass and the sensory hair cells which are mechanically affected by the position of the statolith.
SURTASS LFA	Surveillance towed array sensor system low frequency active sonar system (US military sonar).
Three dimensional (3D) seismic survey	Vessel tows two or more large airgun arrays and several streamers. Streamers are closer to each other (typically 25-75 m) and data density much improved with respect to 2D.
Triaxial accelerometer	Provides simultaneous measurements of vibrations in three orthogonal directions.
TTS	Temporary threshold shift
Two dimensional (2D) seismic survey	Vessel tows an airgun array and streamers, containing several hydrophones along their length. Repeated parallel lines run at intervals of several kilometres and a second set of lines at right angles to the first forms a grid pattern.
UKCS	United Kingdom continental shelf
UKHO	United Kingdom Hydrographic Office
VSP	Vertical seismic profiling
Wavelength	The distance covered by the wave over a full cycle such as from peak to peak
WMP	Welsh marine plan
WNMP	Welsh national marine plan

1. Crynodeb Gweithredol

Mae arolygon acwstig yn darparu offerynnau gwerthfawr ar gyfer casglu gwybodaeth ynghylch yr amgylchedd morol a'i ddaeareg waelodol ar gyfer amrywiaeth o ddefnyddiau. Fodd bynnag, trwy gyflwyno sain anthropogenig i'r amgylchedd morol, gallant arwain o bosib at effeithiau negyddol ar ffawna morol sensitif.

Comisiynodd Cyfoeth Naturiol Cymru'r adroddiad tystiolaeth hwn i ddarparu adolygiad cyfredol o: (i) nodweddion ffynonellau arolygon acwstig; (ii) eu defnydd yn nyfroedd Cymru; (iii) tystiolaeth o'u heffeithiau ar bob agwedd o ffawna morol; a (iv) archwiliad o'r drefn reoliadol gysylltiedig. Yn bennaf, bwriad yr adroddiad hwn yw bod yn adnodd ar gyfer staff Cyfoeth Naturiol Cymru sydd â'r dasg o reoli effeithiau posibl arolygon acwstig ar nodweddion Ardaloedd Morol Gwarchoddedig Cymru, ond bydd o ddefnydd ehangach. Mae'r maes gwaith yn cynnwys ffynonellau arolygon acwstig masnachol, sifil a milwrol sy'n debygol o gael eu defnyddio yn nyfroedd Cymru a dyfroedd cyfagos. Ystyrir tystiolaeth o effeithiau ar draws y grwpiau derbynyddion eang o famaliaid morol, pysgod, infertebratau ac adar sy'n plymio, gan gynnwys nodweddion Ardaloedd Morol Gwarchoddedig Cymru.

Tablir y nodweddion (math o signal, amledd, lefel y ffynhonnell, cyfeirioldeb, defnydd) ar gyfer ffynonellau arolygon acwstig: gynnu awyr, proffilwyr is-waelod (SBPs, gan gynnwys *sparkers*, *boomers*, *pingers*, *chirpers* a phroffilwyr is-waelod parametrig), sonar sganio o'r ochr, ecoseinwyr (paladr sengl ac aml-baladr), proffilwyr cerrynt Doppler acwstig a sonar milwrol. Mae gan y tonffurfiau â phwls a gynhyrchir gan ynnau awyr a phroffilwyr is-waelod *sparker* a *boomer* amseroedd codi byr sy'n fwy niweidiol na thonffurfiau cyfnodol (sinwsoidaidd) ffynonellau arolygon acwstig eraill. Mae araeau gynnu awyr yn cynhyrchu'r signalau â'r osgledau mwyaf a'r amleddau isaf gyda chyfeirioldeb cyfyngedig, gan arwain at fwy o seiniau sonar yn yr amgylchedd morol o'u cymharu â ffynonellau masnachol a sifil eraill. Mae'r signalau o proffilwyr is-waelod *sparker* a *boomer* yn gymharol o ran tonffurf ac amledd, ond o osgled sylweddol is.

Cynhaliwyd arolygon seismig helaeth yn nyfroedd Cymru a dyfroedd cyfagos yn y 1980au a'r 1990au, yn bennaf yn rhannau dwyreiniol Môr Iwerddon ac oddi ar orllewin Cymru. I'r gwrthwyneb, roedd gweithrediad cyfyngedig yn y 2000au a'r 2010au. Ers 2015, mae arolygon seismig a chan broffilwyr is-waelod yn cael eu gwahaniaethu yng nghofnodion Cofrestrfa Sŵn Morol y DU (MNR), ac mae'r cofnodion ar gyfer 2015 i 2018 yn dangos bod y mwyafrif o arolygon gan broffilwyr is-waelod yn rhannau dwyreiniol Môr Iwerddon mewn ardaloedd o weithgarwch olew a nwy a ffermydd gwynt; yn ddiweddarach, mae rhai wedi'u defnyddio ar gyfer ymchwil academaidd yn nyfroedd glannau Cymru ac Ardaloedd Morol Gwarchoddedig.

Mae llwybrau at ganiatáu arolygon acwstig tanddwr yn amrywio, yn dibynnu ar ddiben y gweithgaredd yn hytrach na'r math o weithgaredd. Nid yw hyn yn alinio â'r cysyniad yn y Gyfarwydddeb Cynefinoedd o asesu pob cynllun a phrosiect ar sail ei effeithiau amgylcheddol posibl. Mae gan arolygon ar gyfer

archwilio a chynhyrchu olew a nwy neu storio nwy lwybr clir ar gyfer asesu, cydsynio ac olrhain amgylcheddol. Ar gyfer arolygon at ddibenion eraill, mae'r llwybr yn llai clir. Mae prosesau'n amrywio rhwng rheoleiddwyr gwahanol, ac mewn rhai amgylchiadau nid oes awdurdod cymwys amlwg i ymgymryd ag asesiadau o'r fath. Mae'r defnydd o fathau penodol o offer arolygon acwstig yn dod o dan drefn trwyddedu morol *Deddf y Môr a Mynediad i'r Arfordir 2009* (fel y'i diwygiwyd), ac mewn nifer o amgylchiadau maent yn weithgareddau esempt o dan orchmynion perthnasol a wnaed o dan y Ddeddf. Fodd bynnag, gweithred offer dyddodi, yn hytrach nag allyrru sŵn (llwybr allweddol yr effaith amgylcheddol bosibl), sy'n penderfynu a yw'r gweithgaredd yn drwyddedadwy, ac felly nid yw pob ffynhonnell acwstig yn cael ei hystyried yn drwyddedadwy. At hynny, mae amrywiad yn yr hyn a ystyrir i fod yn ddyddodyn rhwng gwahanol reoleiddiwyr y DU yn arwain at weithredu'r drefn trwyddedu forol yn anghyson ar draws awdurdodaethau mewn perthynas ag arolygon acwstig.

Mae'r rhan fwyaf o'r dystiolaeth ar effeithiau arolygon acwstig yn ymwneud â ffynonellau gynnau awyr seismig. Heblaw am sonar milwrol a mamaliaid morol, mae gwybodaeth am effeithiau ffynonellau arolygon acwstig eraill yn gyfyngedig ar gyfer yr holl grwpiau o dderbynyddion. Ystyrir mamaliaid morol, yn enwedig morfilod, fel y rhai mwyaf sensitif i effeithiau sŵn tanddwr, a dyma'r grŵp y mae'r sylfaen dystiolaeth fwyaf yn bodoli ar ei gyfer. Mae pysgod hefyd yn sensitif i sŵn ac wedi derbyn sylw, yn enwedig rhywogaethau o werth economaidd. Mae astudiaethau o effeithiau sŵn ar infertebratau morol yn fwy cyfyngedig ond mae'r sail dystiolaeth yn ehangu. Gall adar sy'n plymio fod yn sensitif i sŵn tanddwr osgled uchel, ond prin yw'r dystiolaeth o effeithiau, ac ychydig o astudiaethau sydd wedi mynd i'r afael â'u galluoedd clywed o dan y dŵr neu effeithiau dod i gysylltiad â sŵn.

Mae ansicrwydd ynglŷn ag arwyddocâd biolegol effeithiau a'u goblygiadau ar lefel poblogaeth. Mae problemau gyda'r sail dystiolaeth ar gyfer effeithiau a nodir yn gyffredin yn cynnwys: mesur ac adrodd annigonol ar y lefelau a dderbynnir yn yr anifail; diffyg mesuriadau a dealltwriaeth o elfen mudiant gronynnau sain tanddwr; anawsterau arbrofion trwyadl gydag anifeiliaid rhydd; a'r heriau o ddehongli canlyniadau arbrofion labordy i lefelau amlygiad realistig yn y môr agored.

Mae'r dystiolaeth a adolygwyd yn awgrymu bod y ffocws presennol ar ffynonellau acwstig amledd isel, osgled uchel yn briodol o safbwynt rheoli. Yn nyfroedd Cymru (a dyfroedd eraill), mae gan arolygon gynnau awyr seismig y potensial mwyaf ar gyfer effeithiau negyddol ar rywogaethau morol. Mewn rhai achosion, gellir canfod ffynonellau amledd uwch ac osgled is ac felly, mewn egwyddor, enbyn ymatebion ymddygiadol unigol mewn rhywogaethau morol, ond ymddengys eu bod yn annhebygol o arwain at effeithiau cronig neu ar lefel y boblogaeth.

Mae diffygion ac argymhellion penodol sy'n cael eu hamlygu gan yr adolygiad yn cynnwys:

1. Gall arolygon acwstig tanddwr fod (neu beidio â bod) yn destun prosesau cydsynio, hysbysu ac asesu ffurfiol yn dibynnu ar eu diben, y ffynhonnell

acwstig a ddefnyddir, a sut mae'r rheoleiddiwr wedi gweithredu'r ddeddfwriaeth. Yn benodol, ar gyfer arolygon nad ydynt yn dod o fewn cyfundrefn y *Ddeddf Petrolewm* neu'r *Ddeddf Ynni*, mae'r broses yn aneglur, gyda'r potensial i rai arolygon acwstig tanddwr gael eu cynnal heb wybodaeth na chraffu ymlaen llawn gan Cyfoeth Naturiol Cymru a chyrrff cadwraeth natur statudol eraill.

2. Mae'r amrywiad ar draws cyfundrefnau rheoleiddio o ran a oes angen caniatâd ar gyfer arolygon acwstig tanddwr ar sail diben yr arolwg yn ddryslyd. Mae diffyg cydsyniad ac felly awdurdod cymwys yn codi cwestiynau ynghylch sut y gellid cymhwyso Aseiad Rheoliadau Cynefinoedd pe bai effaith sylweddol yn debygol.
3. Yn absenoldeb llwybr i drwyddedu arolygon acwstig tanddwr yn nyfroedd Cymru, gallai system hysbysu ymlaen llaw gwirfoddol (e.e. ffurflen ar-lein) ddarparu llwybr dros dro defnyddiol ar gyfer monitro arolygon na ellir eu trwyddedu. Gallai ei mabwysiadu trwy bolisi neu ganllawiau roi'r cyfle i graffu a chynghori ar fesurau lliniaru neu'r risg o drosedd Rhywogaeth a Warchodir gan Ewrop, lywio asesiadau cronrus, a hwyluso cofnodi sŵn perthnasol yn fwy cyflawn yn y Gofrestrfa Sŵn Morol. Gallai system o'r fath wella dealltwriaeth o weithgareddau na ellir eu trwyddedu yn nyfroedd Cymru ac a oes angen adolygiad o'r hyn sy'n drwyddedadwy. Dewis arall fyddai mabwysiadu dull y Sefydliad Rheoli Morol (MMO) o weithredu *Deddf y Môr a Mynediad i'r Arfordir 2009* (fel y'i diwygiwyd), a fyddai'n dod â ffynonellau acwstig wedi'u tynnu a'u gosod ar bolyn o dan y drefn trwyddedu morol, ond nid ffynonellau wedi'u gosod ar gorff llong. Waeth beth fo'r camau a gymerir, anogir gweithredu rhannau perthnasol o'r Ddeddf yn gyson ymhlith gwahanol awdurdodaethau yn y DU, ynghyd â'r canllawiau cysylltiedig sy'n berthnasol i arolygon acwstig.
4. O fewn ffurflenni adrodd ac mewn canllawiau lliniaru, mae angen diweddarau categorïau a diffiniadau offer o bryd i'w gilydd wrth i dechnoleg ddatblygu.
5. Mae trothwyon clywedol ar gyfer mamaliaid morol yn wahanol ar gyfer synau ergydiol a synau nad ydynt yn ergydiol; mae'n aneglur sut y gellir gwahaniaethu signalau o'r gwahanol ffynonellau acwstig, yn enwedig ar gyfer y ffynonellau hynny lle gall paramedrau gweithredu fod yn amrywiol iawn. Mae angen canllawiau clir i gefnogi asesiadau effaith cyson.
6. Mae'n amlwg bod angen nodweddu meysydd sain, o bob arolwg acwstig, yn well, gan gynnwys mudiant gronynnau.

2. Executive Summary

Acoustic surveys provide valuable tools for collecting information on the marine environment and its underlying geology for a variety of applications. However, their introduction of anthropogenic sound into the marine environment has the potential for negative effects on sensitive marine fauna.

Natural Resources Wales (NRW) commissioned this evidence report to provide an up-to-date review of: (i) the characteristics of acoustic survey sources; (ii) their use in Welsh waters; (iii) evidence of their effects on all components of the marine fauna; and, (iv) an examination of the associated regulatory regime. This report is primarily intended as a resource for NRW staff tasked with managing the potential impacts of acoustic surveys on Welsh Marine Protected Area (MPA) features, but will be of wider utility. The scope includes commercial, civilian and military acoustic survey sources likely to be used in the waters of Wales and adjacent waters. Evidence of effects is considered across the broad receptor groups of marine mammals, fish, invertebrates and diving birds, including features of Welsh MPAs.

The characteristics (signal type, frequency, source level, directionality, application) are tabulated for acoustic survey sources: airguns, sub-bottom profilers (SBPs, including sparkers, boomers, pingers, chirpers and parametric SBPs), side-scan sonar, echo-sounders (single- and multi-beam), acoustic doppler current profilers and military sonar. The pulsed waveforms generated by airguns, and sparker and boomer SBPs, have short rise-times which are more injurious than the periodic (sinusoidal) waveforms of other acoustic survey sources. Airgun arrays generate the highest amplitude and lowest frequency signals with limited directionality, resulting in greater ensonification of the marine environment compared to other commercial and civilian sources. The signals from sparker and boomer SBPs are comparable in waveform and frequency, but of considerably lower amplitude.

Extensive seismic surveys occurred in Welsh and adjacent waters in the 1980s and 1990s, mainly in the eastern Irish Sea and off west Wales. In contrast, there was limited activity in the 2000s and 2010s. Since 2015, SBP and seismic surveys are distinguished in the UK Marine Noise Registry (MNR) records for 2015-2018 show most SBP surveys were in the eastern Irish Sea in areas of oil & gas and windfarm activity; more recently, some have been used for academic research of Welsh inshore waters and MPAs.

Routes to the consenting of underwater acoustic surveys vary depending on the purpose of the activity, rather than the type of activity. This does not align with the concept in the Habitats Directive of assessing all plans and projects for their potential environmental effects. Surveys for oil & gas exploration and production or gas storage have a clear route for environmental assessment, consenting and tracking. For surveys for other purposes, the route is less clear. Processes vary between different regulators, and in some circumstances there is no obvious Competent Authority to undertake such assessments. The use of certain types of acoustic survey equipment fall within the marine licensing regime of the *Marine and Coastal Access Act 2009* (as amended),

and in many circumstances are exempted activities under relevant Order made under the Act. However, it is the action of depositing equipment, rather than the emission of noise (the key pathway of potential environmental effect), which determines if the activity is licensable, and therefore not all acoustic sources are considered licensable. Furthermore, variation in what is considered to be a deposit between the different UK regulators results in inconsistent implementation across jurisdictions of the marine licensing regime to acoustic surveys.

Most evidence on the effects of acoustic surveys relates to seismic airgun sources. With the exception of military sonar and marine mammals, information on the effects of other acoustic survey sources is limited for all receptor groups. Marine mammals, and in particular cetaceans, are regarded as the most sensitive to underwater noise effects, and for which the greatest evidence base exists. Fish are also sensitive to sound and have received attention, particularly species of economic value. Studies of noise effects on marine invertebrates are more limited but the evidence base is expanding. Diving birds are potentially sensitive to high amplitude underwater noise, but little evidence of effects exists, and few studies have addressed their underwater hearing abilities or the effects of exposure to noise.

There is uncertainty about the biological significance of effects and their implications at a population level. Commonly cited issues with the evidence base for effects include: inadequate measurement and reporting of received levels at the animal; a lack of measurement and understanding of the particle motion element of underwater sound; the difficulties of rigorous experiments with free-ranging animals; and, the challenges of interpreting the results of laboratory experiments to realistic exposure levels in the open-sea.

The evidence reviewed suggests that the current focus on high-amplitude, low-frequency acoustic sources is appropriate from a management perspective. In Welsh (and other) waters, seismic airgun surveys have the greatest potential for negative effects on marine species. Higher-frequency and lower-amplitude sources may, in some cases, be detectable and so, in principle, elicit individual behavioural responses in marine species, but appear to be unlikely to result in population-level or chronic effects.

Specific shortcomings and recommendations highlighted by the review include:

1. Underwater acoustic survey may or may not be subject to formal consenting, notification and assessment depending on its purpose, the acoustic source used, and the regulator's implementation of the legislation. In particular, for surveys which do not fall within the *Petroleum Act* or *Energy Act* regime, the process is unclear, with the potential for some underwater acoustic surveys to be undertaken without prior knowledge or scrutiny by NRW and other SNCBs.
2. The variation across regulatory regimes as to whether a consent is required for underwater acoustic surveys on the basis of the survey's purpose is confusing. The lack of a consent and therefore a Competent Authority

raises questions over how Habitats Regulations Assessment could be applied, should a significant effect be considered likely.

3. In the absence of a route to licence underwater acoustic surveys in Welsh waters, a voluntary prior notification system (e.g. an online form) could provide a useful interim avenue for monitoring non-licensable surveys. Its adoption through policy or guidance could provide the opportunity for scrutiny and advice on mitigation measures or risk of an EPS offence, inform cumulative assessments, and facilitate more complete recording of relevant noise in the MNR. Such a system could enhance understanding of non-licensable activities in Welsh waters and whether a review of what is licensable is needed. An alternative would be to adopt the MMO's approach to the implementation of the *Marine and Coastal Access Act 2009* (as amended), which would bring towed and pole-mounted acoustic sources under the marine licensing regime, but not hull-mounted sources. Regardless of the actions taken, consistent implementation of relevant parts of the Act among different jurisdictions within the UK is strongly encouraged, as is accompanying guidance relevant to acoustic surveys.
4. Within reporting forms and in mitigation guidance, equipment categories and definitions need to be periodically updated as technology develops.
5. Auditory thresholds for marine mammals differ for impulsive and non-impulsive sounds; how signals from the different acoustic sources may be distinguished is unclear, especially for those sources where operating parameters can be highly variable. Clear guidance is required to support consistent impact assessments.
6. There is a clear need for improved characterisation of sound fields, including of particle motion, from all acoustic surveys.

3. Introduction

Acoustic techniques provide valuable tools for surveying the marine environment, the seabed and its underlying geology, and a variety of methods are used in Welsh waters and elsewhere. However, the introduction of anthropogenic sound into the marine environment has the potential for negative effects on marine fauna, particularly those which use or are reliant upon acoustics for essential biological processes.

Regulations and guidelines have been developed to manage acoustic surveys, although the legislation in the UK and its devolved administrations is complex. Under some circumstances, and when carried out for certain purposes, there is a clear pathway for consenting and assessment of potential environmental effects. However, in other cases, the situation is less clear, and there appears to be the potential for acoustic surveys to proceed without the opportunity for regulatory bodies or their advisors to track these activities or scrutinise potential impacts on marine species.

Along with other sources of anthropogenic sound, the effects of acoustic surveys on marine fauna has been the subject of much research with the bulk of the work investigating effects of the more powerful sources on the more sensitive receptors (i.e. seismic airguns and marine mammals). While many reviews have been undertaken on this topic, these and their underlying studies are not always readily accessible, or may lack a certain focus required by a particular stakeholder. Further, this is a rapidly developing field with important new studies reported in recent years.

There is a need for an up-to-date distillation of information covering knowledge of the characteristics of all relevant acoustic survey sources, their effects on all components of the marine fauna, and an examination of the associated regulatory regime. In particular, there is a need for such an exercise focussed on the needs of Natural Resources Wales (NRW) as a Statutory Nature Conservation Body (SNCB) responsible for providing conservation management advice on acoustic surveys and a network of Marine Protected Areas (MPAs) in Welsh waters.

3.1. Aim, objectives and scope

In October 2019, NRW commissioned Hartley Anderson Ltd to prepare an evidence report to summarise the key information surrounding the topic of acoustic surveys and their management in Welsh waters, to inform NRW conservation management advice. Specific objectives are:

1. Outline the range of acoustic surveys that could potentially be used in Welsh waters, including a description of the method, the characteristics of emitted sounds, and an indication of their current use in Wales (Section 5)
2. Describe the regulatory regime for each type of acoustic survey in respect to assessment of environmental impacts (Section 6).

3. Review evidence of impacts on marine species from different types of acoustic survey, and identify the survey methodologies of most concern with regard to potential impact on marine species in Wales (Section 7).
4. Provide recommendations which could potentially be implemented to improve the management of acoustic surveys in Wales (Section 8).

In addition, we provide a high-level introduction to underwater sound (Section 4), including physical principles, metrics and units, to assist the reader in their interpretation of subsequent sections.

The scope includes commercial, civilian and military acoustic survey sources that are likely to occur in waters of Wales, the wider UK and adjacent nations. Evidence of effects is considered across the broad receptor groups of marine mammals, fish, invertebrates and diving birds, with a focus on species occurring on shelf waters of the north-east Atlantic, including features of Welsh MPAs where data are available.

In addressing objectives (1) and (3), consideration has been given to the extensive body of existing literature on the effects of acoustic surveys on marine species, and the intention of adding value to, rather than duplicate, existing reviews. We do not attempt to provide a systematic literature review on this topic; rather, we identify key existing resources, summarise their findings, and supplement these with more recent evidence and other relevant material. While a useful summary is provided for all acoustic survey sources and receptor groups, particular attention is given to distilling recent research on non-airgun acoustic survey sources, and the growing body of studies assessing the effects of anthropogenic noise on marine invertebrates.

This project falls under the Wales non-licensable activities project, which aims to review and collate further evidence, where required, on the distribution and impacts of non-licensable activities in Wales which are considered to have the greatest impact on the Welsh MPA network. This report is intended as a resource to NRW staff tasked with managing the potential impacts of acoustic surveys on Welsh MPA features, but also to be of use to those involved in the management of environmental effects of acoustic surveys on marine species more broadly, and in the wider UK.

4. Introduction to underwater sound

This section provides a high-level introduction to underwater sound, the terminology and metrics used and basics of propagation. The focus is on the characteristics of sound most relevant to an understanding of sound effects on the marine environment. For a more in-depth understanding of the physics of underwater sound, the reader is referred among the many excellent texts available (e.g. Urick 1983, Leighton 1998, Bradley & Stern 2008, Ainslie 2010 and Robinson *et al.* 2014).

Sound is a disturbance in pressure that propagates its energy as a mechanical longitudinal wave in fluids. Sound can only exist in a medium such as a fluid (gas or liquid) or a solid but not in a vacuum because it relies on the interaction of particles vibrating around their fixed position. The sound wave moves through the medium as particles are compressed and released along regions of high and low pressure. Refer to the DOSITS website <https://dosits.org/science/sound/what-is-sound/> for helpful illustrations, further details and additional resources. Therefore, changes in both pressure and particle motion are inherent to any sound wave. The unit of pressure is the Pascal (Pa) while particle motion, a vector quantity with both magnitude and direction, can be described in terms of particle displacement (m), velocity (m/s) and acceleration (m/s²).

International standards for underwater acoustic terminology have recently been published (ISO 2017 (ISO 18405:2017 Underwater Acoustics - Terminology <https://www.iso.org/obp/ui/#iso:std:iso:18405:ed-1:v1:en>); if adopted widely, these will succeed in reducing misinterpretation and improving comparability among studies, something which has been a hindrance in the past (Hawkins *et al.* 2015).

By convention, sound levels (for both pressure and particle motion) are expressed using decibels (dB) relative to a fixed reference value. As defined in ISO 2017, the reference values underwater for sound pressure, particle velocity and particle acceleration are 1 μ Pa, 1 nm/s and 1 μ m/s² respectively. Reference values underwater are different from those in air; any direct comparison of dB levels in air and underwater is therefore meaningless. The decibel scale is not linear but logarithmic (to base 10) to help deal with the wide range of possible values encountered. Familiarity with the dB scale avoids the potential interpretation of results based on common linear expectations (which are not valid); for example, the addition of two sounds of equal energy will result in an increase in overall energy level of 3 dB, irrespective of sound levels of the two signals. Note: This is true for sounds that are incoherent (not in phase), like in the common example of two motorbikes driving by; coherent sounds (in phase) double with an increase of 6dB.

Sound can be described as having one of three typical waveforms; a pulsed waveform, a periodic (sinusoidal) waveform and random pressure fluctuations. The waveform matters for several reasons, including quantifying sound and estimating the potential for hearing damage, as described below. Sources

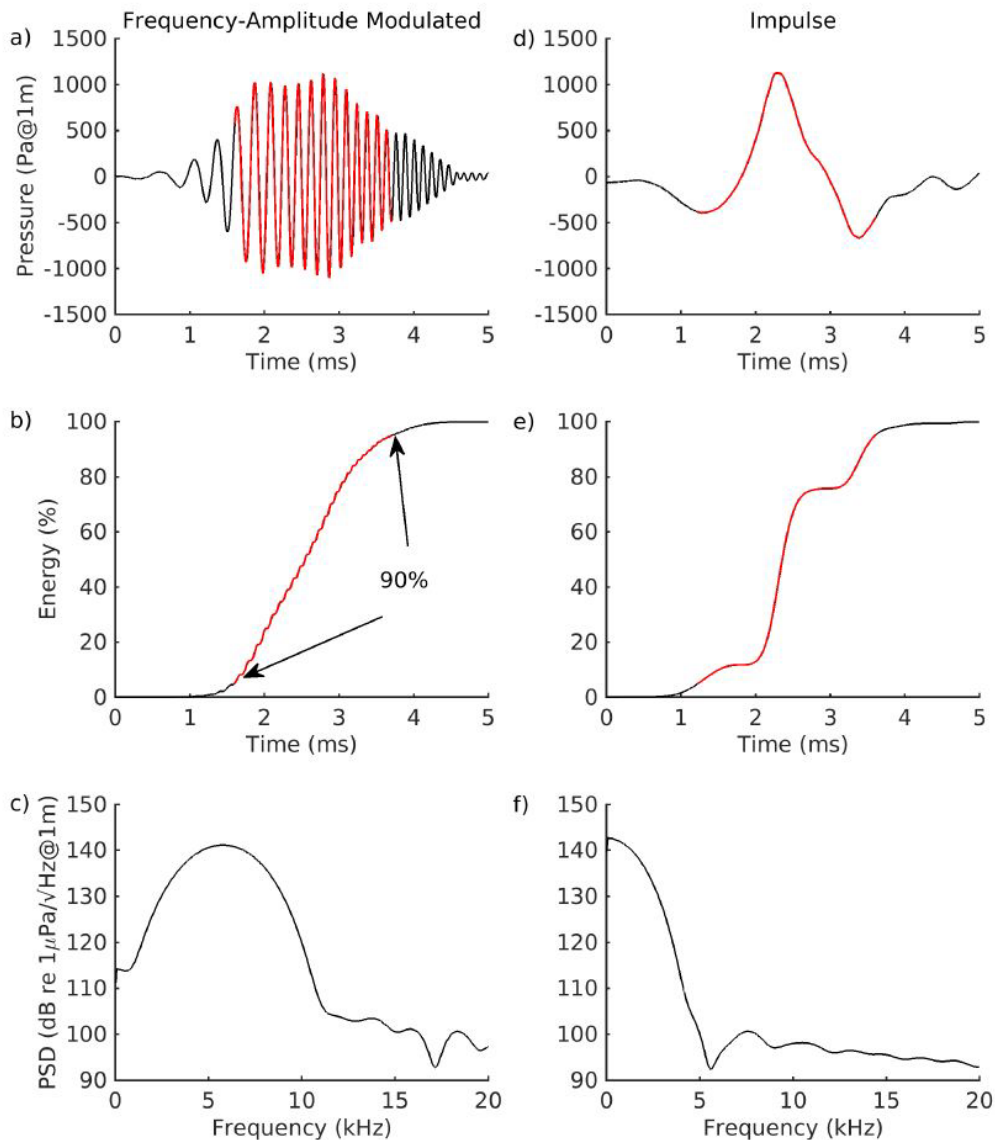
used in acoustic surveys produce either pulsed (e.g. airgun) or periodic waves (e.g. sonar ping); random pressure fluctuations are characteristic of ambient and vessel noise. Figure 1 (a & d) illustrates pulsed and periodic waveforms from two different acoustic survey sources.

Sound is typically quantified differently depending on its form. For example, in the case of amplitude, peak (or peak-to-peak) levels are ideal for a pulsed waveform; however, for a periodic waveform, and especially for random pressure fluctuations such as ambient noise, amplitude may be best expressed by an average over time (i.e. as root-mean-square, RMS). A valid measure for both pulsed and periodic waveforms is sound exposure, often used as a proxy for the energy content of the sound wave; by integrating the acoustic output over the duration of the pulse, it allows for meaningful comparisons between signals (e.g. Figure 1, b & e). Refer to page 29 for details of common metrics and quantities of underwater sound.

With regards to effects of sound on marine mammals, a distinction is commonly made between impulsive and non-impulsive sounds. This is because for the same amplitude, impulsive sound is considered to have greater potential to cause injury to the mammalian auditory system and/or result in threshold shifts (Henderson & Hamernik 1986). Applying the common definition of an impulsive sound (e.g. a typically transient sound, brief (<1 s), broadband, and with a high peak pressure with rapid rise time and rapid decay) to classify acoustic surveys is not always straightforward. The waveform is an important determinant, but there are additional metrics such as pulse duration, rise time and crest factor to consider (Figure 2). A pulsed waveform is more likely to fit the impulsive definition but signals with a periodic waveform can be classified as impulsive in some cases (see page 29).

A fundamental characteristic of a soundwave is its acoustic frequency, i.e. the number of waves per unit of time, measured in Hertz (1 Hz = 1 wave oscillation per second). Frequency is inversely proportional to wavelength (i.e. the distance covered by the wave over a full cycle such as from peak to peak); the higher the frequency the shorter the wavelength. A soundwave oscillating at a single frequency is described as a 'pure tone'; more commonly, acoustic signals contain several frequency components and are described as 'narrowband' when energy is distributed across a relative narrow range of frequencies and 'broadband' when energy is spread across a wide frequency range. All signals containing several frequency components can be distinguished mathematically (Fourier analysis) to give the soundwave spectrum where amplitude is expressed as a function of frequency. It is common for broadband signals to group frequencies into standard sets of logarithmic frequency or bands, such as one-third octave bands or deci-decade bands; for narrowband signals, 1Hz bands are used. Figure 1 (c & f) illustrates frequency spectra for the two example sub-bottom profilers. In addition to a graphic representation, the spectrum of the signal is often reported as range of bandwidths, half-power bandwidths (i.e. -3 dB bandwidth) or dominant frequencies.

