ASSESSMENT OF BLASTING NOISE ON FISH AND MARINE MAMMALS FROM EXPLOSIVES USED DURING BERTH EXPANSION AT BAE SYSTEMS, SCOTSTOUN

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LIST OF ACRONYMS/ABBREVIATIONS/UNITS/TERMS

>	Greater than
<	Less than
≤	Less-than or equal to
ADD	Acoustic Deterrent Device
AHD	Acoustic Harassment Device
AMD	Acoustic Mitigation Device
BAE	British Aerospace
C-4	Composition C-4
C	Celsius
ca.	*Circa* or approximately
c_{hm}	Harmonic median sound speed
CPT	Couplable Plastic Tube
dB	deciBel
DoN	Department of the Navy
e.g.	*Exempli gratia* or 'for example'
EIA	Environmental Impact Assessment
HF	High Frequency
Hz	Hertz
i.e.	*Id est* or 'that is'
kg	kilogram
kHz	kiloHertz
km	kilometre
LF	Low Frequency
L_p	Peak Sound Pressure Level
µ	micro
m	metre
mm	millimetre
MMO	Marine Mammal Observer
N	North
O&G	Oil & Gas
OSC	Ocean Science Consulting Limited
Pa	Pascal
PCW	Phocid Carnivores in Water
PPV	Peak Particle Velocity
PSD	Power Spectral Density
PSU	Practical Salinity Unit
PTS	Permanent Threshold Shift
re	reference
RMS	Root Mean Square
s	second
SEL	Sound Exposure Level
SL	Source Level
SPL	Sound Pressure Level
TNT	TriNitroToluene
TTS	Temporary Threshold Shift
UK	United Kingdom
USA	United States of America
UXO	UneXploded Ordinance
VHF	Very High Frequency
W	West
ZOI	Zone of Influence

SUMMARY

Ocean Science Consulting Limited (OSC), was commissioned by Arch Henderson LLP to perform a desk-based noise-propagation modelling study to investigate potential effects of explosives on fish and marine mammals in the river Clyde, Glasgow, Scotland. The deep-water berth at BAE Systems Scotstoun is due to be deepened in 2021, requiring use of explosives, which produce high-intensity noise and can impact marine species. This document reviews underwater drilling and blasting, impacts of noise on aquatic fauna, noise exposure criteria for fish and marine mammals, as well as the aquatic conditions and species present in the River Clyde.

Many aquatic fauna are sensitive to noise and some use sound perception as their primary sensory modality; therefore, impacts of noise can be lethal, cause injury, hearing impairment and/or behavioural alterations. Noise thresholds have been established to estimate mortality from explosions for fish and Temporary and Permanent Threshold Shifts (TTS and PTS respectively) for marine mammals. Several species of fish and marine mammals are present in the River Clyde, with brown trout (*Salmo trutta*), three-spined stickleback (*Gasterosteus aculeatus*), Atlantic salmon (*Salmo salar*), and flounder (*Platichthys flesus*) being the most common marine/anadromous fish species recorded in decreasing order of prevalence. The most prevalent marine mammals are harbour porpoise (*Phocoena phocoena*), common (*Phoca vitulina*) and grey (*Halichoerus grypus*) seals. A pod of northern bottlenose whales (*Hyperoodon ampullatus*) entered the River Clyde in October 2020, which is considered highly unusual.

From an assessment of available literature, it is estimated that the Peak Sound Pressure Level (L_p) of the proposed 12.5 kg charge will be 282.9 dB re 1 μPa with a frequency range of 10–100 Hz. This was modelled using normal modes and relevant environmental parameters to investigate acoustic propagation. Potential impacts to fish and marine mammals were investigated using published noise exposure criteria (*e.g.* Popper *et al.*, 2014; Southall *et al.*, 2019).

Noise from blasting could potentially propagate to a maximum of 1.4 km from the explosive site, due to curvature of the river. Fish may experience mortality to a maximum distance of 140 m. Harbour porpoise and seals may experience TTS up to a maximum range of 368 m and 248 m respectively and PTS up to 361 and 227 m respectively. Dolphins were found to be least sensitive, with range for TTS of 188 m and PTS at 167 m.

Use of standard mitigation procedures – *e.g.* Marine Mammal Observers (MMOs) and Acoustic Harassment Devices (AHDs) – should be sufficient to ensure no marine mammals are present during blasting and minimise risk of TTS/PTS to marine mammals in the vicinity.

1. INTRODUCTION

A commercial shipyard has been at Scotstoun, on the River Clyde in Glasgow, for 160 years. Since then, over 370 vessels have been built at the site, which was renamed British Aerospace 'BAE Systems Surface Ships' in 2009 (BAE Systems, 2021). The deep-water berth at Scotstoun is due to be excavated in 2021, which will require use of explosives to remove some areas of rock and concrete. Explosives produce short, high-intensity noise, which can propagate considerable distances underwater in optimal conditions. Many marine species are particularly sensitive to noise, often using sound as their primary sensory modality; therefore, its assessment and mitigation is required.

This document reviews underwater drilling and blasting, potential and known impacts of noise on aquatic fauna, noise exposure criteria for fish and marine mammals (*e.g.* Popper *et al.*, 2014; Southall *et al.*, 2019), as well as the aquatic environment of the River Clyde and species present. The report identifies likely noise that could be produced during blasting, and models how this may impact fish and marine mammals.

1.1. Underwater drilling & blasting

Underwater blasting, also referred to as 'submarine blasting', is a demolition technique implemented commonly during the initial stage of civil engineering projects and, more generally, construction works. Developments requiring underwater excavation for foundations are often hindered by presence of hard-bottom sediment or bedrock, a phenomenon that is common in freshwater (rivers), estuarine, and marine environments (coastal and offshore waters). Soft or suspended sediment is removed typically through dredging operations; however, underwater drilling and blasting is required to fragment bedrock to enable it to ultimately be dredged (IADC, 2016). Underwater drilling constitutes the first phase of the demolition process, where boreholes are drilled into rock 'obstructions' for placement of explosive charges that are detonated successively during the second phase of demolition works, *i.e.* blasting. Projects that require underwater drilling and blasting include, *inter alia*, deepening or expansion of channels/harbours, excavation of trenches for subsea cables or pipelines, and demolition and foundation-excavation work. Different projects tend to require different blasting approaches (IADC, 2016), the most common being (i) trench blasting, characterised by 1–3-m deep drilling for lengths ≤300–500 m, (ii) foundation preparation blasting, less common than trench blasting and characterised by closely spaced drill holes and usage of reduced charge weights to prevent overbreak, and (iii) line drilling and blasting, characterised by drill holes spaced inches apart on the desired line of breakage and usage of reduced charges to prevent excessive damage to the rock mass.

Underwater blasting produces a high-velocity spherical shock wave (Popper *et al.*, 2014). In the immediate vicinity of the blast source, the pressure rise time – defined as the time necessary to achieve a target pressure – varies with differing types of explosive. TriNitroToluene (TNT) explosives are characterised by a virtually instantaneous pressure rise time, followed by exponential decay; on the other hand, non-TNT explosives may experience longer rise time and slower decay of the wave pulse (Urick, 1983). Explosive-specific rise time affects the frequency signature of the noise generated by the explosion event, with longer rise times associated typically with lower-frequency noise. Despite the physical principles of underwater blasting being well understood, knowledge gaps remain in the extent to which such understanding can be applied to specific scenarios. These gaps hinder usage of a full range of biological models for investigation of blast-induced effects on living organisms, including, *inter alia*, the impulse metric model (Yelverton *et al.*, 1975), and the bladder oscillation parameter model (Goertner, 1978), devised to anticipate risk to aquatic fauna from the pressure wave generated by underwater blasting operations.