Figure 1 - Examples of periodic (left panels) and pulsed (right panels) waveforms from measurements of two acoustic survey sources



Periodic waveform (left panels, a - c, in this case also frequency-modulated) from the EdgeTech 512i chirper sub-bottom profiler (a - c) and FSI Bubble-Gun (d - f; an electromechanical source similar to a boomer sub-bottom profiler). Panels illustrate pressure/time (upper row), cumulative energy/time (middle) and source spectrum (lower). The measurement period for each acoustic signal, i.e. the time centred period with 90 % of the signal energy, is indicated in red. Source: Crocker & Fratantonio (2016).

4.1. Propagation

Once a sound is emitted, its characteristics will alter with distance from source. The amplitude of the signal and its frequency content will change and, in the case of impulsive sounds, the injurious elements will be reduced through propagation (i.e. amplitude and rise-time decrease with distance while pulse duration increases).

The main process that reduces the amplitude of the wave as it propagates is geometrical spreading; as the range increases away from a point-source, the energy at the wave front is spread out across an ever-increasing area i.e. the expanding ensounded sphere. Depending on environmental conditions, other processes come into play to combine with geometric spreading; these include reflection, refraction, scattering, reverberation and absorption. All of these are frequency-dependent so that the quality of sound may also be altered with distance from source, as described below.

The speed of sound depends on the density of the medium (hence speed of sound in water exceeds that in air by a factor of 4.4). The speed of sound (i.e. the longitudinal motion of wavefronts) is related to frequency (f) and wavelength (λ) of a wave by $c = f * \lambda$. Sound travels at a speed of approximately 1,500 m/s in seawater and only 340 m/s in air. Within the water column, changes in density occur as a function of pressure, temperature and salinity. Sound may propagate along a linear path only when sound speed is constant; any gradual variation in sound speed in the water column will affect its path through refraction (i.e. bending). When changes in sound speed are abrupt such as in the case of stratification (i.e. layering of water masses with different temperature or salinity) certain conditions can be met resulting in the formation of 'shadow zones' where underwater sound of specific direction and frequency does not penetrate or 'sound channels' where sound paths may converge and propagation can be significantly enhanced above simple geometric spreading.

The depth of the water column (and the position of the source within the water column) determines how far sound can propagate before coming into contact with the physical boundaries of surface and seabed; when this occurs, several other factors come into play:

1. Geometric spreading changes from spherical toward cylindrical with a resulting decrease in attenuation (or transmission loss). Transmission loss (TL) during spherical spreading is $20\log(R)$ while TL during cylindrical spreading is $10\log(R)$, where R is the radius in metres. For helpful illustrations of the difference, refer to <https://dosits.org/science/advanced-topics/cylindrical-vs-spherical-spreading/>. Note that a 'transmission loss' between source and receiver is commonly referred to as 'propagation loss'.
2. Sound waves are reflected by the sea surface and the seabed so that at a distance from source, the original sound may arrive as several signals (from the direct path between source and receiver and from all the reflections) and may have been further reduced or enhanced depending upon any destructive or constructive interference between pathways.
3. In shallow depths, a process referred to as low frequency 'wave-guide cut off' may take place whereby lower frequencies enter the seabed and do not propagate horizontally through the water column, and are effectively filtered out. The exact cut-off frequency depends on depth relative to wavelength and on acoustic properties of sediments relative to water and can be estimated from first principles; as an approximation, frequencies below 40 Hz are likely to be cut-off in depth of ca. 20 m (Robinson & Lepper 2013; Nedelec et al. 2016).

Therefore, the spectrum of sound received several kilometres from a low frequency source such as an airgun array is expected to differ in deep vs shallow water. The spectrum of a single airgun pulse in shallow water changes with distance to contain proportionally more energy in the medium- to high-frequency portion, as shown by Hermannsen *et al.* (2015).

At the seabed, sound may be reflected (i.e. bounced back into the water column) or refracted (transmitted into the sediment but at a different angle). The geoacoustic properties of a seabed vary largely as a function of grain size, with coarse sand being most reflective and mud/fine clay least reflective i.e. the same sound at source will be received as a higher amplitude signal by a receiver at a given distance over a sandy bottom compared to a muddy bottom. Furthermore, the greater the sound amplitude the greater the potential to propagate into the sediments; with an airgun array for deep geophysical prospecting, deep sediment layers and not just surface sediments play a fundamental role in altering the sound wave and its pathway (with the potential for reflections back in the water column to emerge at considerable distance). Reflection and refraction are frequency-dependent and it is possible for different frequency components in a broadband signal to become separated in time through these processes.

A flat seabed will affect sound in a relatively simple and predictable manner, but a complex topography offers a multitude of interactions for the incoming soundwave.

In the absence of wind and waves, the sea surface forms a highly reflective boundary for underwater sound. However, as wind speed increases and wavelets form, the mirror like effectiveness of the surface is reduced. Since energy is scattered on hitting the sea surface at frequencies where the wavelength is comparable to the wave height, this process is most relevant to the higher portion of the spectrum e.g. above 1 kHz (with a sound speed in seawater of ca. 1,500 m/s, a signal with frequency of 1 kHz has a wavelength of 1.5 m and 10 kHz = 0.15 m etc.).

Finally, absorption needs to be considered; this is a process that removes energy from a soundwave (through chemical relaxation processes of dissolved salts and by converting it into heat due to particle viscosity) dependent on seawater properties, such as temperature, salinity and acidity. Absorption is frequency-dependent; its effect in attenuating sound is negligible at low frequencies but increasingly effective at high frequencies (Ainslie & McColm 1998) and therefore important when understanding the potential consequences of sound generated by some of the very high-frequency sources considered in this review. As a rule of thumb, absorption has the same attenuation effect as spherical spreading for sound at 230 kHz i.e. 60 dB reduction per kilometre (in seawater at 10 °C, pH = 0.8); the effect is reduced to <1 dB/km at 10 kHz and drops to <0.1 dB/km below 100 Hz.

Directionality is also important; a point source of sound will propagate equally in all directions, but when sound is produced for a specific purpose e.g.

echolocation or side-scan sonar, the output tends to be directional with energy beam-formed in the main axis of interest. Among geophysical surveys, sources vary from almost point source (e.g. a single airgun) to complex beam patterns with multiple sidelobes (e.g. multi-beam echo-sounder, MBES); to predict sound exposure both distance and angle from the emitted sound beam need to be taken into consideration.

It can be concluded that in many field situations, and particularly so in heterogeneous shallow environments, the sound field can be very complex and the assumption that sound level decreases at a constant rate with distance does not hold. Several modelling approaches have been developed to predict a sound field on the basis of knowledge of the characteristics of sound at source and of the environmental conditions encountered (Spiga 2015; Etter 2018). Sound modelling is complex; the accuracy and precision obtained will depend on choice of model, heterogeneity of the environment and on availability of suitable environmental data at the appropriate scale. Validation of models against field measurements may be necessary to ensure predictions are accurate; particularly in heterogeneous coastal environments (see Farcas *et al.* 2016).

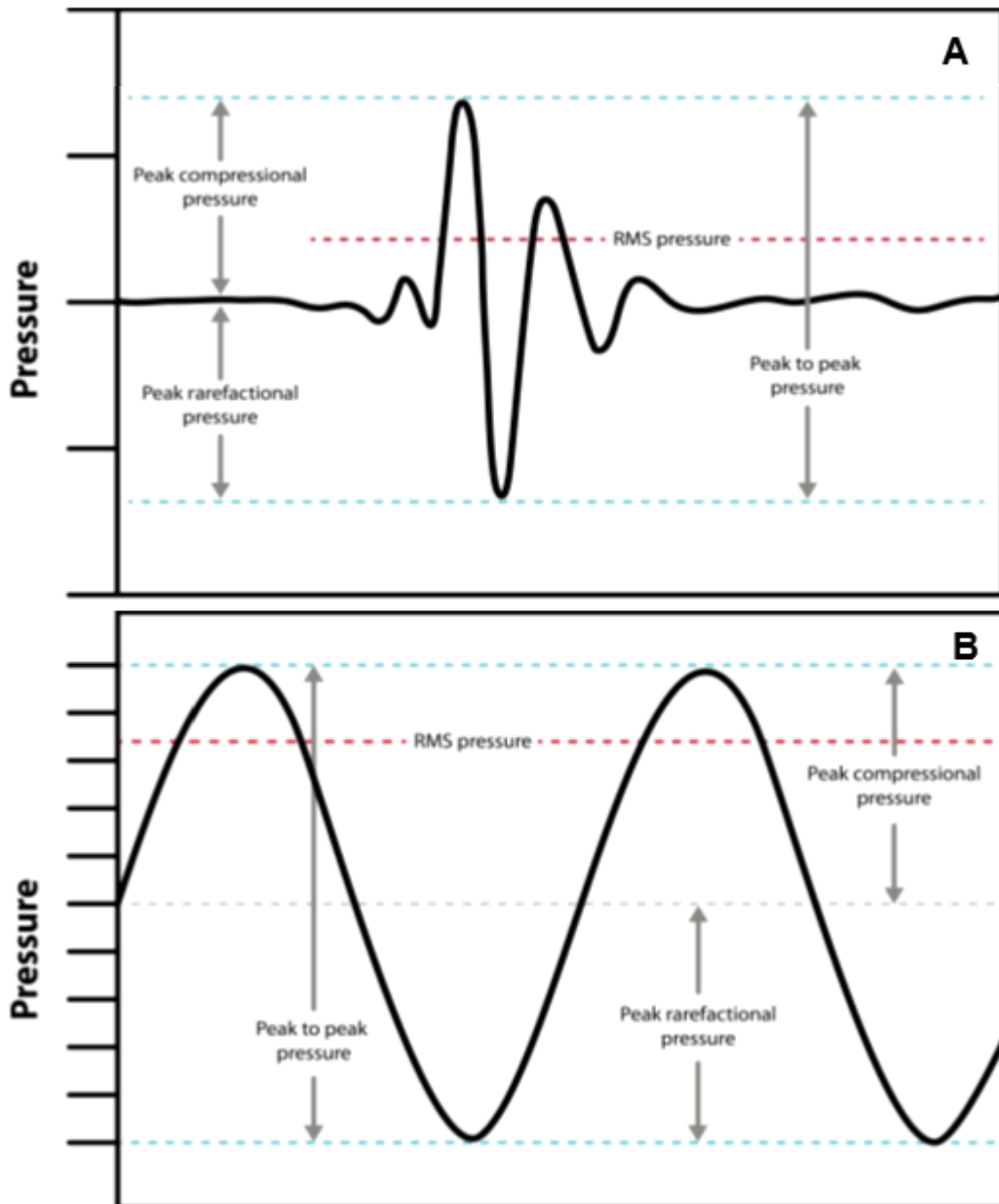
4.2. Measurements

Underwater sound is most commonly measured only in terms of its pressure component. Measuring changes in pressure is straightforward and it is done routinely in water using hydrophones. A hydrophone is an underwater acoustic transducer which converts acoustic pressure in the sound wave to electrical voltage, just as a microphone does in air. Measuring changes in particle motion is technically much more challenging (particle displacements are of the order of nanometres). Measurements can be obtained directly with neutrally buoyant triaxial accelerometers or indirectly using an array of pressure-sensitive hydrophones, but the lack of cheap and readily-available instrumentation remains a problem (Hawkins *et al.* 2015; Nedelec *et al.* 2016; Popper & Hawkins 2018).

The relationship between pressure and particle motion is not constant and not always easily predictable; in particular, in shallow water and close to boundaries (e.g. sea surface, seabed, walls of an experiment tank), the sound field can become very complex and particle motion is difficult to calculate from sound pressure measurements, so that direct measurements are necessary (Nedelec *et al.* 2016; Carroll *et al.* 2017). In addition, close to sources (in the acoustic near-field) the sound pressure and particle motion have a more complex relationship. As discussed below, knowledge of the pressure component of sound is a perfectly reasonable approach with respect to understanding sound effects for receptors which are capable of detecting changes in pressure (e.g. mammals and some fish) but not for receptors which are largely (i.e. fish) or completely (i.e. invertebrates) reliant on detecting changes in particle motion.

Figure 2- Relevant acoustic metrics and quantities

Pulsed (A) periodic (B) waveforms, illustrating metrics for sound pressure:



Sound pressure (or “instantaneous sound pressure”) is the difference between instantaneous total pressure and pressure that would exist in the absence of sound. This is in effect the quantity represented when a sound pressure waveform is plotted as illustrated above.

Peak sound pressure (or zero-to-peak sound pressure) is the maximum sound pressure during a stated time interval. A peak sound pressure may arise from a positive or negative sound pressure. The levels is:

$$\text{peak sound pressure level: } L_{p,pk} = 20 \log_{10} \left[\frac{P_{p,pk}}{P_0} \right]$$

where $P_{p,pk}$ is the peak sound pressure and p_0 is the reference value, of 1 μPa in water. Units are dB re 1 μPa .

Peak-to-peak sound pressure is the sum of the peak compressional pressure and the peak rarefactional pressure during a stated time interval. The level is:

$$\text{peak to peak sound pressure level : } L_{pk,pk} = 20 \log_{10} \left[\frac{P_{pk,pk}}{P_0} \right]$$

where $p_{pk,pk}$ is the peak to peak sound pressure, p_0 is the reference value, of 1 μPa in water. Units are dB re 1 μPa .

Root-mean-square (RMS) sound pressure is the square root of the mean square pressure, where the mean square pressure is the time integral of squared sound pressure over a specified time interval divided by the duration of the time interval. The RMS sound pressure is calculated by first squaring the values of sound pressure, averaging over the specified time interval, and then taking the square root. The sound pressure level (SPL) is given by:

$$\text{sound pressure level: } SPL \text{ or } L_p \text{ or } L_{p,rms} = 10 \log_{10} \left[\frac{\hat{p}^2}{p_0^2} \right] = 20 \log_{10} \left[\frac{\hat{p}}{p_0} \right]$$

where \hat{p} is the root mean square (RMS) sound pressure, p_0 is the reference value, of 1 μPa in water. Units are dB re 1 μPa . Note that the time interval used in the calculation of SPL must be stated (it is a time-averaged quantity).

Sound exposure is the integral of the square of the sound pressure over a stated time interval or event (such as an acoustic pulse). The quantity is sometimes taken as a proxy for the energy content of the sound wave. When applied to an acoustic pulse, the integration time is the pulse duration and the quantity is sometimes called “single pulse sound exposure”. Pulse duration is commonly defined as the time occupied by the central portion of the pulse, where 90 % of the pulse energy occurs; this definition is necessary as the exact start and end of a pulse are not always obvious (see examples below). The level is:

$$\text{sound exposure level: } SEL \text{ or } L_{E,p} = 10 \log_{10} \left[\frac{E_p}{E_{p,0}} \right]$$

where E_p is the sound exposure and $E_{p,0}$ is the reference value, of 1 $\mu\text{Pa}^2 \text{ s}$ in water. Units are dB re 1 $\mu\text{Pa}^2 \text{ s}$.

Note that the sound exposure level is a useful measure of the exposure of a receptor to a sound field, and a frequency weighting is commonly applied. If a frequency weighting is applied, this should be indicated by appropriate subscripts. It is also common to use ‘cumulative sound exposure level’ when the quantity is applied to an extended period or sequence of pulses/events; duration should be specified with subscripts, such as SEL_{24h} or $L_{E,24h}$.

Signal duration is the time interval between the arrival of specified fractions (most typically 5 % and 95 %) of the total energy in the signal. Units are s.

Rise time is the time between the onset and the peak sound pressure in a signal. Onset is defined as the 5th percentile of the cumulative pulse energy. Units are ms.

Crest factor is the difference between the peak sound pressure level of the pulse and the root-mean-square sound pressure level calculated over the signal duration. Units are dB.

Sources: *Robinson et al. (2014)*; *ISO 18405:2017 Underwater Acoustics - Terminology*; *Hastie et al. (2019a)*.

Are all sounds from acoustic survey equipment impulsive?

Temporally, a sound is either continuous or transient. All acoustic surveys emit transient sounds i.e. short duration signals, emitted in a predictable pattern of bursts of sound and silent periods. However, transient sounds are not all equal when it comes to their potential to cause damage to the mammalian ear. Transient sounds which are brief, broadband, with a rapid rise time and rapid decay are more damaging; these are broadly defined as impulsive. Non-impulsive transient sounds (which may be broadband, narrowband or tonal and typically do not have a high peak sound pressure with rapid rise and decay times) are less damaging and are classified together with continuous sounds in terms of potential for hearing damage. Exposure level thresholds for marine mammals for the onset of PTS (and TTS) have been developed to reflect this distinction; thresholds for impulsive signals are lower than for non-impulsive sounds (*Southall et al. 2007*, *NMFS 2018*, *Southall et al. 2019*).

Despite the recognition that risk of hearing damage depends partly upon a sound being impulsive vs. non-impulsive, no single mathematical definition exists and distinguishing between 'impulsive' and 'non-impulsive' on the basis of current broad definitions is not always clear in practice. As pointed out by *Southall et al. (2007)*, impulsive signals at source may meet the non-impulsive definition at greater distances and certain signals such as acoustic deterrents and harassment devices may have characteristics of both. Recent measurements from a deep water multi-beam echo-sounder have shown that depending on the settings and operational modes employed, the variable characteristics of signals may not fit easily into either sound type (*Miksis-Olds et al. 2019*).

In acoustic surveys, signals can be distinguished on the basis of their waveform; equipment producing a pulsed waveform is likely to fit the impulsive definition (airguns, boomers and sparkers) but a periodic waveform may not mean that a signal is classified as non-impulsive, as shown in the examples below.

In *Southall et al. (2007)*, the distinction between impulsive and non-impulsive (termed 'pulse' and 'non-pulse') is empirical, based on measurements of sound using different temporal weightings as originally proposed by *Harris (1998*, in *Southall et al. 2007*). This distinction has been retained in *Southall et al. (2019)* but with a greater emphasis on the need to apply thresholds based on the characteristics of the received sound, rather than sound at source (with work ongoing in that respect). On that basis, anthropogenic underwater sound sources were distinguished in *Southall et al. (2007)* as follows:

- 'pulse' (single and multiple): airguns, waterguns, explosions, sparker pulses, but also pings of certain active sonars (IMAPS), depth sounders and pingers.
- 'non-pulse': vessel/aircraft passes, drilling, certain sonar systems (LFS, tactical mid-frequency), acoustic harassment/deterrent devices, Acoustic Thermometry of Ocean Climate (ATOC), some depth sounder signals.

Sources generating a periodic waveform (e.g. sonars, pingers, depth sounders, acoustic harassment devices, ATOC) are, therefore, found in both impulsive and non-impulsive categories.

In contrast, a statement in the report by James Finneran in support of the Technical Guidance published by NMFS (2018) appears to fit the waveform distinction "*sonars, other coherent active sources, and vibratory pile driving are considered to be non-impulsive sources, while explosives, impact pile driving, and air guns are treated as impulsive sources*". Similarly, documents prepared by the US Navy refer to sonars and underwater transducers as lacking the characteristics of impulsive sources (e.g. United States Department of the Navy 2017).

In support of indicator 11.1.1 of the Marine Strategy Framework Directivity on low- and mid- frequency impulsive sounds, sound thresholds have been developed to decide whether an activity should be 'impulsive' and be included into the Marine Noise Register. The focus of the register is on disturbance (not auditory injury) and 'impulsive' has been defined ad hoc for this indicator as "a sound for which the effective time duration of individual sound pulses is less than ten seconds and whose repetition time exceeds four times this effective time duration" (van der Graaf et al. 2012). Consequently, sonar and acoustic deterrents are included into the Register for the impulsive indicator, when exceeding a given sound level threshold (Dekeling et al. 2014).

5. Characteristics of sources used in acoustic surveys

Sound has been used over the last 100 years to survey the marine environment and deep into the earth using technology based on the principle of echo-location, i.e. the determination of the time interval between the sound emitted and the arrival of its reflection/ refraction at detectors. Early efforts aimed to make shipping safer, detecting seabed topography (fathometer or depth sounder), icebergs and U-boats during the First World War; today, acoustic surveys at sea are carried out for a multitude of applications. Geophysical surveys are used to map geological strata down to several kilometres below the seabed, or to focus on details at the surface of the seabed, with different equipment deployed according to the depth of acoustic penetration and resolution required. Acoustic surveys are also used routinely within the water column to collect information on the distribution, abundance and behaviour of fish (See for example work by ICES Working Group of International Pelagic Surveys (WGIPS) <http://www.ices.dk/community/groups/Pages/WGIPS.aspx>), zooplankton or study physical properties of the water column. Navies worldwide have continued to develop sonar (Sound Navigation And Ranging) systems.

In this report, we describe the equipment and methodologies deployed in acoustic surveys that are likely to occur across Welsh waters and the wider UKCS (Section 5.1-5.3), provide a description of their known and likely propagation in the marine environment (Section 5.4), and summarise their use in Welsh and adjacent waters (Section 5.5). We only consider active sources (i.e. those emitting acoustic energy, not passive systems). Summary characteristics of all sources are presented in Appendix 1, with their main operating frequencies illustrated alongside reported hearing ranges of marine species in Appendix 2.

5.1. Seismic (airgun) sources

The characteristics of seismic survey sources have been widely reviewed (e.g. Richardson *et al.* 1995; Caldwell & Dragoset 2000; MMS 2004; OGP 2011), and a useful synthesis is provided as part of each Offshore Energy Strategic Environmental Assessment (see latest in DECC 2016; p.111).

Airguns are the most common marine seismic source used to explore geophysical layers below the seafloor, especially during the exploration, development and production of oil and gas reserves. An airgun is an underwater chamber capable of rapidly and consistently releasing compressed high-pressure air to create a bubble generating the required loud impulsive sound. Depending on survey objectives and required depth of penetration into the seabed, airguns are deployed alone, in clusters (2-4 airguns) or most commonly in arrays. Larger arrays, often referred to as 'tuned airgun arrays', may consist of a large number of airguns (e.g. 16, 32, 48) of varying volumes (40-480 in³) towed behind a vessel in an arrangement of 1-3 strings spreading the airguns across a small area (e.g. 14 x 14 m). These are the typical characteristics of large arrays deployed across the UKCS; worldwide, larger

arrays have been reported, e.g. with up to 6 strings of airguns, for total volume exceeding 8,000 in³.

Different seismic survey operations can be distinguished across the UKCS as follows:

- Early exploration stages require a two dimensional (2D) seismic survey which can cover large areas with relatively low resolution. A 2D survey involves a vessel towing an airgun array at depth 5-10 m and streamers (3-12 km long), containing many hydrophones at equal spacing along their length. Repeated parallel line surveys are run at intervals of several kilometres (minimum 0.5 km) and a second set of lines at right angles to the first is used to form a grid pattern; it is common for 2D lines to cover very large distance, >50 km.
- For improved data acquisition at a regional or reservoir scale, a vessel undertaking a three dimensional (3D) seismic survey tows two or more large airgun arrays and several streamers (up to 32). When two arrays are deployed, they tend to operate alternately. Streamers are closer to each other (typically 25-75 m) and data density is much improved with respect to 2D. These surveys may take several months to complete and cover areas of 300-3,000 km². A 3D survey often follows a race-track design to maximise operational time; completing a turn between the end of a line and the next is a complex operation that can take >2 hr due to the length of streamers.
- For hydrocarbon/gas storage reservoir management (i.e. monitoring changes), a 3D survey may be planned to be repeated and compared over time; this is referred to as a four dimensional (4D) seismic survey (time is the 4th dimension).
- Alternatively, seismic surveys may be referred to as ocean bottom seismic (OBS) or ocean bottom components (OBC); these use airgun arrays similar to 2D or 3D as the source of sound but instead of hydrophones in streamers, acquisition of information occurs by static geophone sensors placed directly on the seabed (either along cables or within sensor nodes). Special multicomponent sensors that combine geophones and hydrophones have also been developed. These surveys can be described on the basis of sensor type e.g. 1C, 2C, 3C, 4C, multicomponent.
- Vertical Seismic Profiling (VSP) is employed to assist with well evaluation, by linking rock strata encountered in drilling to seismic survey data. A number of geophones are lowered into a well while the airgun array is deployed from either the rig itself, or from a vessel which may be stationary or moving. Sound sources are typically a cluster of airguns (3 x 250 in³) mounted on a frame. These surveys are short operations of one or two days at most.
- When the focus is on high resolution data for shallow geology and shallow hazard assessment (e.g. to inform infrastructure placement and drilling operations) within a specific operational site, the seismic survey is often referred to as a high-resolution geophysical survey (HRGS) or a 'site survey'. A small airgun array of 4x40 in³ is the most common configuration adopted. Alternatives to airguns for site surveys are impulsive SBPs, including sparkers and boomers (described in Section 5.3.1). A vessel tows the airgun array and receiving streamers (600-1,200 m in length) and the area of interest (usually only 25 km²) is covered using a race-track design within approximately 10

days of operation. Site surveys once a platform is in place may require the use of 'undershooting', whereby the sub-surface beneath the platform can be imaged by deploying the source and the receiver on separate vessels. To achieve the highest possible resolution data, a site survey may also deploy a mini airgun (a single airgun of small volume). In the JNCC guidelines for minimising the risk of injury to marine mammals from geophysical surveys (JNCC 2017), a mini-airgun is defined as a single gun volume equal to or less than 10 in³ but in commercial seismic equipment catalogues (e.g. Sercel) mini-airguns may have volumes up to 60 in³. The same techniques used on site surveys / HRGS can be applied along tracks for pipeline or cable routes.

The characteristics of sound generated from airguns are summarised in the section below; from a practical point of view, a useful distinction (as adopted in the development of Guidance on Noise Risk Assessments from seismic surveys by BEIS (currently under development) is made between airguns used as sources for site surveys, VSP surveys and large regional or reservoir surveys (the latter encompassing 2D, 3D and OBS).

A single airgun or a small cluster or array as in site and VSP surveys is approximately an omnidirectional (equivalent to a point-source) sound source, and sound intensity is directly related to volume and pressure (operational pressure is usually constant at 2000 psi). On the other hand, a large tuned airgun array is designed specifically to maximise the quality of sound (pulse shape, frequency and amplitude) that is most effective from a geophysical mapping perspective; the relationship between amplitude and array volume is a more complex one. A main outcome of an array is that amplitude is increased above what any single airgun can produce by ensuring the signal from each airgun arrives simultaneously at the required point below the array to combine additively in the downward vertical. Off vertical, signals do not arrive at the same time, reducing the signal amplitude; thus, an array is a directional source of sound with measured levels in the horizontal 15-24 dB lower than in the vertical.

In terms of frequency spectrum, seismic surveys require low-frequency sound which has the greatest propagation; the sound generated from an airgun is broadband with the bulk of energy in the low frequency (<200 Hz) but with some reaching into the higher frequency (>10,000 Hz) (Breitzke *et al.* 2008; Landrø *et al.* 2011; Hermannsen *et al.* 2015). High quality airgun measurements have been collected and analysed to validate airgun models, but the focus for industry is on the low frequencies; most source models have not yet been fully calibrated above 1 kHz. Efforts to validate the higher frequency component are currently underway (e.g. Prior 2018; Sidorovskaia *et al.* 2019) in response to recent environmental concerns. It is also worth noting that not all airguns are equal; airgun technology has been developed to minimise bubble oscillation and improve signal performance; however, recently, efforts are also being made to reduce the unwanted higher frequency component of the spectrum (e.g. Watson *et al.* 2016), with at least one commercial product available (e-Source by Teledyne Bolt <http://www.teledynemarine.com/sound-source/esource>). Overall, however, field measurements of seismic pulse spectra above 1 kHz are few, limiting our

ability to predict effects for species sensitive to higher frequency sound (Ainslie *et al.* 2016).

5.2. Marine vibroseis

As the widespread use of airgun technology has come under scrutiny from an environmental point of view, research is ongoing to develop alternatives which can deliver the seismic resolution required by industry while minimising potential impacts; prime among these is marine vibroseis (for which some data are available) but also novel technologies such as tuned pulse source (TPS), low impact seismic source (LISS), and the ultra-low-frequency marine energy source Wolfspar (Lee 2019).

Vibroseis is a well-established technology for geophysical surveys on land, but its application in the marine environment is still under development. In contrast to airguns, marine vibroseis (MV) is an electromechanical source which generates a more controlled signal (in terms of frequency, duration and amplitude) of longer duration (10-40 s), lower amplitude, and with less energy above target frequencies than airguns (Duncan *et al.* 2017; Matthews *et al.* 2018). The technology has yet to be widely field tested and much of the current understanding is based on modelled synthetic signatures. A modelling study estimated a marine vibroseis array to generate broadband sound levels of up to 181 dB re 1 μPa ($L_{p,pk}$) and 171 dB re 1 $\mu\text{Pa}^2 \text{ s}$ ($L_{E,p}$) at 500 m from the source, with the majority of energy between 10-100 Hz and a rapid drop-off of pressure above 100 Hz (Duncan *et al.* 2017). By comparing signals from an airgun array and an idealised MV array with similar acoustic energy outputs (broadband $L_{E,p}$ of 218-233 dB re 1 $\mu\text{Pa}^2 \text{ s}$ at 1 m for the airgun arrays, and 215-233 dB re 1 $\mu\text{Pa}^2 \text{ s}$ at 1m for the MV arrays, in the vertical direction), Matthews *et al.* (2018) highlighted the differences in amplitude ($L_{p,pk}$ is 8-55 dB higher in airgun than MV) and frequency content and bandwidth (e.g. L_E at frequencies between 1-2 kHz is 40-80 dB lower in MV than in the airgun array).

Airguns (various configurations)

Summary description

An airgun explosively releases a high-pressure bubble of air into the surrounding water to generate the main acoustic pulse.



Teledyne Bolt Model 1500LL

Signal type

Airgun pulse has a broadband pulsed waveform; pulse duration is characteristically short, with a very brief rise time (about 0.3 ms).

Frequency

Energy is maximal in the low frequency, with 95 % of energy <200 Hz but the full pulse spectrum extends into the higher frequency (>10 kHz).

Source Level

Large arrays (regional and reservoir surveys) combining several airguns with a total volume of 2,340-6,300 in³ can generate the highest nominal source levels ($L_{p,pk}$) ranging 250-260 dB re 1 μ Pa at 1 m. Airguns are activated about every 10 s.

Sources used in VSP (e.g. 3 x 250 in³) are expected to have a lower amplitude, around $L_{p,pk}$ 240 dB re 1 μ Pa at 1 m, and commonly operated at slightly longer intervals of 20 s.

On site surveys, to obtain high-frequency resolution, the interval between pulses is 3-5 seconds; the smaller source used (e.g. 4 x 40 in³) generates a source level in the range $L_{p,pk}$ 235-240 dB re 1 μ Pa at 1 m, or even lower in the case of a mini-airgun (e.g. $L_{p,pk}$ 230-235 dB re 1 μ Pa at 1 m).

Directionality

A large airgun array is a directional source with levels emitted in the vertical below the array some 20 dB higher than in the horizontal plane. Single airguns or airgun clusters as used in site and VSP surveys act as an omnidirectional source.

Application

Airguns are used in a variety of applications, from regional deep geological exploration to shallow site sub-surface mapping, which determines the choice of survey design and source characteristics deployed.

5.3. Sub-bottom profilers

Sub-bottom profilers (SBPs) encompass a range of acoustic sources which are designed to collect information on the characteristics of strata below the seabed. Their acoustic signals penetrate the seabed to a range of depths, from a few metres to several hundred metres, and with vertical resolutions from a few centimetres to a few metres. Most are towed behind a survey vessel, either at/near the surface or at depth, whereas some smaller devices may be hull-mounted or lowered over the side of a vessel on a pole mount.

A key distinction within acoustic sources grouped as SBPs is between those which generate a broadband pulsed acoustic waveform and those generating a periodic (or sinusoidal, continuous or quasi-continuous) waveform. Pulsed waveform SBPs generate the acoustic pulse either through the impulsive physical processes of electrostatic discharge, as in sparkers, or electromechanically via accelerated water mass, as in boomers. All periodic waveform SBPs i.e. pingers, chirpers and parametric SBPs are electromechanical sources which employ piezoelectric transducers; to emit a deterministic signal with characteristics specified by an associated computer processor. Piezoelectric materials (such as crystals and certain ceramics) directly convert mechanical stress (e.g. pressure) into electric energy, and vice versa. Piezoelectric transducers generate an acoustic waveform by converting electrical energy into mechanical movement i.e. vibrations. Through the reverse of this process, the transducers can also detect sound. As such, these sources are highly customisable; in many cases, the signal is modulated in frequency and/or amplitude to improve its detectability and performance.

In the sections below, we describe the characteristics of those sources which are typically regarded as SBPs for consenting within the regulatory framework for oil and gas, several of which will also be used in high-resolution geophysical surveys (HRGS) for other purposes (e.g. offshore renewables, aggregates). A distinction is made between SBPs generating pulsed and F/AM waveforms. While small volume airguns (mini-guns) used singly or in small arrays may often be categorised as a SBP and used in HRGS, these are not considered here as they are covered above under seismic airgun sources.

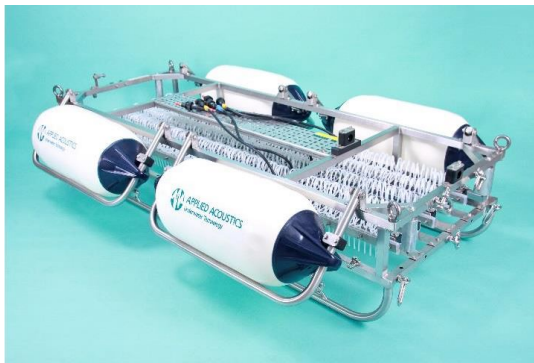
For SBPs, in addition to side-scan sonar and echo-sounders (Section 5.3), a key resource is a study commissioned by the US Bureau of Ocean Energy Management (BOEM): for a variety of equipment used in HRGS, calibrated source characteristics were measured under controlled conditions in a test tank (Crocker & Fratantonio 2016; Crocker *et al.* 2019). Further information is drawn from other calibrated source measurements (Risch *et al.* 2017; Cotter *et al.* 2019; Pei *et al.* 2019), manufacturer product specifications, and relevant reviews (Lurton & DeRuiter 2011; Lurton 2016; English Heritage 2013).

5.3.1. Pulsed waveform sources

Sparker SBP

Summary description

Sparkers are a small seismic source, comprising a towed unit containing a cluster of electrodes. A high voltage impulse is discharged across the electrode tips, with the consequent heating of the surrounding seawater generating a rapidly expanding steam bubble. It is this generation of the steam bubble which results in an acoustic impulse. A separate towed receiver array is required.



Applied Acoustics Dura-Spark UHD

Signal type

Sparkers generate a broadband pulsed waveform signal, of short duration and short rise time. While peak pressure is achieved within 1 ms, subsequent oscillations of diminishing amplitude (resulting from continued expansion and collapse of the steam bubble) result in longer measured signal durations of up to ~10 ms [1]. Repetition rates of 1-2 pulses per second are typical when operated at maximum power (e.g. 2,000 J).

Frequency

Broadband with energy primarily distributed at low frequencies (~100 Hz to 5kHz), typically peaking around 1 kHz or lower and with most energy between 200 Hz and 3 kHz [1,2].

Source Level

Typically in the range $L_{p,pk}$ 215-225 dB re $1\mu\text{Pa}$ at 1 m when operated at maximum power. Maximum calibrated source levels measured by [1] were $L_{p,pk}$ 225 dB re $1\mu\text{Pa}$ at 1 m ($L_{E,p}$ 188 dB re $1\mu\text{Pa}^2\text{s}$ at 1m); these were similar to those specified by the manufacturer.

Directionality

Approximately omnidirectional, although energy strongest at 90° from vertical.

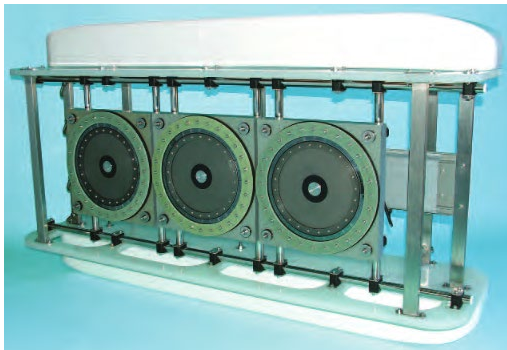
Application and performance

Most commonly used in high-resolution geophysical surveys for oil and gas. Provides data on the sub-bottom geology to a penetration depth of several hundred metres.

Boomer SBP

Summary description

Boomers are an electromechanical acoustic source in which the discharge of a high voltage impulse across a coil between two metal discs generates a magnetic field which drives the rapid downward displacement of the lower disc (boomer plate). This displacement generates a water-mass acceleration to transmit an impulsive waveform. Devices can feature a single or multiple boomer plates, which are positioned just below the sea surface within a tow-body. A separate towed receiver array is required.



Applied Acoustics S-Boom

Signal type

Boomers generate a broadband pulsed waveform signal, of short duration and short rise time. Signal duration is typically in the range of 0.5-1.0 ms. Repetition rates of 1-3 pulses per second are typical when operated at maximum power (e.g. 1,000 J).

Frequency

Broadband, with energy primarily distributed at low frequencies (~100 Hz to 15 kHz), typically peaking around 1 kHz or lower and with most energy between 200 Hz and 8 kHz.

Source Level

Typically in the range $L_{p,pk}$ 205-215 dB re $1\mu\text{Pa}$ at 1 m when operated at maximum power. Maximum calibrated source levels measured by [1] were $L_{p,pk}$ 212 dB re $1\mu\text{Pa}$ at 1 m ($L_{E,p}$ 174 dB re $1\mu\text{Pa}^2 \text{ s}$ at 1 m). Measured levels were similar to those specified by the manufacturer given the power levels tested.

Directionality

Measurements [1] indicated a -3 dB beam width of between 46 and 90°, and typically ~75° (relative to the main response axis).

Application and performance

Most commonly used in high-resolution geophysical surveys for oil and gas. Provides data on the sub-bottom geology to a penetration depth of up to ~100 m.

5.3.2. Periodic waveform sources

Pinger

Summary description

Pingers use a piezoelectric transducer to transmit a controlled pulse at a single frequency, typically between 2 kHz and 20 kHz. They are small devices which are generally hull-mounted or deployed over-the-side on a pole for shallow-water applications, but may also be deployed in a tow-body. A topside processor controls the signal type.



Kongsberg GeoPulse

Signal type

Pingers emit a short signal, typically of a few milliseconds or less, which can be configured to durations of ~0.5 ms to ~30 ms. Repetition rate is highly customisable, ranging from 1 up to 10 or 20 pings per second.

Frequency

Pingers transmit at a single frequency with a narrow bandwidth of ~1-2 kHz. The frequency is selectable, and may range between 1-40 kHz, although more typically between 2-15kHz and with 3.5 kHz being a commonly used frequency.

Source Level

Independent calibrated measurements [1] are not currently available for pinger SBPs. Manufacturer specifications for the Kongsberg GeoPulse indicate a source level of 214 dB re 1 μ Pa at 1m (Unspecified if $L_{p,pk}$, $L_{pk,pk}$ or $L_{p,rms}$).

Directionality

Manufacturer specifications for the Kongsberg GeoPulse indicate a beam widths of 55°, 40° and 30° at 3.5 kHz, 5.0 kHz and 7.0 kHz respectively.

Application and performance

While still frequently used in marine surveying, their use has declined with the development of chirper SBPs. Vertical resolutions of up to 10 cm can be achieved, with penetration depth ranging between a few metres in coarse sand and up to 50 m in soft sediments.

Chirper SBP

Summary description

Chirp (Compressed High Intensity Radar Pulse) sources, often referred to as 'chirpers', are a category of SBPs which use one or more transducers to generate a frequency-modulated (FM) signal. Transducers may be hull-mounted or deployed over-the-side on a pole for shallow-water applications, or housed within a tow-body. While optimum performance may be achieved from a tow-body positioned close to the seabed, for logistical simplicity they are often towed within a few metres of the sea surface, particularly in shelf depths. A topside processor controls the signal type.



Example Edgetech chirp sub-bottom profiler tow-body and transducer arrangement. The arrows in the right image identify the two transducers: one larger, low frequency and one smaller, higher frequency (Source: Crocker & Fratantonio 2016).

Signal type

Chirp SBPs generate a FM signal sweeping through a band of frequencies throughout the duration of the transmission pulse. Devices typically allow a wide range of different signal duration configurations to be selected; while signal as short as 1 ms can be specified, they are more commonly operated in the range of 5-40 ms. Repetition rate is highly customisable, up to ~30 signals per second.

Frequency

Energy is distributed across a fairly wide bandwidth (selectable) as the signal sweeps from low to higher frequency during the pulse. Manufacturer specifications indicate a typical configuration to be a nominal low/high frequency combination achieving a ~5-20 kHz bandwidth with the lower limit between <1 kHz and ~4 kHz. Measurements [1] for different chirp SBPs showed the 3 dB bandwidth to be narrower than manufacturer specifications, with peak energy generally occupying a 3-4 kHz band within the nominal specified bandwidth, and mostly lying between frequencies of 2 kHz and 13 kHz.

Source Level

Typically in the range $L_{p,pk}$ 185-215 dB re 1 μ Pa at 1 m when operated at maximum power. Maximum calibrated source levels measured by [1] were $L_{p,pk}$ 214 dB re 1 μ Pa at 1 m ($L_{E,p}$ 193 dB re 1 μ Pa² s at 1 m). Measured levels were similar to or lower than those specified by the manufacturer.

Directionality

Measurements [1] indicated a -3 dB beam width of between 36 and 80° and a -10 dB beam width of between 80 and 153° (relative to the main response axis). Signals with more content at higher frequencies had more focussed beams.

Application and performance

Chirper SBPs are widely used in HRGS for a variety of purposes; they are highly configurable and address the trade-off between resolution and penetration. Vertical resolutions of <10 cm can be achieved, with penetration depth ranging between a few metres in coarse sand to 100+ m in soft sediments.

Parametric (non-linear) SBP

Summary description

Parametric SBPs utilise a piezoelectric transducer to emit two different higher frequency signals ('primary'); these undergo a non-linear interaction during sound propagation through the water column to generate a resultant lower frequency signal ('secondary'). For example, emission of primary signals in the range 85-115 kHz, with the resulting secondary signal in the 4-15 kHz range (Innomar SES-2000 Standard model). Transducers are compact and frequently hull-mounted; they may also be deployed over-the-side on a pole for shallow-water applications, or housed within a tow-body for deployment at depth. A topside processor controls the signal type.

Signal type

Programmable, including FM (chirp) pulses or other configurations of periodic/quasi-continuous waveforms. Pulse widths are typically short i.e. <5 ms, and may range between <0.2 ms up to 20-30 ms. Maximum repetition rates are between 40-60 pings per second.

Frequency

The majority of energy is distributed across a fairly wide bandwidth at the higher primary frequencies. Most Innomar SES-2000 models indicate a centre frequency of ~100 kHz with a 3 dB bandwidth from 85-115kHz. Models designed for deeper water applications and greater seabed penetration have a primary signal centred on a lower frequency, with bandwidths in the 30-45 kHz range, although some models may be as low as 10-20 kHz.

Source Level

Parametric SBPs typically emit primary signals with high sound pressures, as the generated secondary signal will contain only a small proportion of the input energy. Across a variety of devices, manufacturer specifications indicate source levels of the primary signal to be in the range 238-247 dB re 1 μ Pa at 1 m and the secondary signal to be 200-206 dB re 1 μ Pa at 1 m (Unspecified if $L_{p,pk}$, $L_{pk,pk}$ or $L_{p,rms}$). Independent calibrated measurements [1] are not currently available for parametric SBPs.

Directionality

Parametric SBPs have a highly focussed beam width of <5°, with one manufacturer indicating a typical -3 dB beam width of 3.0-4.0°.

Application and performance

Parametric SBPs are a relatively modern development of sub-bottom profiling tools. Their advantages are the ability to generate a low-frequency pulse from a small transducer, and a much narrower beam width than other SBPs, making them more suitable for precision data collection. The disadvantage of a narrow beam width is more limited coverage of the seabed per survey line. Models transmitting higher frequency primary signals (i.e. >70 kHz) typically achieve seabed penetration of up to 50-100 m depending on the sediment type, vertical resolutions of up to 5 cm, and can operate in water depths (below transducer) up to several hundred metres. Those transmitting lower frequency primary

signals (e.g. 10-40 kHz) typically achieve 100-200 m seabed penetration, vertical resolutions of up to 10-15 cm, and can operate up to several thousand metres water depth.

5.4. Seafloor and water column mapping sources

In the section below, we describe the characteristics of those acoustic sources which are used for surveying features of the seabed and water column, for commercial, civilian and military purposes. All these sources use piezoelectric transducers and generate highly customisable signals with a periodic waveform, commonly frequency and/or amplitude modulated.

Side-scan sonar

Summary description

Side-scan sonar is a seabed imaging technique where two small piezoelectric transducers, typically mounted within a tow-body operated at depth, generate high-frequency acoustic pulses which are directed either side of the tow-body. The transducers can also be mounted either side of ship's hull, in a remotely-operated or autonomous underwater vehicle (ROV or AUV). The transducers are oriented such that the acoustic signal covers a wide angle perpendicular to the path of the device through the water, providing information on a strip either side of the device. The range (width of the strip) is dependent upon the frequency, power and other source configurations, but is typically between 50-500 m per transducer.



[Klein Marine Systems 3000 side-scan sonar.](#)

Signal type

Acoustic signals can be tone-burst or FM chirps. Signal durations are short, but vary between models and configurations. For example, longer signal durations are required to survey greater ranges. Among tested models [1], the Klein devices were typically <0.4 ms in duration, whereas the signal generated by the EdgeTech 4200 was typically ~1 ms. Repetition rates are customisable, up to several tens of pings per second

Frequency

Side-scan sonar sources typically offer a selection of two operational frequencies in the range of 100-500 kHz, or may operate both simultaneously. Some models may offer an upper frequency of up to 900 kHz for applications requiring the highest resolution data. Test results [1] did not report 3 dB bandwidth as for other sources, but pressure-density plots showed peak energy to be approximately ± 10 -30 kHz of the target frequency. Most devices showed notable harmonics (lesser secondary peaks in energy above the target frequency) which diminished in strength with increasing frequency. There were no clearly resolved sub-harmonics (below target frequency).

Source Level

Typically in the range $L_{p,pk}$ 205-230 dB re 1 μ Pa at 1 m. Maximum calibrated source levels, (sound pressure) measured by [1] were $L_{p,pk}$ 227 dB re 1 μ Pa at 1 m for a 0.1 ms pulse, whereas the highest energy source level of $L_{E,p}$ 205 dB re 1 μ Pa² s at 1 m corresponded to a longer pulse of 1.1 ms at lower maximum pressure ($L_{p,pk}$ 210 dB re 1 μ Pa at 1 m).

Directionality

Measurements [1] indicated a -3 dB beam width in the along-track direction of $\leq 2.6^\circ$ (main lobe) for all models tested. Manufacturer-reported across-track beam widths are typically 40-50° per beam.

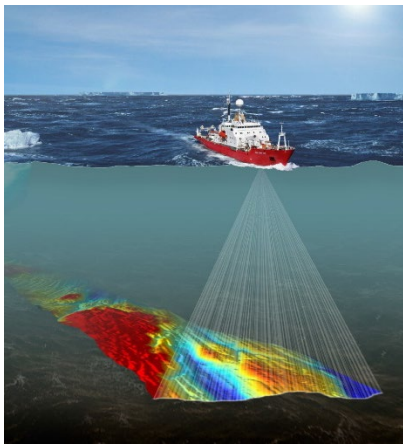
Application and performance

Side-scan sonar is widely used to provide high-resolution seabed mapping for a variety of purposes. Obstacles rising above the seafloor, such as shipwrecks, can cast shadows on the resulting seafloor image where no acoustic signal is returned. The size of the shadow can be used to determine the size of the feature casting it. Across-track resolutions vary between 1-8 cm with finer resolution at higher operating frequencies.

Echo-sounders (including single, multi-beam, scientific, fish finders)

Summary description

Echo-sounders, sometime referred to as commercial and civilian sonar, are a diverse group of acoustic sources used to collect information on bathymetry, seabed features and objects in the water column (e.g. scientific echo-sounders/ fish-finders). While they all use one or more piezoelectric transducers to generate an acoustic signal, the variety of applications for which they are used result in a diversity of devices and configurations, and, subsequently, the acoustic characteristics of signals vary considerably. They are typically hull-mounted, although high-frequency devices may also be housed in tow-bodies alongside other acoustic sources (e.g. side-scan sonar). Single beam echo-sounders emit a pulse of sound in a single narrow cone, whereas multi-beam echo-sounders (MBES) use multiple beams elongated in the across-track direction to cover a fan-shaped sector (or swath). A topside processor controls the signal type.



Representation of MBES in operation (Source: [British Antarctic Survey](#))

Signal type

The acoustic signal emitted by echo-sounders is short duration, typically of a few milliseconds or less, and can be configured to within the range 0.05-10 ms for certain systems. Some echo-sounders, including modern fish-finders, are also capable of producing FM chirp signals. Repetition rates are highly customisable, varying with signal frequency and water depth; rates of up to 10-20 pings per second may be used in very high frequency systems, whereas there may be several seconds between pings in low-frequency deep-water applications.

Frequency

The operating frequency of echo-sounders is one of the characteristics which shows the greatest variability, typically falling between 10 kHz and 1 MHz with the nominal frequency chosen depending on water depth, and specific application. Higher frequencies provide higher-resolution data from more compact devices, but suffer from high signal attenuation and are therefore less

suited to deeper water applications. For collecting information on the seabed, lower frequency systems (typically 10-50 kHz) are designed for deep waters, with the lowest frequencies generally reserved for depths of several thousand metres. Medium frequency systems (typically 70-150 kHz) are generally designed for continental shelf depth, although lower frequencies in this range are effective at continental slope depths of up to 1,000 m. High-frequency systems (200+ kHz) are designed for shallower shelf depths (down to tens of metres), or an equivalent distance above the seafloor if deployed at depth [3]. Depending on transducer configurations, echo-sounder systems may simultaneously transmit on multiple frequencies.

Most conventional fish finders mounted on recreational vessels utilise frequencies between 50 kHz and 200 kHz. For commercial fish-finders and scientific echo-sounders, the range of frequencies is slightly wider, from 15 kHz to 200 kHz. Scientific and advanced fish-finder echosounders regularly utilise multiple frequencies, including those <100 kHz, to assist in species identification.

Measurements by [1] showed clearly resolved harmonics for all echo-sounders tested and no sub-harmonics. Harmonics were also reported for a single-beam scientific echo-sounder [4], along with energy below the target frequencies (at 70-100 kHz for 120 kHz transducer, and 90-150 kHz for 200 kHz) albeit ~30 dB lower than the amplitude at the 1/3 octave band of the target frequency.

Source Level

Maximum source levels of MBES typically range from 210-240 dB re 1 μ Pa at 1 m [5], with the highest levels corresponding to the lowest frequency systems such as the 12 kHz system, often called 'high-power' [3], which can be approximately 10 dB higher than a typical 100 kHz MBES [9]. The highest measured [1] source levels among three MBES systems when operated at maximum power for central operating frequencies of \geq 100 kHz was between $L_{p,pk}$ 225-228 dB re 1 μ Pa at 1 m ($L_{E,p}$ 181-197 dB re 1 μ Pa 2 s at 1 m), while the single beam eco-sounder was $L_{p,pk}$ 197 dB re 1 μ Pa at 1 m ($L_{E,p}$ 163 dB re 1 μ Pa 2 s at 1 m) for a central operating frequency of 200 kHz. Calibrated tests of a single-beam scientific echo-sounder [4] measured levels of $L_{p,pk}$ 209 dB re 1 μ Pa at ~6 m distance from either a 120 kHz or 200 kHz transducer source.

Directionality

The narrow cone covered by single beam echo-sounders typically spans 5-15°, with the 3 dB beam width for one device measured as 7° [1]. Measurements of the wider across-track beam from MBES showed 3 dB beam widths of 150-160°; in the along-track orientation beam width is narrow, typically ~1.5-3.0° [1].

Application and performance

Echo-sounders are used for a variety of commercial and civilian purposes, including depth-sounding, navigation, habitat mapping and detecting fish and other marine life within the water column. MBES are primarily used in structured surveys of the seafloor for commercial purposes.

Acoustic Doppler Current Profiler (ADCP)

Summary description

ADCPs use the Doppler effect to measure the speed and direction of currents in the water column. The change in frequency of a wave in relation to an observer who is moving relative to the wave source. In the case of an ADCP, signals bounced back from a particle moving away from the profiler have a slightly lowered frequency when they return, whereas particles moving toward the profiler send back signals of a higher frequency than those transmitted. The difference in frequency between the signals the profiler sends out and the waves it receives is called the Doppler shift and allows the calculation of how fast the particle and surrounding water is moving. The device can be attached to a buoy, fixed to the seafloor or mounted on a boat. One or more (typically 3-4) small piezoelectric transducers emit high-frequency pulses which reflect off small particles in the water. The frequency of reflected pulses provides information on how fast the particle and surrounding water is moving. Triangulation calculations from the multiple transducers provide information on direction.



[Teledyne Workhorse Sentinel ADCP](#)

Signal type

Acoustic signals can be tone-burst or FM chirps. Signal durations range between ~1-10 ms for higher frequency models and up to ~40 ms for lower-frequency models. Ping rates range between 2 per second for high frequency models to one every 3 seconds for lower frequency models.

Frequency

ADCPs come in a wide variety of configurations and with nominal operating frequencies ranging from a few tens of kHz for deeper water applications to several megahertz for short-range fine resolution applications. In coastal and shelf seas they are most likely to use an operating frequency between 150-500 kHz. Bandwidths are narrow: approximately $\pm 10\%$ or less of the central frequency.

Source Level

In a technical note from ADCP manufacturer Teledyne [6], estimated source levels along each beam for the more powerful, lower-frequency devices are indicated to be in the range 223-227 dB re $1\mu\text{Pa}$ at 1 m, while higher-frequency devices are between 213-217 dB re $1\mu\text{Pa}$ at 1 m (Unspecified if $L_{p,pk}$, $L_{pk,pk}$ or $L_{p,rms}$). Further, it was noted that the sound pressure level in the

main beam would drop to ~180 dB re 1 μ Pa at <200 m from the source for all devices.

Directionality

Beam widths are narrow: typically a few degrees per transducer. [6] noted that the SPL would drop to ~180 dB re 1 μ Pa within a few metres at 20° off the main lobe - indicating high directionality.

Application and performance

Primarily oceanographic studies. An ADCP anchored to the seabed or from a surface buoy can measure current speed at equal intervals throughout the water column. Alternatively, an ADCP can be mounted horizontally on seawalls or piles to measure the current profile across estuaries and at different distances to shore.

Military sonar

Summary description

Military sonars typically comprise an array of piezoelectric transducers. These may be arranged in a vertical array on a cable below a vessel, in a hull-mounted array on a vessel, or an array may be lowered from a helicopter (dipping sonar). Their primary application is submarine detection and tracking (anti-submarine warfare). Most systems are broadly categorised as low-frequency active sonar (LFAS) or mid-frequency active sonar (MFAS).



Left: Hull-mounted AN/SQS-53 series MFAS on the USS Cowpens; source: [Wikipedia Commons](#). Right: AN/AQS-13 series dipping sonar (MFAS) deployed from a helicopter; source: [Wikipedia Commons](#).

Signal type

Conventional military sonar generates a periodic signal of approximately 1-2 s duration followed by a long listening time, resulting in a low duty cycle of up to 5-10% (known as pulsed active sonar, PAS). Continuous active sonar (CAS), a more recent development of military sonar technology, emits much longer signals (e.g. 18-19 s) with a very high duty cycle of 90-95 % [7]. The signal is typically a FM upsweep.

Frequency

LFAS operates at <1 kHz and typically between 100-500 Hz (for example, the US Navy's SURTASS LFA (Surveillance Towed Array Sensor System Low Frequency Active) sonar system). MFAS operates between 1-10 kHz and most typically with centre frequencies between 3.5 and 8 kHz. Sources with centre frequencies >10 kHz are less commonly used.

Source Level

The US Navy's SURTASS LFA generates a source level of $L_{p,rms}$ 230-240 dB re 1 μ Pa at 1 m. The AN/SQS-53 series of MFAS used by the US Navy generates a source level of up to $L_{p,rms}$ 235 dB re 1 μ Pa at 1 m [8, 9]. Source levels used by UK vessels are typically lower when used in training exercises and/or in areas of known sensitivity to marine mammals. An example is the Joint Warrior training exercises. The UK-led [Joint Warrior](#) war exercises are the largest multi-ship, multi-threat exercise conducted by the Royal Navy in UK Waters; they take place in spring and autumn each year. In both 2018 and

2019, individual anti-submarine sonars were generally limited to a maximum source level of 211 dB (assumed pulse length of 1 s, max 6 pulses per minute); higher source levels were only to be used if the risk was assessed as low.

Directionality

Energy is primarily directed horizontally and within a few degrees thereof, and omnidirectional within this plane. The hull-mounted AN/SQS-53C has a nominal 40° vertical beam width, directed 3° down from the horizontal, and can broadcast over 360° horizontally (with some interference to the stern from the hull and wake) [10].

Application and performance

MFAS is generally effective up to 10 km range, while LFAS provides greater range. The majority of use in UK waters relates to MFAS for testing and training exercises.

References for sections 5.1 to 5.4 are as follows: [1] Crocker & Fratantonio 2016; [2] Pei *et al.* 2019; [3] Lurton 2016; [4] Risch *et al.* 2017; [5] Lurton & DeRuiter 2011; [6] Teledyne RD Instruments 2016; [7] Lam *et al.* 2018; [8] D'Amico & Pittenger 2009; [9] Hildebrand 2005; [10] Hildebrand 2009.

5.5. Emitted sound fields

The acoustic descriptions so far have focused on sound characteristics at source but what matters in terms of effects are the characteristics of sound at the receiver. Information on source characteristics can be combined with details on environmental conditions to model transmission loss across space (sound fields) or at specific locations of interest. However, as highlighted in Section 4.1, this can be a complex endeavour, depending on the accuracy required and the level of detail available for the input parameters; models tend to predict sound levels and frequency, other pulse characteristics are not estimated.

It should be noted that when the sound from an acoustic survey is of relatively low amplitude, e.g. when levels are low at source or when interpreting conditions at large distance from a high-amplitude source, the contribution of all other sources of underwater sound become increasingly more important in terms of overall sound received by marine fauna. Other sources of underwater sound include the noise from the survey vessel and any other recreational or commercial vessel present in the area, but also natural contributors to ambient noise (e.g. wind, wave, rain and biological sounds). When low-amplitude sounds are considered, variability in ambient noise can lead to a significant variability in audibility i.e. a sound at any given frequency is audible only when it is both above the receptor's hearing threshold (or audiogram) and ambient noise.

There is much value in making measurements of realistic sources in the field to establish a more direct understanding of likely exposure, which in turn can also be used to further validate models.

5.5.1. Seismic (airgun) sources

Seismic surveys have received a lot of attention and while different survey designs and environmental conditions may warrant survey specific modelling and/or measurements to assess impacts, general expectations of received levels from airguns can be made. In terms of peak sound pressure levels, while the nominal levels for a large airgun array are never reached, levels >230dB re 1 μ Pa can be expected in close proximity (metres); levels are commonly reported to have decreased below 200 dB at a range of 100-1,000 m, and below 160 dB at a range of 10-11 km (e.g. Breitzke *et al* 2008). At any given distance, variation in received sound levels from airgun pulses can be large (10-25 dB), due to the combination of propagation effects and variability in physical properties of the environment (Blondel *et al.* 2016); a reminder of the complexity of the real world as opposed to modelled estimates. Between pulses, sound levels may also be raised above ambient (e.g. up to 9 dB in very shallow water, Guan *et al.* 2015). In terms of long-range detection, airgun pulses can reach out to hundreds of kilometres with some recorded on hydrophones at distances of 4,000 km from seismic vessels (Nieukirk *et al.* 2012).

5.5.2. Other acoustic survey (non-airgun) sources

Very few empirical field data are available on the sound field emitted from acoustic surveys using non-airgun sources. The most relevant work to date is part of the study funded by the US BOEM: following the calibrated measurements of multiple HRGS sources in test tanks by Crocker & Fratantonio (2016), measurements were made in shallow (≤ 100 m depth) open-water environments to investigate the propagation of sound from these sources (Halvorsen & Heaney 2018). Unfortunately, problems were encountered during the open-water testing resulting in a lack of calibration in the reported sound source levels (Labak 2019). The accompanying advice note (Labak 2019) emphasises that these uncalibrated data should not be used to provide source level measurements, and consequently the reported isopleths (summarising sound propagation) should not replace project-specific sound source verifications. A further project to calibrate these measures and provide an expanded assessment of propagation commenced in 2019.

Despite the caveats of the currently available open-water test results, it is worth noting some general patterns observed. In all test environments, broadband received levels from all MBES, side-scan sonar and SBP chirper or boomer devices tested were rapidly attenuated with distance from source, with particularly pronounced fall-off for directional sources when the receiver was outside of the source's main beam. Acoustic signals from the SBP sparkers tested showed slightly greater propagation, as would be expected from the lower-frequency and less directional impulsive signals these devices produce. The greatest propagation was generally observed at the deepest test site (100 m water depth) from sources generating low frequencies (<10 kHz); by

contrast, at 100 m water depth, some of the highest frequency sources (>50 kHz) experienced such attenuation that they were only weakly detectable or undetected by recording equipment. In all open-water test environments, broadband received levels did not exceed $L_{p,rms}$ 160 dB re 1 μ Pa beyond a few hundred metres from any SBP, echo-sounder or side-scan sonar device tested (Halvorsen & Heaney 2018). For comparison, such levels extended between several hundred metres and approximately 1 km for the mini-airgun tested. While recognising that these results require refining, preliminary evidence suggests that SBPs and other HRGS sources generate a very limited sound field in the marine environment, and of a much lower magnitude than those generated by seismic airgun sources.

5.6. Acoustic survey use in Welsh waters

5.6.1. Seismic (airgun) sources

Seismic surveys using medium to large airgun arrays are undertaken for the purposes of petroleum exploration or to characterise deep geological structures which could be used for carbon dioxide or natural gas storage. Spatial data on 2D and 3D seismic survey activity in UK waters from 1963 to July 2019 is published by the UK Oil and Gas Authority (Available via the [UK National Data Repository](#)); similar data for Irish waters from 1965 to 2015 is published by the Department of Communications, Climate Action and Environment. It is collated by the Petroleum Affairs Division and available from [data.gov.ie](#): [2D](#), [3D](#). These data include georeferenced 2D seismic lines and areas covered by 3D seismic surveys, accompanied by information on the date of survey and a range of other attributes, although not specific source characteristics.