Underwater blasting also produces high-intensity noise, through generation of a large oscillating gas bubble that radiates sound (Popper *et al.*, 2014). Blast size and impact on local fauna, depend largely on the explosion's Source Level (SL) and frequency, weight of explosive charge, quantity of explosives used, and delays separating subsequent detonations. Lastly, underwater blasting is associated with generation of ground vibrations, which can cause substantial damage to surrounding structures (*e.g.* quay walls), aquatic fauna – from invertebrates to fish and marine mammals, and passing or stationary vessels; however, ill effects can be somewhat controlled through implementation of controlled blasting, reducing potential impacts to acceptable levels (Tripathy and Shirke, 2015).

During the expansion of Mumbai Port, Tripathy and Shirke (2015) used confined explosive charges (*i.e.* placed in boreholes) to reduce effects of shock waves on submerged structures and aquatic fauna. This approach, in combination with use of non-electrical delay detonators and blasting each hole with a separate delay, minimised effects of underwater rock blasting on the surrounding environment. Tripathy and Shirke (2015) used KELVEX-P, Couplable Plastic Tube (CPT) explosives, each loaded with a 125-mm-diameter, 6.25-kg cartridge; each hole was loaded with a maximum of 1–2 cartridges, and a typical pattern of 12.5-kg charge per delay was used throughout the project. The protocol adopted during expansion of Mumbai Port recommended a safe Peak Particle Velocity (PPV, *i.e.* peak vibration level) of (i) 5 mm s^{-1} for frequencies <10 Hz, (ii) 5–30 mm s^{-1} for frequencies between 10–100 Hz – when works were conducted for historic buildings, (iii) 25 mm s^{-1} for frequencies <40 Hz, and (iv) 25–75 mm s^{-1} for frequencies between 40–100 Hz – when works were conducted for engineered structures; therefore, the delays adopted by Tripathy and Shirke (2015) were as follows: 200-ms in-hole delay, 17-ms delays between holes in the same row, and 25-ms delays between two rows.

An alternative approach to minimise blasting-induced effects on the surrounding environment is usage of software and modelling tools to identify the minimum charge size that is sufficient to fulfil project requirements, thus substantially reducing potential impacts; however, when selecting explosive charge weights, it is important to consider that the relationship between the latter and blast pressure is of a non-linear nature. For deep shots, for example, peak pressure is approximately proportional to the cube root of explosive weight (Cole and Weller, 1948). Keevin (1998) demonstrated that, at a distance of 4 m, a 1-kg charge of high explosive produced 9,600-kPa peak pressure. A 2-kg shot, modelled on the 1-kg charge pressure, exhibited an increase in peak pressure to 12,000 kPa at the same 4-m distance. To double the pressure to 19,200 kPa, the charge weight had to be increased to 8 kg. **Table 1** presents Peak Sound Pressure Level (L_p) and Sound Exposure Level (SEL) for an array of charges with differing weights.

Charge weight (kg)	TNT-equivalent weight (kg)	L_p (dB re 1 μPa)	SEL (dB re 1 $\mu Pa^2 s$)	References
0.025	0.033	262	218	Robinson *et al.* (2020)
0.048	0.062	265	221	
0.25	0.325	270	228	
5	6.5	280	242	
10	13	283	245	
55	55	287.4		Subacoustech Environmental Ltd. (2018)
120	120	290.0		
150	150	290.7		
227	261	292.5		
250	250	292.4		
430	525	294.8		
700	770	296.1		

Table 1: Estimated Peak Sound Pressure Level (L_p) and Sound Exposure Level (SEL) for different charge weights. L_p and SEL refer to TNT-equivalent weights.

1.2. Noise & aquatic fauna

Sound represents a major sensory channel for fish, marine mammals, and other aquatic taxa, rendering them susceptible to anthropogenic noise generated by activities such as underwater blasting – *e.g.* harbour construction or UneXploded Ordinance (UXO) – seismic exploration and vessel traffic. Adverse impacts of noise have been reviewed in the literature (*e.g.* Thomsen *et al.*, 2006; Popper and Hastings, 2009; Popper and Hawkins, 2018), and include mortality (Caltrans, 2001; Danil and Leger, 2011; Broner and Huber, 2012), injuries, ranging from hematomas and organ haemorrhages (Ketten, 1995; Halvorsen *et al.*, 2012; Casper *et al.*, 2016), to damage to auditory tissues and hearing loss (Ketten, 2002; Casper *et al.*, 2013), and behavioural alterations (Mueller-Blenkle *et al.*, 2010; Gomez *et al.*, 2016). Not all studies report an impact of impulsive activities, such as pile/conductor driving or explosions (Nedwell *et al.*, 2003; Ruggerone *et al.*, 2008). It should be noted, however, that whilst not causing obvious effects, it is possible that noise exposure may reduce fitness, thus rendering individuals more susceptible to predators, or unable to catch prey or impacting reproductive success. Noise source characteristics – as well as pressure level – play an important role when considering impact of noise on fish and marine mammals. In general, biological damage is related to total quantity of energy received by a receptor; therefore, a continuous source operating at a given level is more damaging than an intermittent source reaching the same level. Harmful effects of high-level underwater noise can be summarised as lethality, physical injury, hearing impairment, and behavioural alteration.

1.2.1. Lethality

In the immediate vicinity of the noise source, high peak pressure levels from impulsive noise have potential to cause death – or severe injury leading to death – of fish and marine mammals. Due to the narrow nature of the River Clyde, it is possible for fish and marine mammals to occur within close proximity to the noise source. Impacts that can cause death or mortal injury may be barometric pressure effects due to shock experienced by the animal, rather than acoustic effects *per se*.

Considerable research effort has been devoted to investigation of levels of incident peak pressure and impulse causing lethal injury in species of fish and in human divers. The work of Yelverton *et al.* (1973; 1975; 1976) highlighted that, for a given pressure wave, the severity of injury and likelihood of a lethal effect is related to duration of the pressure wave. Although risk of injury is related to peak pressure of the blast, the impulse (*i.e.* integral of peak pressure over time) of the shock wave has also been shown to be a predictor of injury to fish. In the Yelverton model, smaller fish are generally more vulnerable than larger individuals.

Dahl *et al.* (2020) investigated physical effects of blast-noise exposure on Pacific sardines (*Sardinops sagax*). Fish were placed in mid-depth cages positioned at differing distances from the blast source, *i.e.* from 18–246 m. A single Composition C-4 explosive of 4.66 kg was detonated at mid-water depth in a selected coastal site characterised by waters 19.5 m deep. Injuries recorded included burst capillaries (<20 m), fat hematoma (recorded at every distance), reproductive blood vessel rupture (>50 m), swim bladder and kidney rupture (both organs <50 m and 125–150 m). As evidenced by the values reported from Dahl *et al.* (2020), in the case of swim bladder and kidney rupture, injury severity failed to decrease with distance from the blast source. Rupture of swim bladder and kidney is likely to cause eventual death.

The USA Department of the Navy (2010, as cited in, Danil and Leger, 2011) studied the impacts of a 4.5-kg C-4 explosive on long-beaked common dolphin (*Delphinus capensis*), and estimated mortality events would occur within 36.6 m from the blast source. **Table 3** presents the Zone of Influence (ZOI) for various types of injury induced by the selected explosives.

Impact	**ZOI (m)**
Mortality (30.5 psi ms)	36.6
50% tympanic membrane rupture	73.2
Onset of slight lung injury	146.3
TTS (182 dB re 1 m μPa^{2}s)	219.5
TTS (23 psi)	329.2

Table 2: Estimated detonation event Zone Of Influence (ZOI) for long-beaked common dolphin: 4.5 kg C-4 explosive detonated on a sandy-silt bottom of 7.3–22 m in depth. TTS = Temporary Threshold Shift. *Source*: DoN (2010), as cited in, Danil and Leger (2011).