In Figure 3, data are presented by decade from 1980 to July 2019 (UK data) or 2015 (Irish data) for Welsh and adjacent waters. This illustrates the extensive seismic survey activity occurring in the region in the 1980s and 1990s, with large amounts of activity in the eastern Irish Sea and off west Wales. By comparison, there was limited activity in the 2000s and 2010s, with the majority occurring in the Celtic Sea and very limited activity in Welsh territorial waters. This pattern is further illustrated in Table 1, which shows 2D seismic lines and 3D seismic coverage clipped to the Welsh Marine Plan area (territorial and offshore waters) plus a 15 km seaward buffer. While it is acknowledged that there may be acoustic surveys occurring >15 km outside of Welsh waters which are audible within Welsh waters, the 15 km buffer is considered appropriate to capture acoustic survey activity which may result in significant energy propagating into Welsh waters. It is noted that a distance of 15 km is adopted in Habitats Regulations Assessment of seaward licensing rounds for oil and gas (see BEIS 2019) as a criteria for screening in SACs and SPAs for which likely significant effects on relevant qualifying features from underwater noise (including 2D/3D seismic survey) cannot be ruled out.

2D seismic survey activity in Welsh waters in the 2010s is largely attributable to a single survey in the Celtic Sea in 2016, along with a survey primarily in adjacent Irish waters in 2014.

Table 1 - Seismic survey effort within the Welsh Marine Plan area + 15 km buffer

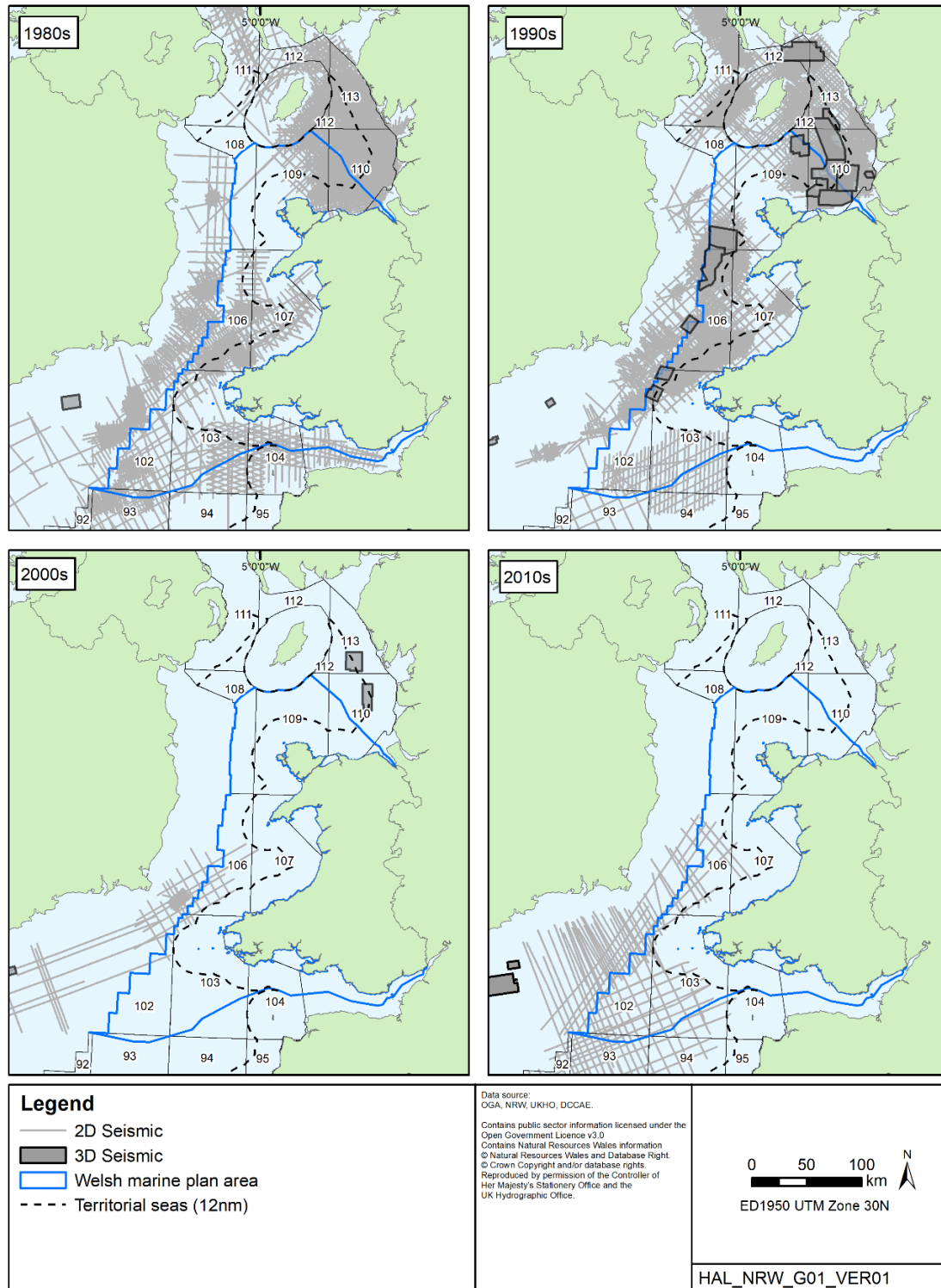
Decade	2D (km)	3D (km ²)
1980s	39,726	0
1990s	33,032	3,276
2000s	1,071	1
2010s	3,954	0

Notes: Values rounded to the nearest whole number.

Sources: UK Oil and Gas Authority; Department of Communications, Climate Action and Environment.

It is noted that Figure 3 and Table 1 only include deep geological seismic survey from towed arrays for the purpose of reservoir characterisation, and do not include VSP or site surveys using small volume airgun arrays to characterise shallow geological features. Therefore, they cannot be considered a complete record of seismic surveys in Welsh and adjacent waters, but do capture the majority of activity, including the highest amplitude sources. Site survey activity is primarily associated with exploratory drilling and infrastructure development, and so will historically have been focussed in what is now the mature area of oil and gas field development in the eastern Irish Sea, off the north coast of Wales.

Figure 3 - 2D and 3D seismic survey activity in Welsh and adjacent waters



Note: Duplicate 2D lines and 3D areas between the two data sources have been removed.

Image description

These four maps illustrate the extensive seismic survey activity occurring in the Irish Sea in the 1980s and 1990s, with large amounts of activity in the eastern Irish Sea and off west Wales. By comparison, there was limited activity in the 2000s and 2010s, with the majority occurring in the Celtic Sea and very limited activity in Welsh

territorial waters. The maps only include deep geological seismic survey from towed arrays and do not include VSP or site surveys using small volume airgun arrays to characterise shallow geological features. Therefore, they cannot be considered a complete record of seismic surveys in Welsh and adjacent waters, but do capture the majority of activity, including the highest amplitude sources.

5.6.2. Sub-bottom profilers and seafloor and water column mapping sources

Sub-bottom profilers are used in a wide variety of applications, and often in combination with side-scan sonar and echo-sounder sources as part of high-resolution geophysical surveys. In addition to investigations of seabed sediment structure for offshore industry (e.g. oil and gas, renewables, aggregates, communications) and geological academic research, applications include those seeking to image buried/partially buried objects such as shipwrecks, unexploded ordnance, cables, pipes and other infrastructure, and archaeological features. Consequently, while their use is generally focussed around centres of offshore industry such as the eastern Irish Sea (hydrocarbons and renewables), they are also used in applications closer to shore, such as along pipeline and cable routes which make landfall.

Information on SBP use in Welsh and adjacent waters is presented from Marine Noise Registry records described below in Section 5.6.3. A specific example of recent SBP use in Welsh inshore waters is the [Lost Frontiers project](#), where a boomer SBP (Applied Acoustics S-Boom) was operated in Cardigan Bay over a period of two weeks in summer 2019 as part of an archaeological investigation of submerged paleo-landscapes. Another example is the [CHERISH project](#), which used both MBES (central operating frequencies of 300 kHz and/or 400 kHz) and a parametric SBP (primary central operating frequency of 100 kHz) to survey geomorphological and archaeological features at several nearshore sites around the Welsh coast in recent years.

More or less all commercial vessels, small and large, are equipped with some form of commercial echo-sounder for water depth sounding, and, in the case of most fishing vessels, to detect fish. Most recreational vessels are also equipped with echo-sounders, generally of a lower power suited to shallow, inshore waters. Consequently, routine use of echo-sounders is widely distributed in Welsh waters, and reflects the distribution of commercial shipping, the relative density of fishing effort, and density of recreational craft.

MBES are used in structured surveys of the seafloor, for example in baseline or monitoring surveys related to seabed infrastructure (e.g. renewable energy devices, cables, pipelines and other oil and gas infrastructure), marine aggregate sites, for purposes of navigation (e.g. [MCA's Civil Hydrography Programme](#)), or researching archaeological or habitat features.

Scientific echo-sounders are widely used in fisheries surveys; for example, the [PELTIC Acoustic Survey](#) of pelagic fish in the English Channel and eastern Celtic Sea, conducted annually each autumn since 2012 and including Welsh waters of the Bristol Channel and off south-west Wales. Additionally, the [Celtic Sea Herring Acoustic Survey](#) of waters south of Ireland also occurs annually in

autumn/winter, and, since 2012, has extended into the south-west corner of Welsh offshore waters. These surveys use echo-sounders operating at multiple frequencies between 18 and 200 kHz. Additionally, single and multi-beam echo-sounders are used to monitor the movement of fish, marine mammals and diving birds around tidal energy devices (Williamson *et al.* 2017; Hastie *et al.* 2019b), including a trial period of monitoring of the DeltaStream turbine in Ramsey Sound, Wales.

5.6.3. Military sonar

Military sonar use in training takes place in MoD Practice and Exercise Areas (PEXAs); the only PEXA for submarine exercises which overlaps Welsh waters (X5001) lies 70km south-west of Skokholm Island, 26km from Welsh territorial waters and overlapping the Welsh Marine Plan (WMP) area in its SW extent. The next closest lies to the west of the Isle of Man (X5403), a minimum of 71 km from the Anglesey coast, 46 km from Welsh territorial waters and 13 km from the WMP area. Anti-submarine sonar activity is not permitted within the Human Dive Zone (HDZ), this being an area extending from the coast to the 50 m depth contour. PEXAs to the north of the WMP area are among those used in recent years during the UK-led [Joint Warrior](#) exercises conducted by the Royal Navy in UK Waters; they take place in spring and autumn each year. Information on UK military sonar use in Welsh and adjacent waters is inferred from Marine Noise Registry records described below in Section 5.6.3.

5.6.4. The UK Marine Noise Registry: low-frequency impulsive noise

The UK Marine Noise Registry (MNR) was developed by JNCC and Defra to record human activities in UK seas that produce loud, low to medium frequency (10 Hz - 10 kHz) impulsive noise (JNCC 2016). The MNR collates records of seismic surveys, SBP surveys, military sonar and MBES with a central operating frequency of ≤ 12 kHz. Impact pile-driving, the use of explosives, and some acoustic deterrent devices are also recorded. Declassified military sonar use is submitted to the MNR on a voluntary basis, whereas operational use is not. However, submissions from the Ministry of Defence do not differentiate between military sonar checks, their use in practice exercises, or the use of explosives.

Activities may be entered by regulators or industry via an online form. Depending on the activity type and relevant licensing procedures, submission of activities to the MNR may be mandatory or voluntary (see Section 6). For example, for licensed activities such as seismic or SBP survey for oil and gas exploration and production, submission of data to the MNR is a licence condition. While the proportion of low-frequency impulsive noise-generating activities being submitted to the MNR is considered to be increasing, this is not an exhaustive record of such noise generation; known missing data, along with other caveats, are outlined in a document accompanying data downloads. Those relevant to acoustic surveys in Welsh waters include:

- Classified MoD sonar use, sonar use by non-UK military in UK seas, and declassified MoD sonar use from January-April 2015.

- Some non-licensable geophysical surveys (non-oil and gas surveys, e.g. pre-installation surveys for offshore renewables; see Section 6).
- Some oil and gas related SBP activity. Follow up procedures are currently being established for outstanding close-out reports.
- Incomplete data for seismic survey effort in Welsh waters in 2016 (see below).
- A small amount of activity for which a close-out report was not submitted in time for publication of annual reports.
- Seismic and SBP survey and military sonar use in adjacent Irish waters (but see Section 5.6.1 for Irish 2D and 3D seismic survey).

Despite these caveats, these data provide an indication of the spatio-temporal distribution of low-frequency acoustic surveys undertaken in waters of Wales and the wider UK.

Official data outputs for 2015-2017 were downloaded from data.gov.uk, which provide a summary of pulse block days (PBD) by activity type at the scale of oil and gas licensing blocks. PBD are the number of days per year within each oil and gas block where at least one impulsive noise event occurred. Data for 2018 were obtained from JNCC directly; these data have yet to be processed into official outputs, with several close-out reports yet to be submitted. Consequently, records for 2018 presented here refer to proposed activities, with summary PBD values not yet available.

MNR records for seismic survey, SBP survey and MoD activity for the years 2015-2018 are illustrated in Figure 4. These identify the regional seismic survey activity occurring in the Celtic Sea in 2016 (see also Section 5.6.1), although it is noted that these records are incomplete, with reported activity extending further north to waters off west Wales. SBP surveys were largely restricted to the eastern Irish Sea, reflecting oil and gas and offshore activity in the region. There were no records of ≤ 12 kHz MBES use in Welsh and adjacent waters in the MNR from 2015-2018, likely due to the water depths in this region not requiring MBES to operate at frequencies as low as ≤ 12 kHz.

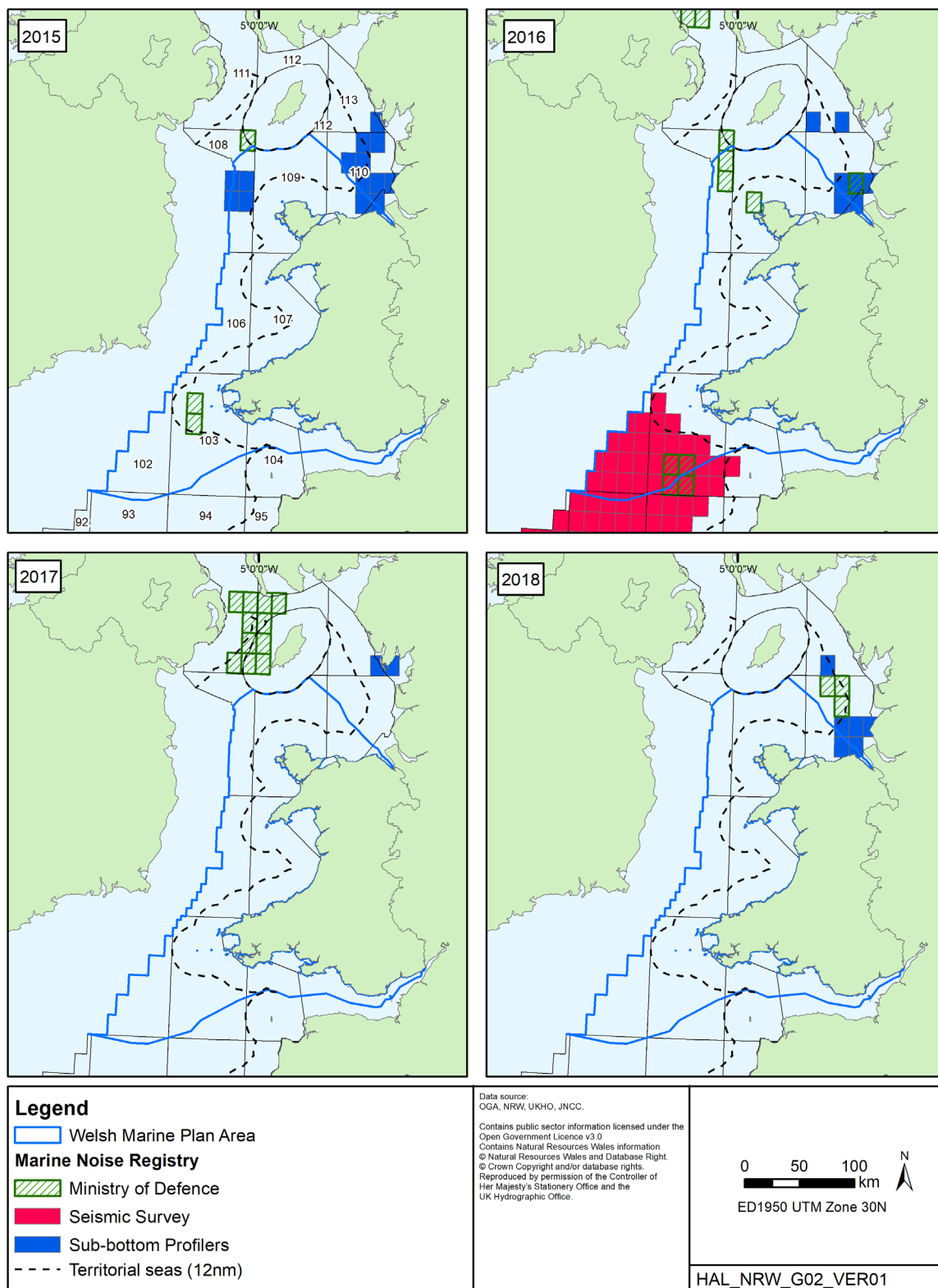
MNR records for blocks within or overlapping the Welsh Marine Plan Area plus a 15 km seaward buffer were selected and are summarised in Table 2. These show seismic survey to be the greatest contributor to pulse block days in the region, albeit from a single regional survey in 2016. SBP surveys occurred in most years, with up to 77 PBD per year, while MoD activity of ≤ 10 PBD was reported in every year. Considering the distribution of MNR records in Welsh and adjacent waters for MoD activity relative to the distribution of submarine PEXAs in the region, it is likely that only a small proportion of these records correspond to military sonar use.

Table 2 - Marine Noise Registry records for 2015-2018 for blocks relevant to Welsh waters

Year	Seismic survey Blocks	PBD	SBP survey Blocks	PBD	MoD Blocks	PBD
2015	0	0	11	77	3	3
2016	43	130	6	16	9	10
2017	0	0	0	0	2	4
2018	0	0	5	-	2	-

Notes: Records are limited to Blocks within or overlapping the Welsh Marine Plan area plus a 15km buffer, for acoustic survey sources and reported MoD activity, showing the total number of different blocks and pulse block days (PBD). There were no records of ≤ 12 kHz MBES surveys for the period 2015-2018 for these blocks. PBD summary statistics are not yet available for 2018. Source: JNCC.

Figure 4 - Marine Noise Registry records in Welsh and adjacent waters



Notes: Seismic survey records for 2016 are incomplete, with reported activity in the Celtic Sea extending further north to waters off west Wales (see Figure 3). Not all Ministry of Defence records relate to military sonar use.

Source: Marine Noise Registry, available from data.gov.uk and mnr@jncc.gov.uk.

Image description

Figure shows MNR records for seismic survey, SBP survey and MoD activity for the years 2015-2018 in four maps. These identify the regional seismic survey activity occurring in the Celtic Sea in 2016, although it is noted that these records are incomplete, with reported activity extending further north to waters off west Wales. SBP surveys were largely restricted to the eastern Irish Sea, reflecting oil and gas and offshore activity in the region. Ministry of Defence activity has occurred in various locations between 2015 and 2018 and they do not all relate to military sonar. There were no records of ≤ 12 kHz MBES use in Welsh and adjacent waters in the MNR from 2015-2018, likely due to the water depths in this region not requiring MBES to operate at frequencies as low as ≤ 12 kHz.

6. Regulatory regime

6.1. Introduction

The following sections provide a description of the relevant regulatory regime for underwater acoustic surveys undertaken in Welsh waters, and for context those elsewhere in the UK. The description includes a consideration of the apparent limits and exclusions to the remit of the relevant Regulations.

As this work falls within the broader non-licensable activities project being undertaken by NRW, the overview of the regulatory regime for underwater acoustic surveys has been split into two sections: one covering where there is a clear consenting path (Section 6.2), and another which looks at the potential for survey activities to be undertaken without requirement for formal consent (Section 6.3).

The two sections are presented as tabulations, and accompanied by a flow diagram (Figure 5) which provides a high-level overview of the approach to licensable and non-licensable activities. The lack of clarity over the roles and routes to any form of environmental scrutiny for non-licensable activities are reflected in the detail provided in the flow diagram.

6.2. Licensable or otherwise consented activities

Principal regulatory regime

The [*Offshore Petroleum Activities \(Conservation of Habitats\) Regulations 2001*](#) (as amended) specifically covers the consenting of certain geophysical surveys under Regulation 4.

Also of relevance in terms of legislative remit are: the [*Petroleum Act 1998*](#) (as amended), the [*Energy Act 2008*](#) (as amended), [*The Energy Act \(Consequential Modifications\) \(Offshore Environmental Protection\) Order 2010*](#), and the [*Offshore Petroleum Production and Pipelines \(Assessment of Environmental Effects\) Regulations 1999*](#) (as amended).

Regulator

The Department for Business, Energy and Industrial Strategy (BEIS); specifically, the Offshore Petroleum Regulator for Environment and Decommissioning (OPRED)

Overview

Covers consent for “geological survey” (see below for definitions relevant to this legislation) where these are undertaken for the purposes of oil and gas exploration and production, and for gas storage and carbon dioxide storage. While the 2001 Regulations generally indicate that geological survey should not be undertaken without consent, the focus of the Regulations is the implementation of the Habitats and Birds Directives in relation to oil and gas activities. Note that Regulation 28(7) of *The Conservation of Offshore Marine Habitats and Species Regulations 2017* (as amended) effectively disapplies these Habitats Regulations for any Petroleum Act related consent. Petroleum Act consents are considered under the *Offshore Petroleum Activities (Conservation of Habitats) Regulations 2001* (as amended).

Geographical remit

For offshore oil and gas exploration and production BEIS retain environmental regulatory functions covering all UK waters, defined as including the territorial waters (for these Regulations, defined as the low water mark to the seaward of the limit of the territorial waters (12nm)) of England, Wales, Scotland and Northern Ireland, and the wider UK Continental Shelf (UKCS). BEIS similarly have environmental regulatory functions for gas storage and carbon dioxide storage, covering the territorial waters of the UK and the wider Exclusive Economic Zone (EEZ). Note that the limits of the UKCS still apply for the purposes of oil and gas licensing, but those of the EEZ, as defined in *The Exclusive Economic Zone Order 2013*, are those which specifically apply to gas storage, including for carbon dioxide.. The only exception to this is that Scottish Ministers have remit over carbon dioxide storage in their territorial waters.

Consenting route and avenue for environmental scrutiny

Applications are made through the BEIS Portal Environmental Tracking System (PETS).

Applicants provide an assessment of the environmental implications of the proposed survey activities. The assessment is reviewed by OPRED environment managers, which may include consultation (see below). Two types of application may be made (for consent or notification), and the level of assessment undertaken reflects the type and location of the proposed activity.

Consultation (e.g. with relevant statutory conservation bodies, other Government departments and the public):

Under the *Offshore Petroleum Activities (Conservation of Habitats) Regulations 2001* (as amended), the Secretary of State (for BEIS) is required to consult with the “appropriate nature conservation body” (Regulation 5(2)) on any Appropriate Assessment undertaken. An appropriate conservation body

means such body with responsibilities for providing relevant advice on nature conservation in relation to the land or waters within or adjacent to the relevant site, which the Secretary of State considers appropriate (Regulation 2(1)). This revised definition of the conservation body to consult with was made under amendment in 2007, and better reflects the varied remits of the agencies within England and the devolved administrations, for what is a reserved matter.

An Appropriate Assessment is an assessment, conducted by the Competent Authority (in this case, BEIS), of whether a plan or project will result in an adverse effect on the integrity of a European Site (SAC, SPA). Also there is consultation with the public if it is considered to be appropriate. This does not require the regulator to consult with the nature conservation bodies where AA is not required, but the 2005 PON14A guidance indicates that when an application is received for consent or notification, it is sent to JNCC to obtain comments, with other consultees made aware for other concerns (e.g. navigation, fisheries, military activity).

Note that where surveys are also considered as part of a wider plan of activity assessed in an EIA submitted under the *Offshore Petroleum Production and Pipelines (Assessment of Environmental Effects) Regulations 1999* (as amended), broader consultation would be needed including with relevant prescribed bodies (which would include NRW in Wales), and the public.

Definitions, exemptions or limits to remit

While there are no specific definitions in the Offshore Petroleum Activities (Conservation of Habitats) Regulations 2001 as to what constitutes a “geological survey”, further clarification is given in regulator guidance (DTI 2005), which is, “...geophysical techniques, to gain information concerning the character or position of geological features below the seabed sediments... where an airgun, watergun or vibroseis source is used... the definition includes trials of the techniques used for this type of survey, even if the trials do not aim to provide information on geological features...”. Using this definition, the guidance also notes that certain methods require consent, whereas others require notification. The types of survey in each category are clarified in BEIS’s PETS, and are:

Consent required

- Seismic survey (2D, 3D, 4D)
- OBC/OBS seismic survey
- Seismic vibroseis survey
- Seismic refraction survey
- Multiple component 4C survey (shear wave)
- Sub-bottom profiler (pinger, sparker, boomer or CHIRP)
- Vertical seismic profile (VSP)

Notification required

- Echo-sounder survey
- Multi-beam survey
- Side-scan sonar survey
- Acoustic Doppler current profiler (ADCP) survey

Notification does not eliminate the need to consider effects, and is used by the regulator to consider the potential for likely significant effects on relevant Natura 2000 sites and also Annex IV species in relation to the risk of the operator committing an offence, and the possible need for a European Protected Species (EPS) licence.

Deep geophysical seismic survey, whether 2D or 3D, is almost exclusively undertaken for the purposes of petroleum exploration or to characterise deep geological structures such as saline aquifers which could be used for carbon dioxide or natural gas storage. Legislation to regulate such activities has therefore developed around these purposes rather than generally covering seismic survey as an activity to be subject to consenting.

It is unlikely that deep geophysical seismic survey would be undertaken for other purposes in UK (including Welsh) waters, but if these did not fall within the definitions of regulated activities (i.e. Petroleum or Energy Act related consents) the regulator and formal consenting route is less clear (refer to Section 6.3).

Relevant guidance

DTI (2001). [Guidance notes on the Offshore Petroleum Activities \(Conservation of Habitats\) Regulations 2001](#), 15pp. (currently being updated but remains on the regulator website)

DTI (2005). [Guidance notes for oil and gas surveys and shallow drilling petroleum operations notice No. 14A and 14B](#), 21pp. (currently subject to review but remains on the regulator website. Note that the PON14A/B nomenclature is no longer used for these consents)

JNCC (2017). [JNCC guidelines for minimising the risk of injury to marine mammals from geophysical surveys, August 2017](#), 26pp.

Typical consent conditions and reporting requirements

It is usually a condition of any consent issued that the JNCC (2017) Guidelines for minimising the risk of injury to marine mammals from geophysical surveys must be followed. The guidelines make a distinction between surveys using airguns and high-resolution geophysical surveys using non-airgun sources (SBPs, side-scan sonar, MBES); while advice on the latter will be provided on a case-by-case basis, there are some typical differences in procedures between and within these two groups of sources. MBES surveys taking place in deeper waters and operating at lower frequencies are identified as requiring specific consideration.

Prior to the activity taking place, a pre-commencement notification is provided to BEIS on the timing and location of survey activities, which feed into a cross-regulatory tracker. An activity log and close out report must be submitted to BEIS following completion of the survey. BEIS feed this data into the Marine Noise Registry (MNR).

The close out report must also be submitted to relevant data repositories (Schlumberger Integrated Solutions for seismic surveys, feeding into the oil & gas National Data Repository, and MEDIN for site surveys). For certain surveys, a Marine Mammal Observer and/or a Passive Acoustic Monitoring (PAM) operative may be required. Where used, a Marine Mammal Observer's report must be submitted to BEIS and copied to the JNCC within six weeks of the expiry of the geological survey consent.

Activity tracking and reporting

Applications for survey consents and their status may be viewed via the [UK Energy Portal](#) under the "Standalone operation" tab. Their geographical coverage is shown with reference to UKCS licensing Blocks.

Operators should submit spatial data of relevance to their survey either to Schlumberger Integrated Solutions (who manage the [oil and gas National Data Repository](#)) and/or [MEDIN](#).

Where BEIS have undertaken Habitats Regulations Assessments in relation to geological surveys, these are listed on the [oil and gas offshore environmental legislation pages of gov.uk](#).

6.3. Non-licensable activities

Principal regulatory regime

Underwater acoustic surveys undertaken for purposes not related to Petroleum or Energy Act consents (see Section 6.2 above) do not have a clear consenting route for any UK waters or seas however defined, including those of England, Wales, and other devolved administrations, hence the “Non-licensable activities” title of this section. However, as many acoustic surveys involve the deployment of equipment into the sea (which may constitute a ‘deposit’), the provisions of the *Marine and Coastal Access Act 2009* (as amended) and exemptions made by Order under Section 74 of that Act may be implemented such that some acoustic surveys are licensable activities.

Additionally, underwater acoustic surveys are often included in related consents for other activities which are definitively licensable (e.g. as part of a wider survey scope that includes grab sampling) or as part of an Environmental Impact Assessment (EIA). A broader range of legislation is applicable in England and Wales to such applications which includes [The Marine Works \(Environmental Impact Assessment\) Regulations 2007](#) (as amended), the [Transport and Works Act 1992](#) (as amended), the [Planning Act 2008](#) (as amended). The most relevant type of application to date under this Act is for offshore wind farms, which routinely use underwater acoustic survey for pre-installation survey, post-installation survey and monitoring. Note that offshore wind farm environmental statements tend to concentrate on noise generation from piling and rarely include consideration of geophysical survey for pre-installation or maintenance surveys, even though these may form part of activities associated with the wider development. Consent for individual activities that include marine survey (though not specifically acoustic survey), would be made through the marine licensing process as appropriate, and outside of the *Planning Act 2008* process.

Also in Wales, the [Electricity Act 1989](#) (as amended) for offshore generating stations <350MW capacity), [The Conservation of Habitats and Species Regulations 2017](#) (as amended) and [The Conservation of Offshore Marine Habitats and Species Regulations 2017](#) (as amended).

Wider UK context

Scotland has separate marine licensing provisions under the [Marine \(Scotland\) Act 2010](#) (as amended) for their territorial sea, but the *Marine and Coastal Access Act 2009* remains applicable for offshore waters (i.e. those seaward of territorial waters). It should be noted that under this Act, and that of the *Marine and Coastal Access Act 2009*, “territorial seas” are defined as having their seaward extent at 12 nm, and their landward limit at mean high water spring tides, as well as covering, “the waters of every estuary, river or channel, so far as the tide flows at mean high water spring tide.”

These were drafted in an analogous way to the *Marine and Coastal Access Act 2009* and similarly include no specific provision for underwater acoustic survey as a distinct activity. Other activities may be separately captured by [The](#)

[Marine Works \(Environmental Impact Assessment\) \(Scotland\) Regulations 2017](#), (for territorial waters) or [The Marine Works \(Environmental Impact Assessment\) Regulations 2007](#) (as amended) for offshore waters. Marine renewables are a devolved matter; these and associated development are consented under Section 36 of the [Electricity Act 1989](#) (as amended). The Marine Scotland Licensing and Operations Team (MS-LOT) are a one-stop-shop in Scotland for marine licence or Section 36 applications, and deal with all stages of a project from initial contact through to individual activity consenting. Habitats Regulations Assessments in Scotland are made under [The Conservation \(Natural Habitats, &c.\) Regulations 1994](#).

Activities in Northern Irish waters similarly fall under Part 4 of the *Marine and Coastal Access Act 2009*, with the regime being administered by the Department of Agriculture, Environment and Rural Affairs (DAERA) Marine and Fisheries Division. The legislative framework is broadly comparable to that for England and Wales, with a separate marine plan being produced. The current draft plan (<https://www.daera-ni.gov.uk/articles/marine-plan-northern-ireland>) has a policy on noise. The accompanying text suggests the policy is relevant to determining a consent or licence, but also that, "Proposers are strongly encouraged to consider the life time noise impacts of proposals, such as during exploration, pre-construction, construction, operation and decommissioning". It does not address how the policy would apply where there was no formal consenting route.

Regulator(s)

For marine licensable activities, exemptions, and broader consents which may include an acoustic survey component, NRW, MMO, Marine Scotland, DAERA and BEIS would be expected to be those responsible across the various administrations. Where authorities do not consider a stand-alone acoustic survey to be marine licensable (see below), there is no clear regulator.

Overview

Underwater acoustic surveys (with a purpose other than those specifically covered under a *Petroleum Act* or *Energy Act* consent/licence) were not explicitly included as licensable activities under the [Marine and Coastal Access Act 2009](#) (as amended) and equivalent Welsh instrument, nor are they clearly subject to specific exclusions from licensing made by Order under Section 74 of that Act, either in the text of relevant Orders or associated online information, for example <https://www.gov.uk/government/publications/marine-licensing-exempted-activities/marine-licensing-exempted-activities> and <https://naturalresources.wales/permits-and-permissions/marine-licensing/marine-licence-exempted-activity/?lang=en>. Nonetheless, acoustic surveys which involves the deployment of equipment into the sea or onto the seabed from a vessel may, in some circumstances, be considered to be making a 'deposit' of an object into the sea, and therefore may be considered marine licensable under the *Marine and Coastal Access Act 2009* (as amended); they may also subsequently qualify for an exemption under the [The Marine Licensing \(Exempted Activities\) Order 2011](#) (as amended) For example: <https://www.gov.uk/government/publications/marine-licensing-exempted-activities/marine-licensing-exempted-activities> and

<https://naturalresources.wales/permits-and-permissions/marine-licensing/marine-licence-exempted-activity/?lang=en> . Limitations to the application of this regime to acoustic surveys, and further details on its variability between Wales and elsewhere in the UK, are described in the sections below.

Remit

Article 6 of the Habitats Directive (92/43/EEC, as implemented in the UK by various Regulations noted above) requires that, “*Any plan or project not directly connected with or necessary to the management of the site but likely to have a significant effect thereon, either individually or in combination with other plans or projects, shall be subject to appropriate assessment of its implications for the site in view of the site's conservation objectives.*” No formal definition of what a plan or project constitutes is given in the Directive, nor in any of the implementing Regulations in the UK. The most recent guidance on managing Natura 2000 (Commission notice, Managing Natura 2000 sites The provisions of Article 6 of the 'Habitats' Directive 92/43/EEC. C(2018) 7261) indicates that based on judgements made in a number of ECJ cases that the option of exempting certain activities regardless of scale, from the HRA process does not comply with Article 6(3), including where they are not subject to authorisation.

While the UK has not formally excluded underwater acoustic surveys for certain purposes from assessment under the Habitats Regulations, the uncertainty in the consenting route and use of voluntary notifications suggest that there is the potential for activities to take place without a consideration of whether a site could be significantly affected. The EC (2019) guidance suggests that irrespective of whether an activity is subject to consenting, it should not be excluded from the assessment obligation under Article 6(3) of the Habitats Directive. While this does not provide the requirement for consent, prior notification would allow an appraisal of non-licensable acoustic survey activities taking place in Welsh waters, such that the relevant SNCB can consider the implications for conservation sites and species. Without a related consent to tie any such consideration to, this would, however, present a challenging situation for activity proponents, nature conservation bodies, and regulators. It is not clear who the Competent Authority would be in such a case.

In relation to the potential for an offence to occur in relation to EPS, the responsibility for not committing an offence lies with the person undertaking an activity and not with any conservation body or regulator.

Consenting route and avenue for environmental scrutiny

Where underwater acoustic surveys are **proposed as part of a wider set of activities**, for example those which are subject to EIA or licensing under the *Marine and Coastal Access Act 2009* (e.g. where they are part of wider sampling campaign that includes grab sampling or geotechnical investigations), these will be subject to assessment and can be considered by the Competent Authority, SNCBs and others as part of the EIA/licensing

process. Through this process, there is the potential for licence conditions to be applied, should they be required.

For **stand-alone** underwater acoustic surveys, which are not part of a wider marine licence or other consent process, the situation is more complex. . The majority of activities which require a marine licence relate to the introduction or removal of an “*object or substance*” into the marine environment, with a focus on physical objects and substances or chemicals. Specifically, “*A marine licence is required to deposit any substance or object... either in the sea or on or under the sea bed, from: any vehicle, vessel...*” The introduction of energy (acoustic or otherwise) does not fall within the scope of the legislation. Therefore, it is the action of deploying acoustic survey equipment, rather than the emission of noise (the key pathway of potential environmental effect), which can trigger the need for a marine licence from underwater acoustic surveys.

Through the text of the Regulations themselves, along with guidance and other relevant information available online, the applicability of marine licensing and exemptions to underwater acoustic surveys is unclear. It is only through direct dialogue with the regulators that much of the following information has been ascertained.

English waters and Northern Ireland offshore waters

In English waters and Northern Ireland offshore waters (beyond 12nm from shore), the MMO implement the *MaCAA* and its broad definition of *deposit* to include any object placed in the sea from a vessel (see Section 66 criteria), regardless of whether it remains attached to the vessel or not, to be a marine licensable activity. Therefore, in addition to sources left on the seabed (such as moored ADCPs) any towed or pole-mounted acoustic survey source is considered marine licensable, but hull-mounted sources (which are part of the vessel already in the water) are not (MMO pers. comm., May 2020).

For the purposes of marine licensing, acoustic survey equipment is considered to fall into the category of *scientific instruments* (and their *associated equipment*), the deposit (and removal) of which is listed as an activity exempt from requiring a marine licence under the [Marine Licensing \(Exempted Activities\) Order 2011](#) (as amended), providing certain criteria are met. While not explicitly defined in the Order, it is said to relate to “*the deposit of any scientific instrument or associated equipment in connection with any scientific experiment or survey.*” The MMO’s marine licensing interactive tool provides further definition of a scientific instrument as “*A specialist device or tool, designed to measure, record or analyse data for scientific purposes.* ‘*Associated equipment*’ mean *equipment fundamental to the functioning of the instrument itself.*” The exemption does not apply if the deposit or removal of the scientific instrument: is made for the purpose of disposal; tethered to the seabed; poses a risk to navigation; or, likely to have a significant effect on an MPA (specifically, a Natura 2000 site, Ramsar site or MCZ as relevant), unless the activity is directly connected with or necessary to the management of that site. Prior notification of the activity to the regulator is required for the activity to be registered with an exemption.

Where an acoustic survey activity within the MMO's remit is considered to be a deposit of a scientific instrument, notification is made through the MMO's online Marine Case Management System (MCMS). An interactive tool for marine licensing allows the proponent of the activity to answer a series of questions relating to the activity to determine need for a marine licence and qualification for an exemption. The tool asks if the activity will take place within 200 m of an MPA; if yes, a follow-up question asks if it is likely to have a significant effect on a MPA, with a link provided to [guidance](#) on applying these threshold tests of significance. The guidance encourages the proponent to contact the relevant conservation body if they are in any doubt as to the potential for a likely significant effect on a MPA, noting that enforcement action may be taken if it is later determined that the activity breached such threshold tests. The guidance also notes that the proponent must include, within the exemption notification, an explanation of why the activity is considered exempt and details of any engagement with conservation bodies. Thus there is a level of environmental scrutiny applied, albeit at a high level and with the onus on the proponent to appraise and reach a conclusion on the likelihood that activities will affect a MPA. Potential effects beyond those to MPAs are not emphasised, and the 200 m distance between the activity and an MPA flagged in the interactive tool is an inappropriately small screening criterion for acoustic surveys and MPAs with mobile species features. The notification of an acoustic survey to the MMO as an exempted activity ensures that the activity is registered prior to it taking place, and that likely significant effects on MPAs have at least been considered by the notifier, and provides the regulator with information upon which to assess potential effects. However, while spot checks are performed, not all exempted activities notifications undergo environmental scrutiny by the regulator.

More obviously applicable to underwater acoustic surveys is a dedicated [voluntary notification form](#) of the intent to carry out geophysical (including seismic) surveys, administered by the MMO. This covers a wide range of survey types including various seismic airgun surveys, SBPs, MBES and side-scan sonar (similar to those listed in the OPRED PETS system). The MMO's notification form for geophysical surveys provides an avenue for environmental scrutiny as it requests various details of the planned survey activities (including proximity to MPAs and fish spawning areas), an EPS stage 1 risk assessment, planned mitigation procedures and stakeholder engagement undertaken. It is requested that the form be submitted at least 28 days prior to the survey taking place. However, it is understood that the form is primarily used to gather data to pass on to the JNCC for entry into the MNR, and detailed scrutiny of the environmental effects assessment is not guaranteed (MMO pers. comm., May 2020). Information accompanying the notification form notes that developers (or those undertaking activities) do not need to complete this form where they are using the MNR to provide information on acoustic surveys, which gives limited opportunities for environmental scrutiny (see below). Those submitting a voluntary notification form to the MMO are informed of the need to submit prior notification of the activity as a marine licence exempted activity, where applicable, and reminded of their obligations regarding EPS disturbance. The

structure and future use of this form is currently undergoing review (MMO pers. comm., May 2020).

Welsh and Scottish waters and Northern Ireland territorial waters

At the time of writing, the marine licensing teams of NRW, Marine Scotland and DAERA **do not** consider objects which remain attached/tethered to a vessel (such as a towed or pole-mounted acoustic survey source) to be a *deposit* as defined in the *MaCAA* and therefore the majority of underwater acoustic surveys are not considered to be licensable activities.

In Welsh waters, NRW do not operate an online portal for marine licensing, but provide guidance on the exemption for the deposit of scientific instruments on their [marine licensing web pages](#). These web pages indicate that the exemption does not apply if the deposit is likely to have a significant effect on a MPA, and advises that the proponent contacts the marine licensing team (by email) to provide a description of the proposed activity (including details of the proposed equipment, method, duration and location of the works) such that potential effects on a MPA can be assessed. While this process provides for tracking of activities and environmental scrutiny, the interpretation of a deposit to only include scientific instruments which are no longer attached to a vessel means that the process is only applied to ADCPs and sources deployed on other unattached infrastructure, such as an echosounder mounted on a monitoring platform (e.g. Williamson *et al.* 2017). Therefore, notwithstanding the potential need to obtain an EPS / wildlife licence to avoid an offence on a protected species (see Table 4.1 of McGarry *et al.* (2020) for a useful summary of offences in relation to cetaceans and seals across different parts of the UK), no consent or mandatory prior notification is required for the majority of stand-alone underwater acoustic surveys in Welsh and Scottish waters and territorial waters of Northern Ireland.

For activity tracking purposes, voluntary submission of relevant non-licensable activities to the MNR is encouraged; for example, NRW [web pages relating to the MNR](#) encourage registration of all non-licensable noisy activity, including (but not limited to) seismic survey, SBP and MBES use. MNR submissions provide summary details of the survey activities, including type, source properties, location and dates. However, such submissions alone do not alert agencies to proposed activities. Activities may be submitted to the MNR before they take place, as 'proposed activities'; however, doing so does not automatically notify agencies of their existence, and they may not receive information until after the survey has occurred. The MNR process is designed to facilitate strategic reporting rather than project-specific environmental assessment, and these submissions are not subject to review by default. Consequently, without additional dialogue with the regulator and/or SNCB, a planned non-licensable survey submitted to the MNR is unlikely to undergo environmental scrutiny.

No voluntary notification form system for acoustic surveys (e.g. the MMO form) is operated by agencies of devolved administrations. It is likely that many underwater acoustic surveys will be part of wider activities and associated

consents, and that agencies will be made aware of them at an early stage of the planning process. Prior knowledge of some surveys may also be gathered from voluntary engagement with the regulator, for example if they seek guidance on whether a marine licence or wildlife licence is required. In all such instances, sufficient prior awareness should provide authorities with the opportunity to consider potential environmental effects. However, in the absence of a marine licence, it is not clear what consent an assessment of likely significant effects on MPAs would be associated with. While the occurrence is likely to be low, the potential remains for some underwater acoustic surveys to be undertaken without prior knowledge or scrutiny by NRW and other SNCBs. A lack of such knowledge has the potential to confound cumulative effects considerations for other activities.

Throughout all UK waters, awareness of survey activities may also be established through [notices to mariners](#). These are typically submitted by the proponent of any activity to the relevant local harbour/port authority, or the United Kingdom Hydrographic Office for large projects or those in high traffic areas, (UKHO) in order to make other users aware of activities at sea. However, notice to mariners are not satisfactory means of ensuring prior notification and the environmental review of activities.

Consultation (e.g. with relevant statutory conservation bodies, other Government departments and the public):

Where underwater acoustic surveys form part of a wider consent application (e.g. for a marine licence or if they are included as part of an EIA for development consent) then they may not be subject to consenting in their own right but details are available to consider the potential for effects, and consultation would be as per the standard marine licensing process.

It is noted that for notification of marine licensing exempted activities, or voluntary notification, the onus is on the proponent to determine if there is a likely significant effect on an MPA or the need for an EPS licence, albeit with advice available from the regulator/SNCB where requested. In Wales, if an exemption for scientific instruments is requested, the Marine Licensing Team will consult with NRW conservation advisors to assess the potential for a likely significant effect.

Definitions, exemptions or limits to regulatory remit

As noted above, the approach to regulation of underwater acoustic surveys in the UK has historically resulted from a focus on oil and gas activities, and a lack of specific definition in legislation for undertaking such surveys for other purposes makes their definition in consenting unclear. It would seem that they still have the potential to constitute a “project” within the meaning of the Habitats Directive, and also should be considered in relation to whether an offence could occur in relation to EPS.

A key limitation to the remit of the *Marine and Coastal Access Act 2009* (as amended) and relevant Orders with regard to underwater acoustic surveys is where it is implemented such that an activity is **not** considered to fall within the definition of a deposit of a scientific instrument, with different implementations

in England to Scotland, Wales and Northern Ireland. This equipment deposit approach, and lack of definition of what acoustic sources are considered to be a deposit, results in gaps in the application of marine licensing to underwater acoustic surveys, and a lack of clarity for those undertaking activities.

Tracking of activities through the MNR is limited to impulsive acoustic sources of ≤ 10 kHz, and multibeam echosounders ≤ 12 kHz.

The Welsh National Marine Plan (WNMP) was adopted in November 2019, and includes a specific policy (ENV_05) on underwater noise, such that, *“Proposals should demonstrate that they have considered man-made noise impacts on the marine environment and, in order of preference:*

- a. avoid adverse impacts; and/or*
- b. minimise impacts where they cannot be avoided; and/or*
- c. mitigate impacts where they cannot be minimised.*

If significant adverse impacts cannot be avoided, minimised or mitigated, proposals must present a clear and convincing case for proceeding.” Further, paragraph 196 of the plan indicates, *“Proposals should include a noise impact assessment when required by a public authority”*, but this only relates to proposals requiring consent.

Relevant guidance

MMO [Statutory guidance: Marine Licensing exempted activities, Updated 30 May 2019.](#)

MMO Marine Licensing [Interactive Tool](#).

NRW [Marine Licensing information](#) and [description of exempted activities](#).

Scottish Government (2011). [A Guide to Marine Licensing: Marine Licensing In Scotland’s Seas Under The Marine \(Scotland\) Act 2010 and The Marine And Coastal Access Act 2009.](#)

JNCC (2017). [JNCC guidelines for minimising the risk of injury to marine mammals from geophysical surveys. August 2017.](#)

Typical consent conditions and reporting requirements

Depending on the nature of the activity and its consenting route (e.g. as part of wider survey) there may be no formal conditions. It would be expected that JNCC (2017) Guidelines for minimising the risk of injury to marine mammals from geophysical surveys would be followed, and that where any notification was made, data would be submitted to the MNR as appropriate.

Activity tracking and reporting

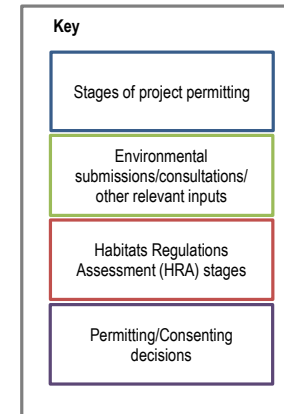
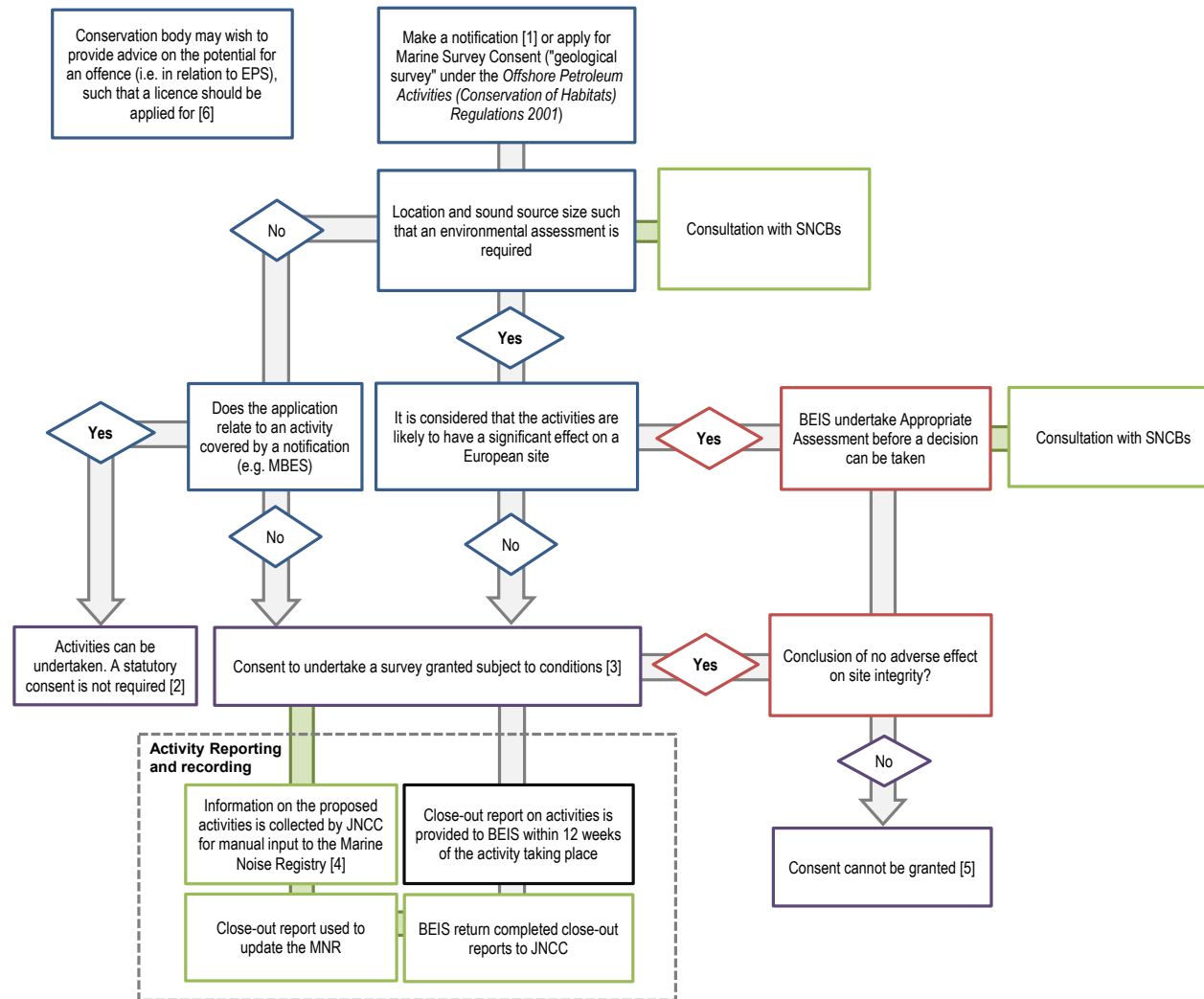
Wales currently relies on voluntary submission of activities to the MNR, while a very small proportion of activities may be tracked through notification as a marine licence exempted activity (scientific instruments). Notification of acoustic surveys as an exempted activity to the MMO (covering a wider proportion of activities), or via direct MNR submissions or their voluntary notification form, provide means of tracking non-licensable acoustic surveys in England. Throughout the UK, knowledge of some surveys may also be gathered from voluntary engagement or else where a marine licence application includes details of an underwater acoustic survey as part of a wider

which has components that are licensable. It is understood from NRW that a limited number of surveys (e.g. two in the past year) have taken place without NRW having prior knowledge.

JNCC (2017) note, "For other industry sectors [other than oil and gas] and respective regulators, it is recommended that similar procedures regarding MMO [marine mammal observer] reporting should be followed, but this should be agreed with the relevant regulator and SNCB(s)."

Figure 5 - High-level overview of consent process for underwater acoustic surveys

A. Licensable or otherwise consented activities



Notes

[1] Note that while a formal consent is not required for activities subject to notification, the submission made through the BEIS PETS generally includes a brief EIA Justification, which includes a description of the activities, an indication of environmental sensitivities and summary assessment.

[2] JNCC record from the UK Energy Portal that MBES is proposed, but this is not entered into the MNR and no close-out reporting or confirmation that the activity actually took place is recorded.

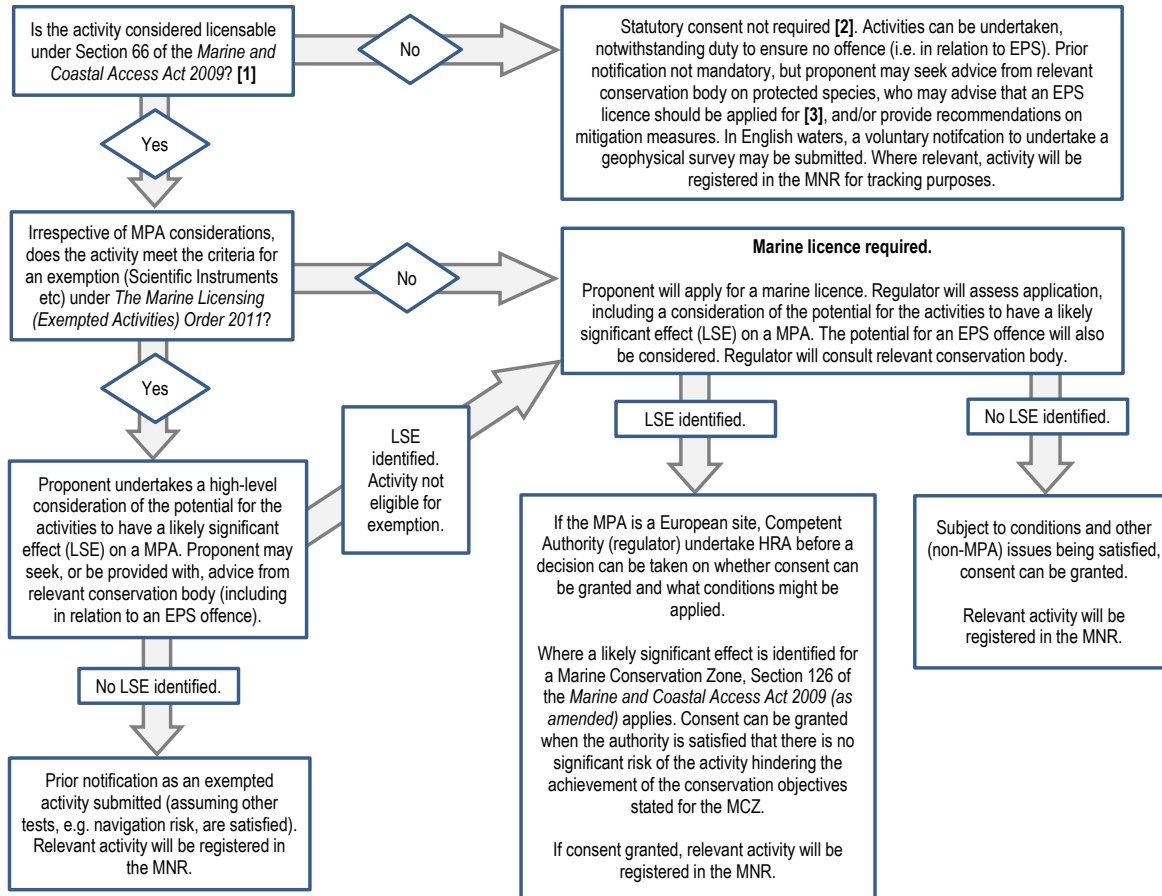
[3] As part of consent conditions, operators would be required to follow the JNCC guidelines for minimising the risk of injury to marine mammals from geophysical surveys (JNCC 2017). Condition of consent that Seismic Survey Closeout Report completed (may include submission of Marine Mammal Observer and Passive Acoustic Monitoring reports)

[4] This information is manually collected at present through the UK Energy Portal, until an integrated system of data capture between the portal and MNR has been established.

[5] Article 6(4) of the Habitats Directive provides a derogation which would allow a plan or project to be approved in limited circumstances even though it would or may have an adverse effect on the integrity of a European site (see: Defra 2012).

[6] Noting that it is the responsibility of the survey applicant to obtain such a licence if it is required

B. Non-licensable activities (excluding where they form part of a related consenting process)



Notes

[1] To be considered licensable, the activity must meet the definition of a deposit of any substance or object within the UK marine licensing area, either in the sea or on or under the sea bed. This is currently implemented differently by the MMO to other regulatory authorities in the UK; in English waters and offshore waters of Northern Ireland, any device placed in the water (including towed or pole-mounted acoustic sources which remain tethered to a vessel) is considered to meet the criteria of a deposit from a vessel and treated as licensable; in Welsh and Scottish waters, and territorial waters of Northern Ireland, devices which remain tethered/attached to a vessel are not treated as licensable. In all waters, hull-mounted acoustic survey sources are **not** treated as licensable; sources tethered to the seabed (e.g. ADCP) are licensable in all UK waters.

[2] If an activity is not licensable, there is no route to issuing a formal consent. Note that under a strict interpretation of the Habitats Directive, activities could constitute a project irrespective of whether there is a formal consenting mechanism, but the practicalities of considering such activities through this process is not clear (e.g. tying this process to a consent, and who the Competent Authority is in such cases). Refer to EC (2020).

[3] Noting that it is the responsibility of the survey proponent to obtain such a licence if it is required.

6.4. Summary and recommendations

Deep geophysical seismic survey (i.e. that using airgun arrays) is almost exclusively undertaken for the purposes of petroleum exploration or to characterise deep geological structures such as saline aquifers which could be used for carbon dioxide or natural gas storage. Legislation to regulate such activities has developed around these purposes rather than generally covering underwater acoustic survey as an activity to be subject to consenting. The regulatory regime covering surveys for such purposes does not clearly define what a “geological survey” encompasses (i.e. specific types of equipment); however, earlier regulator guidance indicates that other acoustic survey techniques (i.e. high-resolution site surveys using SBPs and seafloor mapping sources) are included and require either consent or notification depending on the type of source used. Regardless of the acoustic survey type, this regulatory regime provides a clear route for environmental assessment, consenting and tracking of activities, but for restricted purposes.

As oil & gas and the majority of carbon dioxide or natural gas storage (excluding Scottish territorial waters) activities are reserved matters, the consenting route is the same for all UK seas, albeit with a change in those relevant conservation bodies who should be consulted on the HRA process for related surveys. The differences in how geophysical surveys for other purposes are considered by consenting bodies across constituent countries therefore largely relates to matters which have been devolved; which variously includes all or some renewables (dependant on capacity of proposals) and broader marine licensing in relevant constituent country waters.

Where stand-alone underwater acoustic surveys (i.e. not part of a wider programme of activities) are undertaken for purposes which do not fall within the *Petroleum Act* or *Energy Act* regime (above), the formal consenting route is less clear. In some circumstances, they are subject to marine licensing under the *Marine and Coastal Access Act 2009* (as amended), with many surveys qualifying as exempted activities under relevant Orders made under the Act. However, it is the action of deploying equipment, rather than the emission of noise (the key pathway of potential environmental effect), which results in the activity being licensable, and therefore not all acoustic sources are applicable. Furthermore, definitions are lacking, and different interpretations of a deposit between the MMO and other relevant UK regulators results in inconsistent implementation of the marine licensing regime to acoustic surveys across jurisdictions.

Comprehensive coverage of acoustic survey activities under the *Marine and Coastal Access Act 2009* could possibly be achieved if certain types of acoustic energy were considered to be a deposit of an *object or substance* into the sea. However, this represents a considerable change in the current implementation of the Act, and the practicality of such a change would require careful consideration. For example, it would be necessary to restrict the scope of acoustic emissions considered (e.g. only low-frequency impulsive noise included within the MNR).

While deep geophysical seismic survey for purposes other than those covered by the *Petroleum Act* and *Energy Act* may be uncommon, SBP surveys for characterising the shallow (i.e. <100 m) seabed geology and detailed seabed mapping is widely used in other marine industries; for example, offshore wind, dredging, and archaeological investigation. Consideration of the potential impacts of such activities is often by association with other aspects of an overall plan of work which is regulated; for example, a survey involving geotechnical work that also includes an underwater acoustic survey. For stand-alone underwater acoustic surveys, mandatory prior notification as a marine licence exempt activity, or voluntary prior notification, provide a means of tracking and assessing such activities, but they do not guarantee scrutiny of potential environmental effect, beyond a reliance on the proponent themselves to assess the potential for effects on MPAs or EPS.

Where those undertaking activities which do not have a clear consenting or prior notification route are not proactive in approaching regulators or nature conservation bodies for advice on their operations, then these activities have the potential to be undertaken without knowledge or scrutiny of potential environmental effect. For example, in Wales, a reliance upon MNR submissions as a means of tracking non-licensable acoustic surveys provides very limited opportunity for environmental scrutiny. Even though the scale of such activity is, anecdotally, considered to be small, there is still the potential for effects or even offences to be committed. Where underwater acoustic surveys form part of a project which is more broadly subject to EIA the potential effects of these may be considered at that stage; however, an examination of many recent offshore wind farm EIAs suggests that has not been the case, with the focus of noise assessments being pile-driving.

The plan policy covering underwater noise (ENV_05) in the Welsh National Marine Plan generally indicates that, "*Proposals should demonstrate that they have considered man-made noise impacts on the marine environment...*", without any reference to the limitations of the definitions of the regulatory regime. Further, paragraph 196 of the plan indicates, "*Proposals should include a noise impact assessment when required by a public authority*", but whether this is at the discretion of the authority is not clear. This is not unique to the Welsh marine plan and reflects the broader approach to plan policies in English and Scottish waters.

In conclusion, underwater acoustic survey may or may not be subject to formal consenting, notification and assessment depending on its purpose, the acoustic source used, and where the activity is to take place. The nature of underwater acoustic surveys not subject to the *Petroleum Act* or *Energy Act* regime is such that they are not well captured under the definition of what is licensable under the *Marine and Coastal Access Act 2009* (as amended), and therefore, relevant Orders.

Irrespective of whether a consent is formally required for an underwater acoustic survey, there remains an obligation on any person who could commit an offence with regard to EPS (and species protected under other national legislation), to obtain an EPS / wildlife licence, as appropriate. More broadly,

the variation across regulatory regimes as to whether a consent is required for underwater acoustic surveys on the basis of its end use is confusing, and a lack of a consent to relate any assessment (EIA or HRA) and therefore Competent Authority also raises questions over how HRA could be applied, should it be clear that a significant effect may be likely.