1.2.2. Injury & hearing impairment

At greater ranges, the pressure contained in a blast wave resembles acoustic signals produced by other sources of noise, such as marine piling and seismic operations (Parvin *et al.*, 2007). Noise signals generated by such activities may cause physical injury to organs, such as lungs, liver, intestines, ears, and other soft tissues around gas-containing structures of the body, due to the rapid compression and subsequent overexpansion of the surrounding environment; however, there are very few documented examples of injury to fish or marine mammals from transient pressure waves similar to underwater blasting.

The low-frequency component of an underwater blast-induced noise has potential to cause hearing impairment. This can occur in the form of a permanent loss of hearing sensitivity, known as a Permanent Threshold Shift

(PTS), or a temporary loss in hearing sensitivity, known as a Temporary Threshold Shift (TTS). Due to the narrow nature of the River Clyde, there is potential for hearing impairment to species within a few hundred metres of the source (**Table 3.**).

1.2.3. Behavioural alteration

At still lower levels, underwater sound waves may not injure animals directly or cause hearing impairment; however, they may cause behavioural alterations. Several conflicting reports of behavioural effects of noise on marine species exist in the literature, and a general consensus for criteria has been slow to emerge; however, there is agreement that for marine mammals, the hearing sensitivity of a species should be taken into account with a frequency weighting applied to the received levels (Southall *et al.*, 2019). Frequency weighting provides a noise level referenced to an animal's ability to hear, either for individual species or classes of species, and therefore a measure of the potential of the noise to exert an effect. The measure that is obtained represents the level of the sound that is likely to be perceived by a given animal. This is an important consideration, since underwater noise that is apparently loud may even fail to exert any effect if it is characterised by frequencies that fall outside the animal's hearing range.

1.2.4. Audibility

The audible range – *i.e.* range over which aquatic taxa can hear operational activities – varies between species, and extends until the acoustic signal falls below the perceived ambient noise level or the auditory threshold of a given animal. It is important to note that noise perception does not necessarily constitute auditory or behavioural impact. Audibility is not usually considered during impact assessment, since impact is usually judged in terms of physical or behavioural effects, whereas audibility may not result in any response of the animal. For example, the reader may be able to hear cars or birds outside a window, but these do not cause any negative physical or behavioural impact.

1.3. Noise thresholds

The range over which marine animals hear blasting signals depends on distance from the source and perceived loudness. There are considerable differences in factors that influence observed response, such as an animal's behaviour at the time of exposure, previous exposure history, sex, age of individual, background noise, and the environmental conditions that affect local propagation (McGarry *et al.*, 2020). This study uses mortality for fish, and TTS and PTS for marine mammals as thresholds for investigating potential impact.

Species and individuals are sensitive to sound at different frequencies. In humans, it has been shown that variance in sensitivity is related to an individual's perception of loudness of an acoustic signal (sensation of loudness is expressed in phons). To account for differential sensitivity in humans, measures of sound may be normalised or 'weighted' by applying a filter that matches plots of perceived loudness. Weightings are applied numerically by adding or subtracting specific values on the decibel scale. Noise exposure criteria have been presented in Popper *et al.* (2014) for fish species, and Southall *et al.* (2019) for marine mammals.

1.3.1. Fish

Several countries require Environmental Impact Assessments (EIAs) to address acoustic impacts on marine mammals; however, sound exposure criteria for fish are generally lacking (Hawkins *et al.*, 2020). The number of fish species world-wide (over 33,000) is considerably larger compared to marine mammals (~130 species; Hawkins *et al.*, 2020), which increases complexity when attempting to create general sound criteria for assessment of impacts. Nonetheless, Popper *et al.* (2014) present the most up-to-date and comprehensive advice for assessment of fish exposure to noise, highlighting, however, that it is not possible to determine noise-exposure criteria for every sound source or species of fish. Instead, the authors proposed a set of interim criteria based on morphology of auditory apparatus, primary sound types (*e.g.* explosives, seismic surveys, shipping, *etc.*), and main potential effects of the sound source. They categorised fish species into broad hearing groups, based on presence or absence of a gas-filled swim bladder, and/or whether this organ was involved in sound production or hearing. Due to the transient nature of the acoustic signal of an explosion, thresholds are only presented for Peak Sound Pressure Level (L_p) values (**Table 3**). Additionally for explosives, all fish groups (with or without swim bladder) are expected to experience immediate mortality or serious injury leading to mortality (mortal injury) at the same L_p values; therefore, differentiation of hearing capacities of fish native to the River Clyde is not explored. The Popper *et al.* (2014) criteria do not support using weighting of fish hearing, as there is currently insufficient information to support such an endeavour.

Type of Animal	Mortality & potential mortal injury	Recoverable injury	TTS	Behaviour
Fish: no swim bladder (particle motion detection)	229–234 dB re 1 µPa L_p	(N) High (I) Low (F) Low	(N) High (I) Moderate (F) Low	(N) High (I) Moderate (F) Low
Fish: swim bladder is not involved in hearing (particle motion detection)	229–234 dB re 1 µPa L_p	(N) High (I) High (F) Low	(N) High (I) Moderate (F) Low	(N) High (I) Moderate (F) Low
Fish: swim bladder involved in hearing (primarily pressure detection)	229–234 dB re 1 µPa L_p	(N) High (I) High (F) Low	(N) High (I) High (F) Low	(N) High (I) High (F) Low

Table 3: Popper *et al.* (2014) fish mortality thresholds for explosions. Peak Sound Pressure Levels (L_p) in dB re 1µPa. All criteria are presented as sound pressure even for fish without swim bladders, since no data for particle motion exist. TTS = Temporary Threshold Shift. Relative risk (high, moderate, low) is given for fish at three distances from the sound source defined in relative terms as near (N), intermediate (I), and far (F). *Source:* Popper *et al.* (2014).

Further research is required to address a variety of data gaps, including responses of fish to sound pressure *versus* particle motion, physical effects of sound pressure waves, and existence of a dose-response relationship for various signal characteristics, ecosystem-wide consequences of noise exposure, and effects of noise on free-living fishes in the wild (Hawkins *et al.*, 2020). As more research is published and data gaps are filled, criteria for assessing and managing effects of anthropogenic noise on fish are expected to evolve (Popper and Hawkins, 2018).

1.3.2. Marine mammals

The most up-to-date noise exposure criteria for marine mammals was published by Southall *et al.* (2019). These criteria provide a comprehensive review on impacts of underwater noise on marine mammals and propose criteria for preventing injury based on both L_p and SELs. SEL is the time integral of the square pressure over a time window long enough to include the entire pressure pulse. SEL is, therefore, sum of the acoustic energy over a measurement period, effectively accounting for both L_p and duration over which sound is present in the acoustic environment. These SEL criteria can then be applied to either a single transient pulse or cumulative energy from multiple pulses and are used commonly for continuous or repeating noise sources; however, for impulsive noise, like explosions, L_p is considered appropriate, and has been adopted for this study in the Clyde.

To account for wide-frequency dependence in auditory response of marine species, M-Weighting frequency functions were proposed for five functional hearing groups (Southall *et al.*, 2007). These values have since been updated based on new information (Southall *et al.*, 2019), and more species have been added (*e.g.* sirenians, walrus, polar bears, sea otters, which are not present in UK waters, and are therefore not described here). A useful synopsis of functional hearing groups and definitions of terms is provided in Section 1.5.3. of OSC's Marine Mammal Observer and Passive Acoustic Monitoring Handbook (Todd *et al.*, 2015). The Southall *et al.* (2019) criteria have been developed for each marine-mammal hearing group (**Table 4**). A caveat of these criteria is that they are based on audiograms of a few individuals for a few species only; however, audiogram literature is ever increasing, as is number of test subjects of the same species.