Recommendation

In the absence of a route to licence underwater acoustic surveys in Welsh waters, a voluntary prior notification system (e.g. an online form) could provide a useful interim avenue for monitoring non-licensable surveys. Its adoption through policy or guidance, with subsequent promotion, could encourage engagement, provide opportunity for scrutiny and advice on mitigation measures or risk of an EPS offence, inform cumulative assessments, and facilitate more complete recording of relevant noise in the MNR. Furthermore, such a system could enhance understanding of non-licensable activities in Welsh waters and whether a review of what is licensable is needed.

An alternative approach would be to adopt the same implementation of the *Marine and Coastal Access Act 2009* (as amended) as the MMO, where the placement of acoustic survey equipment in the water that is still attached to the vessel is considered a deposit and therefore a licensable activity. This would bring towed and pole-mounted acoustic sources under the marine licensing regime (therefore including the majority of higher amplitude, lower-frequency sources), but still exclude hull-mounted sources. In many circumstances, the survey activities would be eligible for an exemption under *The Marine Licensing (Exempted Activities) (Wales) Order 2011*. Such an approach would ensure prior notification and an option for consent on which to tie HRA where necessary. However, it would need to be accompanied by procedures which ensure appropriate environmental scrutiny, and does not provide complete coverage of all acoustic sources. Regardless of the actions taken, consistent implementation of relevant parts of the Act among different jurisdictions within the UK is strongly encouraged, as is accompanying guidance relevant to acoustic surveys.

7. Evidence of effects on marine species

Potential effects of anthropogenic noise on receptor organisms range widely, from masking of biological communication and small behavioural reactions, to physiological changes (e.g. stress response), hearing damage, physical injury and mortality. The time component is also important and ranges widely, from instantaneous, temporary, prolonged and chronic. In addition to direct effects, indirect effects may also occur, for example via effects on prey species.

From a management point of view, effects may need to be evaluated both at the individual and at the population level. Not every effect observed in a study at the individual level may have consequences that can affect the health of the population, and not all effects that may ultimately result in a long-term population effect can be measurable at the level of the individual. This presents a challenge when evaluating evidence and its wider implications.

While generally the severity of effects tends to increase with increasing exposure to sound, our understanding of this relationship is still poor and dose-response curves are largely elusive. It is common to draw a distinction between physical (including auditory) injury and behavioural disturbance, especially with regards to marine mammals and fish, and this is reflected in management policy.

For physical injury, broadly applicable threshold criteria have been recommended (marine mammals - Southall *et al.* 2007, 2019; NMFS 2016, 2018; fish - Popper *et al.* 2014) based on pressure levels of received sound. With regard to behavioural disturbance, the development of broadly applicable threshold criteria is problematic; probability of a response is a function of species, individual and context and is highly variable. Received sound level may not be a reliable predictor and in fact in many cases, it is not known which aspect(s) of a sound is the key driver eliciting the behavioural response (i.e. exposure level, peak pressure, rise time, frequency content) (Hawkins *et al.* 2015).

Marine mammals, and in particular cetaceans, are regarded as the most sensitive to underwater noise effects, and are the group for which the greatest evidence base exists (e.g. reviews in Richardson *et al.* 1995; NRC 2003, Southall *et al.* 2007; Gomez *et al.* 2016). Fish are also sensitive to sound and have received considerable attention, particularly species of economic value (e.g. reviews in Popper *et al.* 2014; Slabbekoorn *et al.* 2019), whereas investigations into the effects of underwater noise on marine invertebrates are more limited but the evidence base has grown in recent years (review in Carroll *et al.* 2017 and see Section 7.3). While diving birds have long been recognised as potentially sensitive to high amplitude underwater noise, very little evidence of effects exists, and few studies have addressed their underwater hearing abilities or the effects of exposure to noise.

The bulk of evidence on the effects of acoustic surveys relates to seismic survey and military sonar (the latter almost exclusively for marine mammals). Evidence relating to SBPs and seafloor and water column mapping sources is

very limited. A considerable volume of evidence relating to percussive pile-driving has developed over the past two decades in response to increasing offshore wind development (e.g. Popper *et al.* 2014, Brandt *et al.* 2018, Graham *et al.* 2019); while relevant to the effects of low-frequency impulsive sound, these are beyond the scope of the current review.

7.1. Marine mammals

7.1.1. Hearing abilities and use of sound

All marine mammals produce sound, and sound production has been shown to play a role in a variety of behaviours, including those related to mating, rearing of young, social interaction, group cohesion, and feeding (Erbe *et al.* 2016). Odontocete (toothed) cetaceans possess a biosonar system to locate and identify prey and provide information on the structure of their surroundings (echo-location), and there is evidence that all marine mammals use biological sounds to find prey (Gannon *et al.* 2005) and avoid predators (e.g. Deecke *et al.* 2002).

A comprehensive review of information on hearing, sound production and the effects of noise on hearing in marine mammals has recently been published (Southall *et al.* 2019). We do not attempt to reproduce this here, but note the categorisation of species into different functional hearing groups according to an assessment of their auditory abilities (Table 3 lists those of relevance to species occurring in Welsh waters, and these are represented graphically alongside acoustic survey sources in Appendix 2). For each functional hearing group, estimated audiograms, weighting functions, and underwater noise exposure criteria for the onset of auditory effects (PTS and TTS) of impulsive and non-impulsive noise are provided. Permanent and temporary loss of hearing sensitivity are referred to, respectively, as PTS (permanent threshold shift) and TTS (temporary threshold shift). In both cases, these describe a reduction in hearing sensitivity at one or more frequency bands, as indicated by differences between pre- and post-exposure audiograms of the subject individual. In the case of TTS, the reduction in sensitivity recovers over time (duration variable), whereas in PTS the reduction in sensitivity is permanent and commonly equated to injury. How signals from different acoustic sources may be distinguished as impulsive or non-impulsive is unclear, especially for those sources where operating parameters can be highly variable (see page 29). The Very high-frequency cetacean functional hearing group, which is primarily informed by evidence from harbour porpoise, shows the highest overall sensitivity to sound with the lowest threshold criteria for the onset of PTS.

Recent developments of note in the field of marine mammal hearing, which are relevant to species occurring in Welsh waters, include a further examination of the onset of TTS in captive harbour porpoise and harbour seal, recently presented by Kastelein *et al.* (2019). Recent tests have improved the reliability of the TTS onset curve for both species: results show harbour porpoise hearing to be slightly less susceptible to low-frequency sound, and much less susceptible to high-frequency sound, than formerly assumed. Harbour seal

hearing is much less susceptible to low-frequency sound, and more susceptible to high-frequency sound, than formerly assumed. Tests were not performed on grey seal.

Table 3 - Marine mammal functional hearing groups and estimated hearing ranges for species occurring in Welsh waters

Functional hearing group Species common in Welsh waters	Estimated hearing range (region of greatest sensitivity) [frequency of peak sensitivity]
Low-frequency cetaceans Minke whale (<i>Balaenoptera acutorostrata</i>)	7 Hz to 35 kHz (200 Hz to 19 kHz) [5.6 kHz]
High-frequency cetaceans Bottlenose dolphin (<i>Tursiops truncatus</i>) Common dolphin (<i>Delphinus delphis</i>) Risso's dolphin (<i>Grampus griseus</i>)	150 Hz to 160 kHz (8.8 kHz to 110 kHz) [58 kHz]
Very high-frequency cetaceans Harbour porpoise (<i>Phocoena phocoena</i>)	275 Hz to 160 kHz (12 kHz to 140 kHz) [105 kHz]
Phocid seals in water Grey seal (<i>Halichoerus grypus</i>)	50 Hz to 86 kHz (1.9 kHz to 30 kHz) [13 kHz]

Source: Southall *et al.* (2019). Notes: The region of greatest sensitivity represents parameters f_1 and f_2 , which are the bounds of the flat, central portion of the frequency-weighting curve region; the frequency of peak sensitivity represents parameter f_0 .

Also of relevance to TTS and corresponding thresholds are the results of Finneran *et al.* (2016, 2019), showing that captive bottlenose dolphins could be conditioned to temporarily reduce their hearing sensitivity in response to a warning sound prior to exposure to an intense tone. The level of suppression was frequency-specific, with a reduction in TTS thresholds as large as 40 dB for some frequencies, and could be maintained for at least 31 seconds. The mechanism for this phenomenon is not yet clear. Such 'self-mitigation' of impending noise exposures may allow marine mammals to reduce noise impacts if they are warned of impending high-intensity noise; for example, by ramping up exposure levels. The potential for self-mitigation should also be considered when interpreting TTS data (Finneran 2019).

7.1.2. Evidence of effects on marine mammals

The risk of auditory injury (hearing loss) to marine mammals from acoustic surveys can be assessed by modelling the propagation of sound from the source in relation to threshold criteria corresponding to the sound levels at which onset of PTS would be expected to occur. It is recognised that geophysical surveys (primarily regional-scale 2D and 3D seismic) have the potential to generate sound that exceeds thresholds of injury, but only within a limited range from source (tens to hundreds of metres). For airgun arrays used in site surveys and VSP, the range from source over which injury may occur will be smaller. Within this zone, adherence to the mandatory JNCC (2017)

guidelines is currently considered to be sufficient in minimising the risk of injury.

With respect to disturbance, it has proved much more difficult to establish broadly applicable threshold criteria based on exposure alone; this is largely due to the inherent complexity of animal behaviour where the same sound level is likely to elicit different responses depending on a variety of contextual factors such as behavioural state, group composition (e.g. with/without calf) and exposure history. More severe behavioural responses are not consistently associated with higher received sound levels, and vice versa (review in Gomez *et al.* 2016).

In this review, we focus on behavioural responses of marine mammals to acoustic surveys, summarising key studies and recent research of relevance to Welsh and wider UK waters. This is a particularly active area of research which has benefitted greatly from developments in animal-borne tag technology and the proliferation of passive acoustic monitoring. We focus on responses to seismic surveys and species of relevance to Welsh and wider UK shelf waters, but also give attention to evidence of effects (or potential effects) from other acoustic survey sources (i.e. non-airguns) as these are not widely documented elsewhere. Limited consideration is given to military sonar as evidence suggests activity in Welsh waters is likely to be low (Section 5.5), and the species most at risk of effects are considered to be deep-diving odontocetes, which are rarely recorded in Welsh waters.

Seismic (airgun) surveys

An analysis of 16 years of marine mammal observer data from seismic survey vessels in UK and adjacent waters highlights the variability of behavioural responses, although some general patterns are apparent (Stone *et al.* 2017). For larger airgun arrays (≥ 500 in³), most species showed reduced detections when airguns were active vs inactive; such effects were less evident for smaller arrays (< 500 in³), although detection rates for harbour porpoise were also significantly lower for smaller arrays when active vs inactive. While the median closest distance of approach to airguns was greater when active vs inactive for most species, this was statistically significant in less than half the species for which sufficient data were available (including harbour porpoise, bottlenose dolphin, white-beaked dolphin, white-sided dolphin and killer whale). A strong effect was also reported for common dolphin (median 150 m closest approach when airguns were inactive vs 1,500 m when active), but sample size was low. Several species, including harbour porpoise and minke whales, showed significantly more avoidance (e.g. travelling away) from larger arrays when active.

From a meta-analysis of observer data from seismic surveys (primarily large or very large arrays) undertaken in the Gulf of Mexico and off West Africa and Australia, Milne *et al.* (2019) reported similar findings to those of Stone *et al.* (2017). While there was some variability in results between regions and species groups, there was a general pattern of reduced sighting rates and increased distances from the seismic source during periods of full power airgun activity when compared to periods of inactive airguns.

Also using marine mammal observer data from seismic vessels, Kavanagh *et al.* (2019) examined cetacean sighting rates during 10 surveys conducted between 2013-2016, together covering some 880,000 km² of the north-east Atlantic west of Britain and Ireland. A three-way comparison was made between active and inactive airgun periods from seismic vessels and also independent control data, collected by observers on 16 research cruises across the same region from 2015-2017. Relative to the control data, modelled sightings were significantly lower during active airgun firing periods for both baleen and toothed whales. Modelled sightings were also significantly lower during active airgun periods relative to inactive periods on the survey vessel, but not for baleen whales. No information on source characteristics was provided, although the distribution of seismic surveys suggest that they were primarily regional-scale 2D/3D.

Of particular relevance are acoustic observations of harbour porpoise responses to a 10-day 2D seismic survey in the Moray Firth covering 200 km² (Thompson *et al.* 2013). Source levels of $L_{pk,pk}$ 242-253 dB re 1 μ Pa at 1 m were estimated from the 470 in³ airgun array deployed. Within 5-10 km from the source, received levels were estimated to be between $L_{pk,pk}$ 165 and 172 dB re 1 μ Pa, with $L_{E,p}$ for a single pulse between 145 and 151 dB re 1 μ Pa² s. A large array of acoustic loggers recorded a relative decrease in the density of harbour porpoises within 10 km of the survey vessel and a relative increase in numbers at distances greater than 10 km. Detection rates from concurrent digital aerial surveys showed a decrease during the survey period within 10 km of the vessel and an increase at greater distance; this supports the assumption that changes in acoustic detections corresponded to changes in abundance. However, effects were short-lived, with porpoise returning to affected areas within 19 hours after cessation of activities, and a decline in this 'waiting time' through the 10-day survey - suggesting that the observed disturbance response declined with ongoing exposure, as has also been observed for harbour porpoise in response to pile-driving in the Moray Firth (Graham *et al.* 2019). For those animals which stayed in proximity to the survey, there was a 15 % reduction in buzzing activity associated with foraging or social activity; however, a high level of natural variability in the detection of buzzes was noted prior to survey (Pirodda *et al.* 2014). Overall, it was concluded that while short-term disturbance was induced, the survey did not lead to long-term or broad-scale displacement (Thompson *et al.* 2013).

Thompson *et al.* (2013) note that source levels from the 2D survey were of lower magnitude than some large-scale seismic surveys, and that larger arrays with higher source levels may elicit stronger responses in the near field. A recent study of the effects of a large 3D seismic survey in the Danish sector of the North Sea on harbour porpoise echolocation activity are of direct relevance (Sarnocińska *et al.* 2020). The source comprised a 3,570 in³ airgun array and the survey lasted 103 days, with seismic activity occurring on all but 17 days, covering an area of 1,121 km². Acoustic loggers were deployed inside and adjacent to the seismic survey area, before, during and after the survey over a total duration of 9 months. Harbour porpoises were detected at all stations throughout the study period. Three different measures of porpoise activity

showed a dose-response effect, with the lowest activity closest to the source vessel increasing up to a range of 8-12 km, beyond which baseline acoustic activity was attained; no general displacement could be detected compared to reference stations at 15 km from the seismic activity. The lowest porpoise acoustic activity was recorded at $L_{E,p}$ for a single pulse of 155 dB re 1 $\mu\text{Pa}^2 \text{ s}$ - a similar but slightly higher level to that estimated by Thompson *et al.* (2013) at distances where harbour porpoise detections were reduced. Also similar to Pirotta *et al.* (2014) and Thompson *et al.* (2013), the study found no long-term and large-scale displacements of porpoises throughout the survey. The authors note that it is not known whether the same animals remained in the area during the survey or if displaced animals were continuously replaced by a flux of new animals moving into the area.

The most recent UK Offshore Energy Strategic Environmental Assessment (OESEA3, DECC 2016) concluded that a conservative assessment of the potential for marine mammal disturbance from seismic surveys will assume that operating airguns will affect individuals within 10 km of the source, resulting in changes in distribution and a reduction of foraging activity, but that the effect is short-lived. The applicability of this value of 10 km to other marine mammals is supported by harbour porpoise showing greater sensitivity to hearing damage and apparently stronger responses to anthropogenic noise than other UK shelf species. While it is acknowledged that the airgun array used in Thompson *et al.* (2013) is smaller than those used in regional-scale surveys, the comparable findings of Sarnocińska *et al.* (2020) from a much larger source provide further evidence for the likely spatial and temporal extent of disturbance to marine mammals from seismic survey.

Responses of five harbour porpoise tagged in Danish waters to a brief exposure of pulses from a 10 in³ airgun were reported in van Beest *et al.* (2018). At the time of exposure, porpoises were located between 420-690 m range from the source, and received $L_{E,p}$ of between 135-147 dB re 1 $\mu\text{Pa}^2 \text{ s}$. Results further highlight the variability of responses between individuals, with no quantifiable responses in three individuals, and shorter and shallower dives in two individuals for up to 8 hours post-exposure, one of which also exhibited rapid and directed movements away from the exposure site.

While there is a growing body of evidence to suggest that seismic surveys and other anthropogenic underwater noise may disrupt foraging behaviour (e.g. vessels, Wisniewska *et al.* 2018; pile-driving, Graham *et al.* 2018), very little is known of the energetic consequences of this in terms of impact on survival and reproduction, and the broader implications of such effects at the population-level. Using inputs on estimated levels of disturbance, stochastic population models can be used to assess subsequent effects on population parameters. The Interim Population Consequences of Disturbance (iPCoD) model (King *et al.* 2015) is one such approach, where, for several UK species, expert elicitation has been used to derive probability distributions of the effects of noise-related behavioural disturbance on vital rates such as adult and calf survival. These probability distributions were recently updated to reflect new empirical data and improved elicitation methods (Booth *et al.* 2019). Alternative approaches to estimating population-level effects include models based on

animals movement alongside foraging and energetics, as recently demonstrated by Nabe-Nielsen *et al.* (2018) with respect to North Sea harbour porpoise and offshore wind construction noise.

Military sonar

Understanding of the behavioural responses to military sonar has increased considerably in recent years. Reviews of evidence are provided by Southall *et al.* (2016), and, most recently, in Harris *et al.* (2018). This is an area of research which has benefitted greatly from improvements to animal telemetry, allowing controlled-exposure experiments to provide fine-scale information on the movement parameters of individuals exposed to sonar and other sounds, including accurate measures of received level from an animal-borne hydrophone (e.g. DeRuiter *et al.* 2013; Goldbogen *et al.* 2013; Isojunno *et al.* 2016; Wensveen *et al.* 2019).

The majority of studies have focussed on beaked whales and other deep-diving odontocetes, following atypical mass strandings that were spatio-temporally associated with MFAS activities (review in Bernaldo de Quirós *et al.* 2019) with evidence of decompression-like injuries in some stranded individuals suggesting alteration of dive behaviour (e.g. Jepson *et al.* 2003). More recently, evidence for responses of baleen whales has been accumulating (e.g. minke whales - Kvadsheim *et al.* 2017, Harris *et al.* 2019a; blue whales - Southall *et al.* 2019; blue, fin and humpback whales - Harris *et al.* 2019b). Studies have shown that responses vary between and within individuals and populations, with many contextual variables likely to affect the probability of response. However, in most species studied, individuals responded to active sonar sounds in a manner similar to, but typically less severely than, their responses to the calls of predators (killer whales). Cessation of echolocation, horizontal avoidance, increased travel speed and alteration of dive parameters are characteristic responses and may be energetically costly (e.g. Isojunno *et al.* 2016; DeRuiter *et al.* 2017).

Controlled exposure experiments on smaller cetaceans in the field are more challenging due to their lack of suitability for most tag designs. Recent work by Casey *et al.* (2019) investigated the responses of dolphins to sonar exposure off southern California without tags, instead using combined land-and vessel-based observations, unmanned aerial vehicles and passive acoustic monitoring, although this was logistically complex. Behavioural responses of harbour porpoises to various sonar sounds have been investigated among small numbers of animals in a captive facility (e.g. Kastelein *et al.* 2015, 2018), but not in free-ranging animals. Increases in respiration rates, movement away from the source and leap behaviours have been reported in some circumstances, although responses are variable. The presence of higher frequency side bands appears to increase behavioural responses (Kastelein *et al.* 2015). Exposure of captive bottlenose dolphins to simulated MFAS signals showed that while they may quickly habituate to sound exposures below a certain level (received $L_{p,rms}$ of ≤ 160 dB re 1 μ Pa), particularly if there is food motivation, a rapid increase in abandonment of behaviours occurred at received $L_{p,rms} \geq 175$ dB re 1 μ Pa (Houser *et al.* 2013).

Other acoustic survey sources

In comparison to the work on airguns and military sonars, potential effects from other acoustic surveys have received much less attention. This is largely to the higher frequency signals and greater directionality typical of many SBPs and seafloor mapping sources, which, even with high source levels, cannot achieve comparable exposure levels and coverage. Data to quantify emitted sound fields have only recently been systematically collected (see Section 5.4.2) and, although the work is partly ongoing, it does support the long-held assumption of a lesser potential of effects on marine mammals (Halvorsen & Heaney 2018). Available evidence on the effect of acoustic sources other than airguns is presented below; it includes a report on a sparker survey, one on an ADCP, and the rest on echo-sounder equipment.

Di Iorio and Clark (2010a) reported the vocal behaviour of blue whales to be affected by a survey using a sparker SBP; increased call production was detected on days with the sparker in operation even though exposure was low (mean estimated exposure: $L_{pk,pk}$ 131 dB re 1 μ Pa and $L_{E,p}$ 114 dB re 1 μ Pa² s). It has been argued that uncertainty remains on the potential for other factors to have affected the whales, given the lack of knowledge of specific survey details and the opportunistic nature of this analysis (Pinet *et al.* 2010, Di Iorio & Clark 2010b).

Risch *et al.* (2012) found singing in humpback whales to be reduced at the same time as an experiment using ocean acoustic waveguide remote sensing (OAWRS) was in operation. This OAWRS experiment was proof-of-concept for a unique fish monitoring technique capable of imaging instantaneously across an area of 100 km diameter (Makris *et al.* 2006); it used a vertical source array to emit low-frequency modulated pulses (1 s duration, 50 Hz bandwidth, centred at 415, 735, 950 and 1,125 Hz). The study site where the reduction in singing was reported was approximately 200 km from the source, but hydrophones there detected low level signals which were clearly from OAWRS based on their frequency and duty cycle. The observations were contested by the OAWRS research group which investigated the synchronous behaviours of humpback whales and spawning herring as part of the OAWRS efforts and found no effect of sonar on song occurrence in their study areas (Gong *et al.* 2014). At least in part, the difference in observations could be related to different behavioural contexts between the study sites (Risch *et al.* 2014).

A key event in focusing attention on potential impact from acoustic surveys was the highly unusual mass stranding of melon-headed whales in Madagascar in 2008 for which a high-powered 12 kHz multi-beam echo-sounder system (MBES) was implicated as the only plausible behavioural trigger. Before reaching this conclusion, a model of sound generated during the survey was developed; the system's high output power, low frequency and complex combination of 100+ beams resulted in a large area (tens of kms) ensonified at levels detectable by the whales, but not at levels likely to cause any direct physical and auditory damage. This MBES operation may have triggered an avoidance behaviour but the ultimate mass stranding is likely a consequence of the combination between behaviour and local topography, with the whales unable to return to deep water once they had entered a

shallow lagoon (Southall *et al.* 2013). Whether marine mammals in areas of greater anthropogenic activity, such as the North Atlantic, would be less or more prone to respond adversely to a similar sound exposure is unknown. Nonetheless, in response to the findings of the investigation into the Madagascar mass-stranding, high-powered MBES systems with a central frequency of ≤ 12 kHz have been identified as requiring inclusion into the Marine Noise Registry (JNCC 2016).

In recent years, the potential effect of other echo-sounders has been examined. It was generally assumed that higher frequency operations would be outside the hearing range of marine fauna but the evidence has shown that most systems emit energy not just within the specified centre frequency of interest but also above and below it (i.e. harmonics and sub-harmonics), broadening the potential for overlap. For example, it has been shown that the scientific echo-sounder SIMRAD EK60 operated at 120 kHz and 200 kHz also produces broadband energy in the range 70-100 kHz and 90-150 kHz respectively, which are within the hearing ranges for odontocetes and seals (Risch *et al.* 2017). This and higher frequency systems are also being increasingly applied in marine mammal studies to monitor prey distribution and their interaction, and are being explored as monitoring tools to assess risk of collision by tracking the behaviour of marine mammals, fish and seabirds around tidal turbines. In all cases where echo-sounders are used to monitor behaviour, it is particularly important to establish whether the signals emitted by these sources have the potential to elicit a behavioural response, to avoid any erroneous interpretation of results.

During broad-scale cetacean assessment surveys conducted as part of the Atlantic Marine Assessment Program for Protected Species (AMAPPS), acoustic detection of beaked whales were found to be reduced to a minimum (3 %) on days when a suite of Simrad EK60 echo-sounders was used concurrently to characterize the distribution of prey along survey lines (Cholewiak *et al.* 2017). The echo-sounders were operated simultaneously at frequencies ranging from 18 to 200 kHz, and a maximal power output of 1,000 W to reach down to 3,000 m depth. The effect was not as obvious when analysing abundance data from visual surveys (156 groups of beaked whales were sighted on days without echo-sounder as opposed to 100 groups with active transmission) suggesting that whales remained in the wider area of operation but changed their behaviour and ceased echo-location almost entirely. This observation is comparable to studies of naval sonar on beaked whales and other cetacean species where a cessation of feeding and a change in vocalisation are a characteristic early response (e.g. Tyack *et al.* 2011; de Ruiter *et al.* 2013; von Benda-Beckmann *et al.* 2019).

A Simrad EK60 operating at 38 kHz with 2,000 W power was the focus of a very carefully-designed and executed tagging experiment to investigate the behavioural responses of short-finned pilot whales (Quick *et al.* 2014). Signals were within the whales' hearing range and maximum received levels at each tag were in the range of 117-125 dB re 1 μ Pa (Unspecified if $L_{p,pk}$, $L_{pk,pk}$ or $L_{p,rms}$); no overt response, no direct avoidance or change in foraging behaviour were observed during exposures but the authors identified a subtle but

consistent change in heading, likely to be a vigilance response to maintain awareness of the location of the echo-sounder.

Several recent investigations have used acoustic surveys from vessels and Autonomous Underwater Vehicles (AUVs) to identify prey species and depth distribution during foraging dives of tagged marine mammals, providing novel insights into foraging behaviour, prey choice and diurnal patterns (e.g. Arranz *et al.* 2018; Friedlaender *et al.* 2019). In these studies, interference from sonar equipment does not appear to feature, even when efforts are made in the analyses to check for sampling effects, suggesting potential detection of sound may result only in a very limited effect on animals' gross behaviour (Benoit-Bird *et al.* 2019).

As part of the development of a tracking device for collision risk monitoring at tidal turbines (Hastie 2012), grey seals were shown to respond negatively to two experimental high-frequency active sonars tested in a captive setting; when sonars were active, avoidance behaviour was observed (swimming away from source or hauling out of pool); despite sonar fundamental peak frequency being at 200 kHz and 375 kHz, increased levels were measured within seals' hearing ranges with maximum sensation levels estimated at 20 kHz and 25 kHz (Hastie *et al.* 2014). Ultimately, the sonar system chosen for further development and deployment as a 3D animal movement tracking tool operates at 720 kHz and although some low-frequency components in the signal may still be present their amplitude is deemed sufficiently low to avoid the risk of eliciting a behavioural response when in use (Hastie *et al.* 2019).

Also related to the use of acoustic sources for monitoring marine fauna around tidal turbines, Cotter *et al.* (2019) characterised acoustic emissions from two different MBES operating at central frequencies of 720 kHz, 900 kHz and 2.25 MHz in addition to an ADCP with a central frequency of 500 kHz. A hydrophone positioned at 6 m below source provided calibrated measurements of energy up to 250 kHz (sampling rate-limited), from which the audibility to different marine mammal hearing groups was assessed using the most recent frequency-weighting curves (NMFS 2018; Southall *et al.* 2019). While all sources produced measurable levels below 160 kHz (the reported upper limit of hearing in very high-frequency cetaceans), for all devices and hearing groups the estimated limits of audibility were no more than ~100 m within the main beam. Further, it was estimated that a harbour porpoise would need to remain within a few metres of the transducer and close to the centre of the beam (i.e. stationary) for multiple hours in order to receive sufficient energy to exceed the cumulative threshold for temporary hearing loss.

The potential effects of marine vibroseis are limited to inferences based on the characteristics of modelled synthetic sources relative to airgun arrays. These estimate the emitted sounds to be of lower amplitude and lower frequency bandwidth relative to airgun arrays, presenting a lower potential for injury (Duncan *et al.* 2017; Matthews *et al.* 2018). However, they note that the long signal duration and relatively high duty cycle (45-77 %) is likely to have increased consequences on behaviour and acoustic masking.

7.1.3. Summary assessment of evidence for marine mammals

While thresholds for hearing damage have been tested in few species, broadly-applicable injury threshold criteria are available for different functional hearing groups, facilitating quantitative assessment of the risk of injury to marine mammals from sources of underwater noise. These criteria will continue to be updated as new information becomes available (e.g. Kastelein *et al.* 2019), and the preferential use of good species-specific data (over broad hearing groups) has been encouraged (Southall 2019).

The evidence base for behavioural responses of marine mammals to low-frequency high amplitude underwater noise continues to grow. While not without limitations, two empirical studies (Thompson *et al.* 2013; Sarnocińska *et al.* 2020) of acoustic responses of harbour porpoise to commercial seismic surveys in the North Sea provide valuable information. These studies are complemented by similar approaches to monitoring the response of harbour porpoise to pile-driving for offshore wind (e.g. Brandt *et al.* 2018; Graham *et al.* 2019), albeit with acknowledgement of the differences in emitted sounds. The meta-analysis of a large volume of observer data from seismic surveys presented in Stone *et al.* (2017) is important, and covers multiple relevant species.

Information on the behavioural responses of marine mammals to acoustic survey sources other than airguns or military sonar is very limited. High-frequency sources with central operating frequencies at the upper end of marine mammal hearing ranges or above (e.g. echo-sounders, side-scan sonar, ADCP) have been shown to emit energy at lower frequencies audible to most marine mammals, although at reduced amplitudes and with a small emitted sound field which is unlikely to cause behavioural effects. Evidence of responses to echo-sounders is variable and limited, with the strongest evidence of negative effects relating to deep-diving odontocetes and with echo-sounder use which is not representative of most survey applications in shelf waters. The reported avoidance responses of captive grey seals to high-frequency sonar in close proximity and fairly high received levels (Hastie *et al.* 2014) are noted, although given the evidence of emitted sound fields from such devices (e.g. Cotter *et al.* 2019), such exposure circumstances in an open marine environment are likely to be highly localised.

In their review of behavioural responses of wild marine mammals to noise, Gomez *et al.* (2016) highlight some of the shortcomings of studies to date. These include: few studies appropriately and consistently measuring, estimating, and reporting acoustic metrics; simplistic, broad descriptions of changes in behaviour reported; high variability in the definitions used to differentiate between a state, behaviour, or activity. The authors also note that while the use of real operational sound sources (as opposed to playback of recorded sounds) in controlled exposure experiments makes for a more realistic sound source, the short duration of such experiments (i.e. hours) compared to real operations (days to weeks) is unrealistic.

Several reviews of evidence of behavioural responses of marine mammals to underwater noise have highlighted the variability in responses between

individuals and populations, and the important and complex role which the context of exposure is likely to play (Southall *et al.* 2007; Gomez *et al.* 2016; Harris *et al.* 2018). However, efforts to examine the influence of context variables are in their infancy, with most progress to date relating to military sonar.

Data gaps relating to marine mammal responses to acoustic survey and other noise are numerous and are presented alongside recommendations for research in the reviews cited above and elsewhere (e.g. Elliot *et al.* 2019; Erbe *et al.* 2019). In broad terms, additional research is necessary to establish the probabilistic relationships between exposure to sound, contextual factors, and severity of response (National Academies of Sciences 2017). More specifically, there is a need to better understand the biological consequences of behavioural responses, for example in terms of energetic costs and subsequent implications on fitness, as these connections are critical for extrapolating to population-level effects.