Hearing group	**Example species**	**General hearing range**
Low-Frequency (LF) cetaceans	Baleen whales	7 Hz–22 kHz
High-Frequency (HF) cetaceans	Dolphins, toothed, beaked and bottlenose whales (*Hyperoodon* sp.)	150 Hz–160 kHz
Very High-Frequency (VHF) cetaceans	True porpoises, dwarf sperm whale (*Kogia* sp.), river dolphins, *Cephalorhynchus* dolphins	200 Hz–180 kHz
Phocid Carnivore in Water (PCW)	Seals	75 Hz–75 kHz
Phocid Carnivore in Air (PCA)	Seals	75 Hz–30 kHz

Table 4: Marine mammal functional hearing groups from Southall et al. (2007) updated to correspond to Southall *et al.* (2019) groupings.

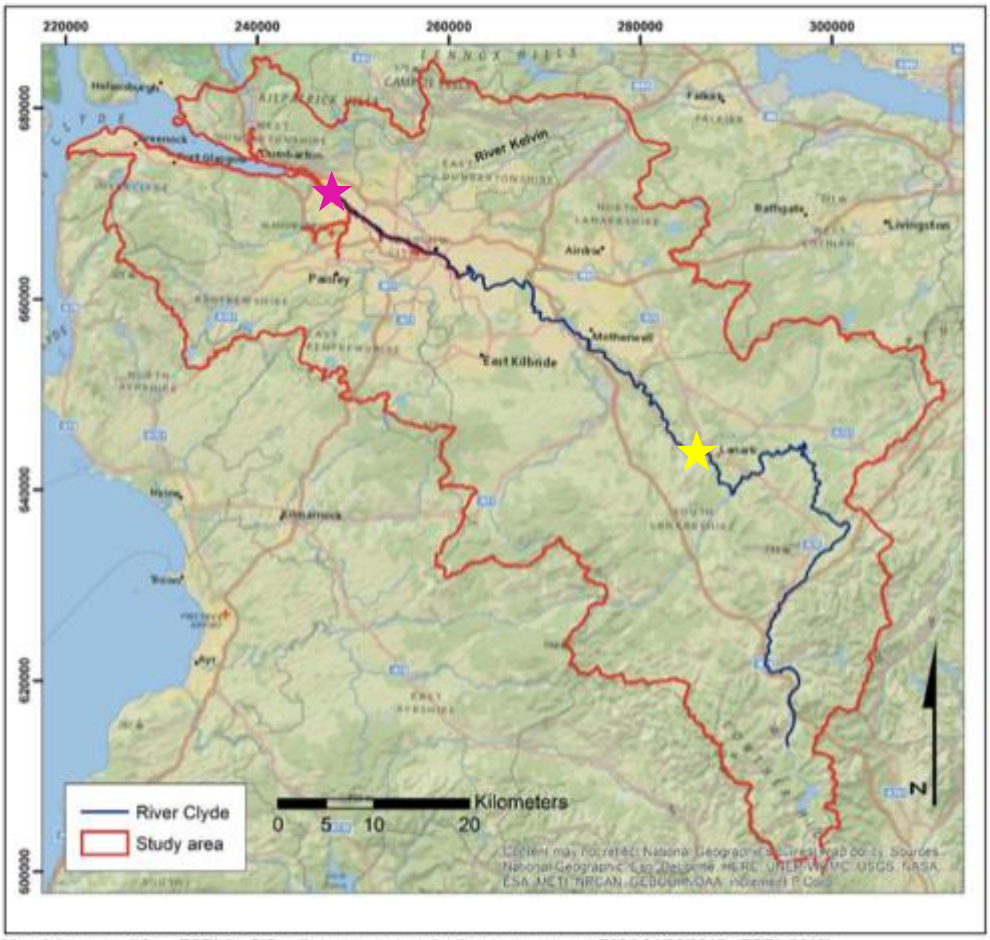
These criteria propose values for onset of TTS and PTS for non-impulsive and impulsive noise (**Table 6**). Blasting would fall into the impulsive category.

Hearing Group	Non-impulsive TTS threshold SEL (W)	Non-impulsive PTS threshold SEL (W)	Impulsive TTS threshold SEL (W)	Impulsive TTS threshold L_p (U)	Impulsive PTS threshold SEL (W)	Impulsive PTS threshold L_p (U)
LF	179	199	168	213	183	219
HF	178	198	170	224	185	230
VHF	153	173	140	196	155	202
PCW	181	201	170	212	185	218

Table 5: Temporary and Permanent Threshold Shift (TTS and PTS respectively) onset for each marine mammal hearing group present in UK waters when exposed to non-impulsive and impulsive noise under water. Sound Exposure Level (SEL) thresholds in dB re 1 μPa^{2}s u. Peak Sound Pressure Level (L_p) thresholds are in dB re 1 μPa. LF = Low-Frequency cetacean, HF = High-Frequency cetacean, VHF = Very High-Frequency cetacean, PCW = Phocid Carnivore in Water. W = Weighted, U = Unweighted. *Source*: Southall *et al.* (2019).

1.4. River Clyde

The River Clyde, located on the west coast of Scotland, originates in the Lowther Hills (55°24’23.8” N 3°39’8.9” W; Fordyce *et al.*, 2017), in the county of Dumfries and Galloway, before winding its way northwards through the city of Glasgow and discharging at the Firth of Clyde past Dumbarton and Greenock, where water eventually flows into the Atlantic Ocean (**Figure 1**). The Firth of Clyde is characterised by a variety of topographical features, from shallow waters surrounding the island of Pladda – favoured by basking shark (*Cetorhinus maximus*) – to the deepest stretch of coastal water in the British Isles, where a variety of aquatic taxa have been sighted, from northern bottlenose whale (*Hyperoodon ampullatus*) to sunfish (*Mola mola*). This review, however, will focus solely on species which have been sighted within the River Clyde itself, east of Dumbarton. **Figure 1** indicates extent of marine species within the River Clyde.



Map data sourced from ESRI ArcGIS online resources under license agreement E204 04/26/2013. (ESRI, 2013)

Figure 1: Topographic map of the Clyde basin. Red line indicates basin boundary; dark blue line indicates the River Clyde. Stars indicate extent of migratory/marine fish (yellow star) and cetaceans (pink) up the River Clyde. *Source*: adapted from Fordyce et al. (2017).

The geology of the River Clyde consists primarily of non-calcareous gleys (sticky waterlogged soil lacking in oxygen, typically grey to blue in colour), with brown-earth soil and red-brown sandy-clay-loam laying over sandstone strata (Fordyce *et al.*, 2017), resulting in a seabed habitat of gravel, sand, and mud, depending on depth and local tidal currents (McIntrye *et al.*, 2012). The area adjacent to Scotstoun is dredged regularly, and therefore has a silty substrate.

The River Clyde measures 170 km in length, and it is the second longest river in Scotland (Encyclopaedia Britannica, 2019). Moreover, the River stretches *ca.* 2 km in width at its mouth between Dumbarton (north shore) and Langbank (south shore), and *ca.* 120 m width in Glasgow city. During the 18th century, some sections of the river were subject to dredging, to deepen and widen the channel prior to the river's edges being populated with docks, quays, and shipbuilding yards from Dumbuck, east of Dumbarton, to Broomielaw quay, Glasgow City (Encyclopaedia Britannica, 2019). The dredged channel varies in depth from *ca.* 10–30 m, with the area of Scotstoun characterised by a depth of *ca.* 7.5 m (GPS Nautical Charts, 2007).

The estuary extends until the tidal weir at Glasgow Green, where the freshwater of the river mixes with salty sea water from the Firth of Clyde (Allen, 1967).

Tides in the Clyde are semi-diurnal, and differences in tidal height across the upper Clyde, river mouth, and Firth of Clyde are presented in **Table 6**. An increase in tidal range of *ca.* 30% characterises the area between Greenock and Glasgow (Allen, 1967), with high tide occurring often with a time lag of 30–60 minutes between the two locations. Such a phenomenon could cause stranding events of large marine fauna east of the tidal weir. The latter comprises three barriers (or gates) which can be raised or lowered – depending on tide and river heights – to control water levels within the River Clyde in the section comprised between Glasgow Green and Carmyle.

Location	High water		Low water		Range	
	Spring	Neap	Spring	Neap	Spring	Neap
Cumbraes	+1.80	+1.22	-1.17	-0.55	2.96	1.77
Greenock	+1.83	+1.28	-1.25	-0.61	3.08	1.89
Glasgow	+2.32	+1.55	-1.80	-0.85	4.12	2.4

Table 6: Tidal heights across the Clyde region (in m above Ordinance Datum Newlyn). *Source*: Allen (1967).

Occurrence of heavy industrial operations during the 19th–20th centuries caused the riverine waters to become polluted, a phenomenon which in turn, led to accumulation of contaminants in sediment and resident bivalve species, *e.g.* mussels (McIntrye *et al.*, 2012). Consequently, poor water quality affected local fauna, causing a substantial decrease in resident and migratory populations of fish. Since the industry's closure in 1975, and an improvement in industrial and sewage effluent treatment over time, the water quality of the River Clyde has improved substantially, from 'bad', to 'moderate', and even 'excellent' in some areas (Scottish Government, 2017). The improved conditions of the water has resulted in a return of species to the River Clyde; however, the Clyde remains under elevated levels of anthropogenic exploitation, with activities such as fisheries, vessel traffic (commercial and pleasure craft), Glasgow's wastewater treatment discharge, and construction works posing substantial threats to the riverine ecosystem.

1.5. Fish in the Clyde

Yeomans and McGillivray (2003) reported 12 species of resident and migratory fish caught at 69 sites between the Clyde estuary and the Falls of Clyde (*i.e.* Stonebyres Falls). The Falls of Clyde, at Lanark, create a barrier that migratory fish cannot pass; therefore, resident populations south (upriver) of this location are not reviewed in this report. Brown trout (*Salmo trutta*) was found to be the most prevalent of the species recorded, occurring at 65 of the 69 sites. Three other marine/anadromous taxa were caught. In order of frequency of occurrence, these were three-spined stickleback (*Gasterosteus aculeatus*), Atlantic salmon (*Salmo salar*), and flounder, *Platichthys flesus* (Yeomans and McGillivray, 2003). The remaining freshwater species that were caught during the study are not covered herein, as the risk of noise-induced effects is limited for such species within the freshwater tributaries of the River Clyde. For completeness, these species include stone loach (*Barbatula barbatula*), minnow (*Phoxinus phoxinus*), eel (*Anguilla anguilla*), grayling (*Thymallus thymallus*), lamprey (*Lampetra fluviatilis*), bullhead (*Cottus gobio*), gudgeon (*Gobio gobio*), and perch (*Perca fluviatillis*). Of the species considered in the present report, Atlantic salmon is protected under Annex II of the European Commission's

Species and Habitats Directive (1994), and has been recorded as far as the rivers Rotten Calder and Avon (Bean, 2001); some reports state that Atlantic salmon has been sighted at the bottom of the Falls of Clyde.

1.6. Marine mammals in the Clyde

The Firth of Clyde is populated by both resident and visiting marine megafauna, including cetaceans, pinnipeds, and basking sharks. Two pinniped species occur regularly in the United Kingdom, namely common (*Phoca vitulina*) and grey (*Halichoerus grypus*) seals. Haul-out sites have been documented within the Firth of Clyde for both species, which are sighted commonly within the Clyde estuary and River (Cacace, 2020). The River Clyde, and its estuary, is also home to harbour porpoise (*Phocoena phocoena*), and a solitary common dolphin (*Delphinus delphis*) – nicknamed 'Kylie' – is sighted regularly in the area (O'Neill, 2018). Kylie has been sighted in the Clyde for the past 17 years, and has adapted her vocalisations to match those produced by harbour porpoise (O'Neill, 2018). In 2011, a harbour porpoise was reported to have become trapped east of the tidal weir at Glasgow Green, and human assistance was required for the animal to return to the estuary at high tide (Daily Record, 2012). Bottlenose dolphin (*Tursiops truncatus*), a coastal species, is also sighted regularly in the waters of the Clyde estuary; however, no reports appear to be available at present with regards to the extent to which the species travels up the River Clyde. **Table 2** summarises furthest sightings of cetaceans up the River Clyde.

Date	**Common name**	**Scientific name**	**Location sighted**	**Passed Scotstoun**
Oct. 2020	Northern bottlenose whale	*Hyperoodon ampullatus*	Glasgow harbour area, near Partick (Duffy, 2020)	Y
Aug. 2020	Bottlenose dolphin	*Tursiops truncatus*	Sighted off Greenock Esplanade and upper Clyde (Young, 2020)	N
Jul. 2020	Grey seal	*Halichoerus grypus*	Floating down the river past the Gorbals eating a fish (Cacace, 2020)	Y
Apr. 2018	Killer Whale	*Orcinus orca*	Pod of 6 sighted around Erskine bridge after following prey (Whiteside, 2018)	N
2018	Short-beaked common dolphin	*Delphinus delphis*	Sighted between Fairlie and Cumbrae hanging around harbour porpoise (O'Neill, 2018)	N
Feb 2011 (updated Jul 2012)	Harbour porpoise	*Phocoena phocoena*	East of the tidal weir at Glasgow Green (Daily Record, 2012)	Y

Table 7: Furthest records of marine mammal sightings up the River Clyde. *Source*: OSC (2021).

Although rare, a pod of northern bottlenose whales (*Hyperoodon ampullatus*) was also recorded in the inshore waters of the Clyde, where the animals remained for several weeks in 2020. Northern bottlenose whale preys typically on deep-dwelling squid and epibenthic fish such as Greenland halibut (*Reinhardtius hippoglossoides*), and its prolonged occurrence in the Clyde was classed as unusual behaviour. Two individuals from the pod became stranded, and later perished in the vicinity of Glasgow airport (Duffy, 2020). It has been proposed that these cetaceans may have mistaken the dredged channel of the Clyde as a canyon and lost orientation. In addition to northern bottlenose whale, a pod of killer whales (*Orcinus orca*) was recorded within the Clyde waters, as the individuals followed prey (pinnipeds and harbour porpoise) up the River Clyde (Whiteside, 2018). This latter pod exited the Clyde successfully.

Sightings of marine mammals up the River Clyde suggest prey movements and/or loss of orientation as the principal driving factors for entrance into the relatively narrow and shallow channel. Production of impulsive noise in the area has potential to exert aversive impacts on transiting species, should they occur in proximity to the noise source; however, only a small subset of marine mammal species sighted in the River Clyde has been recorded also in the proposed project location. Consequently, the marine mammal species most at risk to injury include common and grey seals, and the harbour porpoise.

1.7. Mitigation

Mitigation efforts to limit mortality often include visual surveys conducted by Marine Mammal Observers (MMOs) or use of Acoustic Harassment Devices (AHDs).

1.7.1. Marine Mammal Observer

An MMO is a qualified professional who is responsible for implementing mitigation measures to protect marine life during industrial activities that generate underwater noise. The main role of an MMO is to advise and implement guidelines set out to reduce the possible risk of disturbance and injury to marine mammals and other megafauna. Such guidelines focus on establishing a mitigation or exclusion zone, which is 1,000 m for explosives. If a marine mammal is sighted within this zone, there must be a delay or shut-down of the sound source until the animal is outside the mitigation zone. MMOs ensure that there are no marine mammals close enough to be injured by the blast.