7.2. Fish

7.2.1. Hearing abilities and use of sound

The auditory system in fishes has been extensively reviewed, and all species studied to date are able to detect sound (e.g. Radford *et al.* 2012; Popper *et al.* 2014; Hawkins & Popper 2017; Popper & Hawkins 2018, 2019). While there is much variability in the structure and function of hearing between species, for many species sound plays a key role in communication, mating behaviour, the detection of predators and prey, orientation, migration and finding key habitat (Popper & Hawkins 2019).

The primary mechanism through which they hear sounds is the direct detection of particle motion within the inner ear. Here, sounds cause differential movement between the calcareous, hardened otolithic structures (these are the otoliths in teleost fishes; cartilaginous fishes do not have calcareous otoliths, but possess similar auditory structures (Casper 2011)) and the surrounding tissue and fluid; in turn this relative movement results in bending of cilia and activation of sensory cells, releasing a neurotransmitter and sending a signal to the brain. Exposure to sound may result in damage to the sensory cells; however, permanent hearing loss has never been shown and it appears unlikely as, unique to fishes, sensory hair cells of the inner ear can be replaced if damaged (Smith *et al.* 2006).

Among species, there is much variability in the structure of the inner ear anatomy, along with the structure of gas-filled chambers and their distance and connectivity to the inner ear, resulting in a wide range of hearing capabilities. The number of species for which accurate data are available is still small and measuring the hearing abilities for a wider range of species has been recommended as high research priority (Hawkins *et al.* 2015). In particular, field measurements of particle motion are very limited and require greater consideration in order to improve understanding of the effects of sound on fish and other aquatic life (Nedelec *et al.* 2016; Popper & Hawkins 2018).

The same sensory cells as in the ear are also found in the lateral line system: a series of receptors along the body of the fish that detects water motion from localised sources (i.e. within a few body lengths of the animal). The exact function of the lateral line relative to the ear with respect to sound detection and potential effects from enhanced exposure is unclear (Hastings & Popper 2005).

While acknowledging significant data gaps, for the purposes of assessing how fish might be affected by anthropogenic noise, the following categories have been proposed (Popper *et al.* 2014; Hawkins & Popper 2017):

4. **Fishes with no swim bladder or other gas-filled chamber.** These species are unable to detect sound pressure and so only detect particle motion. Less susceptible to barotrauma. Show sensitivity to only a narrow band of frequencies. For example: elasmobranchs, sandeel (*Ammodytes marinus*), Atlantic mackerel (*Scomber scombrus*).
5. **Fishes with a swim bladder in which hearing does not appear to involve this organ or other gas-filled chambers.** While hearing only involves particle motion, these species are susceptible to barotrauma. Show sensitivity to only a narrow band of frequencies, from <50 Hz to approximately 300 Hz. For example: Salmonidae (e.g. Atlantic salmon, *Salmo salar*), some tunas (Scombridae).
6. **Fishes with swim bladder that are close, but not intimately connected, to the ear.** These species detect sound pressure as well as particle motion. Susceptible to barotrauma. Show a more extended frequency range than groups 1 and 2, up to approximately 500 Hz. For example: Gadidae (e.g. Atlantic cod, *Gadus morhua*), Anguillidae (e.g. European eel, *Anguilla anguilla*).
7. **Fishes that have special structures mechanically linking the swim bladder to the ear.** These species detect particle motion, but are primarily sensitive to sound pressure. They have a wider frequency range, extending to several kHz, and generally show higher sensitivity to sound pressure than groups 1-3. For example: some Clupeidae (e.g. Atlantic herring, *Clupea harengus*; Gulf menhaden, *Brevoortia patronus*; Allis shad, *Alosa alosa*).

Groups 1-3 account for the majority of species tested to date, with a smaller number being able to detect sound pressure to approximately 1 kHz and a much smaller number of species that can detect sounds to 3-4 kHz (Popper & Hawkins 2019). It is noted that Hawkins and Popper (2017) provided the above distinction between species which detect sound pressure, whereas Popper *et al.* (2014) treated these (groups 3 and 4) as a single category for the purpose of setting broad injury threshold criteria.

Of relevance to MPAs in Welsh waters and the wider UK is a recent study of the hearing ability of sea lamprey (*Petromyzon marinus*) (Mickle *et al.* 2019). Consistent with fish lacking a swim bladder, sea lamprey showed a limited

sensitivity to sound, with juveniles detecting tones of 50-300 Hz, but not higher frequencies.

7.2.2. Evidence of effects on fish

There have been numerous reviews of the effects of anthropogenic sound on fish; for example: Popper *et al.* (2014), Hawkins *et al.* (2015), Carroll *et al.* (2017) and, most recently, Slabbekoorn *et al.* (2019). Of particular relevance is Carroll *et al.* (2017), who present a systematic and critical review of scientific studies investigating the impacts of low-frequency sound on marine fish (and invertebrates; see Section 7.3), with a focus on seismic surveys (supplementary Material B of Carroll *et al.* (2017) includes an annotated bibliography of all studies examined). Here, we summarise the findings of their review and supplement with results from more recent and other relevant studies. Unless specified otherwise, results relate to adult or juvenile bony fish.

Among 32 studies examined, 11 reported on physical effects of seismic airguns (e.g. mortality, barotrauma, inner ear damage) at received levels of up to $L_{p,rms}$ 225 dB re 1 μ Pa; the majority showed no effects, three reported inner ear damage or TTS at received $L_{p,pk}$ between 198-209 dB re 1 μ Pa and none showed mortality. Of six studies investigating mortality of fish eggs or larvae, none reported mortality at realistic known exposure levels. Three studies reported on physiological effects, providing mixed evidence of a response/no response in stress bio-indicators; in almost all cases of a response, measures of stress had returned to pre-exposure levels by the end of the experiment or fish habituated after several weeks of exposure.

Behavioural effects have received much attention, numbering 15 studies in Carroll *et al.* (2017), with most being laboratory or caged field experiments. Startle/alarm responses, avoidance of the sound source or changes in vertical or horizontal distribution were widely reported. Startle responses were the most consistently observed response to seismic pulses, being observed in almost all species tested. There was wide variability in the received levels at which behavioural responses were observed, and several studies reported no significant response. Where reported, responses were temporary and fish returned to pre-exposure behaviour typically within less than an hour of the last exposure.

Eleven studies reported on catch rates or abundance, with the majority reporting no response or conflicting results; for example, in one study, bycatch of cod decreased in one trawl gear type but increased in another during the seismic activity (Løkkeborg & Soldal 1993, in Carroll *et al.* 2017). Two studies reported significant reductions in trawl and/or longline catches in response to a seismic survey, including of cod and haddock, while one reported a reduction in the average density of herring and blue whiting. A single study reported on catch rates including elasmobranchs, which observed conflicting results (Przeslawski *et al.* unpublished, subsequently published as Bruce *et al.* 2018). Changes in fish distribution and behaviour, such as vertical movements, are presumed to be responsible for the observed changes in catch rates and abundance (Carroll *et al.* 2017). In an earlier review, it was concluded that the

“consensus is that seismic airgun shooting can result in reduced trawl and longline catch of several species when the animals receive levels as low as 160dB” (MMS 2004); Carroll *et al.* (2017) confirm this potential but place emphasis on the high variability found in responses likely to be influenced by a range of contextual factors, noting that there is a comparable evidence base for no reduction in catch rates and/or abundance associated with seismic survey activity.

Injury threshold criteria suggested by Popper *et al.* (2014) draw upon many of the same studies as reviewed by Carroll *et al.* (2017). These are not reproduced in full here, but the criteria for mortality and potential injury for species lacking a swim bladder is $L_{p,pk} > 213$ dB re 1 μ Pa and for all other groups is $L_{p,pk} > 207$ dB re 1 μ Pa (see Table 7.4, p44 of Popper *et al.* 2014 for all criteria definitions). While thresholds based on pressure may not be equally appropriate for species that respond mainly or only to particle motion, this was the best approach given the lack of particle motion measurements. There were no data on masking by seismic airgun sources, and insufficient data to develop quantitative guidelines for these categories of effect. At near and intermediate distance from the source, the risk of behavioural responses is qualitatively categorised as high for species with more specialist hearing, and progressed from high-medium-low at near-intermediate-far distances, respectively, for other groups. Overall, the risk of masking was considered to be low, but may be moderate at far distance field for species with more specialist hearing, where the seismic noise becomes more continuous in nature (Popper *et al.* 2014).

Since the review of Carroll *et al.* (2017), the following empirical studies on the responses of fish to seismic surveys have been published. Doksæter *et al.* (2017) investigated the behavioural responses of wild-caught Atlantic mackerel (*Scomber scombrus*) in a net pen to seismic noise from an approaching vessel operating a single 90 in³ airgun. No clear sudden responses were identified when the seismic noise escalated from broadband received levels of $L_{p,pk}$ 143 to 169 dB re 1 μ Pa (closest point of approach = 330 m), although an increase in school cohesion was observed. Corresponding particle motion measurements were a 0-peak acceleration of 0.02 and 0.15 ms⁻², respectively. More erratic swimming was observed when the source was suddenly activated 90 m from the net pen, resulting in a received level of $L_{p,pk}$ 184 dB re 1 μ Pa, although a similar response was observed concurrent with both the vessel getting into position and the wake of a large passing vessel striking the pen. Additionally, no responses were observed among captive salmon and rainbow trout (*Oncorhynchus mykiss*) at three commercial farms located a minimum of 2-3 km from the source. The authors acknowledge that the source tested was far lower than commercial airgun arrays, and that limitations may have been imposed on the behaviour of the fish due to confinement in a net. Nonetheless, they conclude that the lack of sudden responses to escalating seismic noise provide support for soft-start / ramp-up as a mitigation tool.

Paxton *et al.* (2017) reported the opportunistic observation from seabed video of a 78 % decline in evening reef-fish abundance on a temperate reef off North Carolina coincident with seismic survey activity 8 km distant, relative to the

preceding three days with no seismic survey activity. The estimated received level was between $L_{pk,pk}$ 180-220 dB re 1 μ Pa; the source was a towed airgun array of up to 6,600 in³. While the decline in abundance was pronounced and goes beyond a simple startle response, data were limited, did not take other nearby vessel traffic into account (Slabbekoorn *et al.* 2019), and lacked observations to measure the duration of the decline in abundance.

Aware of the potentially subtle behavioural effects observed in response to airgun exposure, Davidsen *et al.* (2019) equipped free-swimming cod (*Gadus morhua*) and saithe (*Pollachius virens*) with biologgers and transmitters to collect data on heart rate, body temperature, body acceleration and 3D movement. Fish were held in cages and exposed to sound from a commercial 40 in³ airgun towed from a research vessel along a track from 6.7 km to as close as 100 m from the cage to simulate a ramp-up. Received sound levels were measured both as pressure and particle motion; ambient noise was high and variable (mean $L_{p,pk}$ in the whole period without airgun shooting was 103 ± 11 dB re 1 μ Pa) and the difference between the pulse and background levels was between 18 and 60 dB, depending on the metric (e.g. $L_{p,pk}$ range of 150-185 dB re 1 μ Pa and $A_{p,pk}$ range of 91-121 dB re 1 μ m s⁻²). The study revealed the heart rate of cod was altered (bradycardia) during the short-term exposure but not in saithe (although sample size was smaller) and swimming depth and horizontal position in the cage were altered in both species. Both responses were greater on the first of three experimental days, suggesting possible habituation. As acknowledged by the authors, small sample size and large variability in conditions (stormy weather on day two) were limiting factors; further work is needed to confirm their findings i.e. airgun exposure has elicited only short-term and relatively limited physiological and behavioural effects.

7.2.3. Summary assessment of evidence for fish

Slabbekoorn *et al.* (2019) provide a summary assessment of the evidence relating to the effects of seismic surveys on fish. They note that there are few good case-studies in the peer-reviewed literature that report on the impact of a seismic survey on the behavioural response of free-ranging fish or the direct impact on local fisheries. Existing studies do not yield completely coherent results but suggest that fish could stop foraging and move down in the water column. The paucity of such studies relates in no small part to the complexity of observing free-ranging fish in open water (e.g. Bruce *et al.* 2018).

Studies of caged fish in outside conditions have provided information on physical damage and behavioural responses, although the latter may be affected by the enclosure, prior capture or habituation (e.g. for animals sourced from aquaculture). Evidence suggest that exposure to seismic survey noise does not lead to immediate mortality but may lead to hearing damage at high levels, and can induce temporary behavioural changes. These studies generally suffer from a lack of adequate controls and replication, and insufficient data are currently available for dose-response curves. While studies of captive fish in tanks provide a more controlled experimental environment and greater replication, there are numerous limitations in terms of

their value in terms of understanding effects of realistic exposures in free-ranging animals (Carroll *et al.* 2017; Slabbekoorn *et al.* 2019).

Evidence of effects discussed so far has been gathered in response to very high-amplitude low-frequency noise i.e. seismic airgun surveys (along with percussive pile-driving and explosions). We are not aware of any studies which have experimentally tested the effects of low-frequency SBP sources on fish, but at least on the basis of the reported hearing ranges of fish (See Appendix 1) these cannot be entirely discounted. In particular, sparker and, to a lesser extent, boomer SBPs generate significant energy in the frequencies at which fish species are most sensitive, albeit at a lower amplitude than airgun arrays. SBPs generating periodic waveform signals, such as chirpers, show frequency range overlap only with fish species which primarily detect sound pressure, such as herring.

Seafloor and water column mapping sources operate at central frequencies beyond the hearing range of the majority of fish species, and effects are not anticipated. Echo-sounders are the primary means of detecting fish for both scientific, commercial and recreational purposes, including hearing specialist species such as herring; their ability to do so effectively would be compromised if they resulted in injury or significant behavioural responses.

In response to the limitations of current evidence, a host of recommendations for further research have been identified in the reviews cited above. Additionally, relevant perspectives on key data gaps have been recently identified for seismic noise and marine vertebrates in general (Elliot *et al.* 2019), in relation to intra-specific variation in responses to noise (Harding *et al.* 2019), and specifically to the consideration of particle motion (Nedelec *et al.* 2016; Popper & Hawkins 2018).

Some themes which are common across multiple reviews include:

- A need to develop and refine standards for quantifying sound exposure and audiogram measurement methodology.
- Effects studies need accurate measurements of received levels at the fish, including both sound pressure and particle motion, with the latter being particularly important for species with limited/no sensitivity to sound pressure. Patterns of natural variation in particle motion in fish habitat are also required.
- A need for more research on the potential impacts of masking.
- A need for more research on stress physiological and behavioural effects influencing important biological processes; such effects will affect larger numbers of individuals and are therefore of greater importance at a population-level.
- A need for more research on effects on elasmobranchs.

7.3. Invertebrates

Understanding the potential effects of underwater sound on invertebrates has become an area of growing research interest as demonstrated by the marked increase in poster and presentations on the subject in the latest Aquatic Noise conference (The Hague, July 2019) compared to previous meetings.

Here, we provide an outline of how sound is perceived and produced by invertebrates and review evidence from studies investigating potential impacts of anthropogenic sound on any aspect of invertebrate ecology, from molecular to population level. The recent publication by Carroll *et al.* (2017) on the effects from low-frequency sound exposure is a thorough and critical review of the bulk of results published up to 2016. We report on their review here as the starting point upon which we further build incorporating results from latest and other relevant studies.

Among the multitude of marine invertebrates, most of the work to date concerns crustaceans (lobsters, shrimps and crabs) and molluscs, in particular cephalopods (e.g. squid, cuttlefish, octopus), bivalves (e.g. scallops, oysters, clams) and gastropods (e.g. sea hare). Among the exceptions are studies on cnidaria (jellyfish and reef-building corals) and echinoderms (sea stars). Effects have focused on adults and to a lesser extent to juveniles and larvae; recent efforts on plankton are reported here too.

7.3.1. Hearing abilities and use of sound

Whether hearing occurs in marine invertebrates depends largely on what definition of hearing is used. Marine invertebrates do not possess 'ear-like' sensory organs specialised for hearing and with no gas-filled cavities associated with sensory organs, there is no mechanism that could detect the pressure component of sound. However, detection of the kinetic component of sound is possible via equilibrium receptor systems (Budelmann 1992a).

Equilibrium receptor systems sense local water motion and are involved in controlling animal balance and orientation. They are ubiquitous - described across most taxa from coelenterates to cephalopods, in larval and/or adult stages - but vary greatly in complexity; the more capable an animal of exhibiting complex movement in three dimensions, the more specialised the sensory structures that have evolved (Budelmann 1992a).

There are two main types of receptor systems involved in perception of underwater sound in invertebrates: a superficial system (on the body surface) and one relying on statocysts (internal). The superficial one is comparable to the lateral line of fishes; it relies on epidermal sensory cells with cilia which are mechanically deflected by local water movements. Statocyst receptor systems are seen as the analog to otolith organs; although varying greatly in complexity, all statocysts are based on two structural elements; the statolith (or statoconia) which is a calcareous mass (higher specific weight than the surrounding fluid) and the sensory hair cells which are mechanically affected by the position of the statolith. When the animal accelerates, the statolith

moves, bending the sensory hair cells. The simplest statocysts range from simple gravity receptor systems capable of determining orientation to highly complex organs capable to detect linear and even angular acceleration. The latter are known only in decapod crustaceans and higher cephalopods (for detailed descriptions see Budelmann 1990, 1992b and Andre *et al.* 2016). Statocysts involvement in detection of particle motion has been experimentally proven in both of these taxa (e.g. Kaifu *et al.* 2008, Lovell *et al.* 2005).

As in marine mammals and fish, neurological and behavioural responses have been investigated to establish the range of frequencies that invertebrates are more likely to be sensitive to.

For cephalopods, a realistic upper range appears to be 500 Hz, with best sensitivity in the range 100-300 Hz as demonstrated in a carefully controlled experiment by Mooney *et al.* (2010) using auditory evoked potentials (AEPs) using both near-field acoustic and shaker-generated stimuli testing sensitivity 30-500 Hz. These results corroborate other work, including behavioural investigations (e.g. Kaifu *et al.* 2008; Komak *et al.* 2005; Hu *et al.* 2009). Detections have been reported for higher frequencies up to 1,500 Hz (Hu *et al.* 2009) but these results may have been an artefact of the experimental setup, which unfortunately lacked any direct measurement of particle motion to confirm exposure levels. With regards to the lower range, evidence of sensitivity to as low as 1 Hz has been obtained by Packard *et al.* (1990) applying classical conditioning techniques (training an animal to associate a stimulus with a weak electric shock) and testing sensitivity to vibrations generated in a standing wave acoustic tube which is specifically designed to test infrasound. Mooney *et al.* (2010) suggested that the lower sensitivity obtained <100 Hz in their experiment is likely due to experimental shortcomings associated with their methodology.

Most studies on crustaceans have shown sensitivity to sound and vibration in the range 5-400 Hz, comparable to cephalopods (e.g. see Edmonds *et al.* 2016 and references therein). Detection of higher frequency up to 5 kHz has been reported in two AEP studies (Pye & Watson 2004; Lovell *et al.* 2005); before extrapolating these more broadly as the functional upper range for crustacean sensitivity further corroboration with behavioural investigations under carefully controlled and measured exposures is required.

Larvae of several taxa including those of reef building corals have also been shown to detect low-frequency sound stimuli through attraction/repulsion experiments (Radford *et al.* 2007; Vermeij *et al.*, 2010).

The marine environment is far from silent and invertebrates are also involved in sound production. Bivalves and barnacles may generate sound with their shells and popping sounds have been detected from squid during jet propulsion, but otherwise crustaceans are the most soniferous group with evidence across several species. In most cases, sound is produced incidentally and unlikely to have anything to do with communication; even in lobsters where signal production is linked to individuals being startled or

threatened, the behavioural significance is unknown (Pye Henninger & Watson 2005).

7.3.2. Evidence of effects on invertebrates

Increased emphasis on the potential effects of underwater sound on invertebrates has led to the publication of several reviews on the subject. Probably the most comprehensive and relevant to acoustic surveys is the one by Carroll *et al.* (2017); they critically reviewed studies across all invertebrate (and fish) taxa focusing on seismic surveys and on the challenges encountered when attempting to apply current knowledge to field populations. Others include those by de Soto (2016), Edmonds *et al.* (2016) on high-amplitude sounds effects on crustaceans, Tidau & Briffa (2016) on behavioural responses of crustaceans and also Popper & Hawkins (2018) on the importance of particle motion to invertebrates (and fish) and how to address data gaps.

In terms of impacts, mortality is expected at close range to explosions, but otherwise exposure to anthropogenic sound including airguns appear to show very limited potential for lethal effects across molluscs, cephalopods, crustaceans and cnidarians. Carroll *et al.* (2017) pointed to results on scallops from a recent project in southeast Australia (Day *et al.* 2016) as the exception. Similarly, the bulk of studies reporting on catch rates and abundances have not been able to establish any negative relationship with seismic surveys. In laboratory studies under high-amplitude sound exposure, physical damage to the ultrastructure of statocysts (hair cells) has been demonstrated, providing evidence for a potentially important pathway of effect.

Overall, the reviews identify several aspects of invertebrate physiology and behaviour (including changes in metabolic rate, food consumption, haemolymph chemistry, initiation of startle responses and/or flinching and changes in burying, recessing and righting times) that may be negatively affected by noise exposure. However, the strength of the response observed is often variable and contrasting results between studies are common.

As pointed out in Carroll *et al.* (2017), a disparity exists between effects observed in laboratory investigations and those obtained from field observations, with greatest potential for impact in the former. Given the limitations described above, whether this an artefact of potentially unrealistic conditions in the laboratory or whether such effects may be relevant to field populations will only be resolved through further research effort adopting careful experimental designs and applying measurements of particle motion routinely.

Sole *et al.* (2016b) demonstrated that statocysts in jellyfish can be damaged by exposure to intense sound and that damage severity increases with time post-exposure (e.g. 96 h >48 h). These results are consistent with their previous investigations which provided the evidence that statocysts can be damaged for several species of cephalopods (Andre *et al.* 2011; Sole *et al.* 2013a,b). As emphasised by the authors, these experiments were set up to investigate

whether sound exposure could induce statocyst damage and how lesions would appear, using scanning electron microscopy (SEM); indeed, they represent the first ultrastructural studies for many of these species. In all cases, organisms were exposed to the same 50-400 Hz sinusoidal wave sweeps with 100 % duty cycle and a 1 s sweep period for two hours. A measure of received levels was provided using a hydrophone but given limitations with transducer and tank effects, they are reported only “to provide a global characterization of the received levels from frequencies within the sweep (RL = 157 ± 5 dB re 1 μ Pa with peak levels up to SPL = 175 dB re 1 μ Pa)” (unspecified if $L_{p,pk}$, $L_{pk,pk}$ or $L_{p,rms}$).

The first exposure experiment at sea on cuttlefish *Sepia officinalis* was that of Sole *et al.* (2017). This study aimed to quantify the degree of lesions on statocysts with respect to received levels and was designed specifically to counter some of the limitations of their laboratory studies. Organisms were held in cages at different depths (7, 12 and 17 m) and exposed to the same sound source. Injuries to statocysts were revealed by SEM with severity of damage proportional to the distance from source. Measurements of received sound were made (both pressure and particle motion) but levels were not used in analysis of effect. The authors suggest measured pressure levels ranging from 139 to 142 dB re 1 μPa² at 1/3 octave bands centred at 315 Hz and 400 Hz could be considered a *coherent threshold estimation of noise levels that can trigger acoustic trauma in cephalopods*. However, further refinement of sound exposure measurement and characterisation should be undertaken in future studies to confirm this is the most appropriate metric to be applied.

A large field programme in Tasmania assessed the impact of seismic surveys on southeast Australian scallop and lobster fisheries; the original report by Day *et al.* (2016a) was included in Carroll *et al.* (2017) but more details were recently published in three peer-reviewed papers (Day *et al.* 2017, 2019; Fitzgibbons *et al.* 2017). The programme of work consisted of an experimental airgun towed by a vessel along a predefined track, designed to emulate commercial seismic surveys; experiments compared effects of control (pre-exposure), with 1, 2 or 4 airgun passes. After retrieval, organisms were held in the laboratory and effects studied over 120 days post-exposure in most experiments and in one case over 365 days. Several hydrophones and geophones were deployed across the experimental area before and during exposure. By comparing measured levels with those of a modelled commercial 3D array based on previously collected data, experimental exposure was equated to that would be received at a range of 100-500 m from a commercial survey.

Results of the scallop exposure experiments are reported in Day *et al.* (2017). Calculated maximum exposures values are given as $L_{pk,pk}$ 213 dB re 1 μPa, $L_{E,p}$ 188 dB re 1 μPa² s and Max GR (magnitude ground roll as measured on the seabed via geophone) 37.6 m·s⁻². Mortality rate was increased by exposure, and increasing with the number of passes and with time post-exposure (up to 15-20 % over 120 days). This is the ‘exception’ highlighted in Carroll *et al.* (2017). However, the authors point out that the rates observed are no evidence of mass mortality as natural occurring mortality for this fishery

is in the range 11-50 %. However, mass mortality did occur over the post-exposure period in the last experiment. All scallops including all controls suffered complete mortality and although exposure alone could not have been the cause, it remained unexplained. In terms of behaviour, re-cessing time was found to be quicker in exposed scallops (and the difference persisted over the 120 days post-exposure). This was in contrast with expectations based on energetically demanding stress responses and damage to mechanoreceptors was hypothesised instead.

In the parallel experiment on rock lobsters, damage to statocysts was the main finding (Day *et al.* 2019). Damage to the sensory hairs of statocysts was found following sound exposure and likely related to that, the righting reflex of lobsters was also found to be impaired. The proportion of damaged hairs increased from <0.01 % (max ca. 0.2) in controls to <0.1 (max ca. 0.6) for exposed lobsters; damage remained constant throughout post-exposure even at one year post-exposure and after individuals had moulted (unexpected as statocysts are part of the cuticle that is shed). In this species, no mortality was observed that could be attributed to exposure (Day *et al.* 2019) and changes in haemolymph biochemistry were less pronounced than for scallops (Fitzgibbons *et al.* 2017). The site of the lobster experiment had slightly higher ensonification than the scallop site due to different substrate type.

Another investigation on scallops reported by Przeslawski *et al.* (2018) took place in the same area in southeast Australia, also in response to the urgent need to bring clarity with regards to potential effects of seismic surveys on invertebrate fisheries of high commercial importance. Przeslawski *et al.* (2018) used field observations to look for evidence of mass mortality in scallops at risk from exposure to commercial seismic survey activity (following an unexplained mass mortality event in 2010 which coincided with seismic survey activity). Parameters examined included number of live scallops and condition (adductor muscle and gonad) based on samples collected from standard fishery dredges and on seafloor imagery using an AUV; sampling took place before, two months and ten months after a seismic survey, both within the survey site and approximately 10 km away (control). No physiological or histological examinations were carried out. No adverse effects could be linked to the seismic survey, rejecting the hypothesis that a seismic survey could be the sole cause of scallop mass mortality in the region.

In Atlantic Canada, a similar overlap between seismic activity and the snow crab fishery initiated another large research effort Morris *et al.* (2018). A Before-After-Control-Impact study was repeated over two years to assess the effects of industry scale seismic exposure on catch rates off Newfoundland; power analysis was used to inform design with a decline of 60-70 % expected to be detectable. The results did not support the hypothesis that a seismic survey can affect commercial catch rates. At the last Aquatic Noise conference (The Hague 2019), Cote presented results on behaviour and physiology from the same programme of research and a publication is expected shortly; while effects could not be entirely dismissed, they were small relative to natural variation.

Results from the first *in situ* large-scale investigation of the effects of a commercial 3D seismic survey over a coral reef have been reported by Heyward *et al.* (2018). The analyses focussed on plated and foliose corals across the deeper central lagoon at Scott Reef, Western Australia; damage was assessed from standard towed video transects identified as comparable following broadscale habitat mapping. Eight sites were monitored three times; before, immediately following, and two months after the seismic survey, resulting in a total 1,080 photo observations for analysis. The seismic survey (2,055 in³ dual airgun array) lasted two months and included seismic acquisition lines at 240 m spacing over the broader reef lagoon, generating maximum received cumulative $L_{E,24}$ of 197 dB re 1 $\mu\text{Pa}^2 \text{ s}$ and received $L_{p,pk}$ of 220 dB re 1 μPa at the monitoring sites. No effect of the number of seismic passes was detected on corals in terms of the amount of visible damage, such as skeletal breaks or soft tissue lesions; no visible evidence of any immediate physiological damage or stress response such as mucous streaming from plate and branching corals and no evidence of a behavioural response, such as polyp withdrawal or flaccidity in soft corals. Similarly, the composition and abundance of key biota in the benthic assemblage did not change.

Although the literature was limited, it was common to assume that seismic had a negligible effect on plankton, with only highly localised impacts (e.g. as in fish larvae) until the publication by McCauley *et al.* (2017). The latter investigated the effect of airgun activity on zooplankton in the field, comparing abundance (measured using sonar backscatter and net tows) and mortality (using vital stain standard techniques) before and after repeated exposure to a single airgun (150 in³) towed along a 1.5 km long transect. A significant decrease in zooplankton abundance and a significant increase in mortality of adult and larval zooplankton (from 19-45 %) was shown. Effects were observed up to the maximum range sampled from the airgun pass (1.2 km), corresponding to received sound levels of $L_{E,p}$ 153 dB re 1 $\mu\text{Pa}^2 \text{ s}$ and $L_{pk,pk}$ 178 dB re 1 μPa . The increase in proportion of dead zooplankton provides the most compelling support for a negative impact of the seismic source on zooplankton although the sample size was small ($n = 12$ exposed zooplankton samples). Effects differed between taxa and was most pronounced in krill; all krill larvae (no adults were found in samples) were found to be dead in all exposed samples. The experiment was repeated on two consecutive days; abundance on the second day was too low to measure any difference between pre- and post-exposure, but the effect on mortality persisted.

Using these mortality rates, the large-scale impact of a 35-day commercial seismic survey was simulated by Richardson *et al.* (2017) for a hypothetical survey off north-west Australia, based on received pressure levels associated with the 1.2 km range from McCauley *et al.* (2017). Without a clear understanding of the underlying mechanisms that led to increased mortality, it may be inappropriate to rely on received pressure levels as the currency to extrapolate results into broad-scale predictions, but on this basis a mortality of 14 % was modelled at a distance of 15 km from the airgun array. Richardson *et al.* (2017) concluded that within the survey region (80 x 36 km) up to 35 % of the zooplankton biomass could be removed and recovery could take up to 26 days when ocean circulation was not included in the models, while inclusion of

ocean circulation would result in 22 % biomass loss and a much quicker recovery (3 days after end of survey); in both instances, no discernible consequences could be found at the level of the wider bioregion.

These findings and the limitations inherent in these studies have stimulated calls for further investigations to better understand the true ramifications of seismic surveys on zooplankton, larval recruitment processes and ocean health in general (McCauley *et al.* 2017; Richardson *et al.* 2017).

Fields *et al.* (2019) tested if exposure to blasts from airguns could affect mortality, predator escape response or gene expression for *Calanus finmarchicus*, a dominant copepod species of the North Atlantic and a key food source of many commercial fish species. Cultured copepods were placed in experimental bags at set distances (0-25 m) from static airguns; exposure consisted of a single blast from a 2 x 260 in³ cluster, yielding received $L_{E,p}$ ranging between 221 and 183 dB re 1 $\mu\text{Pa}^2\text{s}$ at 0 and 25 m, respectively. Mortality was greater for exposed copepods at a distance of 5 m or less immediately after exposure and only up to 10 m one week after; in all cases, increased mortality relative to control did not exceed 30 %. No effects could be observed on escape response for copepods from any of the experimental bags while a difference in gene expression could only be observed up to 5 m away. The experimental bags were acoustically transparent but may affect fluid flow; direct measurements were taken inside and outside bags for comparison, and no differences were observed beyond 5 m. Overall, Fields *et al.* (2019) found only limited effects, much less than those reported by McCauley *et al.* (2017), which prompted them to conclude that “*model assessments of the broader impacts of seismic surveys on zooplankton (such as Richardson et al., 2017) will have to be revisited*”.

7.3.3. Summary assessment of evidence for invertebrates

There is agreement across authors on the many challenges involved in trying to infer potential effects to realistic field conditions from current evidence, and similarities can be drawn with some of the issues discussed in relation to fish (Section 7.3.2). Studies are limited in numbers and have focused on only a few species (mainly of commercial interest) and exposure types; at the same time, response parameters have ranged from ultracellular to population levels. At times sample size is small and suitable controls may be lacking. A major issue is to do with exposure type and its reporting; most studies may describe the sound source but actual received sound measurements are either lacking or available only for the pressure component of sound, when for invertebrates what matters is particle motion. Laboratory experiments have to contend with boundary effects in tanks, which may create a complex and unpredictable sound field, and with experimental sound sources which may not always be directly comparable to sources and/or received levels at sea; without direct measurements, it is difficult to establish the exact relationship between exposure and effect. Field studies have to deal with complex logistics as well as contend with natural environmental variability; a lack of observed effect may be a consequence of high variance and low statistical power, but this is not routinely estimated or discussed.

There is confidence in stating that exposure to seismic surveys is highly unlikely to be the sole cause of mass mortality events in invertebrates. The study that reported lethal effects pointed out that the observed mortality rates did not exceed natural variability. There is more uncertainty when looking at sub-lethal effects. The potential for physical damage to motion receptors has been shown both in the field (cuttlefish, lobster) and in the laboratory (jellyfish, cephalopods) and with evidence that damage is irreversible and increasing with time post-exposure, it highlights a potential pathway for effect that needs to be investigated further. Greater emphasis on direct measurements of particle motion are required to identify the characteristics of sound with the greatest potential for injury. Also, the consequences of statocysts' damage to the organism's capacity of survival and reproduction have yet to be fully evaluated.

With respect to other physiological and behavioural effects that have been reported for invertebrates, it appears premature to make any extrapolation or generalisation to what can be expected following a seismic survey or to be able to assess it beyond the single organism response; data are too limited, exposures and parameters are highly variable and results are often in contradiction.

Finally, with regards to zooplankton, the large effect size reported by McCauley *et al.* (2017) needs to be properly duplicated before it can be used with confidence in impact assessments.

As for fish, evidence of effects comes from exposure to airguns; given amplitude and frequency considerations, effects from all other SBP sources are expected to be less, and likely negligible for seafloor and water column mapping sources.

7.4. Diving birds

Information on the underwater hearing abilities of diving birds and evidence of the effects of underwater anthropogenic noise is very limited. Unlike other receptor groups, no dedicated reviews on the effects of noise on diving birds have been undertaken; distillations of available evidence can be found in BEIS (2018) and the DOSITS website (<https://dosits.org/animals/sound-reception/how-do-aquatic-birds-hear/>), while Dooling & Therrien (2012) consider the evidence for hearing in air and the potential effects of underwater noise.

Direct effects from underwater acoustic surveys on diving birds could potentially occur through physical damage, given exposure to sufficiently high amplitudes, or through behavioural disturbance. Deeper-diving species which spend longer periods of time underwater (e.g. auks) may be most at risk of exposure, but all species which routinely submerge in pursuit of prey and benthic feeding opportunities in marine and estuarine habitats (i.e. also including divers *Gavia spp.*, grebes, diving ducks, cormorant, shag, gannet, and Manx shearwater) may be exposed to anthropogenic noise.

7.4.1. Hearing abilities and use of sound

Seabirds are highly vocal on land, where acoustic communication plays a key role in mate and/or offspring recognition. The reported in-air hearing sensitivity for a range of diving duck species, red-throated diver, gannet and puffin have been tested for tone bursts between frequencies of 0.5-6 kHz; results revealed a common region of greatest sensitivity from 1-3 kHz, with a sharp reduction in sensitivity >3-4 kHz (Crowell *et al.* 2015, Mooney *et al.* 2019). Similar results were observed for African penguin; tests of in-air hearing showed a region of best sensitivity of 0.6-4 kHz, consistent with the vocalisations of this species (Wever *et al.* 1969). These results are comparable to the observed hearing sensitivity of numerous land birds (Dooling *et al.* 2000).

At sea, their use of sound is poorly understood, with advances in animal-borne instrumentation only recently facilitating detailed examination of at-sea vocalisations. Gannets have been reported to emit acoustically distinct vocalisations in different behavioural contexts (Thiebault *et al.* 2019a), while surface vocalisations have also been observed among commuting penguins (Choi *et al.* 2017). Underwater vocalisations associated with feeding recently reported for penguins are the first record of underwater sound emission from any diving bird, although the possible function of these vocalisations (which occurred in only a minority of prey capture attempts) is unknown (Thiebault *et al.* 2019b).

Some aquatic birds possess adaptations to their auditory system related to being underwater, which generally relate to protecting against damage from pressure changes (Dooling & Therrien 2012); these include barrier creation (e.g. auks), pressure regulation (e.g. penguins) or cushioning for species which plunge dive (e.g. gannet). Testing on the long-tailed duck underwater showed reliable responses to high-intensity stimuli (>117 dB re 1 μ Pa) from 0.5-2.9 kHz (Crowell 2014). Preliminary results from the first underwater hearing tests on gentoo penguins (*Pygoscelis papua*) indicate consistent behavioural reactions to sound at modest levels, above $L_{p,rms}$ 110 dB re 1 μ Pa (Sørensen *et al.* 2019). An underwater hearing threshold for cormorant of $L_{p,rms}$ 70-75 dB re 1 μ Pa for tones at tested frequencies of 1-4 kHz has been suggested (Hansen *et al.* 2017). The authors argue that this underwater hearing sensitivity, which is broadly comparable to that of seals and small odontocetes at 1-4 kHz, is suggestive of the use of auditory cues for foraging and/or orientation and that cormorant, and possibly other species which perform long dives, are sensitive to underwater sound.

7.4.2. Evidence of effects on diving birds

Very high-amplitude low-frequency underwater noise may result in acute trauma to diving birds, with several studies reporting mortality of diving birds in close proximity (i.e. tens of metres) to underwater explosions (Yelverton *et al.* 1973, Cooper 1982, Stemp 1985, Danil & St Leger 2011). McCauley (1994) inferred from vocalisation ranges that the threshold of perception for low-frequency seismic noise in some species (e.g. penguins, considered as a

possible proxy for auk species) would be high, hence individuals might be adversely affected only in close proximity to the source.

Stemp (1985), documented an investigation of seabird abundance in Hudson Strait (Atlantic seaboard of Canada) during seismic surveys over three years. Explosives were used in the first two years, with airguns of 1,500 in³ total volume used in the third year. From 600 observations of birds, a comparison of periods with and without explosives or airguns in operation showed no significant difference in the abundance of thick-billed murre (Brünnich's guillemot), along with two non-diving species, with differences being less than normal variation due to weather and seasons. Stemp (1985) reported some mortality of birds in close proximity to explosive charges, but none associated with airguns.

Pichegru *et al.* (2017) used telemetry data from breeding African penguins to document a shift in foraging distribution concurrent with a 2D seismic survey off South Africa. Pre/post shooting, areas of highest use (indicated by the 50 % kernel density distribution) bordered the closest boundary of the seismic survey; during shooting, their distribution shifted away from the survey area, with areas of higher use at least 15km distant to the closest survey line. However, insufficient information was provided on the spatio-temporal distribution of seismic activity or penguin distribution to determine an accurate displacement distance. It was reported that penguins quickly reverted to normal foraging behaviour after cessation of seismic activities, suggesting a relatively short-term influence of seismic activity on these birds' behaviour and/or that of their prey (Pichegru *et al.* 2017).

Studies of the responses of diving birds to other acoustic sources are similarly limited. In a playback experiment on wild African penguins, birds showed strong avoidance behaviour (interpreted as an antipredator response) when exposed to killer whale vocalisations and sweep frequency pulses, both focussed between 0.5-3 kHz (Frost *et al.* 1975). The use of acoustic pingers mounted on the corkline of a gillnet in a salmon fishery, emitting regular impulses of sound at *ca.* 2 kHz, was associated with a significant reduction in entanglements of guillemot, but not rhinoceros auklet (Melvin *et al.* 1999). Additionally, underwater playback of boat sounds (recorded from a bird-scaring chase vessel; no acoustic characteristics available) has been shown to reduce the abundance of eider and other sea ducks feeding on mussel farms by up to 80 % (Ross *et al.* 2001). These vocalisation, pinger and vessel sounds all contained significant energy within the reported hearing range of diving birds.

Single and multi-beam echo-sounders have been used to observe the dive behaviour of gannets and guillemots, recording what was assumed to be normal behaviour within ≤ 100 m range of the source (RPS 2010). Additionally, echo-sounders mounted on a seabed platform have been used to monitor the behaviour of diving birds around a marine renewable energy devices, with results informing an assessment of potential collision risk (Williamson *et al.* 2017). While the use of echo-sounders to monitor diving birds is not the same as an *ad hoc* study to test their responses to these sources, the apparent normal diving behaviour at close proximity suggests a lack of effect. This would

be consistent with the expected lack of audibility of the source signal, which, for echo-sounders, side-scan sonar, ADCP, and some periodic SBPs, is of a much higher frequency than the documented hearing range of diving birds (see Appendix 2).

7.4.3. Summary assessment of evidence for diving birds

Data on the auditory abilities of diving birds underwater are very limited, and it is not known how they might use sound underwater. It appears that the range of frequencies they are able to detect underwater is very similar to those in air. While mortality or other negative effects on seabirds have not been reported during extensive seismic operations in the North Sea and elsewhere, the number of studies directly addressing the behavioural responses of diving birds to seismic or other acoustic surveys is very limited: a single study on African penguins (Pichegru *et al.* 2017) showed apparent displacement due to a seismic survey, while another on a single species of auk within one region (Stemp 1985) reported no effects.

A lack of studies investigating the effects of seismic surveys on diving birds should not be taken as direct evidence of a lack of effect, and further evidence of the underwater hearing abilities of diving birds and their responses to a variety of underwater noise sources are desirable. However, it is noted that this has not been raised as a priority issue by stakeholders across multiple underwater noise-generating industries (e.g. UK Offshore Energy SEAs, including post-consultation reports, DECC 2016). While seabird responses to approaching vessels are highly variable (e.g. Fliessbach *et al.* 2019), flushing disturbance would be expected to displace most diving seabirds from close proximity to the survey vessel and any towed equipment, thereby limiting their exposure to the highest sound pressures generated. Similarly, behavioural disturbance of seabirds due to acoustic survey activities is most likely to be temporary displacement associated with the physical presence of the vessel, comparable to that experienced by routine shipping traffic.

8. Discussion

8.1. Summary and prioritisation of acoustic survey methodologies according to potential effects on marine species

Underwater acoustic surveys utilise a variety of sound sources and there is much diversity in the characteristics of the sounds they generate. To summarise some of the information presented in this evidence report, Appendix 1 provides a summary of key characteristics of those sources detailed in Section 5, while Appendix 2 presents a graphical representation of the reported hearing ranges of marine mammals, fish, invertebrates and diving birds alongside the typical frequency ranges of these different acoustic survey sources.

For all species groups, the greatest volume of evidence on the effects of acoustic surveys relates to seismic airgun surveys. Deep-diving odontocetes are a possible exception to this, which have been subject to numerous studies investigating the effects of military active sonar, although these are of limited relevance to Welsh waters. For other acoustic survey sources, information is limited. Consequently, in assessing the relative risk of effects from different sources, it is important to consider specific relevant characteristics of their sounds and how they influence the potential for effect on sensitive marine species.

Frequency. Sources generating sounds within the hearing range of animals are those with the greatest potential for effect, both in terms of auditory damage and behavioural responses (Appendix 2). In this regard, seismic airguns, sparker and boomer SBPs, which produce broadband noise from frequencies of a few tens of Hz to 10 kHz or above, show the broadest potential for effect, overlapping the reported hearing ranges of all species groups. In contrast, side-scan sonars, echo-sounders and ADCPs operate at central frequencies above the reported hearing ranges of fish, invertebrates and diving birds, and so would not be expected to result in effects among those species groups. Pinger, chirper and parametric SBPs, along with MFAS, lie somewhere in between, overlapping all non-sound pressure-specialised fish and invertebrates. The central operating frequencies of most side-scan sonars and ADCPs exceed the upper hearing limits of all marine mammal hearing groups, as do echo-sounders with a centre frequency of ≥ 200 kHz. These high-frequency sources have been shown to also emit energy at lower frequencies where audible to marine mammals, and so the potential for effects cannot be completely ruled out; however, considering the limited sound fields they generate (due to narrow beam widths, high-frequency absorption), the risk of effects is low.

Waveform characteristics. The pulsed waveforms generated by airguns are characterised by steep rise times, which are more injurious (auditory and barotrauma) than periodic waveforms. Sparker and boomer SBPs also generate pulsed waveforms with steep rise times, whereas sources using

piezoelectric transducers (e.g. chirper SBPs, echo-sounders, side-scan sonar; see Section 5 and Appendix 1) generate periodic waveforms.

Amplitude and propagation. The amplitude of sounds are of key importance in considering the potential for auditory and other physical damage. While the source level is important, it is the received level at the receptor, following propagation effects (see Sections 4.1 and 5.4), which is of most importance in terms of the likelihood of effects. Seismic airguns generate the highest amplitude noise, and, in the case of large arrays, by a considerable margin. With dominant energy at low frequencies, and low directivity relative to most other acoustic survey sources, sound from seismic airgun surveys also ensonifies the largest area of all sources. Sparker and boomer SBPs have similar signal characteristics to airguns but lower source levels, so the area ensonified will be less. The emitted sound field associated with other SBP and seafloor mapping sources (i.e. those using piezoelectric transducers) is generally expected to be even less, as preliminary evidence suggests (Halvorsen & Heaney 2018), although the high variability in acoustic characteristics of these sources limits generalisations. Military sonar can operate at a high amplitude and in a largely horizontal orientation, resulting in considerable ensonification.

In addition to the considerations above, it is noted that the area ensonified by the source will also be influenced by the position of the source in the water column. Airguns, sparkers, boomers and military sonar are all deployed close to the sea surface, as are most echo-sounders, typically being hull-mounted. However, side-scan sonar is deployed at depth and many other SBPs are deployed in tow bodies designed to operate most efficiently when towed close (i.e. within 10 m) of the seabed. While deployment at depth may increase received levels for benthic fish and invertebrates, it is reasonable to assume that the total area ensonified will be less.

8.1.1. Prioritisation

In Welsh waters, along with shelf waters throughout the UK, seismic airgun surveys are the acoustic survey source with the greatest potential for negative effects on marine species. While significant gaps and uncertainty remain, there is a substantial body of relevant evidence on the effects of this activity on the most sensitive receptors - marine mammals (see Section 7.1).

Among other acoustic survey sources, sparker and boomer SBPs generate sounds of similar characteristics to airguns, and therefore the evidence of effects relating to airguns can be applied to these sources with more confidence than others. While larger sparker SBPs operated at high energy may result in comparable source levels to a mini airgun, both sparker and boomer SBPs generate energy at lower amplitudes than even small airgun arrays and, in the case of boomer SBPs, with greater directionality; consequently, potential effects on marine species can be expected to be proportionally lower than those observed for airgun sources. While work to quantify the emitted sound fields from sparker and boomer SBPs is ongoing,

initial results support the long-held assumption of a reduced potential of effects on marine mammals (Halvorsen & Heaney 2018; see Section 5.4.2).

For other types of SBPs, including pingers and chirpers, the periodic waveform does not exhibit the same steep rise time characteristic of airguns, sparkers or boomers, and therefore the potential for physical injury is less. Additionally, the maximum source sound pressure levels reported for pinger and chirper SBPs are generally 10 dB lower than those of sparker and boomer SBPs, and with a narrower beam width. Therefore, while these devices may still generate significant energy in fairly low-frequencies of <10 kHz, the area ensonified will be less than that resulting from a sparker or boomer SBP, and therefore the risk of effects is considered to be reduced. Initial results from field tests support this assertion (Halvorsen & Heaney 2018).

There is greater uncertainty in the potential for effects from parametric SBPs, as independent calibrated measurements or quantification of emitted sound fields are not yet available. Manufacturer specifications indicate that source levels may be among the highest of any non-airgun acoustic survey source, albeit typically at high frequencies of ~100 kHz and within a narrow beam width of <5°. These characteristics are more comparable to a single beam echo-sounder than other periodic waveform SBPs, and therefore the emitted sound field is expected to be small. However, empirical measurements are required to support this assumption.

For seafloor and water column mapping sources, side-scan sonar and ADCP have very low potential for effects, and only for marine mammals, owing to their high central operating frequencies and small beam width (particularly for ADCP, which is also typically a static deployment). The potential acoustic characteristics of echo-sounders span a wide range, with some configurations likely to represent a greater potential for effects on marine mammals (central operating frequencies are above the hearing range of other receptor groups). Evidence of responses to echo-sounders is variable and limited, with the strongest evidence of negative effects relating to deep-diving odontocetes and with echo-sounder use which is not representative of most survey applications in shelf waters i.e. high power low-frequency MBES (Southall *et al.* 2013) or a suite of high power single beam echo-sounders spanning a wide range of frequencies (Cholewiak *et al.* 2017). MBES will ensonify a much larger area than single beam echo-sounders, albeit within a swath which is narrow in the along-track direction, and devices operated at high power and/or lower frequencies (e.g. in deep-water applications) can be expected to result in a greater emitted sound field than other configurations. Indeed, preliminary results of emitted sound fields from echo-sounders used routinely in shelf sea applications, in addition to side-scan sonar, suggest very limited propagation.

8.2. Data deficiencies / uncertainties

In assessing the relative likelihood of effects from different acoustic survey sources (Section 8.1), we note the following caveats, data deficiencies and uncertainties:

- While reliable, calibrated source characteristics are now available for a variety of commonly used and representative non-airgun acoustic survey sources, systemic investigation of their emitted sound fields is currently limited to a single study which acknowledges that results are uncalibrated and require refinement (Labak 2019). Once finalised, these results will be of great value and relevance, but there will remain a need for further such field investigations to reduce uncertainty through greater replication of results, to gather data on novel equipment or additional operating parameters, sources and environments. For example, at present, calibrated source characteristics or measurements of the emitted sound field for parametric sub-bottom profilers are lacking.
- Understanding of the detection and use of sound underwater is fairly well-developed for some marine mammals and fish, but limited for diving birds underwater and marine invertebrates. For all receptors, new information will arise and assessments of potential effects will need to be revisited.
- For an ecosystem understanding of the effects of sound, the focus on characterising sources and received levels solely in terms of the pressure component of sound is not appropriate; the particle motion component of sound needs addressing.
- Understanding of the specific sound characteristics which are most injurious and/or important for behavioural responses is limited across all taxa, but especially with regard to organisms that respond to particle motion; this leads to very high uncertainty when trying to predict effects from different sound sources.

Additional discussion of data gaps and research needs are provided in the summary assessment of evidence section for specific receptor groups in Section 7, and are not reproduced here.

8.3. Recommendations for management

The evidence reviewed on acoustic survey sources, their regulatory regime and potential effects on marine species, suggests that the current focus on high-amplitude, low-frequency acoustic sources is appropriate from a management perspective. Higher-frequency and lower-amplitude sources may, in some cases, be detectable and so, in principle, elicit individual behavioural responses, but are unlikely to result in population-level or chronic effects.

The review also highlights specific shortcomings with the current approach in practice; these are reported here together with recommendations. These views and recommendations are not necessarily those of NRW and should, therefore, not be attributed to NRW.

8. Underwater acoustic survey may or may not be subject to formal consenting, notification and assessment depending on its purpose, the acoustic source used, and the regulatory authority's implementation of the legislation. In particular, for surveys which do not fall within the *Petroleum Act* or *Energy Act* regime, the process is unclear, with the potential for some underwater acoustic surveys to be undertaken without prior knowledge or scrutiny by NRW and other SNCBs.
9. The variation across regulatory regimes as to whether a consent is required for underwater acoustic surveys on the basis of its end use is confusing, and a lack of a consent to relate any assessment (EIA or HRA) and therefore Competent Authority also raises questions over how HRA could be applied, should it be clear that a significant effect may be likely.
10. In the absence of a route to licence underwater acoustic surveys in Welsh waters, a voluntary prior notification system (e.g. an online form) could provide a useful interim avenue for monitoring non-licensable surveys. Its adoption through policy or guidance, with subsequent promotion, could encourage engagement, provide opportunity for scrutiny and advice on mitigation measures or risk of an EPS offence, inform cumulative assessments, and facilitate more complete recording of relevant noise in the MNR. Furthermore, such a system could enhance understanding of non-licensable activities in Welsh waters and whether a review of what is licensable is needed. An alternative would be to adopt the MMO's approach to the implementation of the *Marine and Coastal Access Act 2009* (as amended), which would bring towed and pole-mounted acoustic sources under the marine licensing regime, but not hull-mounted sources. Regardless of the actions taken, consistent implementation of relevant parts of the Act among different jurisdictions within the UK is strongly encouraged, as is accompanying guidance relevant to acoustic surveys.
11. Within reporting forms, but also with regard to mitigation guidance, equipment categories and definitions need to be regularly updated and refined as technology develops and its use changes (Section 5). Specifically:
 - a. Parametric SBPs need to be added as a category in the BEIS PETS system, MNR forms and any other relevant notification documentation.
 - b. The definition of a mini-airgun in the JNCC Guidance may need to be revised.
12. Auditory thresholds for marine mammals differ for impulsive and non-impulsive sounds; how signals from the different acoustic sources may be distinguished is unclear, especially for those sources where operating parameters can be highly variable (page 27 and Section 5.3). Clear guidance is required to support consistent impact assessments.
13. The importance of particle motion in characterising sound should not be underestimated (Sections 7.2 and 7.3), and a clear need for improved characterisation of sound fields from all acoustic surveys has been identified. Specifically:

- a. The importance of particle motion needs to be reflected in impact assessments.
- b. The collection of high quality acoustic data including both pressure and particle motion components should be encouraged. Funding and opportunities for relevant research initiatives should be enhanced.

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Appendix 1 - Summary of acoustic survey source characteristics

Seismic survey

Source	Generation mechanism	Waveform (broad category)	Range of operational frequencies*	Typical pulse width (ms)	Typical source level ($L_{p,pk}$ dB re 1 μ Pa at 1m)	Typical beam width (degrees)
Airgun	High-pressure air release	Pulsed	Broadband, 5 Hz - 20 kHz (10 Hz - 100 Hz)	<1	Large arrays: 250 - 260 Small arrays: 235 - 240 Mini-airgun: 230 - 235	Approximately omnidirectional, with increased vertical directionality depending on array configuration

Sub-bottom profiling

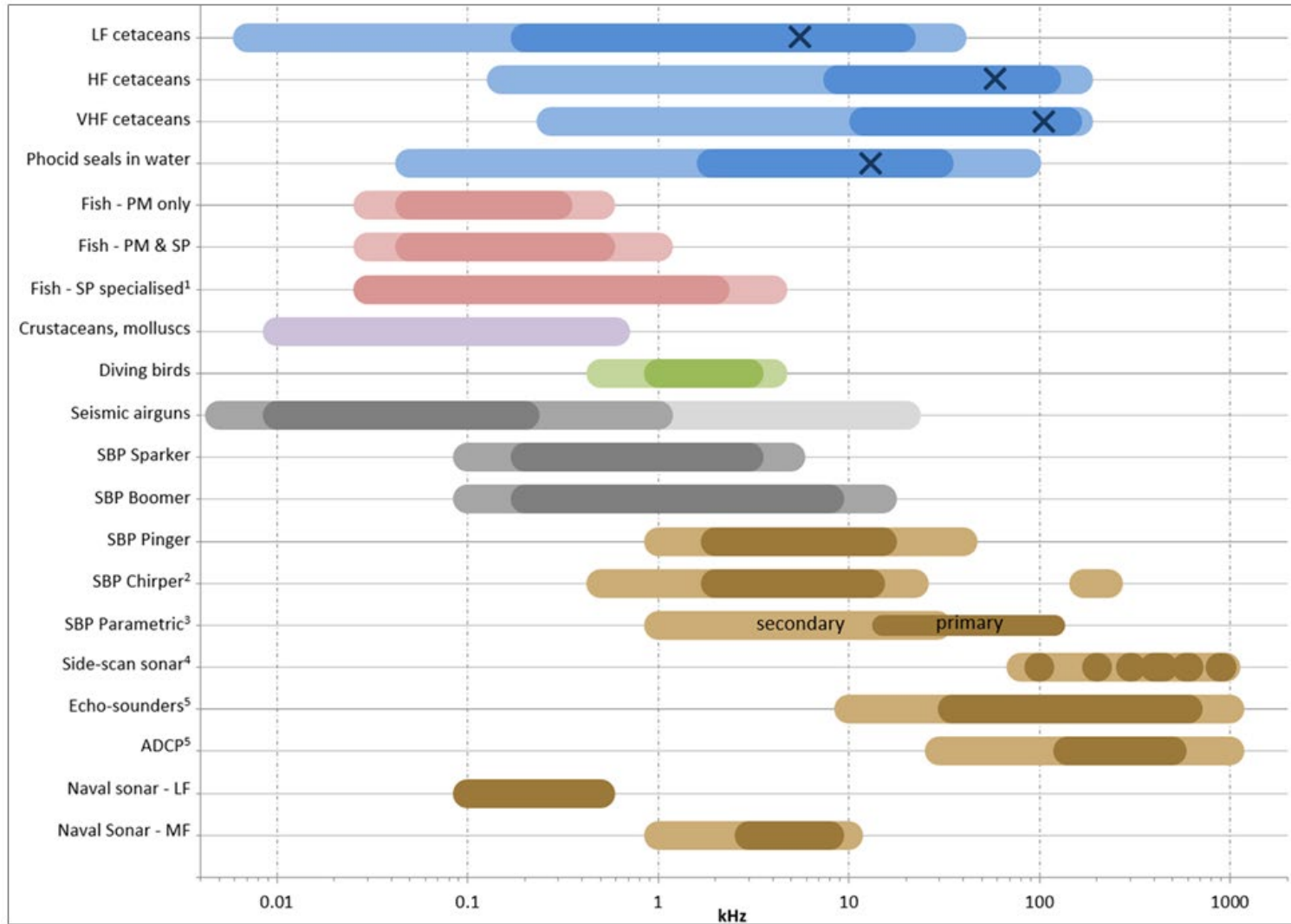
Source	Generation mechanism	Waveform (broad category)	Range of operational frequencies*	Typical pulse width (ms)	Typical source level ($L_{p,pk}$ dB re 1 μ Pa at 1m)	Typical beam width (degrees)
Sparker	Electrostatic discharge	Pulsed	Broadband, 100 Hz - 5 kHz (200 Hz - 3 kHz)	0.5 - 5.0	215 - 225	Approximately omnidirectional
Boomer	Accelerated water mass	Pulsed	Broadband, 100 Hz - 15 kHz (200 Hz - 8 kHz)	0.5 - 1.0	205 - 215	~75
Pinger	Piezoelectric transducer	Periodic	2 kHz - 15 kHz	0.5 - 3	210 - 220	30 - 55
Chirper	Piezoelectric transducer	Periodic	500 Hz - 22 kHz	5 - 40	185 - 215	36 - 80
Parametric	Piezoelectric transducer	Periodic	Primary: 15 kHz - 120 kHz Secondary: 1 kHz - 29 kHz	1 - 5	Primary: 230 - 250 Secondary: 200 - 210	<5

Seafloor and water column mapping

Source	Generation mechanism	Waveform (broad category)	Range of operational frequencies*	Typical pulse width (ms)	Typical source level ($L_{p,pk}$ dB re $1\mu\text{Pa}$ at 1m)	Typical beam width (degrees)
Side-scan sonar	Piezoelectric transducer	Periodic	80 kHz - 950 kHz	0.3 - 1	205 - 230	<3 (along track) 40 - 50 (across track)
Echo-sounder (single- and multi-beam)	Piezoelectric transducer	Periodic	10 kHz - 1 MHz	0.05 - 10	200 - 240	Single: 5 - 15 MBES: 1.5 - 3.0 (along track), 150 - 160 (across track)
ADCP	Piezoelectric transducer	Periodic	30 kHz - 1 MHz	5 - 20	210 - 230	<5
Military sonar	Piezoelectric transducer	Periodic	LF = 100 Hz - 500 Hz MF = 1 kHz - 10 kHz	1 - 2 s (pulsed) 18 - 19 s (continuous)	220 - 240	40 (vertical); up to 360 (horizontal)

*Notes: For **broadband** sources, energy will be distributed throughout the frequency range provided, with values in parentheses indicating the frequencies of greatest energy; for other sources, the transmitted signal will occupy a pre-determined narrower band of frequencies, typically a few kHz, within the range of values given, which represent the possible operational range for the equipment.*

Appendix 2 - Hearing ranges of sensitive marine species relative to operational frequencies of acoustic survey sources - see notes on next page



Notes: This plot provides a high-level indication of the likely overlap between hearing ranges of marine species groups and acoustic survey sources. All values are approximate and based on a variety of literature, some of which is based on limited data and subject to uncertainty.

This plot does not take into consideration other characteristics of acoustic sources, such as source level, pulse duration or beam width. For hearing ranges (blue, red, lilac, green), lighter shading indicates reported or inferred limits of hearing, while darker shading indicates reported frequencies of greatest hearing sensitivity. For broadband pulsed acoustic sources (grey), energy will be distributed throughout the frequency range indicated, with darker values indicating the frequencies of greatest energy. For periodic sources (brown), plots are intended to encompass the range of frequencies at which the devices operate, although it is noted that the transmitted signal will occupy a pre-determined narrower band of frequencies, typically a few kHz, within the range of values given; darker brown shading indicates the upper and lower bounds of the most commonly used frequencies. For all sources, some sound will likely be generated at frequencies beyond those indicated.

Marine mammal functional hearing groups (blue) based on Southall et al. (2019), using values presented in NMFS (2016); darker shading illustrates the frequencies of greatest sensitivity (delineated by parameters f_1 and f_2 : the bounds of the flat, central portion of the frequency-weighting curve region); X markers show frequency of peak sensitivity. LF = low-frequency (i.e. baleen whales); HF = high-frequency (most odontocetes); VHF = very high-frequency (e.g. harbour porpoise); Phocid seals in water e.g. grey and harbour seals. Fish are separated into the three broad groups proposed by Popper et al. (2014). PM = particle motion; SP = sound pressure.

- 1. Some clupeiforms (red: fish - SP specialised) have been reported to be able to detect sounds at frequencies up to several tens of kHz, albeit with low sensitivity.*
- 2. Some chirper and pinger-type SBPs operate dual frequencies, with a higher frequency signal typically centred on 200 kHz.*
- 3. Parametric SBPs generate a signal at higher frequencies (primary), where the majority of energy will occur, with a non-linear interaction in the water column resulting in a secondary lower-frequency signal.*
- 4. Side-scan sonar typically operate at a selected narrow band between 100-900 kHz, often at dual frequencies; darker shading indicates the most common centre frequencies.*
- 5. Darker shading for echo-sounders and ADCPs indicates the typical range of operational frequencies used in shelf waters.*

10. Data Archive Appendix

No data outputs were produced as part of this project.



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