1.7.2. Acoustic Harassment Device

AHDs, also known as Acoustic Deterrent Devices (ADDs), Acoustic Mitigation Devices (AMDs), more colloquially as 'seal scarers' and 'seal scrammers', and also 'pingers', are devices that emit aversive sounds into the marine environment with intention of deterring marine mammals from approaching fisheries, aquaculture facilities, and offshore anthropogenic noise-producing activities. Additionally, when deployed to deter marine mammals from industrial sites, the devices may be referred to as Mitigation Devices (MDs). ADDs or 'pingers' are intended to cause discomfort and deter pinnipeds (Johnston, 1998) by producing intense (≥185 dB re 1 μPa @ 1 m RMS) low-frequency (2–40 kHz) sounds (Lepper *et al.*, 2014) within underwater hearing range of seals, ranging from 50 Hz–86 kHz (NMFS, 2018). To further discourage seals from approaching (and damaging) commercially important fish stocks, acoustic alarms were developed (Mate and Harvey, 1986), emitting sounds that were louder than those produced by ADDs. These came to be known as AHDs or 'seal scarers' (Johnston, 1998). AHD semantics were based on distinctions decided at the International Whaling Commission (IWC) meeting in Rome (Reeves *et al.*, 2001). More recent guidelines (Northridge *et al.*, 2006) stated that ADDs operate typically in the 10- to 100-kHz band and emit SL <150 dB re 1μPa @ 1 m, whereas AHDs operate mainly between 5 and 30 kHz at levels often exceeding 170 dB re 1 μPa @ 1 m (see Madsen, 2005a). Both devices are relatively simple and use a transducer to convert electrical signals into sound signals, which are then emitted into the underwater environment. More recently, there has been some overlap between sound levels that these devices produce and marine mammals being targeted; consequently, both technologies are now commonly referred to as ADDs (Schakner and Blumstein, 2013). Since the term AHD has resurfaced recently (Fjalling *et al.*, 2006; Shapiro *et al.*, 2009; Vilata *et al.*, 2010; López and Mariño, 2011; Tixier *et al.*, 2014; Tixier *et al.*, 2015; Todd *et al.*, 2019), this proposal will refer to the original nomenclature of AHD, which reflects a number of AHDs that emit high amplitude sound across a wide range of frequencies, typically from 2–95 kHz (Lepper *et al.*, 2014).

AHDs used in the UK emit sound pulses within hearing range of both common and grey seals, and are a potential non-lethal means of preventing seals from approaching specific locations (Hastie *et al.*, 2016), such as aquaculture pens (Nelson *et al.*, 2006; Northridge *et al.*, 2010; Coram *et al.*, 2014; Harris *et al.*, 2014) and industry situations where anthropogenic noise could be harmful to marine mammals, such as pile driving/rock blasting/harbour construction.

1.8. Objectives

This report uses acoustic propagation modelling to assess potential impact of blasting at BAE Systems Scotstoun on fish and marine mammals.

2. MATERIALS & METHODS

2.1. Location

Underwater blasting will be used at BAE Systems Scotstoun in Glasgow (**Figure 2**) to expand an existing deep-water berth (**Figure 3**).

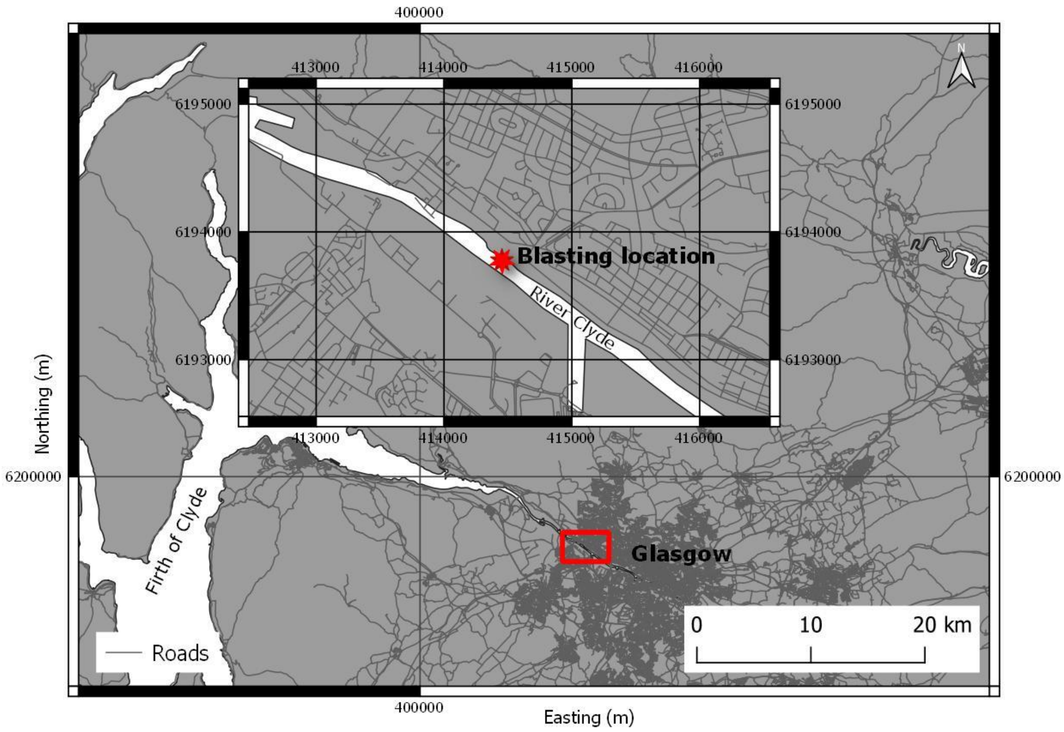


Figure 2: Location of blasting at BAE Systems Scotstoun on River Clyde. *Source*: OSC (2021).

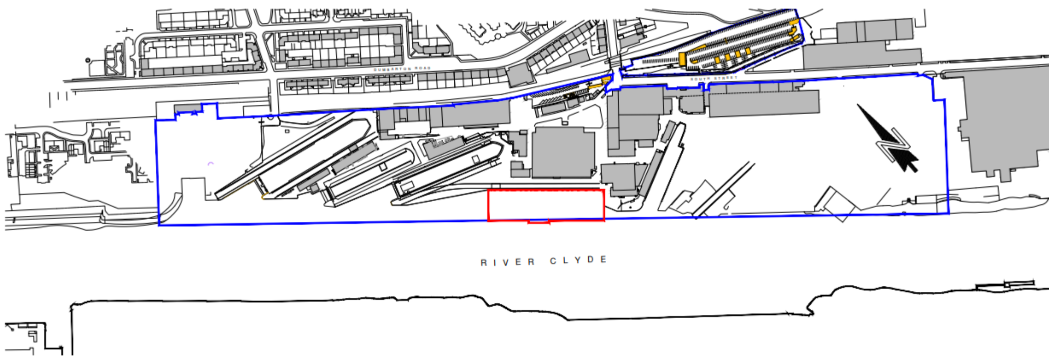


Figure 3: Site layout with current ownership boundary (blue) and extent of proposed works (red). *Source*: Arch Henderson *et al.* (2021).

2.2. Noise-source details

The charge size used for blasting is expected to be 12.5 kg total, comprised of up to 12 smaller charges that go off within a few milliseconds of each other. The entire duration of the blast will be 0.2 s. To estimate L_p, values were sourced from Robinson *et al.* (2020) and Subacoustech Environmental Ltd. (2018), and used to estimate the L_p from a 12.5 kg charge.

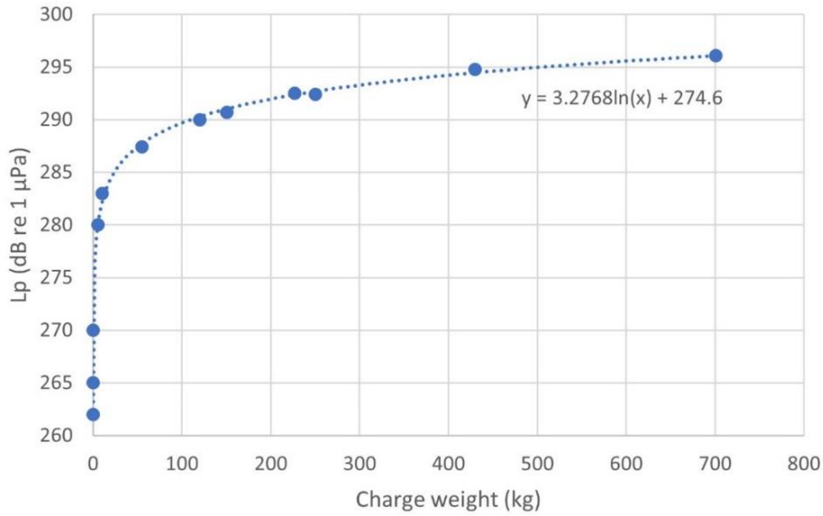


Figure 4: Peak Sound Pressure Level (L_p) from blasting for different charge weights with fitted line. *Source*: values from Robinson *et al.* (2020) and Subacoustech Environmental Ltd. (2018).

Using the formula from the fitted line in **Figure 4**, the L_p from a 12.5 kg charge is expected to be 282.9 dB re 1 µPa. This input value was used in acoustic-propagation modelling, with a signal duration of 0.2 seconds. A frequency of 12.5 Hz (lowest possible for modelling) to 100 Hz was used (Tripathy and Shirke, 2015; OSC, 2019).

2.3. Noise metrics

SEL is a measure of the pulse energy content and is calculated from a pulse pressure squared integral of the pulse in units of Pa^2s, with the value units in dB (Madsen, 2005b). SEL is often used for noise exposure criteria for continuous noise, *e.g.* Southall *et al.* (2019) and Popper *et al.* (2014), because it considers the dose level of a receptor over time; however, in this case, as the duration of explosion is so short (0.2 s), the L_p is most appropriate.

2.4. Bathymetry & oceanography

Bathymetry charts from Nobeltech Time Zero were used to determine that depth of the river adjacent to the blasting location was 7.5 m; therefore, this depth was set for the entire river section analysed. Due to the location (up the river Clyde) bathymetry data could not be obtained from usual sources (*e.g.* EMODnet), so a 10 m x 10 m grid was created covering the study area. A shapefile of the UK was used to set points of the grid which were on land to an arbitrary elevation of 10 m, and points which did not intersect land (*i.e.* the river) were given a depth of 7.5 m.

2.5. Model selection

Due to the low frequency and shallow bathymetry, normal modes (Jensen *et al.*, 2011; Bergman, 2018) was used to predict, and explore propagation of underwater blasting noise within the River Clyde. This is a traditional model for predicting acoustic pressure fields in ocean environments and is most suited to low-frequency scenarios. The bathymetry of the site is extremely shallow; therefore, results may be less accurate than in deeper waters (*e.g.* greater than 10 m).

The sound source depth was fixed at 7.5 m since it is primarily sub-surface. Calculations were set to the gridded-spatial resolution of the bathymetry data (10 m x 10 m), with results exported for visualisation in two-dimensional plots along 500 radial slices (0.72°). Analysis was performed at five depth bands. Results were displayed as the highest value from all depth bands, *e.g.* the highest value from each *x,y* location.

River sediment type was used to define a simple loss *vs.* grazing angle methodology which is used commonly in acoustic models. Geoacoustic parameters of the bottom boundary were assumed to be those of silt (typical of the area), with an estimated speed of sound of 1,575 ms^{-1}, a density of 1,700 kg m^{-3}, and an attenuation of 1 dB/wavelength (Jensen *et al.*, 2011). Absorption is frequency dependent and negligible for low frequencies and short distances. To reduce computer processing time, modelling was restricted to frequencies between 12.5 Hz (lowest possible) and 125 Hz, as the explosion modelled only produced noise from up to 100 Hz. Results were exported as L_p.

To use the normal modes model, sound profiles of the considered area must be known or predicted. Consequently, all simulations assumed a harmonic median sound speed, c_{hm}, of 1,500 ms^{-1}, Beaufort sea state 0, temperature of 8 °C, salinity of 33 PSU, and no influence of currents or ambient noise floor, *i.e.* worst-case scenario signal-propagation conditions. These conditions can, and do occur in the River Clyde, and so were reasonable assumptions for the model.

2.6. Fish assessment criteria

Unweighted thresholds from Popper *et al.* (2014) for mortality and potential mortal injury from explosives were used. All fish hearing groups had the same values (229–234 dB re 1 μPa); therefore, they were grouped together and a general impact assessment for 'fish' is provided. As a worst-case scenario, the single highest L_p value (234 dB re 1 μPa) was used to investigate potential impact.

2.7. Marine mammal assessment criteria

Unweighted impact thresholds (Southall *et al.*, 2019) for TTS and PTS for impulsive noise (based on L_p) were used to investigate potential impacts on marine mammals (**Table 5**).

Hearing groups investigated included Low Frequency (LF), High Frequency (HF), and Very High Frequency (VHF) cetaceans and Phocid Carnivores in Water (PCW) (Southall *et al.*, 2019). Values presented are considered to demonstrate a worst-case scenario in presenting TTS/PTS ranges.

3. RESULTS

3.1. Noise

Noise from blasting will likely have a high L_p and short duration. Due to shape of the river, noise is anticipated to propagate a maximum distance of 1.4 km downriver (north west), and 1.2 km upriver (south east). Noise levels over much of this area will be below thresholds for fish or marine-mammal impact.

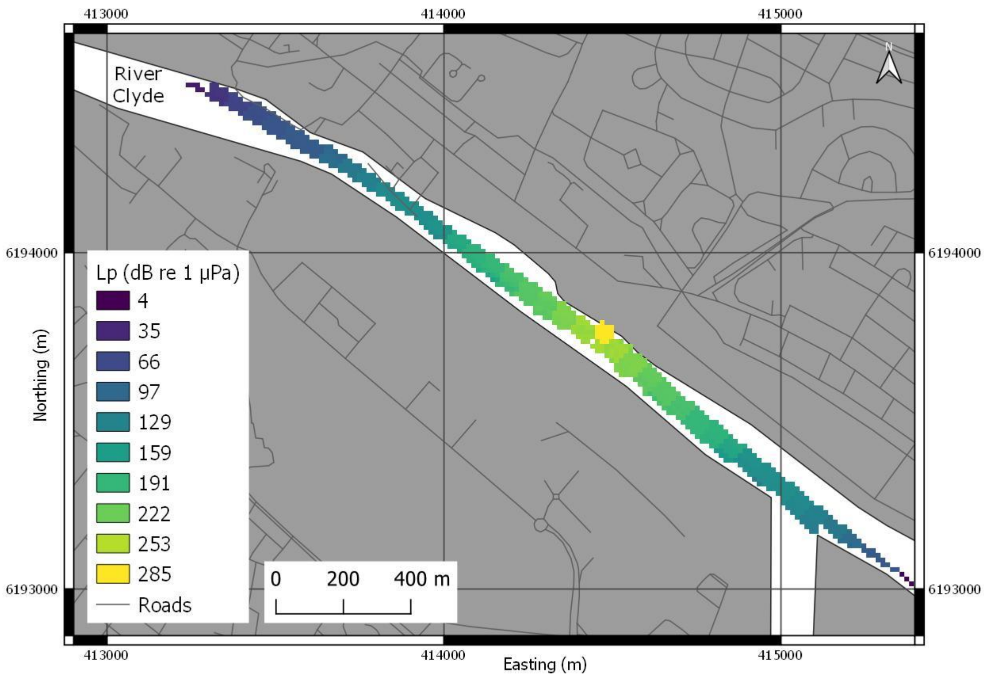


Figure 5: Peak Sound Pressure Level (L_p) from a 12.5 kg charge at BAE Systems Scotstoun in the River Clyde. *Source*: OSC (2021).

3.2. Fish assessment

The maximum range at which fish are expected to experience immediate mortality or delayed mortal injury is 140 m from the detonation site (**Figure 6**). No estimates of distance of injury, TTS or behavioural responses are available, but there is a high risk that fish in the near vicinity will experience these impacts.

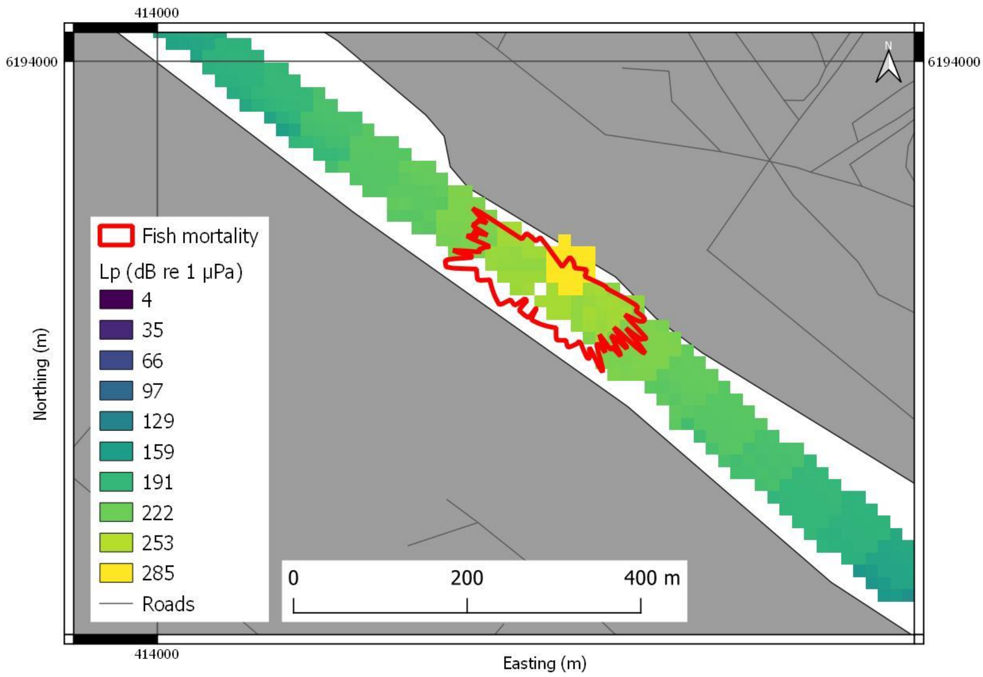


Figure 6: Predicted range of mortality or mortal injury for fish from a 12.5 kg charge at BAE Systems Scotstoun in the River Clyde. *Source*: OSC (2021).

3.3. Marine mammal assessment

Maximum ranges at which marine mammals are expected to experience TTS/PTS are presented in **Table 8**. Due to their higher sensitivity to noise, VHF cetaceans (*e.g.* harbour porpoise) are expected to have the largest potential impact range of 368 and 361 m for TTS and PTS respectively. These results are plotted in **Figure 7**.

	Range (m)	
	TTS	**PTS**
LF	245	211
HF	188	167
VHF	368	361
PCW	248	227

Table 8: Distances at which marine mammals may experience Temporary and Permanent Threshold Shift (TTS and PTS respectively) from 12.5 kg charge. LF = Low-Frequency cetacean, HF = High-Frequency cetacean, VHF = Very High-Frequency cetacean, PCW = Phocid Carnivore in Water. *Source*: OSC (2021).

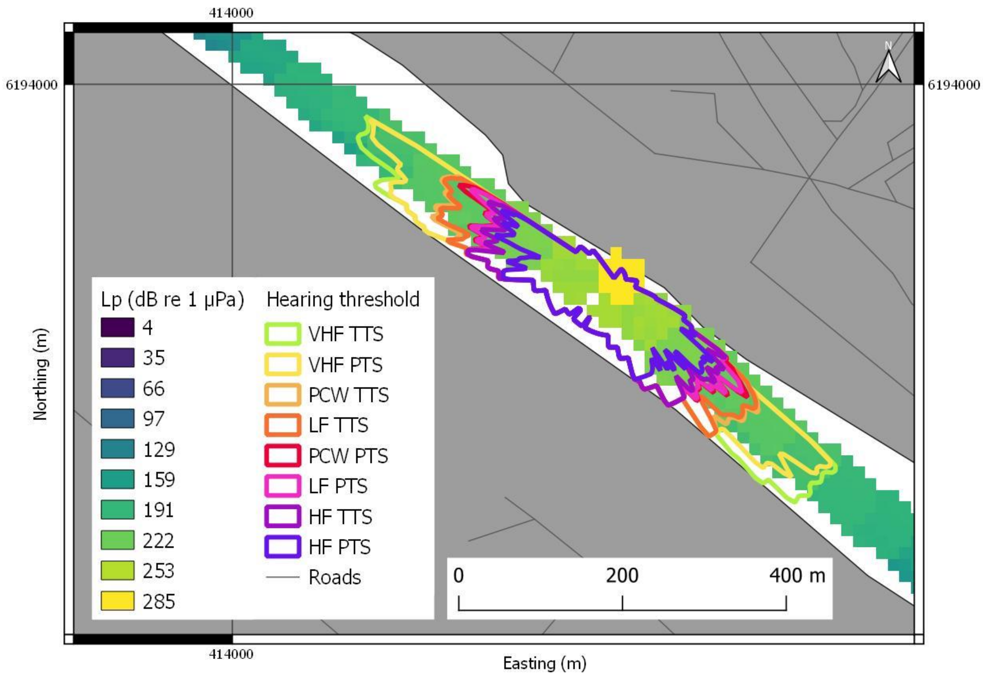


Figure 7: Predicted range of Temporary and Permanent Threshold Shift (TTS and PTS respectively) for marine mammals from a 12.5 kg charge at BAE Systems Scotstoun in the River Clyde. *Source*: OSC (2021).

4. DISCUSSION

Noise from blasting is likely to travel a maximum of 1.4 km from the explosive site, due to curvature of the river; however, levels over much of this area will be below impact thresholds for fish and marine mammals.

Fish may experience mortality to a maximum distance of 140 m, and may experience TTS and behavioural disturbance to larger distances, but no thresholds for this are available in the literature (Popper *et al.*, 2014). Localised monitoring for fish mortality should be carried out after blasts to assess impacts of fish-kill events.

LF and HF cetaceans are unlikely to be as far up the River Clyde as the Scotstoun location, so potential impact to these species is considered negligible. Harbour porpoise and seals may be present (though still uncommon) and may experience TTS up to a maximum range of 368 m and 248 m respectively (**Table 8**). Considering that the standard mitigation zone for explosives is 1,000 m (JNCC, 2010), assuming typical procedures are in place, there should be no risk of TTS or PTS to marine mammals.

Use of standard mitigation procedures (*e.g.* MMO and AHD) should be sufficient to ensure no marine mammals are present during blasting; therefore, preventing TTS/PTS to any marine mammals. Small soft-start charges are also sometimes used prior to the main detonation to deter fish from an area. It is not known if this is intended to be performed but could be investigated as an additional mitigation measure for fish.

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